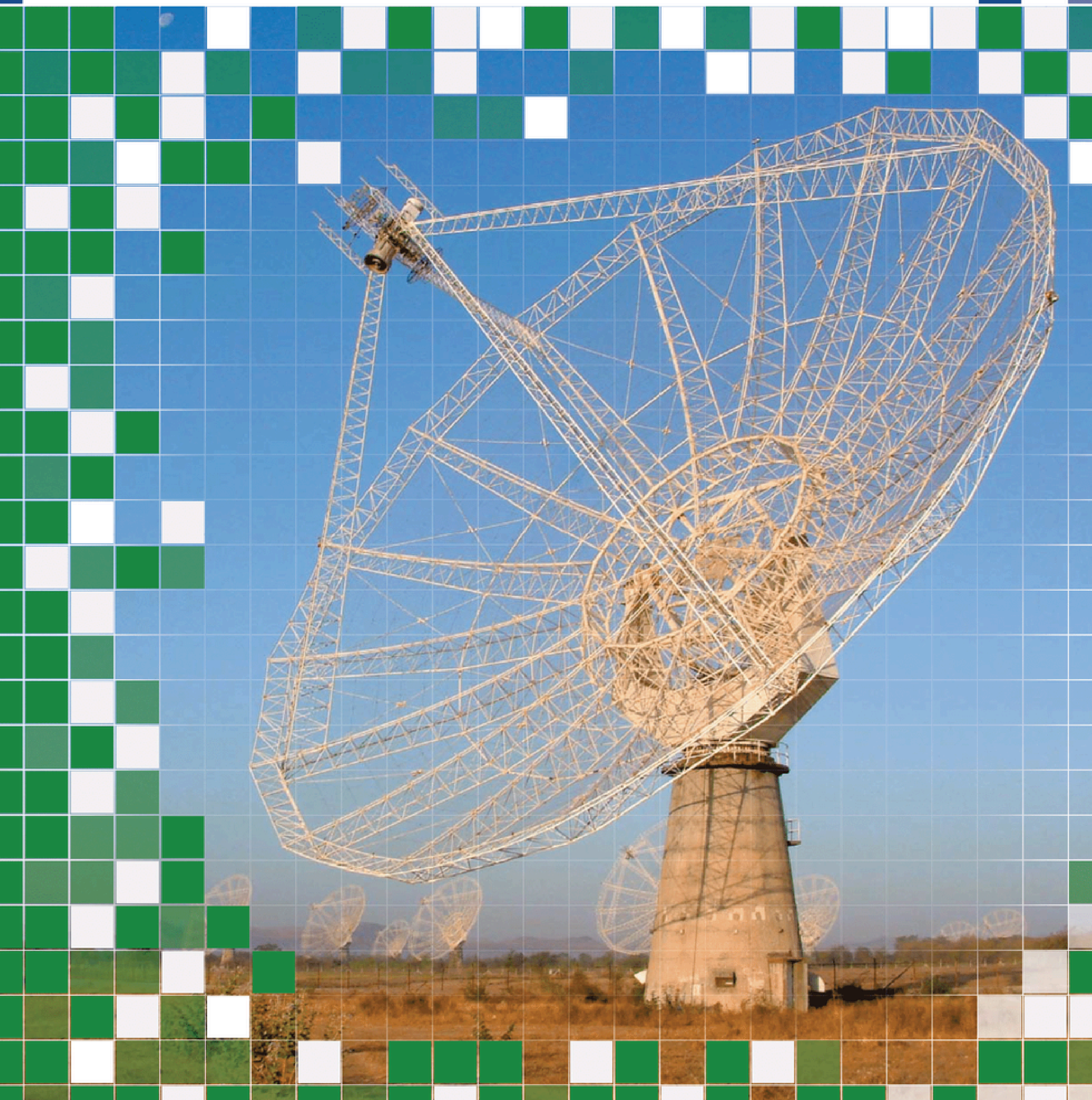
PART C

DEPARTMENT OF ATOMIC ENERGY AIDED INSTITUTIONS

Fostering Knowledge, Innovation, and Collaboration

AMRIT KAAL VISION DOCUMENT



परमाणु ऊर्जा विभाग

DEPARTMENT OF ATOMIC ENERGY

Content: All Units and Institutions of DAE
Compilation: KMG, BARC; CP&CC, NPCIL; TIFR; NCPW, DAE
Editorial Review: KMG, BARC; CP&CC, NPCIL; TIFR
Artwork and Illustrations: SCOPE, PA&MID, DAE
Printing and Publication: SIRC, PA&MID, DAE

Disclaimer: The data, projections, and other information presented in this document correspond to the year 2024, unless stated otherwise.

अमृत काल AMRIT KAAL

संकल्प प्रलेख VISION DOCUMENT

PART – C

Aided Institutes

Table of Content

Atomic Energy Programme for a Sustainable Socio-economic Growth

India is poised for another exciting phase in its history. Riding on the back of glorious achievements of the past seven decades, the country has now set its sight on tapping new and sustainable growth engines to realise an accelerated pace of development. The Government of India's (GoI's) flagship 'Amrit Kaal' 2047 roadmap envisions the country's rapid transition to a global powerhouse of advanced capabilities for sustaining high rates of economic growth. Science and technology will continue to be a mainstay in GoI's long-term goal of transforming the country into 'Viksit Bharat' by the year 2047 by promoting national scientific research and innovation landscape.

Dr. Ajit Kumar Mohanty
Secretary to the Government of India,
Department of Atomic Energy &
Chairman, Atomic Energy Commission

The GoI's 'Amrit Kaal' roadmap envisions a broad-based shift towards clean energy mix to augment the national energy generation capacity and to accomplish the ambitious goal of curtailing emissions to the targeted 'net zero' gradually by 2070. The broader outcomes envisaged by the nuclear energy vision would immensely contribute to India's 'net zero' commitment.

In 1955, Dr. Homi Jehangir Bhabha, in his Presidential address at Geneva Conference, said- "In a broad view of human history, it is possible to discern three great epochs. The first is marked by the emergence of the early civilizations in the valleys of the Euphrates, the Indus and the Nile; the second by the industrial revolution, leading to the civilization in which we live; and the third by the discovery of atomic energy and the dawn of the atomic age, which we are just entering. Each epoch marks a change in the energy pattern of society".

Dr. Homi Jehangir Bhabha emphasized that "for the continuation of our civilization, and its further development, atomic energy is not merely an aid, it is an absolute necessity". At the crucial juncture of the third epoch, deciding the roadmap for achieving a new energy mix for a sustainable socio-economic growth of the world is significant, and nuclear energy would be in the vanguard. In this positive spirit, the Department has now chalked out a robust 'Amrit Kaal' roadmap for guiding its future course of action in core and advanced areas of nuclear energy programme of the country.

Seventy glorious years of Dedication, Advancement and Excellence:

Research Reactors and Nuclear Power Programme

Dr. Homi J. Bhabha recognized the importance of energy for the growth of our nation and the role that nuclear energy has to play in India. Synchronized with this philosophy, the Department of Atomic Energy (DAE) has been successful in delivering the objectives over the last 70 years in the true spirit set in a self-reliant manner. The Indian nuclear energy programme was launched as early as in 1948, when the Atomic Energy Commission (AEC) was constituted and later the Department of Atomic Energy (DAE) was established in 1954. Thus began India's journey for harnessing nuclear energy and radiation technology for peaceful purposes in the areas of power production, applications of radioisotopes in the fields of medicine, agriculture, industry and research. The initial thrust to the nuclear programme was provided with the commissioning of a 1 MW, swimming pool type research reactor 'APSARA' in 1956 at Trombay, Mumbai. In just over a year, scientists and engineers of the department completed the construction of APSARA, and with that India became the first Asian country outside erstwhile Soviet Union to have designed and built its own nuclear reactor. The entire world was eying the phenomenal initiation and development of Indian Nuclear Energy Programme. On 20th January, 1957 during the formal inauguration of APSARA, and Atomic Energy Establishment at Trombay (AEET) by the then Honourable Prime Minister Pandit Jawaharlal Nehru, a delegation of 50 high level foreign dignitaries representing 30 countries witnessed the occasion.

Research reactors are primarily meant to provide neutron source for fundamental research and their applications in a variety of areas including healthcare. All upcoming technologies are first proven in a research reactor prior to their application in a nuclear power reactor. APSARA was instrumental in carrying out advanced research in the field of neutron physics, fission physics, radiochemistry, and R&D on reactor technology for the Indian scientist and engineers. Neutron radiography carried out in APSARA had been used for components of space programme.

This success and experience led to the construction of a vertical tank type 40MW, the second research reactor in 1960, named Canada India Reactor Utility Services or CIRUS. The need was already felt for a high neutron flux high power research reactor, which would cater to the additional requirement of radioisotope production, and for more advanced research. This reactor built under close collaboration with Canada, was similar to Canadian NRX reactor, but with few changes based on location and requirement. CIRUS reactor was solely catering to the country's radioisotope requirements till August 1985, when the third research reactor 'DHRUVA' became operational. This is an even higher neutron flux, 100 MW capacity research reactor designed, constructed and commissioned indigenously. For last 40 years Dhruva has been extensively utilized for engineering and beam tube research, testing of equipment and material, and large-scale production of radioisotopes. Later, looking at the strategic interest of the country, and Bhabha's vision of three stage nuclear programme, indigenously built reactors were, ZERLINA, PURNIMA series at Trombay and KAMINI at Kalpakkam.

In parallel, the nuclear power programme also began its journey with the establishment of the twin units of Boiling Water Reactors (BWRs) at Tarapur in 1969. The power programme has now expanded significantly with 24 reactors being currently operational with a capacity of 8780 MW (excluding RAPS 1) in the country. In addition, 8 reactors with total of 6600 MW are under construction, and 10 reactors with total capacity of 7000 MW are in the advanced stage of beginning the construction. On progressive completion of these reactors by 2031-32, the installed nuclear capacity is expected to reach 22,380 MW (excluding RAPS 1). As a new initiative towards energy security, the Government of India approved 'Anushakti Vidhyut Nigam Ltd.' (ASHVINI), a Joint Venture (JV) between NPCIL and NTPC Ltd., to build, own, and operate nuclear power plants in the country. To start with, the Mahi Banswara Rajasthan Atomic Power Project (MBRAPP), a 4x700 MWe PHWR project has been undertaken by ASHVINI.

Three Stage Nuclear Power Programme

The celebrated three stage nuclear power programme of India envisioned by Bhabha, begins with (Stage -1) the Pressurized Heavy Water Reactors (PHWRs) where natural uranium (U) based fuels are used to generate electricity, and in turn fissile plutonium (^{239}Pu) is produced. In the second stage (Stage-2), Pu based fuels are used to enhance nuclear power capacity, and further to convert fertile thorium (Th) into fissile ^{233}U, a key step for utilisation of vast thorium reserves in India and provide energy security to the country. To achieve success in the Stage-2, Fast Breeder Reactors (FBR) are to be made operational. The Fast Breeder Test Reactor (FBTR), the flagship reactor of the second stage of the Indian nuclear power program, attained first criticality on 18th October 1985, when all eyes were at Kalpakkam. As a signature of advancement, in March 2022, the reactor was successfully operated at its design capacity of 40 MWth. Further to this direction, a 500 MWe Prototype Fast Breeder Reactor (PFBR) is in the advanced stage of achieving criticality. In a historic moment at the 70th year of formation of DAE, the Honourable Prime Minister Shri Narendra Modi witnessed the commencement of "Core Loading" at India's first indigenous Fast Breeder Reactor (500 MWe) at Kalpakkam, Tamil Nadu on 4th March 2024. In line with the true spirit of Atmanirbhar Bharat, PFBR has been fully designed and constructed indigenously by DAE with significant contribution from Indian industries. Once commissioned, India will only be the second country after Russia to have commercial operation of Fast Breeder Reactor. The Stage 3 of the power programme, consisting of advanced thermal and breeder reactors, will use the ^{233}U so produced in Stage 2 for the country's long-term energy security. The three-stage nuclear power programme thus ascertains optimal utilization of uranium and thorium reserves.

The attainment however, is inter-linked with the establishment of an efficient closed fuel cycle approach with recycling of both fissile and fertile components of the spent fuel to appropriate reactor systems. Starting way back in 1964 with the commissioning of a plant based on PUREX technology to reprocess spent fuel from the research reactor CIRUS followed by building a power reactor reprocessing facility, India has mastered in exercising closed fuel cycle involving reprocessing, recycling of fissile material and conditioning of radioactive waste. Looking at the growth of nuclear power programme of the country, the department is constructing an Integrated Nuclear Reprocessing Plant (INRP) at Tarapur. In parallel, to meet the challenges of PFBR spent fuel reprocessing, a Demonstration Fast Reactor Fuel Reprocessing Plant, has been constructed, which was ceremonially dedicated to the nation by the Honourable Prime Minister Narendra Modi on 2nd January, 2024. The large-scale commercial Fast Reactor Fuel Cycle Facility (FRFCF) is also under construction at Kalpakkam.

Harnessing Atomic Energy for Societal Benefits

Cancer Care

In addition to the nuclear power programme, radioisotopes produced in research and power reactors have played a key role in improvement of health care, agriculture, food preservation, and several other areas to benefit the societal programmes of the country. Nuclear medicine, a widely recognized field utilizes trace amounts of radioactive substances for the diagnosis and treatment of various conditions, including cancer, neurological and cardiac disorders. In India, DAE is the sole producer of radioisotopes from the time of the operation of CIRUS and DHRUVA reactors where number of radioisotopes such as ^{99}Mo, ^{131}I, ^{125}I, ^{153}Sm, ^{32}P, and ^{177}Lu for medical applications were produced to meet the demand of radioisotopes of the country. It is worth mentioning that millions of patients in India have been benefitted for nearly half a century from the radioisotopes produced in the CIRUS reactor. The availability of indigenously produced radioisotopes opened up the opportunity of using these isotopes in formulating radiopharmaceuticals in nuclear medicine. DAE is involved in the production as well as the development of targeted disease-specific radiopharmaceuticals for improved outcomes. More than 18 radiopharmaceuticals / radiochemicals and freeze-dried kits have already been developed. These are being used in hospitals for tumour imaging; bone pain palliation; liver, breast, and prostate cancer therapy and so on. The medical cyclotron facility in Kolkata, Cyclone-30 has been facilitating the production of cyclotron-based radioisotopes for healthcare applications. Production and regular supply of ^{18}F-FDG, an extremely critical short-lived radiopharmaceutical used in the PET detection of cancer, Gallium-68 used in Gallium-based radiochemicals such as $^{68}GaCl_3$, for imaging of neuroendocrine cancers and prostate cancer are examples of radioisotopes being produced in the country for the first time using this medical cyclotron. Recently as a significant milestone for scientific and industrial advancement, the Heavy Water Board (HWB) of DAE has achieved a groundbreaking capability in the production of ^{18}O enriched water, which is required for Positron Emission Tomography (PET) scanning for ascertaining the presence of cancer cells / malignancies.

DAE has played pivotal role in country's cancer care programme by employing radiation technology developed in-house. Radiation has the property of killing cancerous cells and radiation therapy can be administered externally for treatment of tumours, which are approachable from outside without collateral damage to healthy tissues. A teletherapy machine, has been developed for this purpose, which has been deployed extensively in India and some centres in abroad as well. A recent contribution of DAE has been the development of an eye plaque for treatment of ocular cancer. Ru-106, a radioisotope recovered from the spent fuel is integrated into circular eye plaques for use in the treatment of eye cancer. Extremely small Yttrium-90 glass spheres measuring just 30 micrometres in size and known as Bhabha Spheres, have been developed for the treatment of a specific type of liver cancer. I-131 based radiopharmaceuticals for thyroid cancer, Lu-177 based radiopharmaceuticals for treatment of neuroendocrine cancer and Sm-153 based radiopharmaceuticals for bone pain palliation are some other prominent examples.

More than five lakh patients receive affordable treatment every year at Tata Memorial Centre (TMC) in Mumbai, which is a constituent unit of the DAE. From 740 beds in 2017, TMC - Hospital has grown to 2700 beds. TMC has now expanded to six other hospitals located in Varanasi, Guwahati, Sangrur, Visakhapatnam, Chandigarh and Muzaffarpur. The Advanced Centre for Treatment, Research and Education in Cancer (ACTREC) has increased its capacity to 900 beds, offering state-of-the-art treatments with specialized facilities for solid tumour chemotherapy, management of haemato-lymphoid cancers, radionuclide isotope therapy, and Proton Beam therapy unit with three gantries, the first-of-its-kind in the government sector. Further, the National Cancer Grid (NCG) has been established with the aim of creating a coordinated system for cancer care that would ensure that patients receive the best possible treatment, regardless of their location or socio-economic status. The NCG includes more than 280 cancer centres and research institutions across India, and it is supported by the Department of Atomic Energy and the Tata Memorial Centre. One of the key objectives of the NCG is to improve the quality of cancer care in India by promoting the use of evidence-based treatments and best practices. The network treats over 750000 new cancer patients annually, which is over 60% of India's cancer burden. TMC has been recognised as an Anchor Centre for the International Atomic Energy Agency's (IAEA) 'Rays of Hope' programme.

Agriculture and food preservation

Continuous mutations in biological systems occur on a very slow time scale, influenced by environmental conditions. However, direct exposure to ionising radiations such as gamma rays from a radioisotope can induce accelerated mutations. DAE has an extensive programme on creating induced mutations in various crops, a technique known as mutation breeding. The method involves exposing seeds to controlled beams of gamma radiation, leading to favourable as well as unfavourable mutations in them. Seeds with desirable traits are selected and multiplied. 71 Trombay crop varieties including groundnut, rice, mustard, mung bean, cow peas, chick peas, and wheat, with enhanced traits such as non-GMO, climate resilience, high-yield, early maturity, and improved disease resistance, have been developed through mutation breeding and are widely cultivated across the country.

Pest infestation, contamination and mould infestation are some of the major problems being faced by the agricultural sector, leading to substantial losses to the extent of 20-30% of the produce. Prevention of post-harvest spoilage is therefore of great significance. The radiation processing offers an eco-friendly solution to this problem. India's first pilot radiation facility 'The Food Package Irradiator', was commissioned in 1967 at BARC. Since then, four additional food irradiation facilities have been commissioned in the Government Sector across Maharashtra and Gujarat. Food irradiation processing is a method approved by several organizations including International Atomic Energy Agency (IAEA), World Health Organization (WHO), Food and Agriculture Organization (FAO), and Food Safety and Standards Authority of India (FSSAI). DAE has also developed irradiation technology for preservation of fruits, vegetables, pulses, spices, sea food etc. by radiation processing and has transferred the technology to private entrepreneurs. DAE has developed an integrated operating procedure utilizing irradiation and onion-specific cold storages, demonstrating the extension of the storage period for 'rabi' onions up to seven and a half months. This breakthrough not only ensures an extended storage life but also maintains the high quality of onions. The KRUSHAK food irradiation facility in Lasalgaon, Nashik, Maharashtra, has been upgraded for conducting the preservation trials and technology demonstrations of the breakthrough protocol in 2024. The successful demonstration of the large-scale trial marked a major milestone in advancing food preservation and hygienisation practices in India, reflecting DAE's unwavering commitment to agricultural innovation. Currently, 28 such commercially operated facilities are available around the country. Radiation processing protocol for mangoes has been developed successfully, and these fruits are now being exported to four countries across the world, USA, Australia, Malaysia and South Africa.

These are just a few glimpses of the vast potential of nuclear energy and radiation technology applications across various aspects of our lives. Achieving a balance between maintaining and sustaining our ecosystem and biodiversity, as pursuing developmental goals, requires innovative solutions. Many of the technologies developed by the DAE are steps in that direction, offering far-reaching benefits in energy, healthcare, nutrition and general well-being in a sustainable manner.

Basic Science Research

It is logical to believe that fundamental research serves as the backbone of scientific discoveries which actually creates the groundwork for applied research and technological advancements, towards improving the quality of human life, as all these are closely connected. Indeed, the history of science has shown that all genuine knowledge has been for the potential use of mankind.

"The pursuit of science and its practical application are no longer subsidiary social activities today. Science forms the basis of our whole social structure without which life as we know it would be inconceivable…"

~ Homi Bhabha
(in his lecture at the inauguration of TIFR in December 1945)

Bhabha believed that science has advanced at an accelerating pace since the early 20th century, widening the gap between the Global North and lower-middle-income countries. It is only by adopting the most vigorous measures and by putting forward utmost efforts into the development of science can bridge the gap. Undoubtedly, by this time Indian scientists including luminaries like C. V. Raman, Satyendra Nath Bose, Meghnad Saha and many others, had made significant contributions to the advancement of science, which are now integral to the fabric of modern science. With the aim of advancing science in India at a pace befitting the country's talent, Bhabha sought Sir J R D Tata's support to provide the necessary conditions and financial backing for establishing a scientific institute. This institute would promote original research at the frontiers of nuclear physics, cosmic rays and high energy physics. With financial support from the Sir Dorabji Tata Trust, Tata Institute of Fundamental Research (TIFR) was initially established within the premises of the Indian Institute of Science (IISc), Bangalore. Later it was shifted to Bombay, where it was formally inaugurated on December 19, 1945. Since 1955, the main funding responsibility of the institute lies on GoI through DAE. Starting with high energy cosmic ray research, TIFR has now grown to become one of the most premier and prestigious research institutes of this country, pursuing research activities across physical, chemical and life sciences. The approach to fundamental research as exemplified by the atomic energy program, has been characterized by a commitment to curiosity-driven research, crucial for driving innovation, creating paradigm shifts, and contributing to long-term national development. Starting with the establishment of TIFR, Bhabha facilitated creation of various other institutions of excellence, such as Saha Institute of Nuclear Physics, Institute for Mathematical Sciences. Later, the DAE has either established or aided institutes like, Harish-Chandra Research Institute (HRI), National Institute of Science Education and Research (NISER), Institute of Physics (IOP) and Institute for Plasma Research (IPR). The latest in this series is the Homi Bhabha National Institute (HBNI), a deemed-to-be university, which continues to advance scientific research and innovation in the country through its constituent DAE, and DAE-Aided institutes. DAE support and nurture basic research in Indian institutes and universities by funding through the Board of Research in Nuclear Sciences (BRNS). Collaborative programmes between researchers in universities and DAE scientists, are encouraged by BRNS in order to increase academic interactions.

Dr. Bhabha initiated the balloon experiments in India at TIFR in 1948 for research in Astronomy, Astrobiology, and High Energy Physics. The TIFR balloon facility in Hyderabad today has the capability to launch heavy pay loads up to 1200 kg gross weight to altitude of 32 km for astronomy experiments and lower payloads for high energy physics research. The facility achieved the landmark of 500 scientific balloon launches in 2018. In cosmic ray research, India thus has a rich and long history. Researchers at TIFR detected the atmospheric Cherenkov radiation in early seventies, and also established an array of 25 distributed Cherenkov telescopes, known as the Pachmarhi Array of Cherenkov Telescopes (PACT), in Madhya Pradesh. Later in 2002 an array of seven telescopes was setup at Hanley to observe high energy gamma rays from celestial objects at lower energy. GRAPES-3, a near-equator astroparticle physics research facility at Ooty is being led by TIFR and operated by international consortium of several institutes of India and Japan.

The Giant Metrewave Radio Telescope (GMRT), an array of 30 radio telescopes used for investigating a variety of radio astrophysical phenomena ranging from the nearby solar system to the edge of the observable universe, is developed by TIFR, a grant-in-aid institution of DAE. Located at Narayangaon in Pune, GMRT has been accorded the prestigious IEEE Milestone status in 2020 in recognition of the global impact of GMRT, with users from 40+ countries worldwide, and the fact that it was designed and built entirely in India, with innovative ideas. GMRT is only the third such IEEE Milestone recognition for an Indian contribution to date, after the one for the pioneering work by Sir J. C. Bose on radio waves in 1895 and the one for the Nobel Prize-winning discovery by Sir C. V. Raman in 1928.

Bhabha Atomic Research Centre (BARC) started the Very High Energy gamma ray astronomy programme by setting up country’s first imaging telescope called TACTIC at Mt Abu in 1997. The same year, it detected gamma ray emission from the Active Galactic Nuclei, Mrk 501 first time along with four other imaging telescope facilities around the globe. A high-altitude research laboratory at Gulmarg is also managed by BARC, where research in the field of cosmic ray astrophysics, radioastronomy, and atmospheric neutron monitoring is being carried out. Recently, the Major Atmospheric Cherenkov Experiment (MACE) Observatory at Hanle, Ladakh was formally inaugurated as a part of the Platinum Jubilee year celebrations of the DAE. MACE is the largest imaging Cherenkov telescope in Asia, situated at an altitude of approximately 4,300 meters, making it the highest of its kind in the world.

The DAE has placed paramount importance on accelerators-based research in the country. Over the years India has achieved the capability to design, build and operate accelerators and carry out accelerator-based research programmes in the frontiers of nuclear science. In the 1960s, a 5.5 MV Van de Graaff accelerator was installed at BARC, Mumbai. Later a folded 7 MV tandem accelerator has also been installed at BARC. These low energy accelerators are meant for basic and applied research in several interdisciplinary areas. The variable energy cyclotron was commissioned in the early 80's and was the first accelerator facility in the country for advanced experimental nuclear physics research. The 14 MV tandem Van de

Graaff (Pelletron) accelerator was set up and commissioned at the TIFR campus in 1989, as a collaborative BARC-TIFR program. Several low energy electron accelerators are being operated at different institutes of the country including DAE for fundamental research and applications. As the beginning of an active programme to develop accelerator-driven technology for nuclear waste transmutation and power generation, BARC has recently demonstrated 20 MeV proton beam in its Low Energy High Intensity Proton Accelerator (LEHIPA) facility.

Two synchrotron radiation sources INDUS-I and INDUS-2, which are 3rd generation light sources, have been designed in the nineties and are being operated at RRCAT, Indore. Indus-1 was the country's first synchrotron generator with a 450 MeV storage ring. Indus-2 has a beam energy of 2.5 GeV and critical wavelength of about 1.98 angstrom. The beam lines developed by DAE scientists in INDUS-1 & 2 are also being used by several universities and institutions for pursuing research in the areas of material science, electronic structures, spectroscopy, imaging and crystallography.

International Collaboration and Mega Science

India is also collaborating with major international accelerator facilities in Europe, USA and Japan. Under the CERN-India agreement, India is making in-kind contributions, to the Large Hadron Collider (LHC) at CERN. The scientists from DAE have also participated in the DØ experiments at the FERMILAB, USA, which led to the discovery of the top quark. As part of Indian Institutes and FERMILAB collaboration, several new and advanced technologies for high-intensity proton accelerators are being developed at multiple centres of DAE. The groups from BARC had joined the PHENIX collaboration for relativistic heavy ion collision experiments using the BNL relativistic heavy ion collider (RHIC) in the past.

As a part of Mega Science, India has conceived an international project, Laser Interferometer Gravitational-wave Observatory "(LIGO)-India", which is a collaborative project between the USA and India. The LIGO-India testing and training facility at RRCAT, Indore was inaugurated in December, 2024, which would serve as a staging and assembly lab for LIGO-India detector subsystems.

DAE-BARC in close association with other defence departments of Government of India, is continuously working on developing technologies for national security. I recall that, two weeks after "Operation Shakti", the then Honourable Prime Minister Shri Atal Bihari Vajpayee stated that "India is now a nuclear weapon state". He further emphasized, "Our strengthened capability adds to our sense of responsibility", a principle that India upholds with pride. The Silver Jubilee of "Operation Shakti" was celebrated on 11th May 2023 in the Pragati Maidan, New Delhi, when the Honourable Prime Minister, Narendra Modi virtually inaugurated five nuclear technology-linked cancer care centres in two states, and a rare earth permanent magnet plant in Visakhapatnam.

Way forward: Entering the era 'Amrit Kaal'

The milestones already achieved by DAE institutions are vast and encompass a broad range of areas. In this positive spirit, DAE has now chalked out prospective growth drivers for nuclear and allied sector expansion in the country in the next two-and-a-half-decade period. It is envisioned to design, construct, install and commission new general purpose research reactors & developmental reactors for special purpose in BARC-Vizag campus, where infrastructure development work is progressing in full swing. Developmental reactors such as high temperature reactor are for green hydrogen production and utilisation of thorium after breeding into uranium. The new reactor programme would also support the three-stage nuclear power programme by emphasizing on indigenous technology development for IPWR and FBR for 1st & 2nd Stage of Indian nuclear power programme as well as for realization of 3rd stage for long term energy security. The nuclear fuel cycle covering front end as well as back end of fuel cycle will back up the ambitious programme. An integrated nuclear recycle plant (INRP) being constructed would integrate all the facilities operating in spent fuel storage, reprocessing, waste management and MOX fuel fabrication. A fast reactor fuel cycle facility (FRFCF) will be commissioned at Kalpakkam.

"The five Public Sector Undertakings (NPCIL, BHAVINI, UCIL, ECIL & IREL) of DAE are primarily responsible for *development* in production of nuclear power to provide support in achieving energy security in a sustainable manner. Together NPCIL and BHAVINI envision to reach installed capacity of about 58000 MW by 2047. The other PSUs will work in tandem and support the programme by augmenting fuel production facility, developing required electronics and instrumentation and by supplying necessary rare materials.

The accelerator programme aims at long term energy security in a sustained manner through phase wise development of high energy proton accelerators typically 1 GeV for accelerator driven sub-critical systems, as well as for transmutation and incineration of nuclear waste. For the same purpose a high-energy high-intensity proton cyclotron systems with a final energy of 800 MeV is also envisaged. It is now proposed to indigenously develop a state-of-the-art 4th generation high brilliance synchrotron radiation source (Indus-3) in India. The proposed Indus-3 (6 GeV, 200 mA) will provide a significant boost to the national scientific and research community as well as applied and industrial research.

In radio astronomy, expanding the GMRT facilities to reach unprecedented sensitivities would enable transformational, high-impact science. In astrophysics research, looking ahead, the MACE project and its proposed expansion with array telescopes aim to foster international collaborations, advance India's contributions to the study of the universe, and bolster India's position in the global scientific community. The observatory will also serve as a beacon of inspiration for future generations of Indian scientists, encouraging them to explore new frontiers in astrophysics. The mega science project LIGO-India will be built at Hingoli in

Maharashtra by DAE and the Department of Science and Technology (DST), GoI, in collaboration with the National Science Foundation (NSF), USA. Honourable Prime Minister Shri Narendra Modi laid the foundation stone of (LIGO-India) on National Technology Day, 2023. The scientific goals of which are to advance research in astronomy and fundamental physics. The source of gravitational waves, which are predicted to be emitted by collision of the objects like black holes, neutron stars and supernova, is expected to be detected.

Progress is an open-ended endeavour and I am confident that DAE institutes together will leverage the insights within the roadmap to propel the organizations forward, contributing to the realization of a brighter and more technologically advanced India.

I am extremely happy to announce the release of the report titled 'Amrit Kaal Vision Document,' a comprehensive document that represents charting a strategic course for the continued success of the R&D Units, PSUs, Industrial Units, and Aided Institutions. All the Unit Heads of DAE anchored this activity, and the collective efforts of all units are commendable. The roadmap will be instrumental in achieving our collective ambition—the creation of a self-sufficient and technologically unparalleled India by 2047.

Jai Hind

Ajit Kumar Mohanty

Dr. Ajit Kumar Mohanty

August, 2025

Secretary, DAE and Chairman, AEC

1. Introduction

This document is the outcome of intense discussions carried out among the Aided Institutions of DAE as a part of the "Chintan Shivir" exercises to develop a roadmap for the future. The plans developed as part of this exercise are: (i) astronomy, space sciences and geo-sciences (ii) atomic, molecular and optical physics (iii) high energy physics (iv) laser plasma science (v) chemical sciences (vi) materials for fundamental science energy and environment (vii) quantum science and technology (viii) biology across scales and environments, from molecules to ecosystems (ix) computer science (x) fundamental theoretical physics (xi) mathematical sciences (xii) redesigning the education and HRD ecosystem of the DAE (xiii) high performance computing facilities – the next decade and beyond (xiv) healthcare (xv) nuclear physics (xvi) plasma physics.

The astronomy and astrophysics initiatives aimed at addressing the most fundamental, as well as broad impact and open problems in space and geosciences. These include space weather prediction, earth science, rare earth element exploration, natural disaster management, climate science, solar system exploration, exoplanets, astrophysics and cosmology, instrumentation for ground and space-based observatories, gravitational-wave astronomy, radio astronomy, and theoretical astronomy.

In atomic, molecular and optical physics, the vision includes devising practical methods to control chemical reactions using low-energy electrons, developing a cryogenic storage ring to study the decay of molecular ions, developing a national network of high-altitude platforms and large-area receivers for both quantum as well as free space optical communication and integrating this with the global high-altitude platform/satellite network. Accurate time-keeping is critical for many of these networks and hence the plan also includes for the development of trapped ion or neutral atomic clocks, as well as building collaborating networks for clock comparison.

High energy physics studies lead one of the frontiers of our understanding of fundamental physics. The proposed vision includes the construction of an end-to-end Indian experiment to study the little explored ultra-light hidden sector, the development of a multi-cavern underground laboratory which would serve multiple scientific communities and not just particle physics, as well as the development of a space-borne particle physics detector covering an energy range that is currently unexplored.

In laser and plasma science, the proposed 25-year programme is divided into three Phases. Phase-I, lasting 5 years, will be dedicated for establishing 1PW laser driven GeV class, mono-energetic, highly collimated electron beams. The Phase-II, lasting 10 years, would focus on generation, detection and applications of MeV-scale bright X-ray and Gamma photon beams. In-parallel, the Phase-II would also have equal contribution invested for development of indigenous high-repetition rate multi-PW lasers. The final Phase-III, spanning over 10 years, would focus on delivering industry standard prototypes. Given the scale and scope of these programmes, the task and expertise would be distributed in a collaborative manner with Indian industry/ MSMEs/ startups and academia.

The chemical and material sciences outline a strategic vision for leveraging material innovations to combat climate change, emphasizing the need for ground-breaking research, state-of-the-art infrastructure, and collaborative excellence. The exploration and development of advanced materials for fundamental science and environmental applications are crucial in addressing the pressing challenges of energy efficiency, sustainability, and climate change. The white paper envisages the development of high energy density and power density batteries, alongside the integration of supercapacitors and hydrogen fuel cells, and the development of a fully operational renewable grid.

In quantum science and technology, it envisages developments along four verticals, viz. (a) Quantum Computing & Simulation (b) Quantum Communication (c) Quantum Sensors & Metrology and (d) Quantum Materials & Devices. These in turn will have a wide range of societal impact, ranging from healthcare to clean energy. In quantum computing, the vision includes India emerging as a major supplier as well as user of quantum computing hardware and software.

The computer science roadmap is towards developing quantum as well as post-quantum cryptography algorithms, formal methods and verification methods which are critical in the development of highly safe systems such as nuclear reactors.

Though spanning across wide length and time scales, the study of theoretical physics uses many common techniques and mathematical frameworks. The white paper details a roadmap for research across multiple dimensions, ranging from cosmology at mega-scales, statistical physics and quantum many body physics at macro- and meso-scales, high energy physics and quantum gravity at micro-scales.

The "biology across scales and environment", proposes a holistic approach to biological systems, which would allow one to address critical challenges in public health, environmental sustainability, and technological innovation. This includes understanding microbial biology and mechanisms of antimicrobial resistance. The research integrates fundamental knowledge with clinical solutions, potentially leading to effective cancer therapies and a deeper understanding of resilience across ecosystems.

The DAE Aided Institutes (AIs) have traditionally played a leading role in the development of modern higher mathematics in the country. This includes being instrumental in the training of talented young people across all levels of higher education, via pedagogical schools and workshops organised by the AIs and, under the activities of the National Board for Higher Mathematics and the National Centre for Mathematics, as well as the doctoral programmes of the AIs which are renowned for having the highest standards. The white paper details a vision to soar higher in research aspirations and significantly increase the pedagogical footprint. The research vision also outlines some of the main themes and problems that will be pursued.

The health science white paper lays out an ambitious vision to enhance India’s healthcare system by 2047, focusing on improving cancer care, combating infectious diseases, advancing healthcare technology, and fostering innovation. The key goals include expanding access to cancer care services, leveraging artificial intelligence & machine learning (AI-ML) and digital health tools, supporting multidisciplinary research, and strengthening expertise across various medical fields.

2. Astronomy, Space Sciences and Geosciences

Humankind's quest to understand the fundamental rules governing everything from our Earth to the farthest reaches of the observable universe has led to the development of our modern civilization. The long-term visions that have driven the scientific revolution have always emerged from grassroots efforts. This chapter on “Astronomy, Space Sciences and Geosciences” in the Roadmap for DAE Vision for 2047 document, is an attempt to identify our ambitious goals that organically emerged from the Department of Atomic Energy (DAE) family of scientists and engineers.

In this white paper, we have identified sub-areas within this field where we believe we can leverage DAE's existing expertise to leapfrog to cutting-edge capabilities. These advancements will address the most fundamental, high broader impact, and open problems in Space and Geo sciences.

2.1 Space weather prediction

Space weather, characterized by solar phenomena such as solar flares, coronal mass ejections (CMEs), and geomagnetic storms, significantly impacts Earth's magnetic field, affecting satellite operations, communication systems, navigation technology, and power grids. The increasing dependency of modern society on technology that is vulnerable to space weather elevates the need for accurate predictions to mitigate risks. This proposal aimed at developing an advanced predictive model for space weather by leveraging data science and machine learning techniques to enhance the accuracy and timeliness of forecasts.

To succeed, the programme would comprise of developing a comprehensive predictive model by utilizing machine learning algorithms to analyse historical space weather data and to identify patterns that precede major solar events. It is important to implement a system for real-time monitoring of solar activities, enabling prompt forecasting of potential space weather impacts. Finally, the impact of evaluating the potential effects of predicted space weather events on critical infrastructure and technology to provide targeted warnings is to be assessed.

All these would improve the awareness and preparedness by disseminating the findings and predictions to stakeholders and the general public through an accessible platform. The proposed programme stands to significantly advance the capability to predict and prepare for space weather events, safeguarding critical technologies and infrastructure. By applying cutting-edge data science and machine learning techniques to the challenge of space weather prediction, this initiative will not only contribute to scientific knowledge but also enhance societal resilience in the face of solar-induced disturbances.

2.2 Earth Science

Critical minerals are metals and non-metals that are essential for economic development and national security but their supply can be at risk due to geological scarcity, geopolitics, trade policies, monopoly on resources, and other factors. In the near future, the global economy will be underpinned by technologies that depend on these minerals as they are essential for telecommunications, defence, electronics, transport, renewable energy technologies etc. Included in the list of critical minerals for India are Lithium & Rare Earth Elements (REE), which are also of particular interest to the DAE. REEs include lanthanides, Sc and Y, and they are valuable for many sectors including electronics, manufacturing, medical sciences, and renewable energy sector. Lithium is primarily used in batteries, ceramics and glass industries, polymer production etc. Thus, an undisrupted supply of these minerals is one of the most critical requirements for India's transition to clean energy, meeting the 'Net Zero' commitment as well as realizing the vision of "Atma Nirbhar Bharat".

Several studies indicated the presence of abundant resources of these metals in igneous rocks, placers, phosphoritic deposits, and residual (soil/clay) environments, but questions remain about the nature of their distribution and amount of these resources. In particular, alkaline igneous bodies may contain Li and REE resources, but their petrogenesis and extent of Li/REE enrichment remains poorly understood. This programme aims to explore alkaline igneous rocks and pegmatites of India for their potential in hosting REEs and Li minerals, and to understand what controls their formation.

The characterization of alkaline igneous bodies, granitoids, and pegmatites will help in identifying new potential provinces of Li/REE-bearing reserves. The petrogenetic model will help in mapping out the exploration strategies in geological terranes of India that were not studied in the framework of critical minerals so far. Further, the study will focus on characterizing how Li/REE are present in each of the studied rock types and in each phase, which will help in designing the metallurgical extraction.

2.3 Developing an India-specific, physics-based hazard assessment framework for earthquakes and landslides

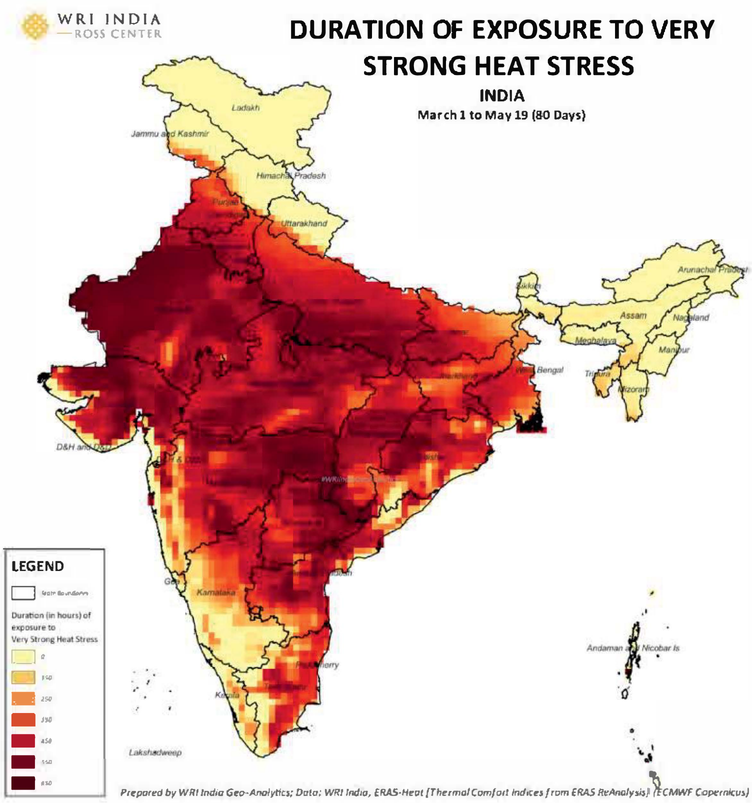
Our knowledge of the earthquake and landslide potentials of Indian fault zones/vulnerable slopes is almost entirely empirical. This makes the assessment of seismic and landslide vulnerabilities of critical infrastructures often uncertain. India is also geologically unique in the sense that even its plate interior is substantially seismically active and its landslide prone areas are not all activated only during monsoon rainfall seasons. The physical processes that control earthquakes and landslides even in the absence of the usual stimuli of such tectonic or climatic forcings are not well understood. Yet, India still does not have a dedicated laboratory setup that can probe and quantify these processes across the many order-of-magnitude variations in strain rates and in-situ conditions that operate during the initiation and culmination of these natural hazards. We propose to establish a state-of-the-art laboratory capable of testing geological samples extracted from fault zones and landslide slopes under in-situ conditions to explore the physics of earthquake and landslide processes at both slow and fast displacement rates. This laboratory will be complemented by field observation/monitoring sites established within regions of active deformation involving both seismic and aseismic fault slip and landslides that will provide in-situ observational constraints and relevant field samples. Using this complementary laboratory-based and in-situ monitoring setup, we are looking to develop India-specific, physics-based, models for earthquake and landslides by integrating field-data, geophysical observations, laboratory experimentation and numerical modelling. These efforts will also align directly with the National Landslide Risk Management Strategy adopted by the National Disaster Management Authority (NDMA) by setting up field-monitoring stations and laboratories that provide micro-scale hazard estimates and developing physics-based early warning models tailored specifically to the geology and hydrology of the region. The proposed facilities will provide vital inputs to physics-based estimation of site-specific earthquake and landslide hazard and early-warning models.

2.4 Climate Science

Process based understanding and vulnerability mapping of the pre-monsoonal heat stress in the Indian subcontinent under global warming is one of the important aspects needs to be attended.

Several important regions in the Indian subcontinent, including the Indo-Gangetic plains, the Ganges and Indus delta and south-eastern India, are projected to witness heat stress at deadly levels under near-future global warming. Pre-monsoonal heat stress is recognized as the most impactful climate change hazard in the subcontinent, already impacting lives, livelihoods and industry. Our understanding of these extreme events is however lacking in tropical regions in contrast to extratropical latitudes where heat-waves are tightly associated with blocking highs controlled by the extratropical dynamics dominated by the Coriolis force. It is proposed herein to analyse the source processes behind pre-monsoon heat stress in the tropics, specifically in the subcontinent, their evolution under global warming and mapping the regions, most vulnerable to these changes under future climate change scenarios. This thematic research area will directly serve the National Action Plan on Climate Change (NAPCC), specifically the National Mission on Strategic Knowledge for Climate Change (NMSKCC). Previous research has identified a key role of near surface atmospheric water vapor in impacting the severity of these heat waves. Following from the existing information and knowledge, the proposed research will explore the role of higher atmospheric water vapor in impacting surface heat stress through a control on atmospheric dynamics and cloud occurrence. The evolution of these processes under global warming will help track the heat wave vulnerability across the subcontinent.

The workflow will include identifying correlations between metrics of heat waves and meteorological conditions, specifically atmospheric water vapor and cloud cover. Tools of ground-based and satellite observations, reanalysis and model data will be employed. A part of such analysis has already been conducted indicating a weak contribution of blocking high events in triggering heat stress conditions as compared to background tropical dynamics which controls the occurrence of mid-level clouds. Also, it is being proposed to establish novel facilities and collaborations with existing ground-based cloud monitoring and atmospheric



Map shows duration of exposure to very strong heat stress (UTCI based) over a period of 80 days.

profiling networks/facilities. Apart from achieving the said objectives, the establishment of ground-based networks will also serve the purpose of general weather monitoring, ground truthing for satellite data retrievals and cyclone monitoring for coastal areas.

2.5 Rising Innovations: Harnessing Balloons for Societal and Scientific Advancements

Balloons have emerged as adaptable tools for advancing societal and scientific goals, serving purposes ranging from disaster relief to pioneering research endeavours. They provide a cost-effective and versatile platform for a multitude of applications. Since its establishment in 1969, the Tata Institute of Fundamental Research's Balloon Facility (TIFR-BF) has played a significant role in crafting zero-pressure (ZP) plastic balloons essential for various scientific endeavours. These balloons are crucial for research in fields such as Astronomy & Astrophysics, Atmospheric Sciences, Astrobiology, and High Energy Physics. Additionally, the facility is also involved in the production of natural-shaped balloons and aerodynamic shape kytoons to meet societal needs.

The objectives of the proposed programmes are to explore the diverse applications of balloons in advancing societal goals, including disaster response, connectivity, and accessibility; and investigating the role of balloons in facilitating scientific research across various disciplines, such as atmospheric studies, environmental monitoring, and space exploration. Important aspects lies in identifying the societal and scientific challenges, conducting surveys, interviews, and literature reviews to understand specific needs and to pinpoint areas where balloons could make significant contributions. Further, collaboration with interdisciplinary teams comprising engineers, scientists and designers is to be considered as advanced modelling and simulation tools is required to optimize balloon designs for various applications.

The utilization of balloons represents a transformative approach to advancing societal welfare and scientific discovery. Through innovative methodologies encompassing design, technology integration, deployment strategies, and interdisciplinary collaboration, balloons have emerged as indispensable assets for addressing diverse societal needs and scientific inquiries. Looking ahead, continued research, investment, and collaboration are essential to further harnessing the potential of balloons and unlocking new opportunities for societal and scientific advancement. By leveraging balloons as versatile platforms for innovation and exploration, we can pave the way towards a more resilient, connected, and informed global community.

2.6 Solar System Exploration

Laboratory study of extraterrestrial materials (e.g. meteorites, micrometeorites, interplanetary dust particles, and samples returned by spacecraft missions) and remote sensing study of different bodies in the solar system provides direct information about the origin of our solar-system and evolution of its constituent bodies (e.g. asteroids, planets). In addition, spacecraft missions give direct insights into planetary habitability and presence of resources. Various past, ongoing and planned solar system exploration missions have provided a wealth of information about different bodies and has also brought back precious pristine extraterrestrial materials for study. Study of these samples and data is changing our understanding about the origin of our solar system and planetary habitability which in turn provides the foundation for future manned, resource utilization and base for planetary missions. The short, medium and long-term objectives of the Indian space mission are also focused in this direction and the present project aims to support this initiative.

Exploration of the Moon, Mars, and other terrestrial planets has garnered a renewed interest among many countries including India. The future plans for lunar habitation, in-situ resource utilization, power generation (nuclear power) and manned mission needs dedicated prior study of data obtained from spacecraft missions. This proposal aims to further expand on the study of remotely sensed data obtained from the Moon, terrestrial planets and from other small bodies by different missions. In addition, the proposal focuses on a dedicated infrastructure facility for study of extraterrestrial samples and samples obtained directly from the Moon, asteroids and comets which is essential for understanding the origin of our solar system, terrestrial planets, Earth and the Moon and in supporting their future exploration.

The objective is to provide confirmed information on the origin & early evolution of the solar protoplanetary disc, asteroids, comets, and planets. Understanding the origin of the Moon and the potential regions for presence of resources (e.g. metal, rare earth elements, uranium and thorium, oxygen, water, hydrogen) for future exploration and manned missions.

Remote sensing study of surfaces of planets and other solar system bodies would be taken up by using data obtained from the upcoming planetary exploration missions.

This proposal will provide the necessary science support to the future manned missions to the Moon, and understanding the origin of Venus, Mars and other terrestrial planets. It will further enhance our understanding about the origin of our solar system and of life on Earth and thereby on habitability of other planetary systems.

Exploration of planetary and solar system bodies is one of the major future goals of the humanity, and India has significant plans in its "National Space Mission."

2.7 Exoplanets

Over the last 25 years with the advancement in technology, we have been on the path of revolution in astronomy and astrophysics, and this revolution has been the discovery of exoplanets. Discovery of exoplanets has opened an entire new paradigm to explore the Universe. Are we alone in the Universe? Is life on Earth just a mere coincidence, or very common across various other planetary systems out there? Are there many more intelligent civilisations in the Universe? All these are among the most profound questions of humanity and our search for habitable planets has the potential to answer these questions. Moreover, the search for habitable planets will also show us the diversity of exoplanets in our Universe, many of which are unlike anything we have in our solar system. However, this search for habitable planets is very challenging. It consists of finding planets that could be of terrestrial nature, constrain their size and mass, and finally perform atmospheric characterisation to accurately assess their habitability.

Internationally, Kepler and TESS missions have discovered large populations of transiting planets constraining their radius along with detection with many ground-based radial velocity surveys constraining their mass. India has also started making great efforts in being part of this revolution of exoplanets, utilizing the ground-based telescopes like Himalayan Chandra Telescope (HCT) and Devasthal Optical Telescope (DOT) for exoplanet science. However, their capabilities are limited in comparison to other ground-based facilities around the world. Keeping this in mind, we highlight herein the possible areas where India could contribute over multiple time scales, short-term, medium-term and long-term in the search for habitable planets.

The specific objectives of the proposed programme are: how do the properties of exoplanets correlate with the characteristics of their host stars and why? Can we detect and characterize Earth-like terrestrial exoplanets and remotely detect spectroscopic signatures of life or habitability on them? It is to be noted that development of in-house 1D, 2D, and 3D models for exoplanet formation, atmospheres, and interiors, both forward and retrieval would be important step in achieve the goal. In addition, creation of in-house data reduction pipelines and frameworks, establishment of in-house molecular databases are futuristic steps.

The research on exoplanets will help in understanding the diversity of planets and their atmospheres in the Milky Way galaxy. It will also enable understanding of various physical and chemical processes in action in the large range of temperature, pressure and composition that we encounter in these diverse exoplanets. Exoplanet modelling research will help in developing a planetary climate modelling community in India. The said cutting edge research will help bolster the engineering research for developing precision instruments for space and ground-based telescopes.

2.8 Instrumentation for ground, balloon and space-based observatories

Astronomy instrumentation has always pushed the frontiers of technology in a country. Motivated by the science goals, TIFR has a long heritage of building state of the art cryo infrared instruments for all the ground-based telescopes in the country, and have also developed/developing multiple balloons and space-based observatories.

GROUND-BASED IR ASTRONOMY

TIRCAM2 @3.6m DOT

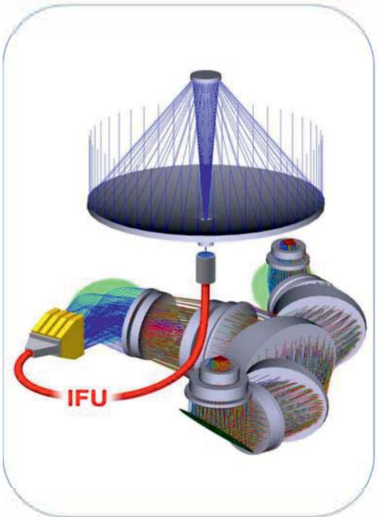
TIRSPEC @ 2m HCT

TANSPEC @3.6m DOT

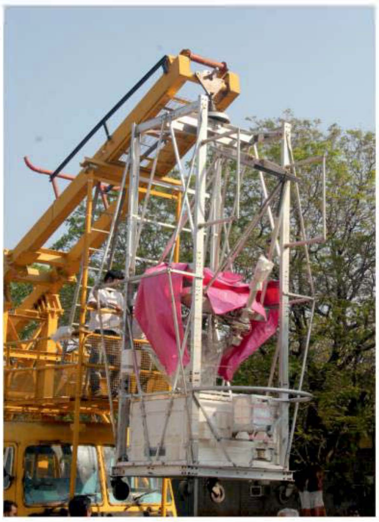
Ground-based Cryo Infrared Instruments developed for astronomy at TIFR, DAE

SPACE-BASED IR ASTRONOMY

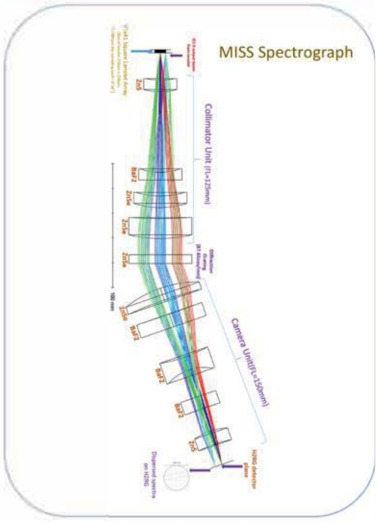
IRSIS LAB MODEL



T100 BALLOON BORNE + FPS



IR PAYLOAD FOR L2 POINT



Balloon and Space-based Cryo Infrared Instruments developed for astronomy at TIFR, DAE

On the ground-based instrumentation front, the objective is to develop novel spectroscopic and imaging instruments for the upcoming large telescopes in India (NLOT, 6-m sub-mm telescope) as well as for extremely large telescopes across the world (like TMT). In the balloon frontier, the idea is to deploy UV to Far Infrared telescopes for high precision spectroscopy, photometry and nulling interferometry. In the space frontier, the need is to have large observatory class flagship satellites that will enable probing the origins of planets, stars as well as the universe.

The strategy is to have a continuous development of pathfinder technologies driven by a combination of immediate science requirements as well as long term vision to unlock the mysteries of planet, star and universe formation. For instance, building on our previous instruments like TIRCAM II, TIRSPEC and TANSPEC we are currently developing two novel multi-object spectrograph technologies indigenously (MOIS and TA-MOONS). We are also setting up a digital signal processing laboratory, primarily for building state-of-the-art backend spectrometers both for the upcoming sub-millimetre facility in India as well as for other observatories.

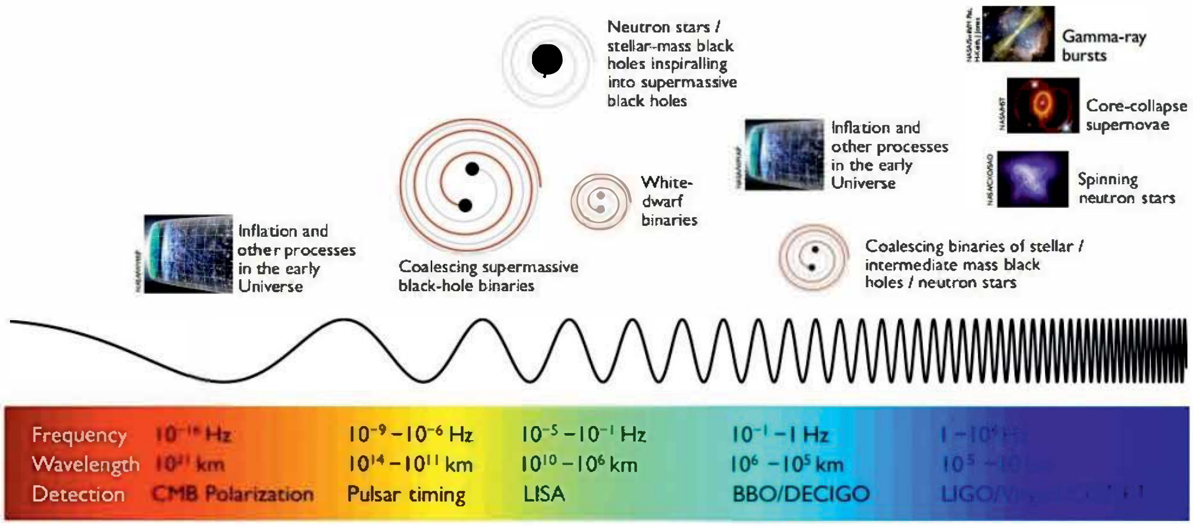
We are also part of the instrumentation team for the upcoming 10 m National Large Optical Telescope. India is also part of the TMT project, and we will contribute to building second generation instruments for the TMT in the next two decades. With the in-house development of key precision optomechanical technologies, we will be able to position ourselves as global leaders in astronomical instrumentation. We also plan to take advantage of our in-house AI/ML expertise to integrate AI capabilities to the instrument design process itself.

The TIFR balloon facility, in Hyderabad, is one of the world's top scientific ballooning facilities. Leveraging on our long legacy and in-house technologies, we are developing highly stabilised 2 m class balloon born telescopes for UV to Far Infared observations. This is to address a plethora of science cases needing deep field imaging, nulling interferometry, and high precision spectroscopy of exoplanets. Scientific ballooning platform offers a very inexpensive, environment-friendly alternative to many of the experiments otherwise possible only from space. Long-term goal is to establish India as a major player in building and operating state-of-the-art astronomical space observatories that will address frontier and foundational questions in astrophysics and space sciences.

Development of novel instruments with capabilities that didn't exist before opens up new discovery spaces. Only by excelling in the instrumentation field, India can become leaders in both basic science research as well as in technology. In-house development of technology will open up avenues for collaborations with international telescopes, which the Indian Astronomy community currently do not have the access. Apart from new astronomy discoveries, the technological spinoffs will greatly benefit Indian Industry and the AtmaNirbhar Bharat Mission.

2.9 Gravitational-Wave Astronomy

Gravitational wave astronomy is gearing into a new field that is capable of exploring physics ranging from astrophysics, cosmology, and fundamental physics from the early epoch of the Universe until the current epoch of the Universe with the aid of multi-band observations of gravitational wave signals ranging from ultra-low frequency (atto-hertz) to ultra-high frequency mega/giga-hertz. Observations accessible from the network of LIGO-Virgo-KAGRA detectors have made it possible to detect several binary gravitational wave sources, starting the era of gravitational wave astronomy over the frequency range of a few tens to nearly up to a kilo-hertz frequency. Also, the observation in the nano-Hertz gravitational wave signal using pulsar timing array observations has made it possible to hint toward the detection of the stochastic gravitational wave background. These observations primarily focus on a limited frequency range and sensitivity. In the future measurement of the signal over a wider frequency range and better sensitivity will open discovery spaces, which are inaccessible from any other observations. These multi-band observations of gravitational waves and in synergy with other probes make it possible to explore the Universe using multi-messenger observations.



The multi-wavelength spectrum of GW signal, which can probe physics from the early Universe to the internal structure of neutron stars, making it feasible to study the Universe with a new cosmic window from the upcoming and planned next-generation GW detectors.

Mission concept

Deci Hertz range gravitational wave detectors: Detection of the GW signal in this range 0.01 Hz to 1 Hz is feasible from the moon using seismometers by measuring the vibration of the moon due to the passing of gravitational waves. An array of seismometers placed on the surface of the moon can measure this signal quadrupolar pattern of the gravitational wave signal in this frequency range. The strength of the moonquakes is weak in this frequency range by orders of magnitude than earth, which makes it possible to detect this signal.

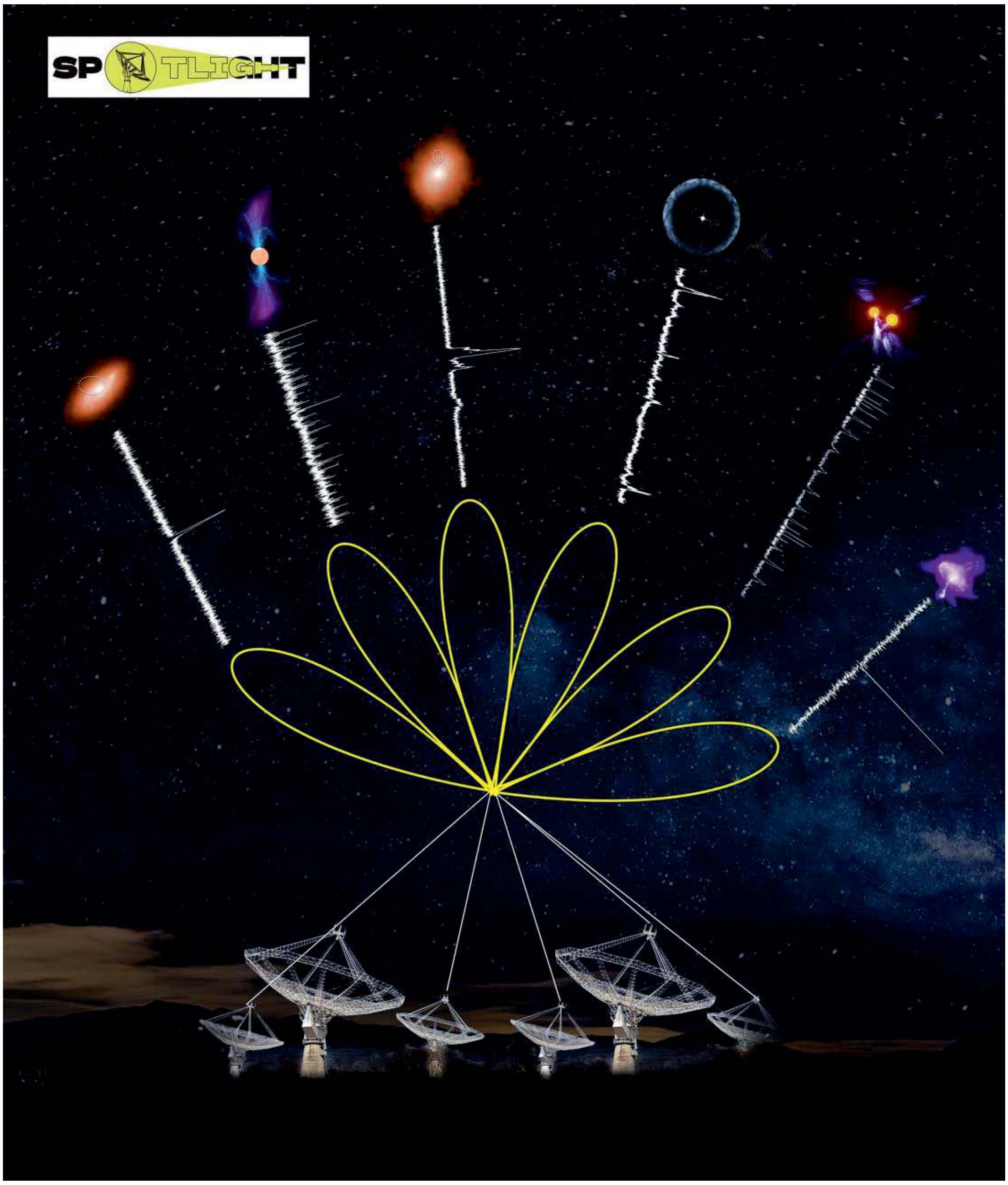
Above kilo hertz range gravitational wave detectors: Detection of above kilo hertz gravitational wave signal is possible from optically levitated dielectric sensors. Dielectric nanoparticles suspended at the anti-node point of a laser standing wave that can measure a passing gravitational wave signal. A cryogenic 100 metre cavity can explore above kilo hertz signal. The expected outcomes would include discovery of the intermediate-mass black holes and cosmological gravitational waves.

Indigenous gravitational wave detectors on the moon and Earth operating from deci-hertz to giga-hertz have the capabilities to discover a plethora of science that can change our understanding of the Universe. Building such experiments in India will bring technological development in the country which will impact several other branches beyond natural science. These experiments will make a strong footing for Indian science in an international community and play a lead role in advancing the frontier of basic science and engineering capabilities in space science and technology.

2.10 Radio Astronomy Research

Radio astronomy, which started in the 1940s, taps into radio signals coming from celestial sources, over the range of the radio spectrum accessible from the Earth (about 30 MHz and higher). India is one of the leading countries in radio astronomy research having facilities like the Giant Metrewave Radio Telescope (GMRT), built and operated by the National Centre for Radio Astrophysics (NCRA). The GMRT is one of the most sensitive instruments in the world for cutting-edge research in low-frequency radio astronomy (110-1450 MHz) in the field of High redshift galaxies, Active Galactic Nucleus (AGN), Clusters, Interstellar medium (ISM), time-domain study for Pulsars and Fast Radio Bursts (FRBs). Along with the emergence of modern astronomical facilities like the GMRT, the international mega-science project, the Square Kilometer Array (SKA), is expected to be a state-of-the-art global facility in the next decade. Looking further ahead, on a horizon beyond 20 years from now, the most important and exciting new frontier would be radio astronomy from space allowing us to escape from the ever-growing problem of radio pollution and accessing radio sky at ultra lower radio frequencies (beyond the ionosphere).

SPOTLIGHT (https://spotlight.ncra.tifr.res.in/), a real-time survey instrument funded by the National Supercomputing Mission (NSM) under MeitY and DST of Govt. of India to explore a completely new programming paradigm both in HPC and in AI to leverage GMRT's potential in delivering cutting-edge time-domain astronomy transient sciences. This multi-beam commensal system, powered by petaflops of computing and petabytes of storage, efficiently probes the transient sky across timescales ranging from nanoseconds to seconds, targeting coherent emitters.



Artistic impression of the SPOTLIGHT system simultaneously spanning the fast transient timescales from nanoseconds to seconds with an energy range of 1027 erg/s to 1042 erg/s

The whole idea is enabling transformational, high-impact science with the GMRT by adding new facilities; expanding the GMRT facility to reach unprecedented sensitivities in hitherto unexplored parameter space; contributing with required science and technology development to support participation in SKA mega-project; and finally working on a roadmap for India to become a leader in space-based radio astronomy.

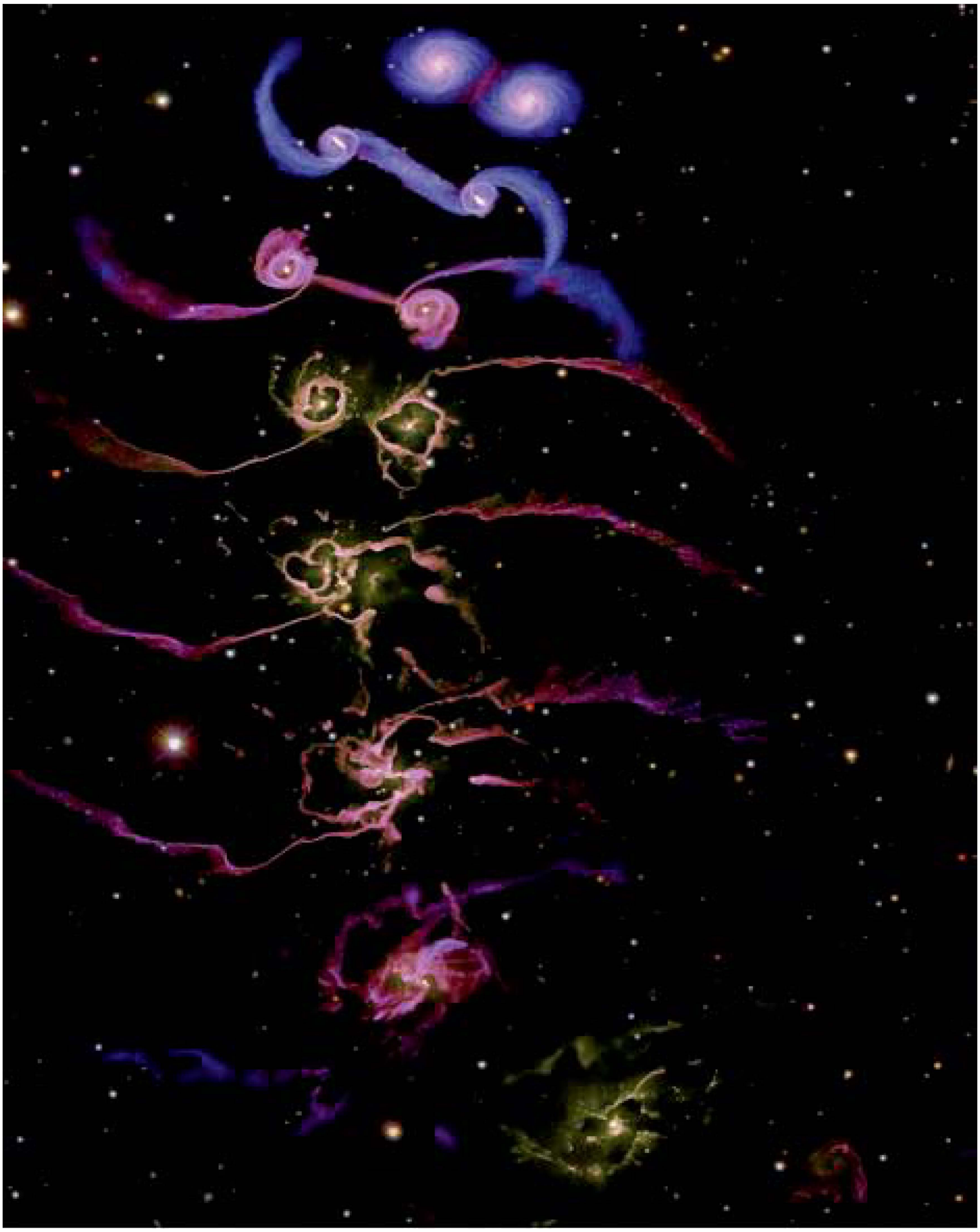
All these radio astronomy instrument developments will further strengthen the unique position of India in the world by rapidly building systems using COTS components largely designed by our Indian scientists/engineers as well as having a timely implementation of AI modules (e.g. ML/DL) to increase GMRT's sensitivity towards genuine cosmological signals. Other specific outcomes of the proposal are the development of GPU-Powered HPC application with Exascale computing in radio astronomy. Working on technology challenges ranging from quantum technology for computing and communication, self-sustaining energy solutions would enable space-based radio astronomy in synergise with other S&T aspirations that India is looking for.

The proposed roadmap will also build facilities for the students and early career researchers with rich resources of astronomical data at unprecedented sensitivity leading to the enhancement of the intellectual property of the nation as well as developing a skilled human resource in the country in the field of high-performance computing, artificial intelligence, networking and energy production.

2.11 Theoretical Astrophysics Using Large-Scale Simulations

Large-scale hydrodynamic (HD) and magnetohydrodynamic (MHD) simulations have become indispensable tools in astrophysics research. However, India lacks the large-scale facilities on which such simulations are being carried out. Thus, while astrophysicists have successfully made use of and contributed to the development of such tools during their previous positions, once working in India they are forced to scale down or change their science objectives or rely on international collaborations to continue this work, which is not always feasible or desirable. Hence, there is a need for vast improvement in computational facilities to help Indian astrophysicists to use their skills and knowledge effectively and help to train the next generation. In particular, DAE scientists at NISER are using such tools to study the following cutting edge fields: (i) the merger of stars in a binary star system, (ii) the evolution and effects of magnetic fields in and around galaxies, (iii) The formation and evolution of the first galaxies and quasars as seen by JWST, (iv) the gravitational wave signal from merging supermassive blackholes, (v) the distribution of metals of different ionization states in gas around galaxies as a probe of galactic feedback, (vi) the role of cold atomic gas in the formation and evolution of galaxies.

One of the specific objectives is to understand the common envelope (CE) phase of binary star evolution, which is responsible for various enigmatic phenomena including luminous red novae and the progenitors of gravitational wave-driven mergers of neutron stars and black holes. The CE phase is extremely challenging to model and still not well-understood owing to the large dynamic range of spatial, temporal and density scales and inherent asymmetry, which necessitates 3D simulations with adaptive spatial resolution.



Source: Tiziana Di Matteo et al. 2005, Energy input from quasars regulates the growth and activity of black holes and their host galaxies, Nature.

Different phases of the merger of two galaxies with central supermassive black holes. From top to bottom, the individual images of the sequence show the gas of two colliding spiral galaxies.

DAE scientists are capable of carrying out excellent research in computational astrophysics related to astrophysical fluids. New discoveries are made when one is able to resolve even larger dynamical scales in the simulation. These days, large-scale simulations are becoming more and more necessary to tackle the most interesting and important problems in the field, but knowledge about and experience in using and developing the leading simulation tools is not enough; computational resources in the form of high-end facilities are also significantly necessary for India to take a leading role and become a place where astrophysicists from around the world want to work.

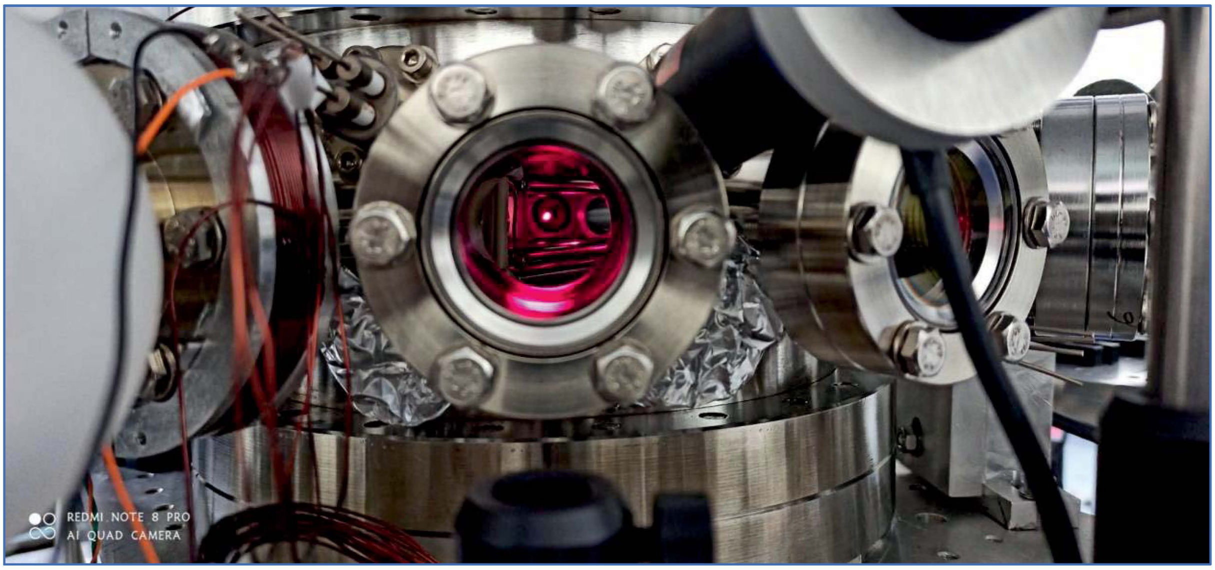
3. Atomic, Molecular and Optical Physics

This white paper describes the vision of TIFR in the broad field of Atomic, Molecular and Optical (AMO) Sciences. The AMO vision-2047 builds on the strong foundation and long tradition of AMO sciences in TIFR Mumbai and, additionally, encompasses the new initiatives and forthcoming opportunities in the TIFR Hyderabad campus. Following are the key areas which shape the AMO science vision:

3.1 Ultralow energy (<1 meV) and low energy (~eV) collisions

Studies of collisions at ultralow energies (< 1 meV) are possible using the techniques of laser cooling, supersonic expansion and a combination thereof. Atomic and molecular collisions at such low energies allow precise control over the quantum state of the particles and enable detailed understanding of molecular structure and dynamics. We propose to develop experiments towards these goals, making use of existing expertise as well as hiring new members. In the low energy (~eV) regime, we propose to focus on electron induced chemistry on surfaces and in high pressure gases which are actively pursued by groups within TIFR. Of particular interest are devising methods to control chemical reactions using low energy electrons, developing new techniques of imaging surfaces based on atom scattering, build predictive models and develop techniques for surface characterization.

For collisions between atoms or between atoms and molecules at ultralow energies (<1 meV), the collision cross section is dominated by only a few partial waves and at extremely low energies by a single partial wave, known as the s-wave collision regime. This implies that classical treatments of collisions breakdown and full understanding of the experimental outcomes is possible only through a quantum mechanical treatment. Such calculations are sensitive to the underlying long-range interaction potential between the colliding partners and therefore, a joint experimental-theoretical approach provides precise knowledge about the interaction potential. In many cases this enhances our understanding of collisions and chemical processes, some of which may result in uncovering of new fundamental physical phenomenon. Another important aspect of extremely low energy particles is that they can be trapped and their quantum state can be manipulated with exquisite precision, therefore enabling studies of quantum-state resolved molecular dynamics. A complementary approach is implemented for collisions between molecules and electrons at low energies (~eV). Here effusive or supersonically cooled molecular beams interact with the low energy electrons whose energy can be tuned to break molecular bonds and the resulting fragments can be imaged to reveal the underlying molecular potentials and dynamics. The approach allows selective breaking of bonds and has been instrumental in revealing underlying symmetries, electron correlation or new mechanisms. Another area which remains relatively unexplored is the interaction of electrons and molecules with surfaces. It is well known that surfaces alter chemical reactions (e.g. in catalysis) but the detailed molecular level understanding is lacking partly because of challenges in surface preparation and probing techniques. Exploration in these directions further, are being proposed herein.



Setup for laser-cooled lithium atoms in TIFR Mumbai.

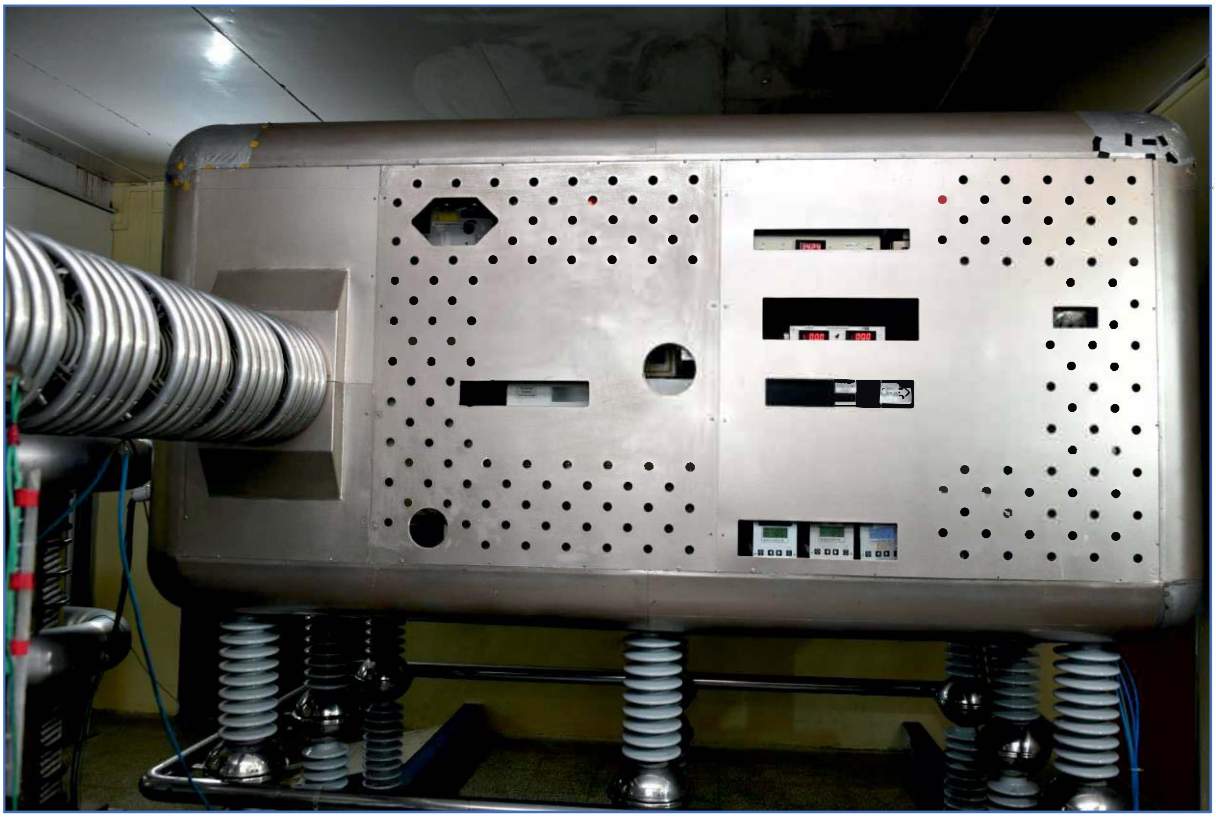
The short term (0-5 years) goals are to produce ultracold polar molecules, study quantum-state controlled collisions and reactions and surface induced chemistry.

The long term (5-15 years) goals are to study dynamics of long-range interacting systems, Insights into cluster formation, devising methods to control chemical reactions using low energy electrons.

3.2 Accelerator-based atomic and molecular physics

The relatively unique facilities such as the Electron Cyclotron Resonance Ion Accelerator (ECRIA) and the Pelletron makes TIFR Mumbai suited to carry out experiments involving highly charged ions and ions with energies ranging from keV to MeV.

The interaction of highly charged ions with molecules, in particular molecules of astrophysical and biological relevance is important from the view point of interaction of solar wind with PAH molecules and for the biological molecules it is important from the radiation therapy point of view. Interaction of highly charged ions with PAHs sheds light on the formation of smaller hydrocarbons and hydrogen in the interaction of PAHs with cosmic rays and solar wind. The measurement of absolute cross sections gives insight into the chemistry happening in the interstellar medium. The measurement of absolute cross section of biologically relevant molecules provides input for the dose calculation in the hadron therapy. Besides, the study of fragmentation dynamics of small molecules is important to gain knowledge about fundamental interaction of highly charged ions with molecules. Another important aspect is the electron capture by highly charged ions from He atoms and H_2 molecules which is important in the role of electron capture in TOKAMAK plasma.



The Electron Cyclotron Resonance Ion Accelerator in TIFR Mumbai.

The specific road map has been drawn, which include studies on breakup of PAH molecules due to collisions and relevance to production of molecular hydrogen in space, biomolecular breakup, cancer therapy.

Participating in building a High Energy Accelerator for GeV ion beam (e.g. GSI type), Developing a Cryogenic Storage Ring, Rare decay of molecular ions using the CSR, Study structure and dynamics of larger PAH molecules are chosen further as long-term goals.

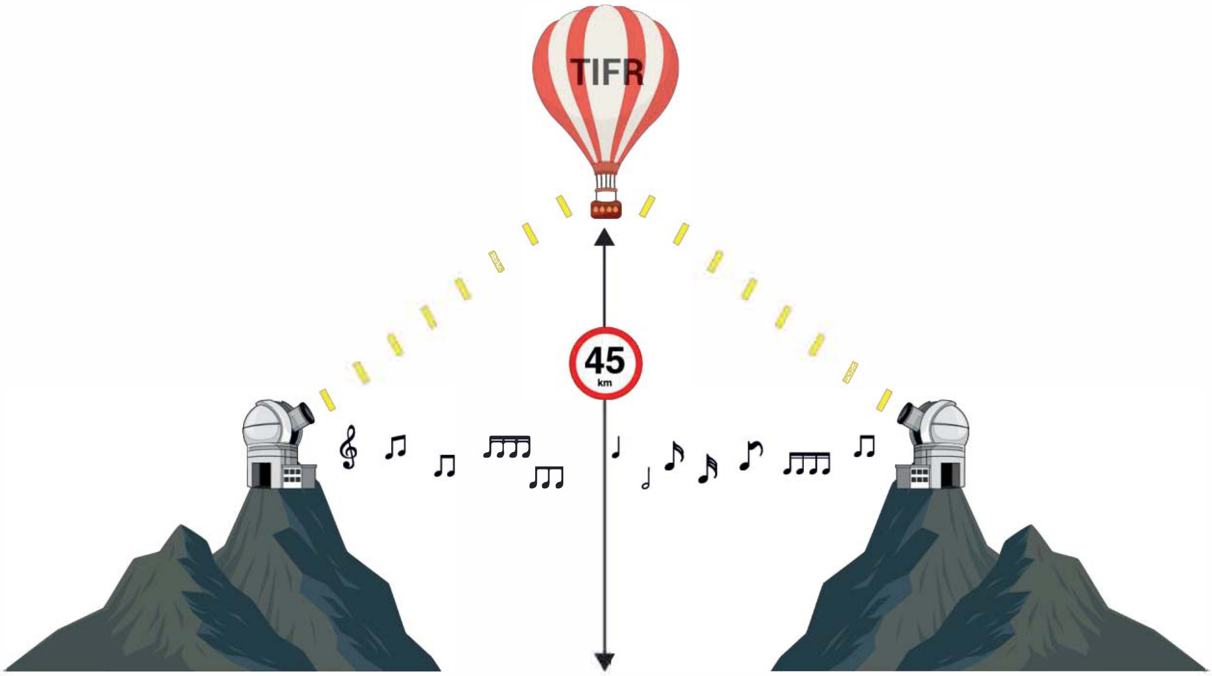
3.3 Quantum and Optical Communication

Investing in long distance quantum communication and optical communication using the TIFR Balloon Facility in Hyderabad and designing and developing the necessary hardware are proposed in this programme. High altitude platform (HAP) node for quantum communication over 800-1000 km is proposed also. Further, the eventual handshake with the Indian Satellite Program, expansion of LAN to national length-scales by adding nodes and large area receivers and integration of the National HAP/Satellite network with the global HAP/Satellite network is envisioned.

Establishment of communication facilities from local to global scales has shrunk the world to its effective size today. The security of communication has become a vital aspect in communication in regard to financial organizations, government offices, or strategic locations. Currently, technological advancements are happening over increase in the speed or bandwidth of the carrier, and augmentation of the security thereof. Towards secure communication, an indomitable solution that has been uncovered is quantum communication. In this technology, principles of quantum physics are exploited to realize a hard-to-break protocol of communication, with the additional security layer in which any attempts to break the protocol are detected. Long-distance free-space quantum communication is perceived as a global solution by creating a quantum network consisting of satellites, drones, aerostats etc. It is, therefore, advisable to be part of this effort by launching indigenous technologies. In the domain of high-speed communication, maximum effort is being invested in optical communication. Several advantages exist in free-space optical communication, particularly with regards to accessibility to difficult areas. With advanced optical, optomechanical and optoelectronic technologies, free-space optical communication has the potential to become the mainstream technology connecting any two locations on the globe and thus global efforts are mounting where a communications network is being envisioned. Interestingly, the very same vehicles such as satellites, drones, aerostats etc. are being evaluated for the high-speed optical network and there are several overlaps in the hardware and software aspects of quantum communication and free-space optical communication. Investing in the indigenous efforts using similar high-altitude vehicles will place India perfectly to harness and exploit the technological advancements happening globally.

The entire programme is ambitious and may be achieved in stages. Initially, design and development of hardware for quantum and optical communication, wide area optical receivers, and high-altitude platform (HAP) node for quantum communication over 800-1000 km are important.

In the second stage, demonstration of a network of HAP nodes and large area receivers (≥3) towards both quantum / FSO communication, is planned.



Concept of high-altitude platform for free space optical communication

A long-term goal, LAN is to be expanded to national length-scales by adding nodes and large area receivers and thus, integration of the National HAP/Satellite network with the global HAP/Satellite network would be attained.

3.4 New Initiatives in Precision Measurements

Historically, precision measurements have played a pivotal role in expanding our understanding of physics e.g. the observation of Lamb shift that led to the development of quantum electrodynamics. In recent years, precision measurements in atomic and molecular systems have focused on two, broad but somewhat interlinked, fields. The first is to do with improvement of "optical clocks" which includes optical clocks based on atomic systems (e.g. strontium lattice clock) as well trapped ion systems (e.g. aluminium ion clock). These optical clocks have demonstrated staggering frequency stability at the level of 10^{-18} or better, surpassing the current SI standards (based on caesium microwave transition) by several orders of magnitude. It is only a matter of time before the SI unit of time is redefined using optical clocks. In India, there are no optical clocks in operation although efforts have just begun in a couple of places. It is of immense strategic and social importance that India develops its own optical clocks within the next decade and demonstrate operation at the level which is commensurate with the global standards. The second focus of precision measurement is on uncovering new physics including physics beyond the standard model of particle physics, search for dark matter etc. The idea is to replace the high energy in collider-based experiments with extreme precision in low energy atomic physics experiments. Recently, optical clocks based on highly charged ions have been proposed as good candidates to study new physics and TIFR, with the ECRIA source for highly charged ions, is particularly well suited to take up such a program. In addition, the interdisciplinary expertise in both nuclear physics and atomic physics makes TIFR a great place to initiate laser spectroscopic studies on radioactive isotopes and measure isotope shifts.

3.5 New Initiatives in Quantum Computing using Atomic Systems

Quantum computing has the potential to solve problems that are intractable using classical computers. It is expected to have a huge impact in several fields including financial modelling, drug discovery, materials discovery, cybersecurity and so on. Trapped ions and, separately, ultracold atoms have emerged as the leading platforms for quantum computing. These systems rival, and in some cases outperform, other platforms such as those based on superconducting qubits. The advantage of atoms as qubits is that atoms are identical, resulting in qubits that are identical, and that they have long coherence times. Recent developments in the field include the demonstration of >50 qubits trapped ion quantum computer and >1000 qubits in trapped neutral atomic arrays. Very recently, the operation of a logical quantum processor with error corrected logical qubits based on reconfigurable atom arrays has been demonstrated. The progress in this field has been rapid and has attracted significant commercial attention. Taking cognizance of these developments, the Government of India has launched the National Quantum Mission with a Vertical dedicated to Quantum Computing. TIFR and DAE institutes would contribute toward this, especially since some relevant expertise, e.g. in laser cooling and trapping of atoms and ions, already exist.

Within a short period, setting up experiments on trapped ions and/or trapped atom quantum computing with up to 8 qubits and performing single qubit gate operations and measure fidelities would be completed. However, the challenges in expanding it to higher number of qubits, demonstration of two-qubit gate operation with high fidelity, a fully operational quantum machine capable of implementing quantum algorithms are envisaged to be addressed in the next step.

4. High Energy Physics

In the past few decades, physicists working in the field of High Energy Physics (HEP) have devoted their efforts in understanding the Standard Model (SM) of particle physics. With the discovery of the Higgs boson in 2012, the remaining puzzle of mass generation was solved SM and it remains the best theory describing the fundamentals laws of particle physics up to a few hundred GeVs till now. However, few open-ended fundamental questions that SM does not describe are: origin of the neutrino mass, matter-antimatter asymmetry in the universe, the nature of dark matter and dark energy, to name a few. Thus, search for beyond the SM (BSM) has become the focal point for the last few years. The vision is to have a full-fledged particle physics program that is conceived, built, maintained and run by the Indian particle physics community to carry forward future international experiments in a substantial way.

4.1 Collider Physics

For more than half of a century, the principal focus of the particle physics community has been geared towards finding new degrees of freedom (particles) and learning about these by relying on measurements that directly/indirectly depend on the couplings of these new particles. However, one critical aspect of all these strategies generically relies on reasonably large couplings. Even the most elusive of all known particles, namely neutrinos, have quite large couplings to the electroweak bosons, which paved the way for their detection. The same principle has also dictated the construction and design of detectors, search strategies for high energy colliders such as the LHC at CERN, KEKB at KEK, RHIC at BNL, USA etc. Even the decades-long search for dark matter primarily focused on the so-called WIMPs, with weak strength interactions to the visible sector. While this scenario could be the truth of the nature, data from direct observation of dark matter hints that infinitesimal strength couplings scenarios could well be the case. The programme thus needs to have a two prong approach to search for these likely scenarios.

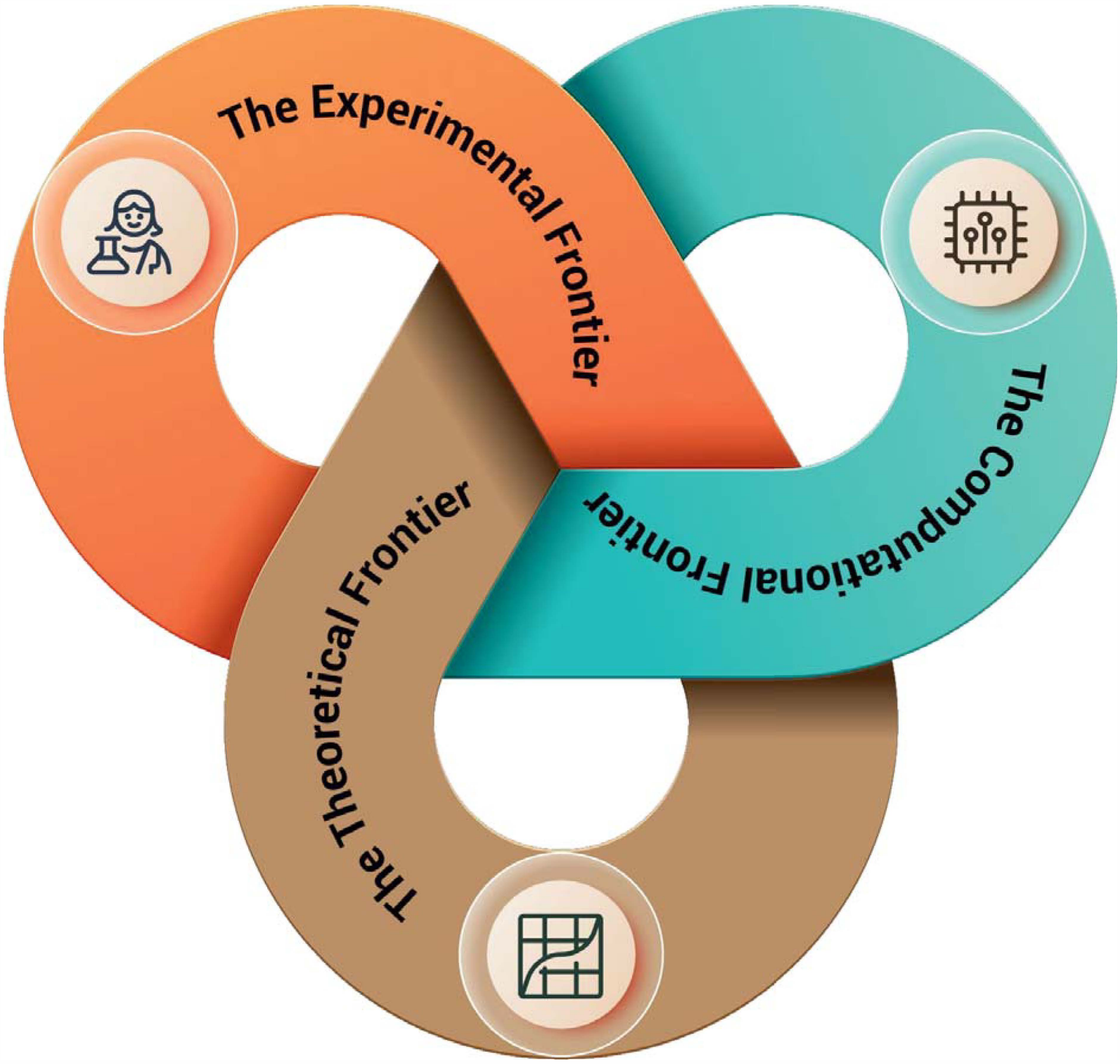
4.1.1 Future collider experiments

Exploration of scenarios that require high energy and high luminosity experiments are only possible when many international collaborations come together as in the case of LHC at CERN, BELLE etc. India is currently involved in the CMS and ALICE experiments at the Large Hadron Collider in CERN, Switzerland, KEKB at KEK, Japan; and the STAR experiment at the Relativistic Heavy Ion Collider (RHIC), US. In addition to it, Indian scientists have been involved in the experiments related to precision measurements of neutrino related parameters at NOvA, and Minerva in Fermilab, USA. Participation in leading experiments around the world gives India the opportunity to play a role in new scientific discoveries and provides exposure to cutting-edge technology.

Apart from providing novel physics opportunities where an end-to-end Indian experiment can potentially deliver competitive results. It also provides opportunities for building specialised expertise to tackle the physics of the light/ultralight hidden sector in the experimental, theoretical, and computational frontiers. While we engage with the global physics by carrying out research in various high energy colliders, building and running a low energy HEP experiment will allow us to have a fully Indian end-to-end HEP program that can be competitive. Moreover, it will pave the way forward for developing capabilities towards setting up and running a world class facility.

Several beam dump experiments around the world including ones at CERN that use electron, muon and proton beams with different absorber materials are available to study various low energy physics. In addition, there is an upcoming LUXE experiment proposed in DESY, Germany to study the non-perturbative effects of QED. The goal of this roadmap is not just being able to establish such facilities in India but achieving more in terms of higher energies, higher magnetic field and higher luminosity down the line.

The program will have a clear roadmap with incremental goals, which at every stage will identify niche areas of R&D, generate expertise all aimed towards attaining the final objective and would engage in verticals ranging from low energy beam related experiments to designing/developing table top experiments, exploring and developing new ideas in improving the existing detector technologies, developing specialized hardware including quantum sensors, to building specialized simulations and algorithms (particularly, AI and quantum machine learning), etc. The developments on the experimental fronts need to have an overarching theoretical support, which would require large roles to be carried out by phenomenologists and theorists. Clearly, in order to face the enormity of this challenge, we need to develop a multi-dimensional approach; bringing three frontiers together:



The multi-pronged approach to the Indian end-to-end HEP Program

Theoretical Frontier: The challenges in the theoretical domains can be broadly classified into the following categories: Charting the space of theories systematically in high energy to be explored in the experimental setup we plan/construct. Deriving observables from these theories at low energies requires techniques of Effective Field Theories, which can give a clear line of connection between high energy operators between quarks/gluons and new physics coupling to nuclear form factors. There has been substantial development in the context of neutrinoless double beta decays, however the program needs to be broadened substantially in the context of our set-up and target theories. Understanding the detector – because of the very nature of the detectors to be built, physics ventures into the subject of material science. Collaborations need to be established in order to bring in the knowledge base to HEP. Understanding the flux and the background – again, the very scale of energy is to be attempted to probe requires collaborations with experts in nuclear and atomic-molecular physics where sources involve collisions. Collaborations with cosmologists and astrophysicists for understanding detectors facing the sky is also very important.

Experimental Frontier: The basic premise of the end-to-end HEP program is to prepare for a diverse set of sources and generate expertise with a myriad of detector technologies.

***Beam dump experiments*:** These experiments are fixed target experiments where the achievable luminosities can be higher compared to the collider type of experiments. These are relatively easier to arrange compared to a collider-based experiment.

***Light shining behind a wall class of experiments*:** The basic principle behind such experiments is that in the presence of a strong magnetic field photon could be transformed into light particles which could well be dark matter candidates and then those particles again transfer back to light.

Physics from electron - photon collisions: Such experiments can probe non-perturbative effects of QED.

***Low energy electron-positron collider*:** Beam energies of the order of few GeVs (10 GeV or so) can be used to search for various low energy new physics and to study several rare decay channels of mesons. If future R&D allows, this can become a possibility given that electron beam of several GeVs is expected to be available in the near future.

Terrestrial detectors to study cosmic particles:

Large area multi-detector arrays to comprehensively study cosmic rays, their sources and composition targeting the highest energy and Ultra-sensitive haloscope class of detectors

***Space based experiments*:**

- Detectors similar to Fermi-LAT optimized for high energy gamma ray detection
- Scaled down versions of general-purpose HEP detectors similar to what has been implemented by the AMS Collaboration

Computational Frontier:

In order to extract “more from less”, a key focus of the “frugal” HEP program, specialized AI based tools and algorithms for maximizing the extraction of information from a given amount of data to be developed. In fact, the use of AI tools can’t just be limited to data analysis but must be extended to all aspects of the program and particularly to the hardware aspects of the programme.

4.1.2 Contributions in future collider experiments

Collaborations in future collider experiments are very important not only because of their potential to discover new physics if it lies at high mass or large couplings but also because of other factors, e.g., exchange of knowledge and ideas, novel detector technologies, etc. Future colliders bring a completely new era of detector challenge we should be ready in terms of concrete contributions which are not only related to data analyses but need to be augmented by building an end-to-end detector/sub-detector in India for a collider experiment starting from laying down the foundations of the detector concept to its construction, installation and its running for the full data taking period. In addition, the ability to handle very large volume of data throughput has undergone a paradigm shift over the last decade and is expected to keep evolving in the future colliders. The software and computing demands will also increase manifolds by then. This includes the stringent requirements for more accurate simulations in various aspects e.g. for the detector or the machine-detector interface. This is again a good place where we can carve our niche by building a software ecosystem adaptable to any future collider.

4.2 Cosmic Physics

4.2.1 Dark Matter Searches

There is now overwhelming evidence for dark matter at more or less all astrophysical scales, starting from the galactic scale to galactic clusters to the truly cosmological scales. The evidence is extremely strong for the existence of a non-collisional, electrically neutral, non-baryonic tenuous fluid which encompasses most of the matter density of the universe. Within the Standard Model of cosmology, dark matter constitutes about 24% of all the energy density of the Universe. The biggest conundrum of the present time is the lack of any observable evidence or any clue about the particle nature of dark matter. Over the past decade or so, there has been an explosive rise in the study of dark matter through various experimental, astrophysical and theoretical channels. The principal probes of dark matter are done through relic density measurements, direct detection experiments and indirect detection experiments. The relic density is a cosmological observation determined predominantly by the measurements of tiny anisotropies in the Cosmic Microwave Background Radiation (CMBR). These measurements are most accurately done by satellite-based experiments like COBE, WMAP and PLANCK. Together with optical and other probes of Type 1A Supernovae, the dark matter relic density of the Universe is now quite accurately estimated. The direct detection experiments, on the other hand, are ground-based, typically employing large detectors housed in underground laboratories. These can identify direct interactions of dark matter with the ordinary matter in the detector. Such experiments have already produced very high-quality results by putting strong constraints on thermal dark matter cross-sections.

Indirect detection of dark matter is the attempt to measure dark matter properties within the galaxy or nearby, by looking at the indirect products of dark matter decay or annihilation. There are both ground-based and satellite-based probes which look for signatures either in cosmic rays, gamma-rays or neutrinos. In future, ground-based experiments like Cherenkov Telescope Array (CTA) and Tibet AS-γ would also lead to significant constraints on indirect detection of dark matter or even have the potential to provide clues to the nature of the dark matter. Most of the work in order to find the nature of dark matter has been centred on Weakly Interacting Massive Particles (WIMPs), however, in recent times, other forms of dark matter are being explored too. These particles could be detected in high-energy collisions, such as those at the LHC (collider searches), or via annihilation products of particle-antiparticle pairs (indirect detection), or via their elastic scattering with matter showing up as nuclear recoil signals (direct detection). Another set of candidates for the dark matter particles are axions or axion-like particles (ALPs), light pseudoscalars that couples weakly with photons. The study of DM forms a very important bridge between high energy physics and astrophysics. Overall, the future of dark matter research has the potential of opening up an entirely new sector of particles and interactions to study.

India has had a very long and rich history in the field of cosmic rays (CR) and high energy gamma-ray astrophysics. In India, the Atmospheric Cherenkov Radiation (ACR) was first detected by the TIFR group in the early seventies by using search light mirrors and fast photomultiplier tubes. Several technological improvements in the design led to the establishment of an array of 25 distributed Cherenkov telescopes, namely, Pachmarhi Array of Cherenkov Telescopes (PACT) at Pachmarhi in Madhya Pradesh. Later, in the year 2002, a seven telescopes array was set up at Hanle to observe high energy gamma rays from celestial objects at lower energies. BARC group started its VHE gamma-ray astronomy program at Mt. Abu by setting up an imaging telescope called TACTIC. Buoyed by the success brought by these installations which detected very high energy gamma rays from different classes of galactic and extragalactic sources, the BARC group has now installed a new large telescope of 21 m diameter, MACE, at Hanle, which is the currently the world's largest high altitude imaging telescope. GRAPES-3 is a major high-altitude, near-equator Astroparticle Physics experiment at Ooty led by TIFR and operated by an international consortium of several institutions in India and Japan. It is an expanded version of the original GRAPES experiment, which started running more than 30 years ago. It consists of 400 large-area detectors made from scintillators, as well as 4000 massive sealed proportional-counters, making it the world's largest muon telescope. It is well suited for exploring the "knee" region in the energy spectrum of CRs as well as for observing accelerated particles in atmospheric, solar, galactic and extragalactic domains. In addition to the cosmic ray spectrum and composition studies over 1013 to 1017 eV, GRAPES-3 is sensitive to particle acceleration by electric potentials generated in thunderstorms, and performs measurements relevant for space weather and heliospheric studies. Additionally, it looks for gamma ray sources in the multi-TeV to PeV range, diffuse gamma ray emission from the galactic disk, and can also look for decaying dark matter in the galaxy. GRAPES-3 scientists have also demonstrated that cosmic-ray muons can be a powerful tool to measure arrival time of solar storms at Earth with great precision. Such studies are vital for protecting worldwide telecommunication and electrical-grids from disruption.

GRAPES detector array at Ooty

4.2.2 Astroparticle Physics with cosmic rays and gamma rays

Even after a century of intense research, a complete understanding of cosmic rays (CR) is still lacking. Nevertheless, various properties of cosmic rays as regards to their spectrum, elemental composition and angular distributions have been studied extensively. However, one of the major difficulties in identifying sources of cosmic rays is that they are charged particles and are therefore deflected in the interstellar magnetic field. Therefore, cosmic rays cannot be traced back to their sources, the so-called cosmic particle accelerators, except for energies beyond 1020 eV, where the bending effects of galactic magnetic fields become minimal. Thus, much of the current effort goes into identifying and quantitatively describing these cosmic accelerators. Shocks in supernova remnants and/or pulsar wind nebulae systems are thought to be the dominant sources of Galactic cosmic rays.

At energies below 1014 eV, cosmic rays have been primarily studied using space- based instruments where detectors used are magnetic spectrometers and/or calorimeters for momentum/energy determination along with transition radiation detectors and Cherenkov detectors. While direct detection mechanisms in space provided many important results on elemental and isotopic composition, the steep fall in flux of cosmic rays with energy, along with the limited size of space-based detectors, restricts the energy range of detection. Thus, at higher energies, ground-based instruments have a distinct advantage where the Earth's atmosphere acts as a calorimeter in which particle cascades are created when a primary particle or a photon interacts with the atmosphere. Some of the important ground-based cosmic ray experiments are KASKADE, Pierre Auger Observatory, IceTop, GRAPES-3, Telescope Array (TA), Tibet AS-γ and LHAASO. GRAPES-3 represents the only major operational facility in India. Even though many interesting and ground-breaking results have been obtained from the above-mentioned experiments, it is very difficult to identify the sources of charged cosmic ray particles as explained above. Therefore, high energy gamma-ray observations both from space and ground and neutrino observations from the ground are of prime importance in order to establish the directionality of cosmic-ray sources. With a very modest beginning in 1989, the field of very high energy (VHE) gamma-ray astronomy grew rapidly in the last two decades owing to tremendous technological progress and currently, more than 200 high energy gamma ray sources of various classes have been discovered in the last decade.

The most sensitive satellite-based gamma-ray detector currently operating is the Fermi Large Area Telescope (LAT) which has discovered hundreds of high energy sources including several new source classes. However, at higher energies beyond a few tens of GeV photon statistics drops and one needs to start observing from the ground. The most sensitive ground-based approach is the Imaging Atmospheric Cherenkov Technique (IACT), which uses the Cherenkov light produced by the electromagnetic cascade of electrons and positrons in the atmosphere to establish the properties of the primary gamma-ray photon. The current generation of IACT instruments include MAGIC, H.E.S.S. and VERITAS and these have already yielded many ground-breaking results in the field of very high energy gamma-ray astrophysics. These space and ground-based instruments have shown the abundance and indeed ubiquity of cosmic particle accelerators. The BARC group has recently installed a new telescope, MACE, at Hanle. MACE will add to the impressive list of current generation of imaging telescope and its longitude allows it to make observations that are complementary to most other telescopes in the world.

The future proposals can be broadly categorized into three main areas:

- Experiments where we clearly have an advantage over the rest of the world, from the point of view of existing expertise in technology and human resource, availability of material, geography or topology, or new niche ideas that have not been tried out yet elsewhere. In such projects, we can be extremely competitive with the rest of the world and may even be the first ones to discover new phenomena or resolve long-standing scientific puzzles.

- Projects where Indian scientists are a part of international collaborations based elsewhere and would like to perform R&D / prototype testing in the country. This would enable the Indian scientists to play significant roles in the international projects at the forefront of knowledge and fulfil the in-kind commitments of the country in these projects. Over the long run, this would lead to technology-building, and prepare the foundation for the future generations of Indian scientists to lead major projects in these areas.

- New ambitious and challenging ideas, some of which are still in the inception phase that need a clean environment, free of cosmic-ray background. The availability of an underground facility is of paramount importance as it would allow the Indian scientific community to conceive and implement such projects. Once the infrastructure of an underground facility is available, the marginal investment needed for implementing these projects would be much smaller and performing these niche experiments in a timely fashion will be feasible.

A few of these ideas (not exhaustive though) are enumerated below:

Deuterated Liquid Scintillator for solar and supernova neutrinos:

The Deuterated Liquid Scintillator (DLS) project proposes a 1 kt-class detector with either a hydrocarbon-based liquid scintillator with the hydrogen replaced by deuterium, or water-based liquid scintillator dissolved in heavy water (D_2O), instrumented with a few thousand PMTs. This would allow neutrino and antineutrino detection, with sensitivity to all flavours. And low energy, high resolution measurements using the scintillator light along with Cherenkov radiation, to reduce threshold and increase light yield.

Dark Matter Searches: As explained above, dark matter (DM) is the dominant component of mass in the Universe. The fundamental scientific question that remains unanswered is the nature and type of particles DM is composed of. A direct detection experiment involves the interaction of DM particles with detector material. They must be located in deep underground laboratories to avoid the effects of cosmic ray interactions that produce energetic neutrons that could mimic DM particles. Indian groups, several of them already participating in international projects like SuperCDMS, PICO and others, are interested in setting up DM search experiments in India and using the facility to carry out detector R&D in the area. This R&D would focus on the development of technology to enable the improvements in backgrounds and detector performance required to achieve these ever-growing compelling science goals. Such an experiment has been set up in Jaduguda Underground Science Laboratory (JUSL) and has been taking data since last year. This facility will need augmentation and upgradation in the next few years in order to set up detectors of larger masses in order to improve the sensitivity of the instrument. A clear observation of fractional charge would be very important since depending on the type of particle observed, it might mean that confinement breaks down under some circumstances or that entirely new classes of particles exist.

Multimessenger Astroparticle Physics using cosmic rays, gamma rays and neutrinos:

In order to understand the acceleration of particles to very very high energies (way beyond that can be achieved in the laboratories), it is important to combine messengers of different species to understand and probe the key questions that have remained unsolved for many years now. On the neutrino front, Indian physicists are involved in two international MSPs that will study neutrino oscillation physics, the Deep Underground Neutrino Experiment (DUNE) in the USA and the Hyper-Kamiokande (HK) experiment in Japan, both of which are expected to start within the next decade. The DUNE participation of Indian scientists could be a continuation of that in the NOvA and Minerva projects, with further possible contributions to the construction of the near detector. In addition, the IceCube detector at the South Pole, which detects ultrahigh- energy neutrinos, will soon be upgraded to IceCube-Gen2, for which the contribution from Indian scientists in the form of detector assembly, integration and testing is being envisaged. The Cherenkov Telescope Array (CTA) would be the most sensitive very high energy gamma ray astrophysics experiment in the world in the decades. Some Indian institutions have already been participating in CTA, hence a formally coordinated participation is highly desirable. At the same time, the home-grown facilities like GRAPES-3 and MACE need to be upgraded vigorously. Hanle especially has a longitudinal advantage as there are no gamma-ray telescopes operating at this longitude and would thus compliment the observations carried out at other existing facilities around the world. Similarly, GRAPES-3 is located at near the Equator which makes it possible to view both the hemispheres for cosmic-ray studies. Below a few GeV, gamma rays cannot penetrate deep into the Earth’s atmosphere and so they cannot be detected. Instead, one has to rely on detectors flown in satellites or balloons to perform such observations. Hence there is a growing need to build and commission a particle physics detector in space which would carry out observations of astrophysical sources from several hundred keV to a few GeV as currently there is no such detector operational in this energy range. This would involve strong inter-agency cooperation with possible multinational partners with India taking a lead role in the design and development of such a detector in space.

4.2.3 Neutrino properties and Neutrino astronomy

Neutrinos are perhaps the most difficult and challenging particles to study in the Standard Model, as well as some of the most intriguing objects in the Universe. One of the most fundamental open questions in neutrino physics is the absolute mass scale of neutrinos. The oscillation experiments determine the mass-squared differences among neutrinos and guarantee that all the neutrinos are within 0.1 eV of each other. The Standard Model of Cosmology puts reasonable limits on the sum of neutrino masses to be less than 1 eV. The absolute scale for neutrino masses is expected to be partially addressed by the ongoing KATRIN experiment which is trying to measure the effective neutrino mass in tritium beta decay. Several international experiments such as GERDA, CUORE, MAJORANA etc. are planning to address the issue of Dirac or Majorana nature of neutrinos. In the precision sector of oscillation experiments, several experiments like Hyper-K, DUNE, NOvA would be probing oscillation observables at a high precision. Within India, the India-based Neutrino observatory (INO) was conceived to take a major step in that direction, unfortunately the project is currently stalled due to reasons beyond the scope of this document. Apart from measuring the neutrino properties, the neutrinos coming from astrophysical objects or phenomena can give us information about the processes taking place inside stars, or inside dense media like AGNs, from where light cannot reach us directly. Precision measurements of solar neutrinos can help us monitor the nuclear reactions taking place inside the Sun, and thus directly probe the solar core. Experiments like Hyper-K and DUNE are sensitive also to supernova neutrinos. Detection of these neutrinos would lead to a deeper understanding of the stellar life cycle. Additionally, neutrino tomography of the Earth can reveal the size and composition of the core of the Earth.

5. Laser Plasma Science

This white paper describes the roadmap for studies and applications of multi-petawatt laser–matter interactions in the TIFR Hyderabad campus. Followings are the key areas based on which the Vision for extreme field science has been prepared.

Developing the design and manufacturing capabilities for making next generation high-repetition rate Multi-PW lasers. The Petawatt lasers have revolutionized the field of high-energy-density science, compact particle accelerators and MeV photon sources. However, for any practical applications, a fundamental transformation is required in increasing the average power of these laser systems, by making them operate at kHz or higher repetition rate compared to current standard of 0.1 Hz. A few possible directions will be coherently combining many fiber lasers, thin-disk lasers or bulk thulium-doped crystals. These high repetition rate lasers would improve the data collection efficiency with the help of machine learning techniques and statistical and big-data analytical approaches to explore weakest interaction physics.

Bright energetic MeV photon source driven by multi-PW lasers. As an alternative to synchrotron, "Inverse Compton Scattering (ICS)" can be a mechanism of generating bright photon beam by scattering of high-energy electrons with low-energy photons. In the traditional collider scheme of ICS, the electron beam comes from LINAC accelerator, and gets scattered from a laser beam. However, we are proposing a more compact and ultra-short version by opting for an all-optically-driven high-energy source of X-rays where a 1.5 eV NIR photon beam will scatter from a GeV electron beam, and produces MeV peak energy photon beam. The generated ICS photon beam can have divergence of ~ 10 mrad, source size of few μm scale and peak brightness can be 10^{19} photons s^{-1} mm^{-2} $mrad^{-2}$ (in 0.1% BW).

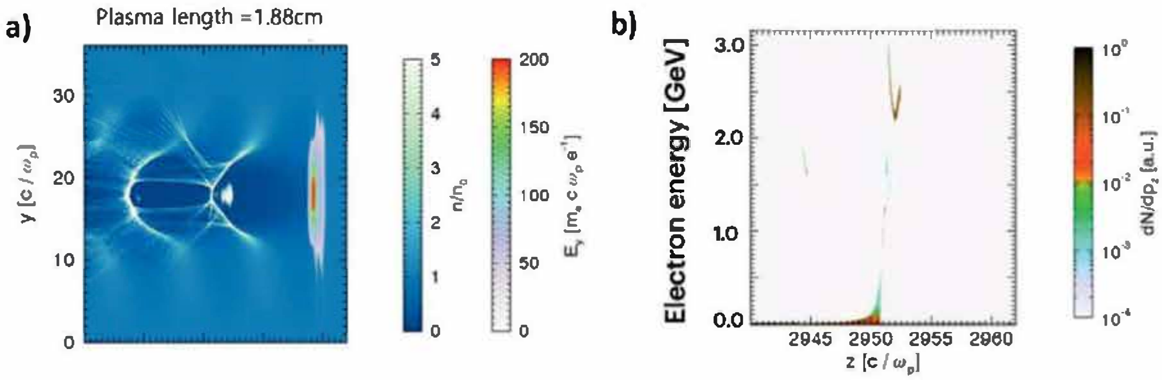
Laser based exploration of Strong-Field QED (SF-QED). The interaction of extreme lasers field with electrons, positrons, and photons may lead to a number of SF-QED effects including vacuum "breakdown" and polarization, light by light scattering, vacuum birefringence 4-wave mixing, high harmonics generation from vacuum, and EM cascades of different types. The multi-Petawatt laser will be used to explore new frontiers of converting a large part of the laser energy into electron-positron pairs, and consequently facilitate the generation of dense neutral gamma-electron-positron plasmas. This would enable access to a new regime dominated by the interplay between strong-field QED effects and collective plasma dynamics.

Gamma ray beam for Nuclear Photonics. The availability of high spectral brilliance laser Compton sources opens a new possibility of basic research in nuclear physics, also known as "Nuclear Photonics". The few prominent areas to explore would be electromagnetic dipole response of nuclei with nuclear resonance fluorescence (NRF), heavy elements synthesis in the Universe and photo-fission phenomena.

5.1 Science/technology/societal goals

Development of ultra-compact, multi-Petawatt laser driven particle accelerators for fundamental discovery science and practical applications:

In 1979, T. Tajima and J. M. Dawson, proposed the theoretical idea of laser wake-field acceleration (LWFA) where a plasma medium can be used to transform laser pulse energy into the kinetic energy of accelerated electrons. The LWFA can operate at plasma wavelength typically around 10 to 100 μm, which is several orders of magnitude shorter than the typical RF period used in conventional accelerators. Similarly, the strength of the electric field can reach 100 GV/m, three orders of magnitude greater than with conventional technology. These features allow the electron beam to reach the same particle energy, in a distance three orders of magnitude shorter than their conventional counterparts. The current Petawatt laser pulses in the relativistic regime can excite plasma waves, which, in turn, can accelerate the electrons to the GeV energy range within a length scale of few centimetres. This can serve as the basis for a compact electron accelerator and future particle colliders.

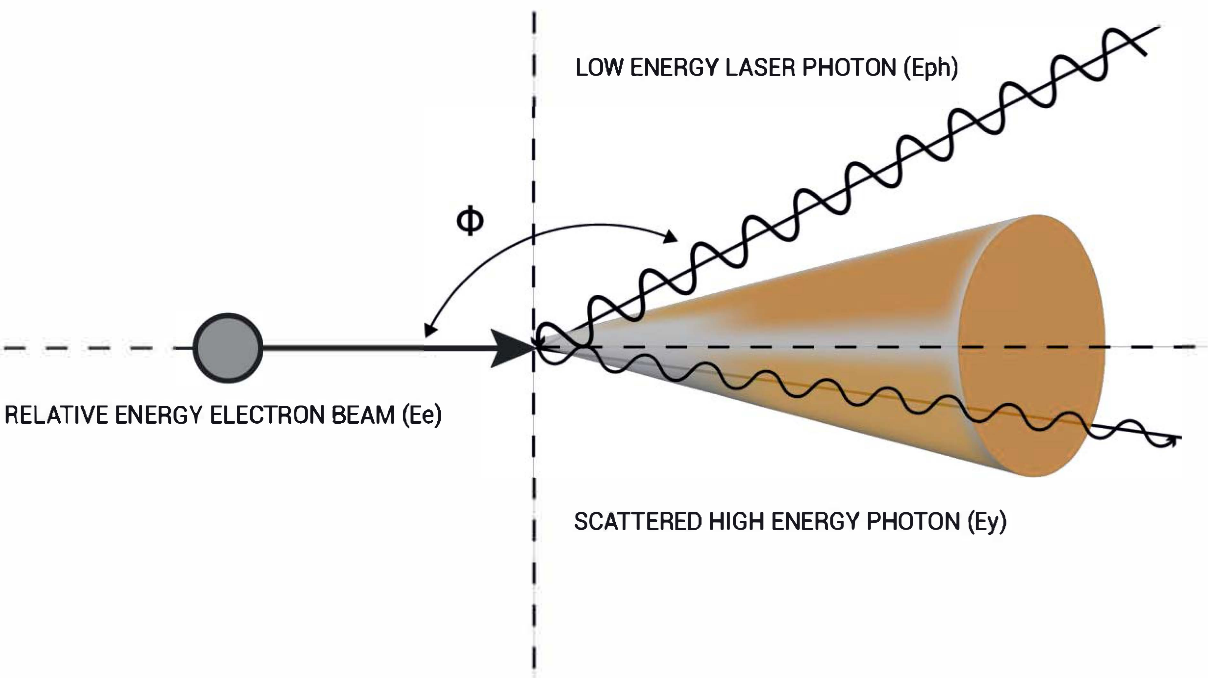


Relativistic intense laser drives a nonlinear plasma wake in an under-dense medium
(a) The quasi-static electric field created in the wake-field bubble traps the electron
(b) Accelerates them to 3.0 GeV (Simulations: Vishwa Bandhu (VIT, India) & Osiris 3.0)

From the application perspective, the secondary sources, produced by GeV-class electrons from LWFA, can span the broad electromagnetic spectrum (from THz to gamma rays)). These photon sources have relevance in medical science, high-energy-density and material sciences, and national security. Processes including betatron emission, Thomson/Compton scattering, bremsstrahlung, free-electron laser generation, and coherent transition/THz radiation are all outcomes of LWFA providing near-term applications. A particularly attractive feature of LWFA is the intrinsic synchronization between the drive laser beam, the generated particle bunch, and any secondary radiation. High-energy-density science and other areas of plasma physics need but do not have routine access to advanced photon probes that could offer greater resolution for precision in the spectral, temporal, and spatial domains.

Laser based Inverse Compton scattering source:

Ever since the discovery of X-rays over a century ago, the high-energy photon sources have become an indispensable tool in fundamental science, medical imaging, and non-destructive testing of high-opacity objects in industry. The broad applicability of this source has been a continuous drive for seeking novel ways of X-ray generation methods, and the field is still looking for compact, bright high-energy X-ray and gamma-ray radiation sources delivering femtosecond pulses with μm scale spatial resolution. One of the methods of generating bright photon beam is via Synchrotron radiation where a high-energy charged particles follows a curved trajectory. Within India, Department of Atomic Energy (DAE) currently runs two Synchrotron facility located in RRCAT, Indore. The first one is Indus-1, an electron storage ring of 450 MeV for VUV radiation source and another one is Indus-2, a 2.5 GeV electron storage ring for X-ray radiation.



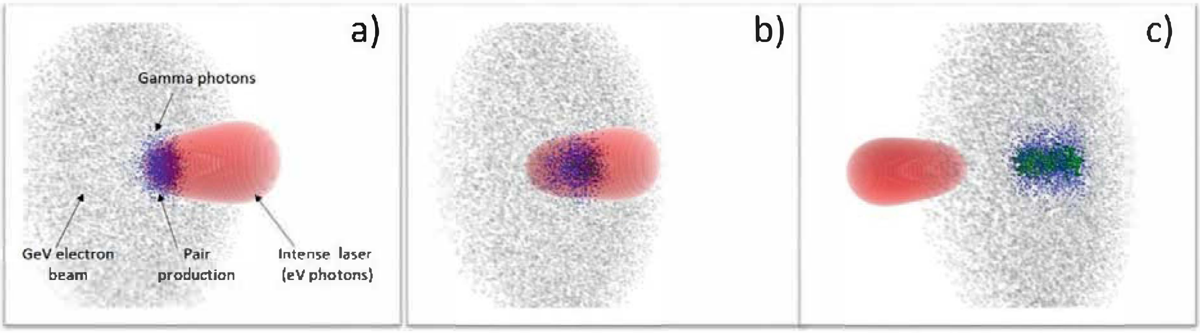
Geometry of inverse Compton scattering between relativistic electron and low energy photon.

Besides synchrotron, "Inverse Compton Scattering (ICS)" can be thought of another mechanism of generating bright photon beam by scattering of high-energy electrons with low-energy photons. In the context of astrophysical scenario this was first investigated as a process by which cosmic-ray particles such as electrons and protons would lose energy during their passage through the galaxy. The Compton sources usually have large spatial foot-print (>100 m) as they are driven by rely on large conventional electron accelerators. However, in contrast to the radio-frequency (RF) cavity, the accelerators can be made more compact and yet generate bright X-rays by laser-Wakefield electron accelerator (LWFA) scheme, which can accelerate electrons to GeV energy in a distance of only a few centimetres.

X-ray free electron laser (XFEL):

X-ray free electron lasers (XFELs), an intense coherent radiation source of sub-angstrom wavelength are indispensable tool to probe ultrafast and ultra-small phenomena across STEM fields. The conventional XFEL facilities in operation, require kilometre-scale radio-frequency electron accelerators, which limits their availability due to size and expense. On the contrary, laser wake-field accelerators can provide accelerating gradients three orders of magnitude higher than those of RF accelerators, and therefore are regarded as a candidate for compact XFEL. Along this direction a proof-of-principle (W. Wang et al, Nature, 595, 516 (2021)) experimental demonstration has been shown where the amplified undulator radiation centred at 27 nm was generated from 490 MeV energy LWFA electrons. Furthermore, the magnetic undulator can also be replaced by electromagnetic fields of a laser pulse, which reduces the undulator period to the laser wavelength and consequently shrinks the overall size of the FEL. These all-optical scheme for FEL uses traveling-wave Thomson Scattering, where the electron-laser overlap by passing the electron beam at angle to a laser pulse with a compensating phase-front tilt. Furthermore, an immediate challenge for LWFA driven XFELs is increasing the repetition rate to match with the conventional facilities. This bottleneck has to be resolve by developing high-repetition rate lasers.

Laser based exploration of Strong-field QED (SF-QED):



Electron-positron pair production in multi-GeV electron beam collision with an ultra-intense short laser pulse. The grey colour represents the energetic electron beam. During the head-on collision between the electron beam (gray) and laser pulse (red), due to the strong-field QED effects, gamma beam (in blue) and electron-positron pairs (in green) are generated (Simulations from: Vishwa Bandhu (VIT, India) and Osiris 3.0).

On a single particle level, the classical electrodynamics and quantum electrodynamics (QED) are one of the best verified theories so far. However, interaction of electrons, positrons, and photons in the presence of strong electromagnetic fields, are not yet well understood. As the fields strength approach or exceed the QED critical field strength (E_{crit}= 1.3 × 10^{18} V/m or B_{crit} = 4.4 × 10^{9} T), the interactions become highly nonlinear. Using most powerful lasers, the highest electric field achieved so far are several orders of magnitude lower than the E_{crit}. However, as the electric field is not a Lorentz invariant, these subcritical electric field strengths may be boosted to the E_{crit} and beyond while going in the rest frame of an ultra-relativistic particle. Therefore, SF-QED processes such as multi-photon Breit-Wheeler electron-positron pair production or multi-photon Compton emission of photons can be realize at much lower field strengths than E_{crit}. The interaction of lasers with electrons, positrons, and photons, whether they act as single particles or plasma constituents, may lead to a number of SF-QED effects including vacuum "breakdown" and polarization, light by light scattering, vacuum birefringence 4-wave mixing, high harmonics generation from vacuum, and EM cascades of different types. The multi-Petawatt laser systems will open up the new frontiers of converting a large part of the laser energy into electron-positron pairs, and consequently facilitate the generation of dense neutral gamma-electron-positron plasmas. This would enable access to a new regime dominated by the interplay between strong-field QED effects and collective plasma dynamics.

Multi-PW Laser driven Gamma ray beam for Nuclear Photonics:

The high spectral brilliance of all optical, multi-PW laser driven MeV Compton sources makes an attractive tool for pursuing basic research in nuclear physics. Intense lasers driven bright beams of energetic photons or particles and nuclear reactions can be used to probe samples, provide quantitative, isotopic composition of large objects, verify the security of cargo, assess the integrity of bridges, buildings, turbines and heal deep tumours in patients. Further a more relevant application to be pursued will be Laser-induced nuclear transmutation and radioactive clean-up. To handle the radioactive waste, common transmutation strategy involves bombardment with neutrons from a reactor or from particle accelerators. Off late, laser-driven high-brightness gamma generation for photo-transmutation has also been suggested as an alternative way. One of the first demonstration being the long-lived I^{129} ($t_{1/2}$ = 15.7 million years) was photo-transmuted to I^{128} ($t_{1/2}$ = 25 min).

The proposed 25-year programme will be divided into three Phases. Phase-I, lasting 5 years, will be dedicated for establishing 1PW laser driven GeV class, mono-energetic, highly collimated electron beam. The Phase-II, lasting 10 years would be focus towards generation, detection and application with MeV scale bright X-ray and Gamma Photon beam. In-parallel, the Phase-II would also have equal contribution invested for development of indigenous high-repetition rate multi-PW lasers. The final Phase-III, spanning over 10 years would focus on delivering industry standard prototypes. Societal benefits span a wide range of applications from national security to diagnostic and therapeutic medicine, and will enable new technologies for the energy security of mankind. Given the scale and scope of these programmes, the task and expertise would be distributed in a collaboration manner with Indian Industry/ MSMEs/ Startups and Academia.

6. Chemical Sciences

6.1 ENERGY and ENVIRONMENT: *Innovations for a Sustainable Future Against Climate Change*

This ambitious goal to achieve net zero by 2070 necessitates the development of not only innovative materials capable of solar energy harvesting, green hydrogen production through watersplitting, and the conversion of CO_2 into valuable products, all using sustainable and efficient all-in-one materials, but also in principle, to take a holistic approach as to how to take these new materials and utilize them effectively in devices at a viable technological scale and do so at a relatively faster pace than what is currently being practised. Addressing the urgent challenge of climate change necessitates significant advancements in chemical science, aiming to create innovative molecules to materials and technologies capable of reducing greenhouse gas emissions, promoting renewable energy sources, and enhancing sustainability across diverse sectors.

Fundamental Breakthroughs and Discovery of Novel Molecules and Materials: Realizing this vision necessitates a comprehensive overhaul not only the goals and objectives, but also of our scientific methodologies and the development of adequate infrastructure. It is noteworthy that most of the groundbreaking achievements in materials science have originated outside India, including the development of aerogels, shape memory alloys, quantum dots, nanocrystals, high-temperature superconductors, metal- and covalent organic frameworks (MOFs, COFs), carbon nanotubes, perovskite solar cells, graphene, two-dimensional (2D) materials beyond graphene like MXenes, quantum materials for computing qubits like nitrogen-vacancy centres, and flexible and stretchable electronics. Even none of the catalysts currently used in industrial processes have been discovered in India.

To realize the aforementioned objectives, the vision, is to establish an Institute of Scientific Excellence dedicated to materials and solar energy, as the National Centre of Solar Energy (NCSE).

Mirroring the success of institutions like the National Centre for Biological Sciences (NCBS), the National Centre for Radio Astrophysics (NCRA), this centre would serve as a focal point for solar energy research, uniting experts from various fields under a single mission to harness the power of the sun for India's energy needs.

The proposed NCRA signifies the strategic importance of solar energy technologies for India's sustainable development. By leveraging advancements in chemical science to improve solar energy harvesting and utilization, this centre will play a crucial role in propelling India towards a sustainable and energy-secure future.

The complexity of materials science and solar energy research necessitates the collaboration of synthetic chemists, spectroscopists, theorists, and chemical engineers. By bringing together the best minds in these fields, the centre will foster an environment of interdisciplinary collaborative excellence. The proposed national centre will serve as a focal point for conducting high-quality fundamental and translational research in solar energy, materials and CO_2 capture-conversion, aimed at combating climate change.

The centre can concentrate its efforts on various research topics, including: *All-in-One Solar Harvesting and Catalytic Transformation Materials; Advanced Energy Storage Materials; Next-Generation Solar Photovoltaics; Biodegradable and Recyclable Plastics; Water Purification and Desalination Materials*.

By focusing on these research areas, the centre would be able to contribute significantly to advancing sustainable energy technologies and addressing the challenges posed by climate change. Additionally, collaboration with academia, industry, and international partners can enhance the centre's impact and foster innovation in this crucial field. NCSE is poised to deliver a multitude benefits, including:

- Cutting-edge Research: NCSE will serve as a hub for cutting-edge research in chemical and materials science and solar energy technology, fostering innovation and pushing the boundaries of scientific knowledge.

- Technology Incubation Centre: The outcome of basic research must help in the developmentof commercial products and technology to help resolve societal challenges. In order to translate such potential into a reality, technology parks/incubators geographically embedded inside the campus need to be built. The policies for such a Centre will be based along with the more "open" consultancy and start-up guidelines to fulfil the “Invent-in-India” and “Make-in-India” dreams.

- Skill Development: By offering specialized training programs and academic courses, NCSE will nurture the next generation of scientists and engineers, equipping them with the skills and expertise needed to excel in the fields of materials and solar energy.

- Industry Partnerships: Through strategic partnerships with industry stakeholders, NCSE will facilitate technology transfer and commercialization of research outcomes, driving economic growth and fostering a vibrant ecosystem for solar energy innovation.

This proposal is a strategic vision for leveraging material innovations to combat climate change, emphasizing the need for ground-breaking research, state-of-the-art infrastructure, and collaborative excellence.

6.2 Beyond Exascale: Leading the Nation Towards Higher Performance Computing

Research in the Chemical Sciences across DAE units aims to further our fundamental understanding of how nature works at electronic and molecular scales and apply such understanding to tackle problems of societal relevance such as the development of clean/sustainable energy solutions and the diagnosis/treatment of diseases. Computational research in the Chemical Sciences is used in both deductive and predictive fashions. Computational modelsare used to rationalize experimental observations and develop design principles for molecular design. The design of molecules which can self-assemble into desired architectures, absorb solar energy efficiently, convert light excitations into charge flow, and electronically couple to inorganic substrates is a requirement in the quest for clean sustainable energy solutions. Computational drug design, on the other hand, aims to design molecules which can shut down orturn on the activity of specific proteins/enzymes while avoiding non-specific interactions with therest of the cellular machinery. Researchers in the chemical sciences at DAE units are today well poised to spearhead both fundamental and applied aspects of Chemical Science research. However,development of a globally competitive high-performance computational infrastructure is asignificant milestone in this effort. DAE has an opportunity to develop a unique andglobally competitive computational facility which will catapult the nation into the forefront of computing technologies.

We envision a DAE-wide computing centre which possesses state-of-art commercial hardware tech in terms CPUs, GPUs, field programmable gate arrays (FPGAs), and Tensor Processing Units (TPUs) along with cutting-edge software technology which is AI/ML enabled. A unique aspect of the centre in enabling the indigenous development and deployment of emerging technology to provide an edge over global competition. Researchers in the chemical sciences are well suited to lead these efforts with emerging technologies with specialized expertise in developing molecular qubits based on electron-paramagnetic/spin resonance spectroscopy, molecular electronic integrated circuits with components such as resistors, diodes, switches, and transistors, and quantum computing algorithms tailored to specific applications in quantum chemistry. Some of this expertise is already present within the DAE system and can be augmented by focused hiring in aligned areas. This facility will serve as a hub for research and applications of cutting-edge hardware and software technologies, providing us with a globally competitive edge in delivering impactful research:

- Artificial intelligence and machine learning tools: This has taken the world by storm over the last decade. With continuous theoretical developments in the field, we are at a crossroads where the applications of this field can be varied and limited only by our imagination. In a completely different application, deep neural networks are now being used to successfully understand atomic interactions. Fitting and predicting the interactions between atoms in a complex chemical system at high levels of accuracy are being made possible through frameworks like DeepMD. This enables for the first time the prospect of simulating reactive chemistry at an atomistic level for large systems.

- Quantum Computing: The vision is to lead research and development efforts in quantum algorithms, hardware, and software frameworks to unlock the transformative potential of quantum technologies. Quantum technologies can influence areas of chemistry such as sensing and computing. While fundamental breakthroughs have occurred in areas of superconducting qubits, it is unclear how these will be scaled up. Researchers in the chemical sciences at DAE units can provide a bottom-up approach towards the scalable design of qubits.

- Molecular Electronics for Next-Gen Hardware: A major challenge in this field is to fit in the molecular componentsto create an integrated circuit which actually performs useful computations. TIFR chemists have for the first time translated the concept of an electronic breadboard to the molecular scale. The researchers have shown a way to combine five molecular circuits within the same scaffold. At present, it is imperative to generate a technological setting wherein researchers can screen molecular scaffold libraries and test them for their computing capabilities and integrate molecular electronics into the existing computing hardware infrastructure.

- Long-Time Scale Simulations: Researchers in the chemical sciences at TIFR have expertise in developing high-performance algorithms for studying the motion of quantum particles like electrons and excitons, and for understanding the motion of large biomolecules like proteins and DNA. A fundamental understanding of these motions and subsequent structural changes iscritical for designing energy-harvesting molecules & materials and discovering chemical, biological, as well as opto-electronic properties of biomolecules

  The DAE Centre would thus fast-forward millisecond simulation for molecular dynamics of biomolecules and nano-second ab initio simulations of electronic motions and energy transfer. The Centre would enable much-needed virtual solutions to nations' health, energy and technology needs.

7. Materials for Fundamental Science Energy and Environment

India's materials research initiatives are strategically aligned with the Sustainable Development Goals (SDGs), playing a crucial role in driving the nation's economic growth and environmental sustainability. By fostering collaborations across academic institutions, government agencies, and industrial sectors, India is poised to make significant strides in key priority areas. A major focus of this research is expanding renewable energy capacity to 450 GW by 2030, a vital step towards achieving net-zero carbon emissions by 2070. This involves developing advanced materials for solar cells, wind turbines, and energy storage systems to enhance efficiency and affordability. Additionally, India aims to reduce emissions by 45% by 2030 through the transition to low-carbon technologies and the adoption of hydrogen technologies. The country also targets a semiconductor revenue of $300 billion by 2026 and a quantum technology industry worth $90 billion by 2030. Materials research is essential for developing cutting-edge semiconductors and quantum devices, which underpin advancements in computing, communication, and defense.

Advancing Sustainable Development Goals through innovative material research in India

Moreover, materials research is vital for creating sustainable infrastructure and manufacturing processes. This includes designing lightweight, durable materials for construction, developing smart cities with advanced materials for energy efficiency and waste management, and creating eco-friendly materials for manufacturing. To achieve these ambitious goals, India must invest in its R&D workforce, streamline policies, and foster collaborations to establish a materials-based economy. By enhancing individual-centric research with large-scale material networks aligned with technology deliverables, India can drive innovation and economic growth.

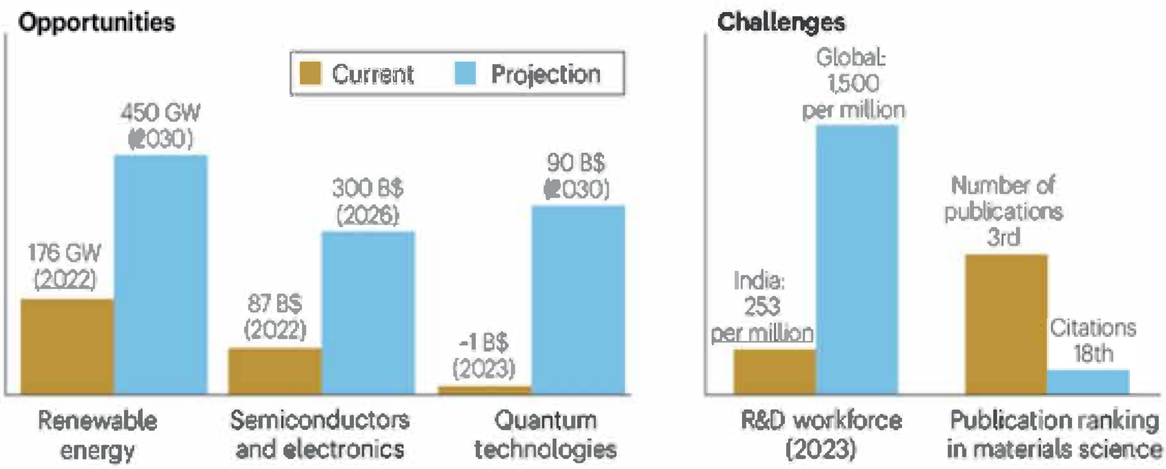
The critical role of materials research in India's economic development underscores the need for strategic partnerships and a cohesive ecosystem to bridge the gap between academic, government, and industrial sectors. Streamlined and transparent policies in areas such as equipment purchase, project funding, and engagement with overseas experts are crucial for maximizing research efficiency and supporting India's goal of becoming the third-largest economy globally.

Transforming the nation’s future through materials research focuses on two key objectives: exploring abundant materials for sustainable development; and promoting a circular economy.

According to Nature Review Materials 2024, the power generated from renewable energy sources is expected to increase from 176 GW to 450 GW by 2030, while semiconductor and electronics revenue is projected to rise from $87 billion in 2022 to $300 billion by 2026. In the realm of quantum technologies, revenue is anticipated to grow from less than $1 billion in 2023 to $90 billion by 2030. The vision for 2047 in materials science emphasizes the exploration of the country's energy resources, including nuclear materials, multifunctional materials, and materials for healthcare and sustainable living. Achieving these objectives requires a deep understanding of materials, extensive characterization, application, and benchmarking. India can unlock its full potential and contribute to a more sustainable future for all.

The proposed energy materials research theme aims to accelerate developing, testing, and deploying advanced materials for various energy applications, supporting India's transition towards a sustainable, low-carbon future. The key elements of this research theme include:

Semiconductor Fabrication Hub: Establishing a dedicated semiconductor fabrication hub equipped with state-of-the-art device and interface engineering facilities is critical to advancing the development of next-generation solar cell technologies. This hub will focus on enhancing the entire solar cell production process, including crystal growth, wafer processing, thin-film deposition, and device fabrication. By concentrating expertise in these areas, the hub will facilitate the innovation of more efficient solar cells, which are essential for meeting the growing global demand for renewable energy.

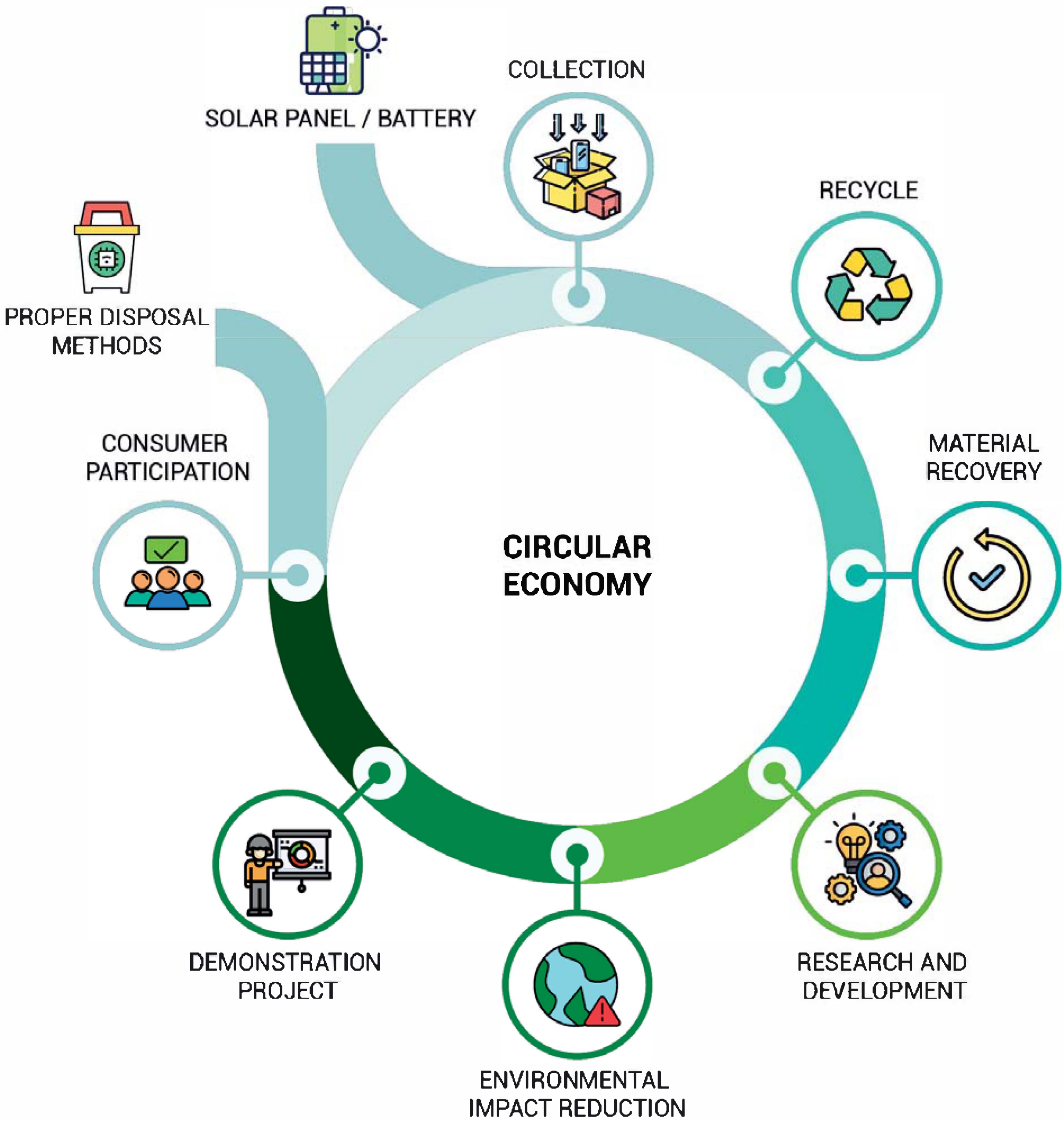


Opportunities and Challenges in the semiconductor manufacturing and quantum sectors in India. Data from SJR - International Science Ranking and the UNESCO science report.

The integration of advanced technologies and methodologies will allow for the production of solar cells with improved efficiency and lower production costs, ultimately contributing to a more sustainable energy future. Central to the hub's operations will be the development of cutting-edge techniques in crystal growth to create large, defect-free crystals for solar cell fabrication. Wafer processing will involve advanced methods like plasma etching and chemical vapor deposition (CVD) to ensure optimal surface quality and electrical properties. Thin-film deposition techniques, including sputtering and atomic layer deposition, will be utilized to create innovative solar cell architectures that enhance light absorption and conversion efficiency. Furthermore, the hub will focus on device fabrication processes that integrate these advanced materials into functional solar cells, ensuring that the final products meet industry standards for performance and reliability. To support this initiative, collaboration with academic institutions, research organizations, and industry leaders will be essential, leveraging collective expertise and resources to drive innovation and accelerate the commercialization of new solar technologies. As the solar energy market expands, the semiconductor fabrication hub will play a pivotal role in positioning the region as a leader in solar cell technology, contributing significantly to global efforts in renewable energy production and sustainability.

Incubation Centres: Creation of incubation centres to nurture the translation of research outcomes into practical applications, fostering collaborations between academia, research institutions, and industry. These centres will help bridge the gap between laboratory prototypes and commercially viable products.

Recycling Program: The initiation of a dedicated program for recycling batteries and solar cells is crucial to address the growing need for sustainable end-of-life management of these components. As the use of batteries, particularly lithium-ion types, and solar panels increases, managing their disposal becomes a significant challenge. This program aims to develop innovative technologies and processes for the efficient recovery and reuse of valuable materials from spent batteries and solar panels, including metals like lithium, cobalt, and nickel, as well as critical materials from solar cells, thereby reducing environmental impact. To implement this program effectively, a comprehensive approach will involve research, development, and demonstration projects.



Socio-economic depiction of circular and Make-use-dispose economy

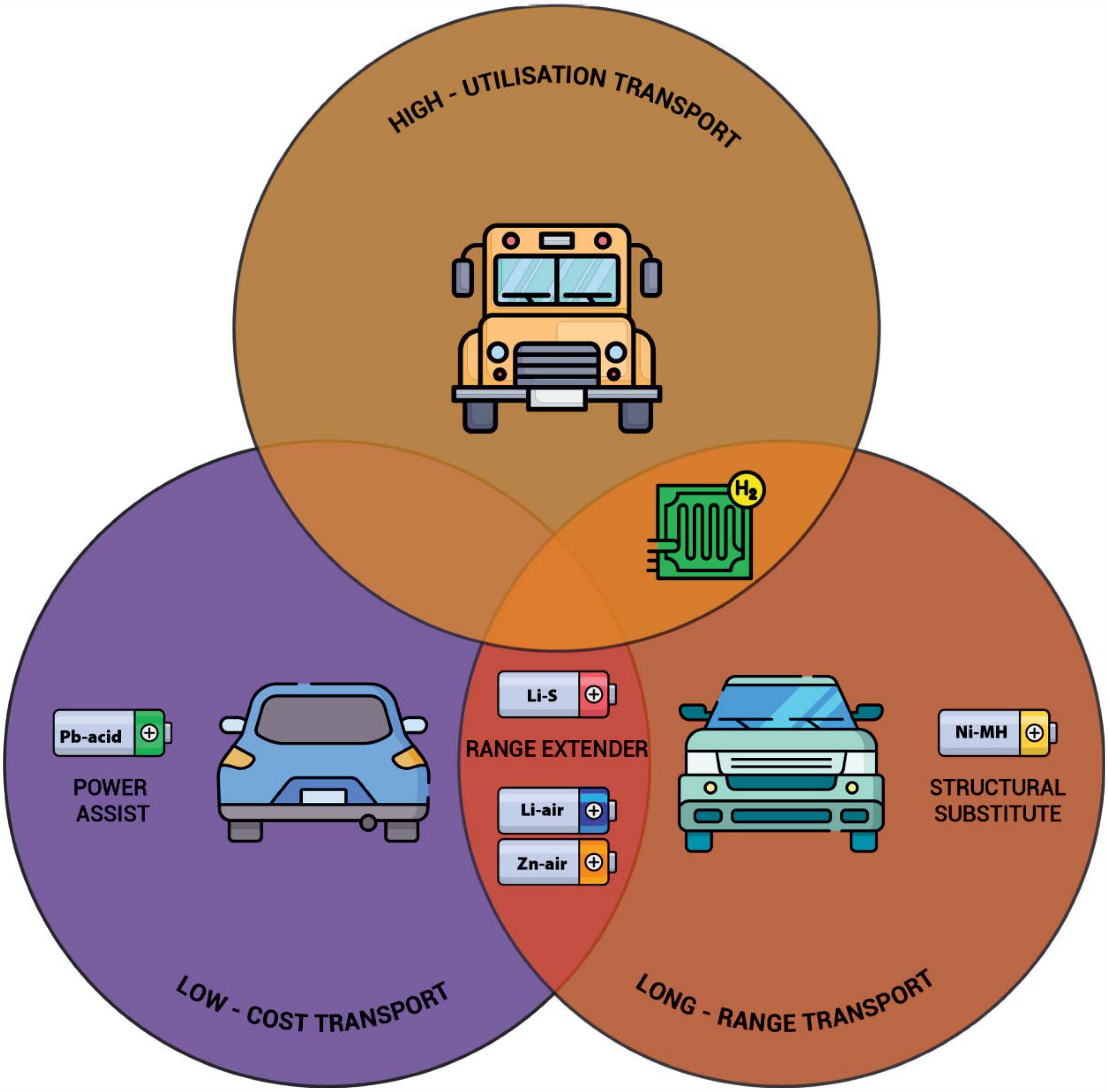
Funding will support initiatives that promote designing batteries and solar cells with recycling in mind, ensuring easier dismantling and material recovery. Strategies will also be developed to enhance consumer participation in recycling programs, addressing barriers to recycling and raising awareness about proper disposal methods. The program will prioritize integrating recycled materials back into production, fostering a circular economy that minimizes waste and maximizes resource efficiency. Collaborations with academic institutions, research agencies, and industry stakeholders will help create a robust infrastructure for recycling, including collection points and processing plants. Ultimately, this initiative represents a significant step toward sustainable management of battery and solar cell waste, contributing to a greener future and supporting global climate change efforts.

7.1 Advanced Energy Storage Systems

Development of high-energy and high-power density electrochemical batteries, including novel concepts like solar batteries and nuclear batteries, high-power density supercapacitors, and waste heat management systems. The focus will be on indigenous materials-based solutions, leveraging the expertise across DAE institutions.

Rechargeable electrochemical energy storage, particularly batteries, stands out as a highly efficient method for storing electric energy, a crucial and versatile form of energy, in the form of chemical energy. Currently, lithium-ion batteries (LIBs) dominate the electronics market; however, their limited gravimetric energy density (~250 Whkg-1) compared to fossil fuels like gasoline (~13000 Whkg-1) restricts their use in high-energy applications such as electric vehicles (EVs). To address this, the development of alternative battery technologies, including metal-air batteries (MABs) and fuel cells, is essential. MABs, leveraging gas as an electrode component, offer ultra-high energy densities comparable to gasoline, making them promising for long-range EVs.

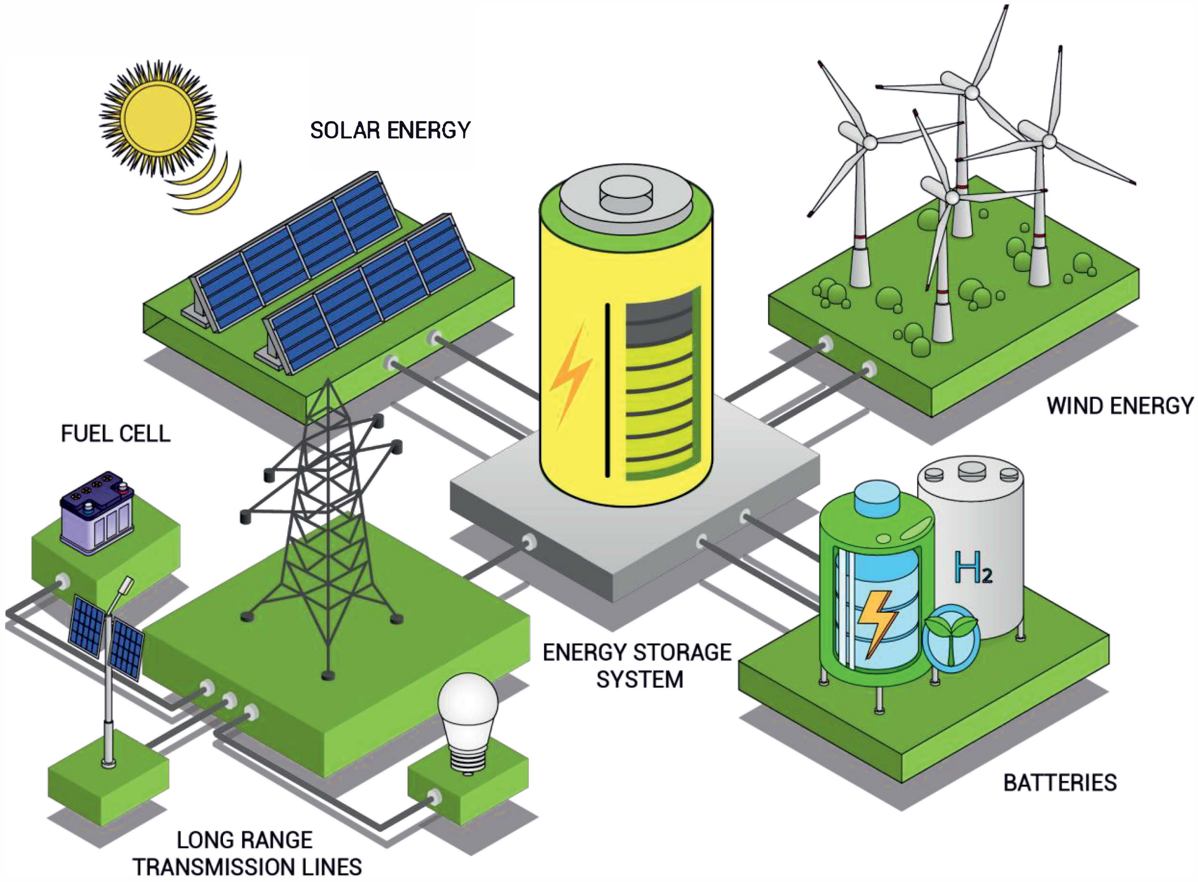
Overcoming challenges like self-discharge, extended cyclability, and suppressing parasitic reactions is crucial for successfully developing high-performance MAB systems, which also hold potential for mini-grid energy storage, replacing existing Pb acid-based systems. The proposal aims to develop a 10kWh capacity MAB (Zn-based) battery pack, highlighting the importance of integrating MABs with higher power density systems like supercapacitors for mini-grid applications, ensuring the utilization of Indigenous materials-based technologies. This comprehensive plan involves fundamental chemistry, physics, and electrical engineering studies, emphasizing collaborative efforts across different institutions to advance electrochemical battery technologies. The electrochemical battery plans encompass a range of advancements beyond lithium-ion batteries, exploring alternatives like sodium (Na), potassium (K), aluminium (Al), and others. The focus extends to developing safer, high-energy density metal batteries, particularly lithium-based systems, high-energy density metal-air batteries utilising materials like zinc (Zn), aluminium (Al), and iron (Fe), high-power density supercapacitors, fuel cell technologies, piezoelectric generator development, thermoelectric energy harvester development, and the creation of highly efficient and durable catalysts. This multifaceted approach aims to revolutionise energy storage technologies, enhancing efficiency, safety, and sustainability across various applications.



Suitability of alternative batteries and fuel cells to emerging EV markets.

Renewable Energy Harvesting: Advancement of stable and efficient semiconductor technologies for solar cells, optimisation of materials, understanding interfaces, effectively coupling harvesting and storage systems, and evaluating carbon footprints. This will involve device and interface engineering to overcome the Shockley-Queisser limit and improve the efficiency of photovoltaic technologies.

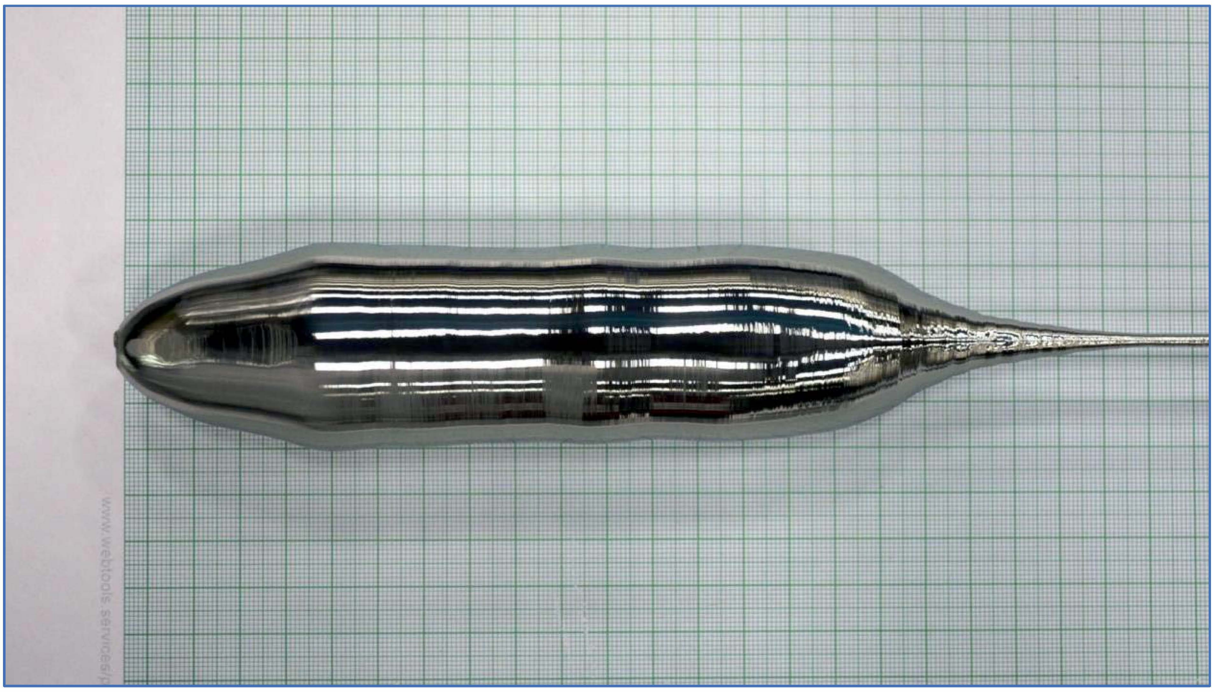
Decentralised Energy Platform: Development of a decentralised energy harvesting and storage platform to identify and implement micro- to megawatt energy storage system solutions, including waste heat management and recycling technology. The aim is to support the transition towards a distributed, sustainable energy ecosystem.



Integrated renewable-decentralized energy systems

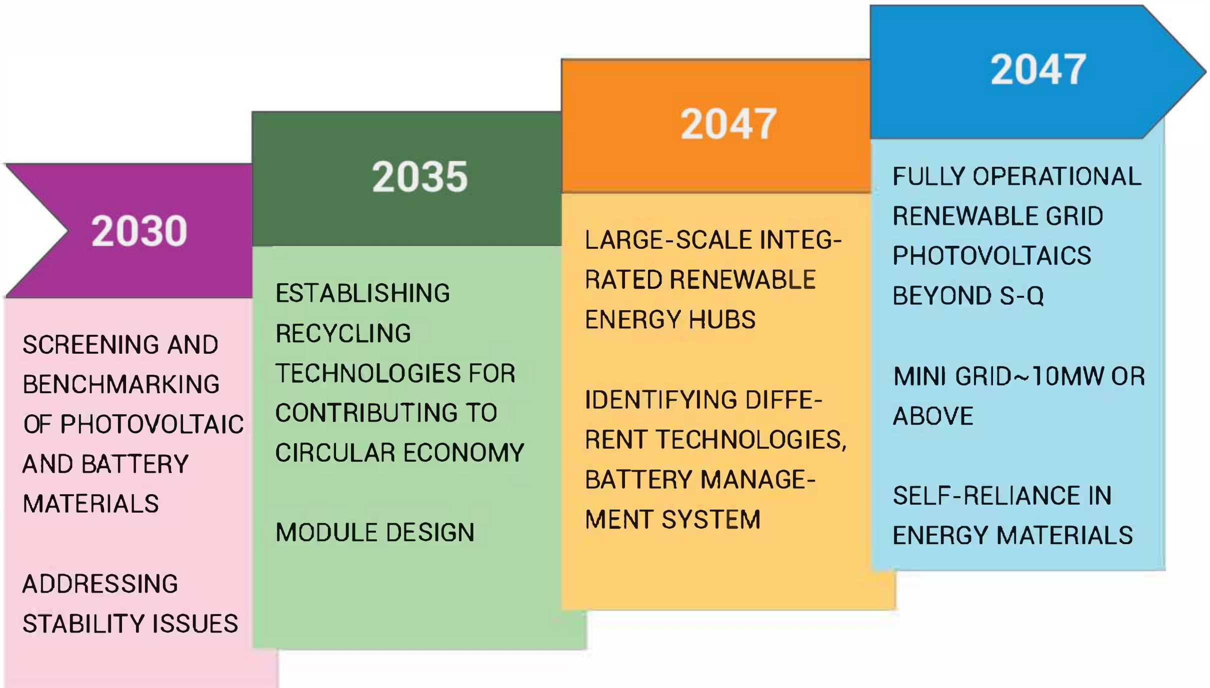
7.2 Radiation detectors:

Gamma-ray detectors are vital across various fields, such as medical imaging, nuclear physics, and environmental monitoring. Developing these detectors involves refining fabrication processes to ensure high quality consistent detector crystals. Additionally, there is significant research into semiconductor-based detectors, particularly high-purity germanium and silicon, which offer superior energy resolution but face challenges in producing large crystals. Advanced crystal growth techniques are being employed to enhance the availability of high-performance detectors for precise gamma radiation measurements. Recent advancements in gamma-ray detector technology have focused on enhancing the performance characteristics of existing materials while also exploring novel compounds. Researchers are investigating new scintillator materials that could potentially offer better light output and faster response times. For example, materials like perovskite crystals and organic scintillators are being studied for their promising properties, which could lead to improved detection capabilities in various applications.



High Purity Ge single crystal for radiation detectors developed by BARC

Additionally, hybrid detectors that combine scintillation and semiconductor technologies are being developed to leverage the strengths of both detectors, aiming to achieve higher sensitivity and better energy resolution. The applications of gamma-ray detectors are continually expanding, driven by advancements in technology and increasing demands for safety and security. In medical imaging, these detectors are crucial for improving the accuracy of diagnostic procedures such as PET scans and SPECT imaging. In the realm of nuclear security, enhanced gamma-ray detection capabilities are essential for monitoring and preventing illicit trafficking of radioactive materials. Ongoing research is expected to focus on miniaturization and integration of gamma-ray detectors into portable devices, enabling real-time monitoring and analysis in diverse environments. As the need for precise radiation detection grows, the future of gamma-ray detectors promises exciting developments that will enhance their effectiveness across multiple domains.

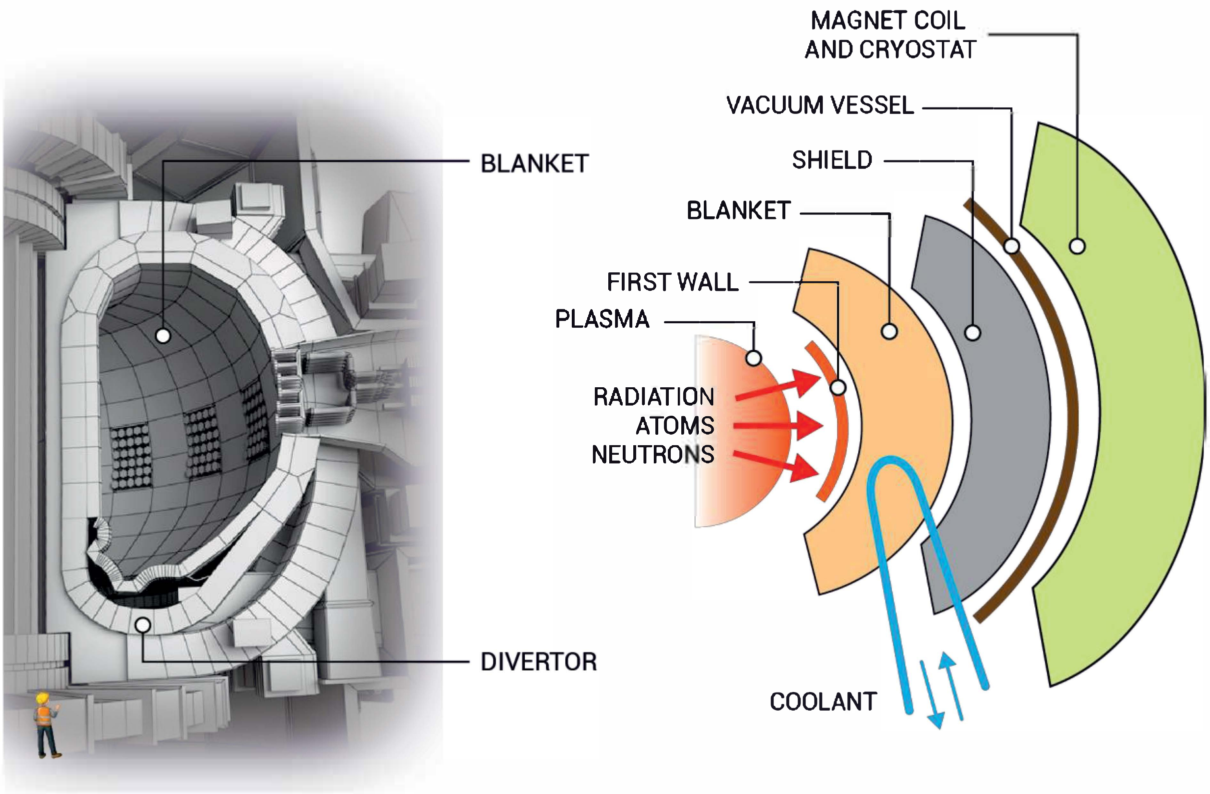


Vision for Energy Materials Research

7.3 Fusion Reactor Materials Research

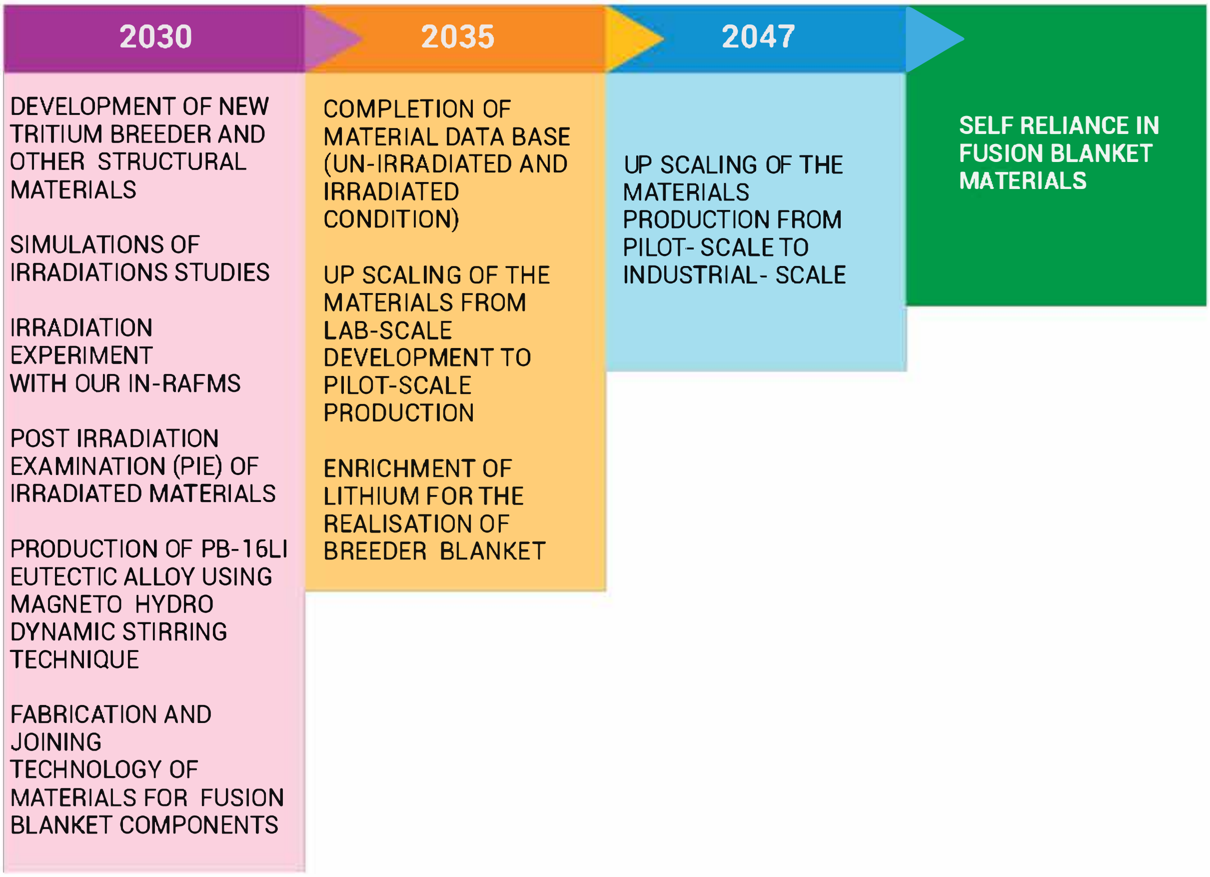
This section highlights the critical requirements for various activities to achieve readiness by 2047 for commencing the construction of a DEMO fusion reactor in India. The key focus areas include:

Fusion Blanket and Plasma Facing Materials: Development, characterization, material joining technologies, fabrication technologies, irradiation studies, post-irradiation examination studies, materials modelling, and simulations to produce large-scale materials and fusion studies, materials modelling, and simulations to produce large-scale materials and fusion reactor components. This involves expertise and facilities to study material interactions with neutrons, develop tritium breeders, neutron multipliers, tritium permeation barriers, and neutron shielding, while minimising activation and transmutation.



Schematic of the Fusion Reactor

Liquid Metal Plasma Facing Components (PFCs): Development, characterization, and testing of Liquid Metal alloys, fabrication and testing of Liquid Metal PFCs, and the establishment of experimental facilities to test these components under thermal, electromagnetic, and plasma loads.



Vision for Fusion Blanket Materials

This requires expertise and facilities for high-temperature loops, high-pressure high-temperature pumping systems, and characterization under plasma conditions.

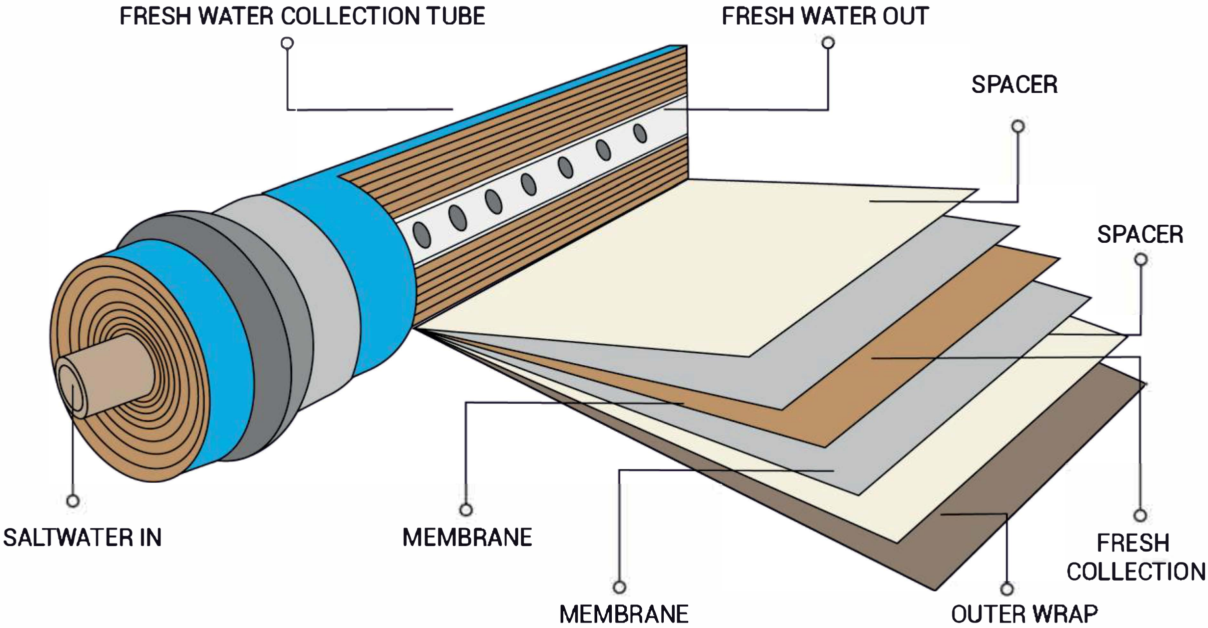
High Power Electron Beam System: Development of a 200kW/50kV Dual Electron Beam Guns system, including dry type-high voltage transformer, low and high voltage power supplies, beam deflection system, data acquisition and control system, and software for beam scan pattern programming. This enables the simulation of high heat flux conditions on PFCs to study material behaviour and advanced PFC designs.

High Temperature Superconductor and Prototype Magnet: Activities involving HTS tape design and fabrication, quench detection and protection systems, current leads for high currents, nano-ohm resistance joints, coil winding technology, and neutron irradiation studies on relevant materials. This initiative requires raw materials, major fabrication facilities, and a skilled workforce to develop and characterize HTS tapes.

7.4 Sustainable technology for purification

Materials play a vital role in addressing global health and sustainability challenges, particularly in energy-efficient filtration, desalination processes, and water harvesting.

d



Membrane based sustainable water purification system

Energy-efficient filters are critical for removing contaminants and pollutants from air and water while minimizing energy consumption. Advanced filtration materials, such as nanoporous membranes, activated carbon, and graphene-based filters, offer high surface area and selective adsorption properties, allowing for the efficient removal of particles, gases, and organic compounds from fluids. These materials can be tailored to target specific pollutants, including fine particulate matter, volatile organic compounds (VOCs), and heavy metals, contributing to improved air and water quality in both indoor and outdoor environments.

Desalination technologies are essential for addressing water scarcity by converting seawater or brackish water into potable water. Energy-efficient desalination processes, such as reverse osmosis (RO) and membrane distillation (MD), rely on specialized membranes and materials to separate salt and other impurities from water while minimizing energy consumption. Thin-film composite membranes, forward osmosis membranes, and novel nanostructured materials enable higher water permeability and salt rejection, improving desalination efficiency and reducing energy requirements. Additionally, innovations in renewable energy integration, such as solar-powered desalination systems, further enhance the sustainability of desalination processes by reducing reliance on fossil fuels.

Water harvesting technologies capture and store rainwater or moisture from the atmosphere for various uses, including irrigation, drinking water supply, and ecosystem restoration. Porous materials, such as hydrogels, zeolites, and metal-organic frameworks (MOFs), exhibit high water absorption capacities and can be incorporated into passive or active water harvesting systems. These materials selectively adsorb water vapor from the air under ambient conditions and release it upon heating or exposure to lower humidity, enabling efficient water capture in arid and semi-arid regions. Additionally, biomimetic materials inspired by natural water collection mechanisms, such as fog-harvesting surfaces and dew condensation devices, offer innovative solutions for harvesting water from fog, dew, and humid air, contributing to sustainable water management practices worldwide.

7.5 Computational methods for Material Science

Computational methods have become an indispensable tool in materials science, as it allows for better understanding, selection, design, optimization, and integration of materials with engineering applications. We can utilise computational methods for material science by leveraging the Inorganic Crystal Structure Database (ICSD) and selecting the optimal combination from data fed into Artificial Intelligence (AI) systems. The integration of artificial intelligence (AI), especially machine learning, into computational materials science research has become a new trend, enhancing materials design, synthesis, property predictions, and accelerating materials development. The use of computational methods, such as density functional theory (DFT), molecular dynamics (MD), and phase-field methods, allows for a deeper understanding of material behaviour across different length and time scales, enabling the prediction of material properties and the optimization of synthesis processes. Additionally, the availability of powerful computing resources has facilitated the application of complex computational techniques in materials science, leading to advancements in materials design and optimization.

Utilizing advanced supercomputing capabilities and cutting-edge methodologies, the Materials Project offers accessible web-based resources containing computed data on existing and potential materials, alongside robust analysis tools aimed at stimulating the innovation and creation of novel materials. Emphasizing the critical role of strategic partnerships and a cohesive ecosystem to bridge the gap between academic, government, and industrial sectors, and to support India's goal of becoming the third largest economy globally.

Pathways for propose Material Research

In summary, the exploration and development of advanced materials for fundamental science and environmental applications are crucial in addressing the pressing challenges of energy efficiency, sustainability, and climate. Collectively, these efforts in material science not only drive technological innovation but also align with global sustainability initiatives, fostering a more resilient and environmentally friendly future. The integration of these advanced materials and technologies will play a pivotal role in achieving energy independence, enhancing public health, and promoting societal well-being through cleaner and more efficient energy solutions.

8. Quantum Science & Technology

Quantum technology has emerged as a frontier in the realms of physics and engineering, embodying an array of technologies derived from the tenets of quantum mechanics. These technologies seek to exploit the ideas of quantum entanglement, quantum superposition, and quantum tunneling, where control is exerted over single quantum entities such as single photons, single spins etc. This burgeoning domain encompasses a diverse spectrum of advanced applications spanning quantum computing, sensors, cryptography, simulation, measurement, imaging, energy harvesting, and space navigation. Quantum technologies promise to bring about transformative changes in the technology landscape, casting profound influences on established domains such as space exploration, cryptography and data privacy, defense and internal security, sustainable energy innovations, nanofabrication, semiconductor advancements, and laser technologies.

Intersections with other themes: The subject of quantum science & technology has a wide overlap with other themes such as biology, materials for fundamental science etc. For example, these days scientists aim to work at the intersection between biology and quantum technology, seeking to deepen our comprehension of biological systems and enhance medical practices. This interdisciplinary pursuit holds promise for illuminating immunology, metabolism and other facets of medical science. Beyond its conventional roots in physics, selected branches of quantum technology may venture into realms such as biophysics, bio-imaging and microbiology, thereby broadening the horizons of its applications and fostering potential contributions across diverse scientific disciplines. Quantum technologies are expected to accelerate design and discovery of new materials for wide-ranging applications from nuclear reactor technologies to novel drugs and pharmaceutical products, which are the topics of interest under the themes of materials for fundamental science, energy, and environment, health sciences, and biology across scale and environments.

The field of quantum science and technology (QST) can primarily be divided into four verticals

A. Quantum computing & simulation
B. Quantum communication (discussed earlier in detail)
C. Quantum sensors and metrology
D. Quantum Materials & devices

In the Indian context the field of QST has already seen a significant attention and several achievements have been obtained. Herein the aim is to lay down a proposed roadmap that we hope would propel India at the forefront of research in quantum science and technologies.

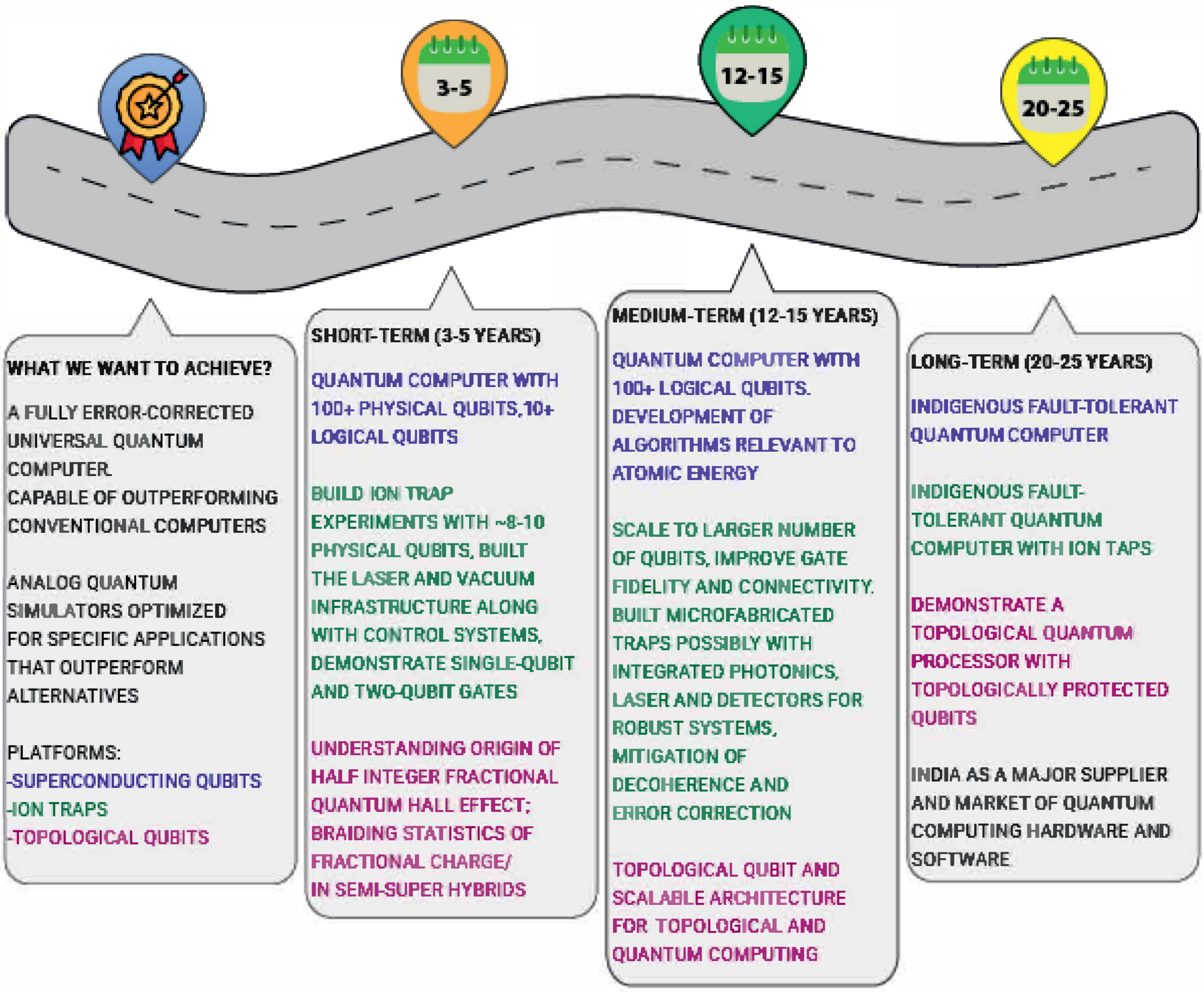
The four-thrust area of Quantum Science and Technology

The scientific, technology, healthcare and societal goals are, *Healthcare; Climate Change; Clean Energy; Novel Materials; Communication & Connectivity; and Fundamental Science and Technology.*

8.1 Quantum Computing and Simulation:

Quantum computers store and process information using quantum two level systems (quantum bits or qubits) which unlike classical bits, can be prepared in superposition states. This key ability makes quantum computers extremely powerful compared to conventional computers when solving certain kinds of problems like finding prime factors of large numbers and searching large databases. The prime factorization quantum algorithm has important implications for security as it can be used to break (Rivest-Shamir-Adleman) RSA encryption, a popular method for secure communication. In addition, quantum computers can be used to efficiently solve quantum mechanical problems which are otherwise intractable on a conventional computer. Since quantum mechanics is at the heart of most physical, chemical and biological phenomena, a quantum computer promises to revolutionize these fields by enabling us to model nature at a very fundamental level. This will potentially lead to the discovery of new molecules, novel materials, clean energy, effective medicines and a deeper understanding of nature. Some of these have been already listed in the previous section.

While several platforms for quantum computing are being pursued, superconducting electronic circuits operating at millikelvin temperatures have emerged as a leading candidate for a scalable quantum processor architecture. This architecture is also the most pursued approach in the world with major efforts in the United States, Europe, China, and Japan, including significant industrial efforts by companies like IBM, Google, Intel and Amazon to name a few. Ion-traps and cold atoms-based quantum computers have also emerged as a strong candidate for building practical quantum processors. On the other hand, topological qubits potentially offer an exciting platform that would not need error correction and hence would be simpler to scale up and expected to be more robust that other competing platforms. This platform is also being actively pursued in several leading research institutes and Microsoft. However, this technology is still in its infancy.

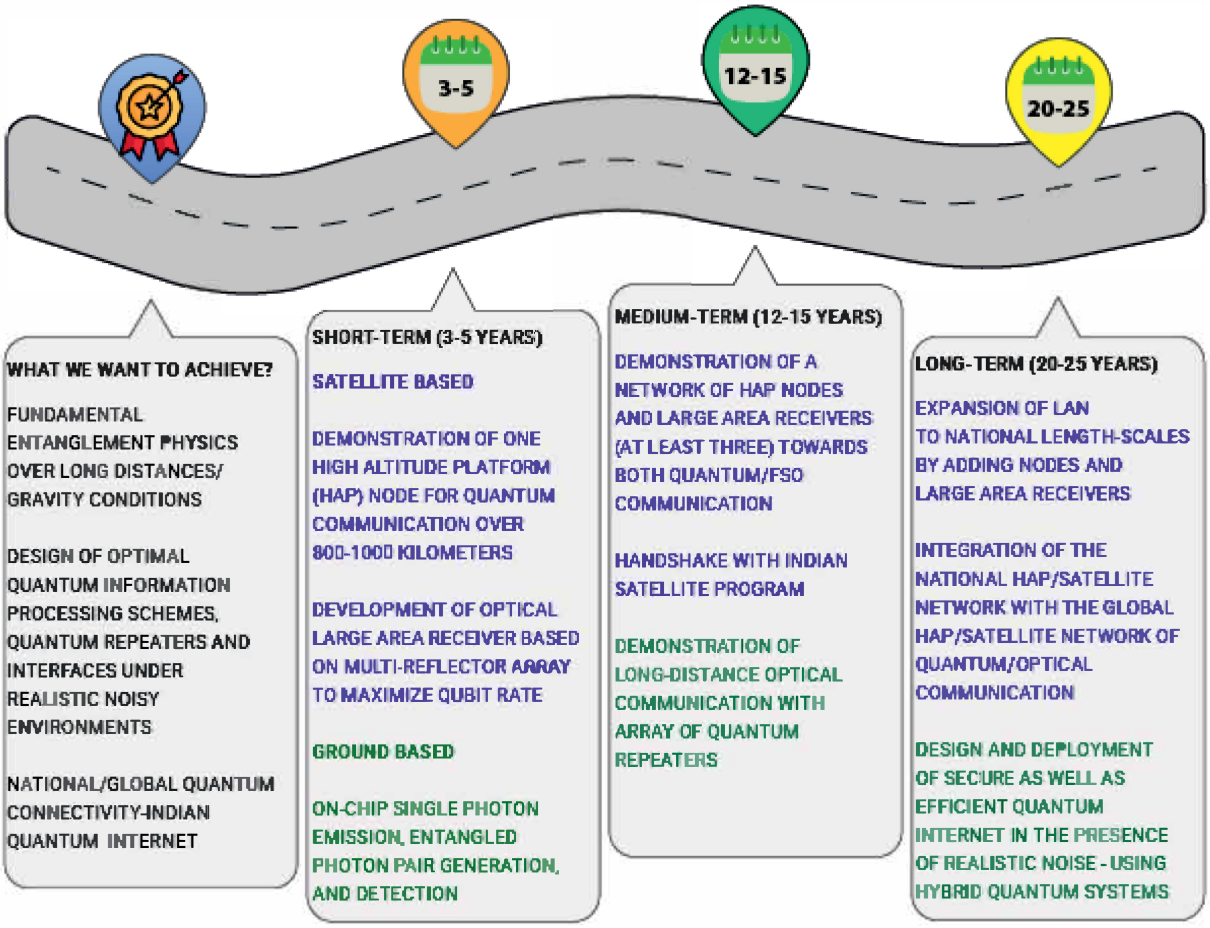


The Quantum Computing Roadmap

Within DAE, the development of a new type of ultra-low noise broadband quantum parametric amplifier for quantum measurements have been developed. Very recently, a fully functional six-qubit quantum processor based on transmon qubits has been developed. This is a joint work between institutes of DAE, DRDO, and TCS, where the quantum hardware, peripheral electronics, and cloud-based platform from where this quantum computer could be accessible has been developed by institutes of DAE, DRDO, and TCS, respectively. There is also work in progress on spin ensemble-based quantum memories for superconducting qubits. This can provide an alternative method to boost performance of quantum processors by combining long lived quantum memories with the fast-superconducting qubit-based processing elements. In addition, collaborations have been initiated between members of aided institutes and DAE core units on quantum control electronics and software, microwave components, and multi-qubit chip design.

8.2 Quantum Communication

This programme lays down the anticipated roadmap towards the development of a powerful high-speed national communications network that has the potential to connect any terrestrial location to any other within the country, with no restrictions on terrain, atmospheric conditions etc. The national network will be based on high-altitude platforms based on stratospheric balloons relaying data to and receiving data from wide-area optical receivers on the ground. The hardware on the payloads will be multi-pronged, a part of which will be aimed at quantum data, while the other part will cater to classical optical communication. This network will also be aimed at plugging into an envisaged global network created using dedicated satellites.

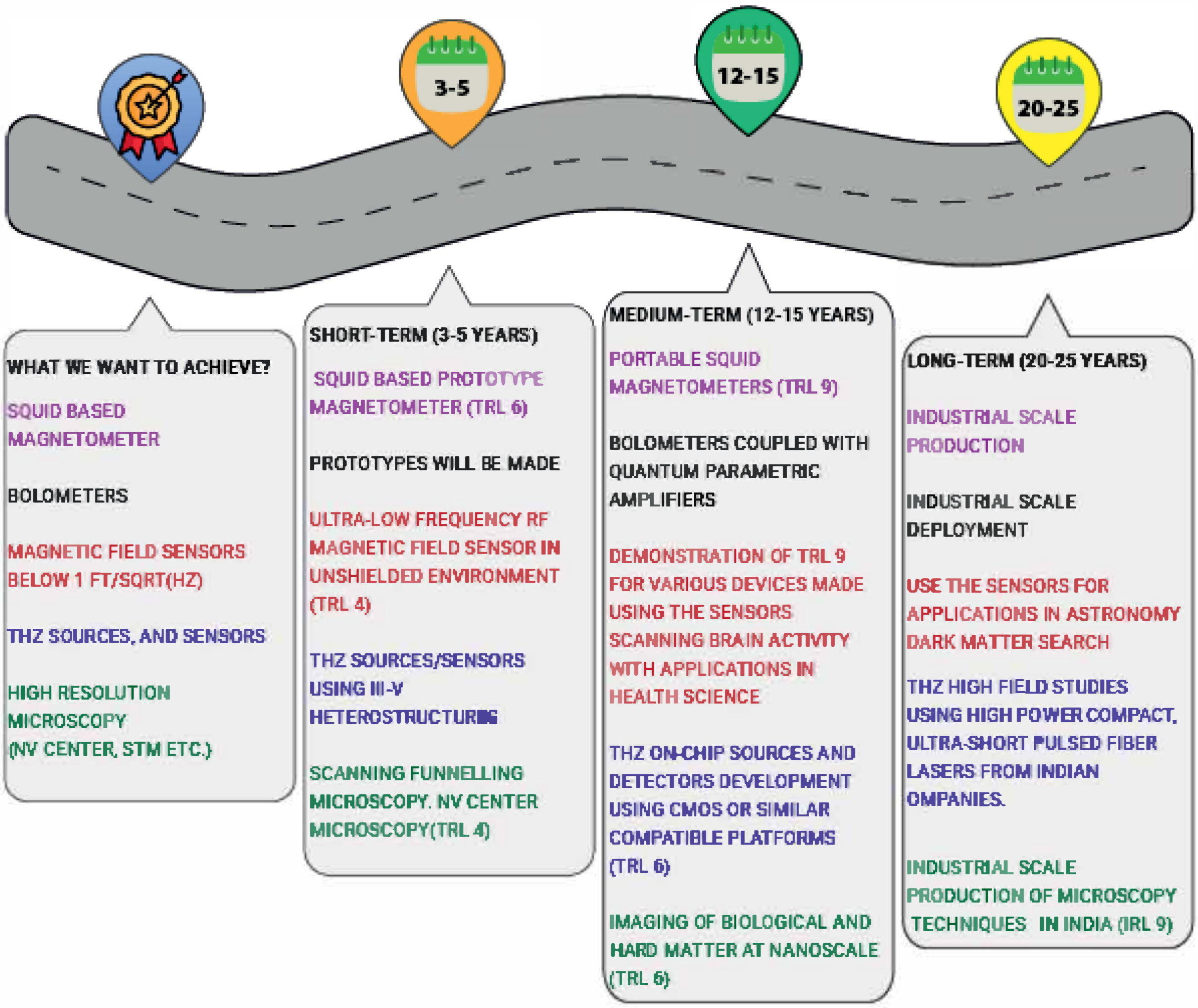


The quantum communication roadmap

8.3 Quantum Sensing and metrology:

Quantum sensing is one of the significant areas which uses quantum protocols of estimation and discrimination to outperform classical sensing strategies. The development of compact quantum sensing systems is crucial for their integration into portable devices for real-world applications. Miniaturization of components, efficient signal processing algorithms, and integration of multiple functionalities into a compact design are essential aspects of advancing quantum sensing technologies for widespread adoption in diverse fields. The focus of this roadmap is to look ahead to the next 25 years and beyond, where exploratory research and technology translation in quantum sensing and metrology both from a generic perspective as well as across specific areas of quantum sensing will be considered.

Researchers across DAE institutions are working on several theoretical and experimental aspects of quantum sensors/metrology including quantum advantage, development of realistic noise models etc. The roadmap for quantum metrology and sensing along specific research directions (but not limited to) are as follows:



The quantum Sensing and metrology roadmap

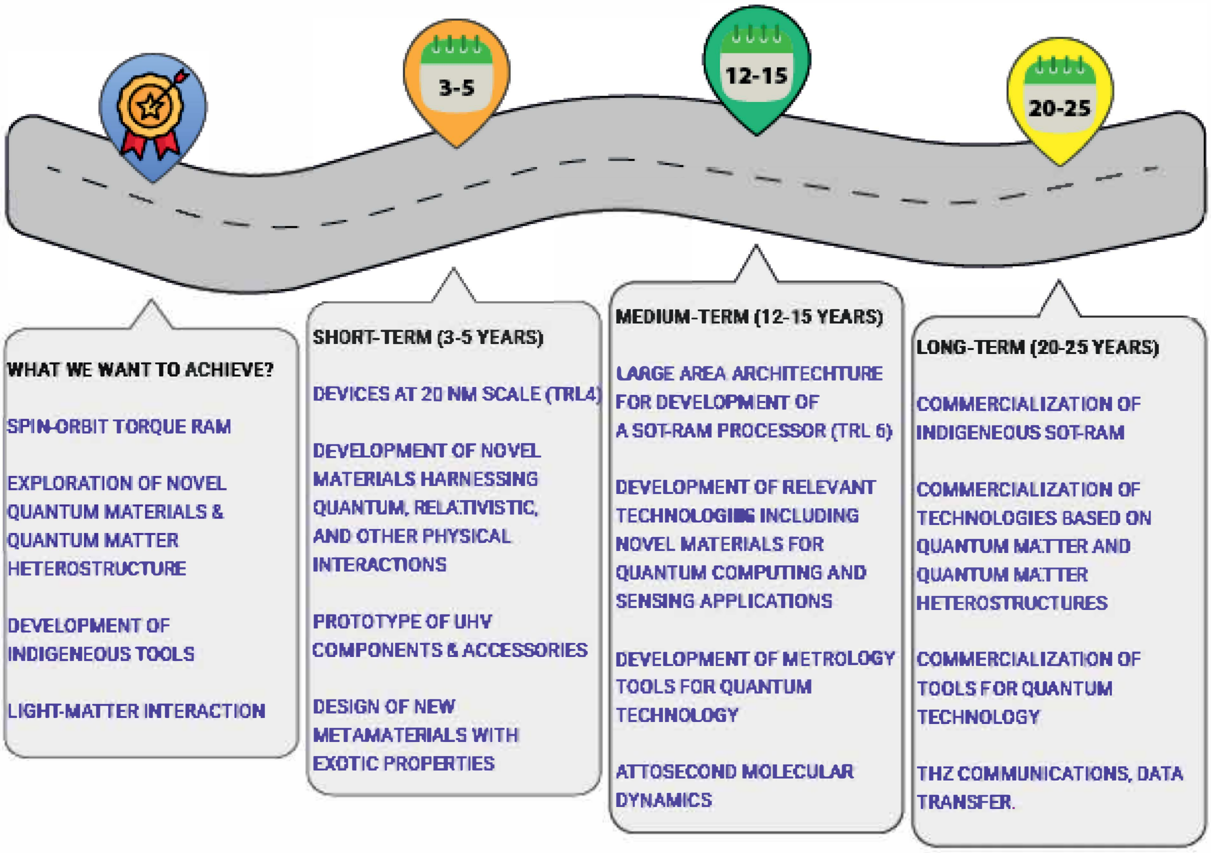
Apart from these specific directions, researchers are working on various other theoretical and practical aspects of quantum sensors and metrological devices, including quantum advantage, realistic noise models, breaking the Heisenberg limit, etc. In this context there is already collaboration between theory and experimentalists within DAE and more such exchange of ideas is envisioned.

8.4 Quantum Materials & Devices:

Quantum materials and devices form the foundational bedrock of advanced quantum technologies, serving as building blocks for groundbreaking innovations. These materials possess unconventional properties due to reduced dimensionality and strong electron interactions, resulting in quasiparticle excitations. The electronic properties of these materials are influenced by electron wavefunctions and their superpositions, leading to a variety of quantum states and phases, which are less classically described than conventional ordered states. Moreover, the role of intrinsic spin-orbit coupling (SOC) effects led to the prediction of materials like topological insulators and superconductors, and the experimental discovery of a new class of quantum materials characterized by topologically protected massless Dirac surface states. The convergence of research areas in the context of quantum technology is best exemplified by the coexistence of strong correlation, quantum criticality, and superconductivity in Moiré materials such as twisted bilayer graphene (TBG). Leveraging these materials, scientists craft sophisticated quantum devices, including qubits, quantum sensors, and quantum transducers. As researchers continue to push the boundaries of quantum materials and devices, they unlock new frontiers in technology, propelling us toward a quantum-enabled future. Research in quantum materials present significant opportunities in controlling and manipulating quantum states at the level of single quantum entities such as electron spin, single photons etc., necessitating extensive research to achieve stable and reproducible quantum properties.

Selected list of quantum materials that have drawn significant attention over last few decades. The materials listed on the right side are emerging materials and possess a lot of potential for quantum technology. Other materials shown with an asterisk (*) are also being studied in the theme of materials for fundamental science

Selected quantum materials for the proposed roadmap have been identified.



The quantum materials roadmap

The world of quantum materials consists of many more candidates under study and new quantum materials are expected to be discovered in time to come. In these materials many interesting and novel physical phenomena relevant to quantum materials and devices can be experimentally and theoretically observed such as, Majorana fermions; Spin Hall effect; Anomalous Hall effect; Quantum Correlations & fluctuations; Many body interactions; Entanglement; Topology; and Non-equilibrium quantum matter

In recent years, among these there is a new field of research called as "Spintronics" has emerged over the last few decades. The read-write head of computers are primarily a gift of spintronics. This field has been sub-divided into several sub-fields, which have their own merits for different types of applications.

An overview of different sub-topics of the emerging field of spintronics. These subject areas have a lot of potential applications.

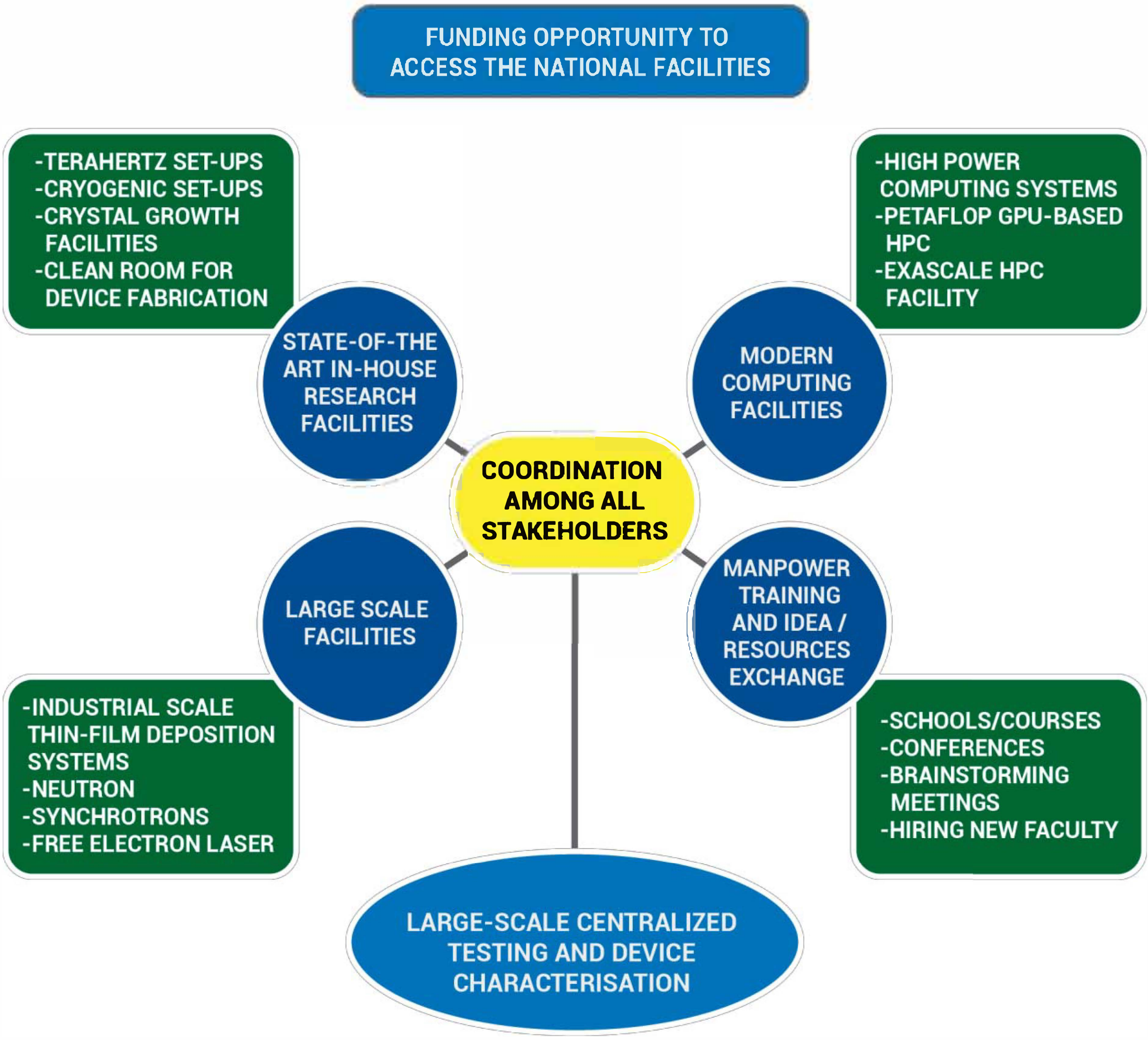
In the field of spintronics, several novel phenomena/effects are the timely topics, which need intense attention include Spin Hall effect; Anomalous Hall effect; Spin Seebeck effect; Spin Peltier Effect; Spin Nernst effect; Rashba-Edelstein effect; Topological Hall effect; Terahertz dynamics; and Magnon Hall effect.

8.5 A proposed centre for "Quantum Science and Technology":

Many researchers in India working on Quantum Science & Technology opined that a big research centre should be opened. In this centre we can hire new faculty and PhD students.

But most importantly in this centre a huge technical support may be incorporated who can help the scientists to improvise the technology readiness levels (TRL) from 2 or 3 to TRL level about 7. The centre should have a state-of-the-art workshop, a dedicated section consisting of engineers who can help in making devices and testing its performance. The new centre can be housed in any of the DAE units/aided institutions or may be established at a new place.

It is desired to have adequate scope for hiring new manpower and training of existing manpower in this emerging technology. We need to hire at the level of scientists, engineers, senior technicians at different DAE units and institutions who can dedicatedly work in the project related to quantum science and technology. At the same there will be opportunity for PhD students and postdocs who can be involved in various projects of quantum science & technology and on occasions can move to scientist positions. We need to develop an ecosystem which will offer a platform for developing our knowhow and at the same time will be able to generate sufficient trained and skilled manpower to innovate, generate and maintain the applications related to quantum technology. This goes in line to the concept of "AtmaNirbhar Bharat". In this context, summarizes our approaches which will be highly required for a sustainable ecosystem in the field of quantum materials & devices.



A chart depicting the requirements to achieve remarkable progress and obtain significant deliverables in the field of Quantum Materials & Devices.

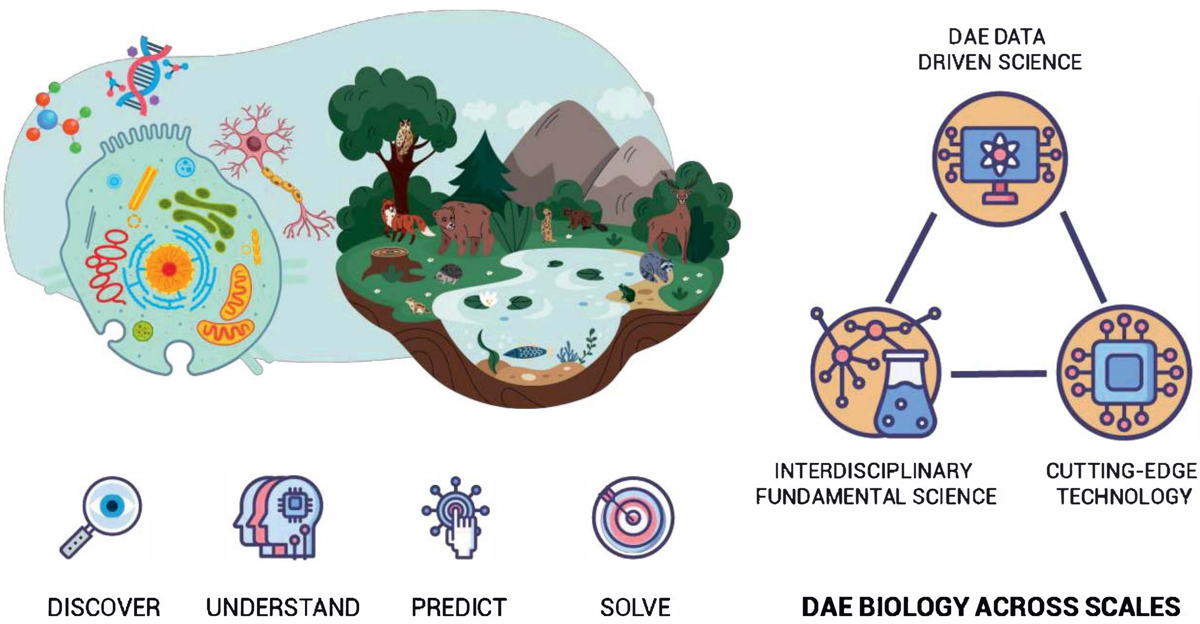
9. Biology across scales and environments: From molecules to ecosystems

Starting from studies to understand radiation resistance in biological systems, biology supported by DAE has expanded significantly and made impacts nationally and globally, from single molecules to entire ecosystems. Examples include novel fundamental discoveries such as the genes for olfaction, memory formation in the brain, and the physical principles of cell membrane organization. Biological scientists have discovered new Indian biodiversity, built databases such as those dedicated to the cataloguing of natural compounds systematically, and have studied the genomics of native plants such as tulsi and moringa. This research has shaped government policy, including but not restricted to aspects of biodiversity conservation. All this has been possible due to the scales and disciplines covered by biological science research at the fundamental level in the DAE, from molecules to entire ecosystems across acres of forest. Such fundamental biological sciences research supported by DAE has already shown real-world and immediate impact during the global challenge of the COVID-19 pandemic. AI centers worked across all levels to mitigate the effects of this disease. From developing testing protocols and capacity building to enabling the application of the same across the country to innovate on new diagnostic kits, sero surveys, and drug discovery, fundamental biological sciences met the essential needs of our country and will continue to do so. Thus, the pursuit of research at this level is critical.

1. ADVANCED CENTRE FOR TREATMENT, RESEARCH AND EDUCATION IN CANCER (ACTREC)
2. SAHA INSTITUTE OF NUCLEAR PHYSICS (SINP)
3. UM-DAE CENTRE FOR EXCELLENCE IN BASIC SCIENCES (UM-DAE CEBS)
4. THE INSTITUTE OF MATHEMATICAL SCIENCES (IMSc)
5. INSTITUTE OF PHYSICS (IOP)
6. NATIONAL INSTITUTE OF SCIENCE EDUCATION AND RESEARCH (NISER)
7. TATA INSTITUTE OF FUNDAMENTAL RESEARCH (TIFR)

- DEPARTMENT OF BIOLOGICAL SCIENCES
- TIFR-HYDERABAD
- INTERNATIONAL CENTRE FOR THEORETICAL SCIENCES
- NATIONAL CENTRE FOR BIOLOGICAL SCIENCES

This proposal covers the following DAE institutes engaged in biological research: TIFR (Mumbai, Hyderabad, NCBS, ICTS), ACTREC, IoP, IMSc, NISER, SINP, and CEBS. Their aims span biological scales from single molecules to single cells, a collection of cells, organisms and environments. The objectives span four key pillars: to discover, understand, predict and solve. This will be achieved by bridging the interdisciplinary expertise in the DAE with big data-driven science and cutting-edge indigenously developed technologies. Thus, these four pillars combine research, development, and new technology innovations to fundamental biological studies.



Executive summary - Biology across scales and environments. From molecules to ecosystems

Specific aims:

DECODE: Resilience in biology. How does life adapt to changing environments? Aim is to understand the mechanism of adaptation and change in biological systems from single-cell organisms, to plants and ecosystems.

***SCALE and TRANSLATE*:** Biological complexity from molecules to organisms. Aim to uncover the laws of biological complexity: how do you go from single molecules to entire organisms interacting in ecosystems?

BUILD: New technology development

9.1 DECODE – *Resilience in biology*

9.1.1 Understanding mechanisms of microbial adaptation

Predicting evolution in antimicrobial resistance and emerging infectious diseases

Microbes (such as bacteria and fungi) are among the most abundant and successful organisms on the planet. They have significant impacts on human health and disease and are ecologically important. It is proposed to develop a thrust area focussed on understanding microbial physiology, adaptation and evolution under changing and stressful environments. Via fundamental approaches, we will discover and understand the basis of microbial resilience and adaptation, thus allowing us to predict evolutionary outcomes.

- Microbial genomes: We propose investigating two new routes for bacterial adaptation via genome modifications: a. horizontal and/ or vertical gene transfer b. stress-induced mutagenesis (SIM). These strategies (recombination and SIM) are contingent on the action of pathways that can modify the bacterial genomes (such as DNA repair mechanisms). We will employ high-throughput computational studies with whole genome sequencing technologies, bacterial genetics and molecular biology as well as biochemistry and cell biology of bacteria to gain molecular mechanistic insights into the pathways contributing to genome modification under stress, understand how these pathways are regulated, and based on this understanding, predict the course taken by the organism to gain resistance to new environments.

- Microbial metabolism: While the need for newer antibiotics is ever-increasing, the target space to develop novel antimicrobials is shrinking. This paradox and the central importance of bacterial metabolism in stress physiology have made metabolic pathways an alternative and attractive target. However, bacterial metabolism is highly plastic and robust. Thus, translational progress in this direction requires a holistic understanding of metabolic adaptabilities. Our existing and proposed requirements put us in an advantageous position to explore this area innovatively, including multi-omics integration, modeling, and simulation of clinical outcomes in laboratory conditions. We propose to investigate the mechanistic details of the emergence of antimicrobial resistance, develop novel targets, and increase the rationality of combination therapy.

- Structure-function studies for new drug discovery: To combat threats of AMR, in the short term (next 5 years), we urgently need to bolster our knowledge base regarding structure-function relationships of potential antibacterial drug targets that are unexplored so far. After such targets are figured out, we will first aim to deduce the high-resolution structures of these entities in apo and ligand-bound forms and complex forms along with their interacting partners. In the long term, we plan to employ this strategy to combat antibacterial resistance and address the challenge posed by antimicrobial resistance arising in viruses, fungi, and unicellular parasites. The structural information from these biological targets would be used to design precision therapeutics based on synthetic bio-conjugated nanomaterials.

9.1.2 Mechanism of Stress Tolerance in Cancer Cells - Understanding and Taming Resilience to Therapy

Cancer Research across DAE institutes covers all aspects of tumour biology, ranging from understanding the molecular basis of cancer epidemiology to uncovering the basis of disease in the Indian population, structure-based drug design and translation of these discoveries to clinics. Cancer research spans all biological scales in space and time. In this context, cancer must be recognised as an 'ecosystem' and treated as an evolving 'organism'. Reliance or resistance to treatment at the primary and metastatic sites remains a formidable challenge and a bottleneck in oncology. The proposed programme focuses the following objectives.

- Investigate/develop model systems, including humanized and genetic mouse models, across scales to test and understand the role of mutations, molecular alterations, TME such as hypoxia, CAFs, mediators of immune response, nutrient deprivation, and mechanobiology of ECM on therapy resistance and disease aggression.
- Collect large longitudinal multi-omics data from bulk and single cells from Indian patients (breast, lung, ovarian, cervical, head and neck, hematolymphoid, and GI).
- Analyse data using informatic tools and computational methods and develop new mathematical models and theoretical concepts for prediction and hypothesis testing.
- Use of model systems to validate computational predictions in a 'closed loop format' until predictions match data and provide probable solutions.
- Discover and validate new biomarkers of early disease, prognosis and resistance using novel de novo chemical tools and activity probes.
- Identify new vulnerabilities that can be validated and targeted using high throughput screening strategies and structure-guided ML-trained algorithms.
- Generate new molecular scaffolds emanating from traditional knowledge systems for preclinical studies.
- Test some of the alternative resilience theories and those originating from the study of Integrated Stress Response in other DAE settings.
- Develop therapeutic vaccines, cellular therapies, and innovative strategies to overcome immune exhaustion.
-

9.1.3 Ecology and biodiversity studies towards a biodiverse and sustainable future

A thrust area to discover, understand, predict and address biodiversity loss and climate change-associated problems to safeguard our future is proposed herein. Scientists at DAE-AIs would work together towards the vision that allows resilience and adaptation to secure India's biodiverse and sustainable future. Much remains to explore, explain, and understand India's biodiversity in terms of species, genetics, behaviours and physiological mechanisms.

Organismal responses across biological scales (molecular, cellular, organismal, populations, communities) to climate stressors, unveiling the underlying mechanisms influencing adaptation, resilience, and vulnerability will be explored. This can be done by leveraging insights from biology, physics, chemistry, and engineering to develop innovative technologies for monitoring, analysing, and mitigating the effects of climate change on biological systems. Species occur in communities, and interactions between communities (predator-prey, host microbiome, etc.) remain poorly understood in the Indian subcontinent. Especially important is how anthropogenic impacts can affect these relationships, potentially resulting in zoonotic spillover. For example, scientists at TIFR-NCBS have previously investigated reservoir dynamics and spillover from bats and rodents. DAE-AI scientists will investigate communities and species relationships and how human habitat modifications impact them. Characterizing ecosystems is critical in understanding how people benefit from nature through ecosystem services. Wide-ranging species invasions, global change and habitat fragmentation have unprecedented impacts on biodiversity, ecosystem, and services. These unprecedented impacts can be mitigated through science-based and action-oriented restoration and conservation. DAE-AI scientists will work with partners to enable restoration and preservation. A specific focus area likely to be developed is urbanization and its impact on ecology, global change and resilience. Projections suggest that 80% of Indians will live in cities by 2050. Collaborative interagency efforts will be expanded across Mumbai, Hyderabad, Bangalore and Bhubaneswar.

The proposed aim will have the following impact.

A. Fundamental research: deep scientific understanding and knowledge generation on

(1) biodiversity and ecosystems of the Indian subcontinent,

(2) how habitat change, fragmentation and contemporary rapid climate change affect different biodiversity assemblages, and how global change will affect biodiversity.

B. Resilience through scientific knowledge: A new centre on Mitigating human impacts on biodiversity.

C. Innovation for an unprecedented future: A working group called 'Urban Futures' on urban ecosystems, projects, and working plans will allow sustainable development in India's urban settings.

9.1.4 Mechanism of Stress Tolerance in Plants - towards climate resistant crops

Food insecurity is a severe problem worldwide. Reducing crop damage and enhancing the overall agricultural yield and productivity is essential to tackle this ever-growing food demand. Thus, it is important to make judicious use of resources (including fertilizers and pesticides) before the disease occurs and employ modern technologies to improve agricultural productivity. Here, we propose to (i) develop an artificial intelligence-based solution for early detection of plant stress (due to biotic and abiotic factors) and use appropriate strategies to combat it and (ii) use genetic and system biology approaches to understand genes regulating responses to biotic, abiotic, yield and development associated traits towards generating climate resilient and disease resistant plants. The former includes using information and electronic technologies to develop wireless sensor networks, robotics, and machine learning with automated technologies to monitor agricultural farms with intelligent solutions. The latter involves recombinant DNA technology to create mutants or epigenetic variants of genes associated with defence, abiotic stress tolerance, yield, fruit development and pigmentation in important crop plants in Indian agriculture, such as rice, banana, tomato and mung bean.

The ideas are to:

- Develop an artificial intelligence-based solution for early detection of plant stresses.
- Screen for natural variations of different crops (varieties, landraces) in field conditions and identify robust accessions resilient to temperature, light, pathogen, etc. Identify the resistance genes/epigenetic variations and evaluate their effectiveness under environmental conditions.
- Identify naturally occurring, nutritionally enriched crops/species and edit signal transduction mechanisms for temperature, light and pathogen sensing with delicate precision.
- Manipulate fruit development and ripening to identify the regulators of stress tolerance associated with pigment accumulation under variable conditions of light and drought.
- Genomic (ATAC-seq, RNAseq) and epigenomic (miRNAs, siRNAs, histone modifications) studies to identify clusters and modules of developmentally, diurnally and stress-associated genes that can be used in crop engineering.
- Use micro gas sensors as readouts in pathogen attack situations, and develop a prototype to combat pathogen and disease spreading much before the disease causes damage.

- Elucidate the impact of the rhizosphere microbiome on the general fitness and defence of the host and anticipate engineering a universal resilient microbiota that could determine the growth defence trade-off by acting as probiotics.

9.2 SCALE AND TRANSLATE – *Biological complexity from molecules to organisms. We aim to uncover the laws of biological complexity. How do you go from single molecules to entire organisms interacting in ecosystems?*

9.2.1 Principles of organismal development

Developmental biology stands at the forefront of scientific inquiry, seeking to unravel the mysteries of how a single fertilised egg transforms into a complex multicellular organism. This proposal aims to delve into the intricate principles governing the development of tissues, organs, and organisms, focusing on the following themes: gene *to geometry*, developmental diversity across an organism, evolution, and developmental diseases. By understanding the mechanics and molecular mechanisms driving morphogenesis and comprehending gene regulatory networks underpinning the developmental processes, we aim to uncover fundamental insights into the development process and potentially engineer novel solutions for gene therapy, regenerative medicine, and biotechnology.

The focus is to elucidate the mechanisms underlying morphogenesis, combining insights from cellular signaling and metabolic state with the mechanics of cells and tissues. Building upon foundational insights gained in the immediate future, organoids and engineered tissue systems will be further developed to recapitulate complex developmental processes in vitro, enabling high-throughput screening of genetic, metabolic, environmental, altered climate changes and pharmacological interventions for developmental defects. Synthetic biology approaches will be harnessed to engineer precise spatial and temporal control over gene expression, allowing for the construction of synthetic morphogen gradients and patterning cues. Moreover, manipulating the extracellular matrix using bioengineering strategies will sculpt tissue architecture and mechanical properties, facilitating the assembly of functional tissue constructs that can be used for regenerative medicine and therapies.

By unravelling the principles of development, this initiative aims to advance our understanding of morphogenesis, and it will pave the way for innovative approaches in regenerative medicine and biotechnology. We aspire to make transformative contributions to scientific knowledge and societal well-being through collaborative efforts and sustained investment. Ultimately, this research endeavour holds the promise of unlocking the full potential of developmental biology to address pressing healthcare challenges and drive economic growth through biotechnological innovation.

9.2.2 Brain and mind

The brain at all levels, will be investigated from the single cell and molecule to microcircuits and networks, to understand cognition, emotion, and behaviour. In parallel, investigation on brain diseases of neurodevelopmental, neurodegenerative, psychiatric and cancerous origin in model organisms and iPSC-derived brain organoids will be carried out.

First step of investigations would be at the single cell and microcircuit level for unbiased insights into the brain's cellular subtypes and intercellular interactions. We will delve into deciphering heterogeneity and its functional relevance during brain development, function and pathologies. The last few years have seen a transformational shift in the ability to define large-scale connectome of the brain. We will integrate our ongoing investigations with new revelations of brain connectome for a more accurate understanding of synaptic, dendritic and neuronal computations. We will employ this to gain insights into the neural regulation of breathing, sleep, memory, emotion and motor regulation. We will leverage the power to manipulate neural circuits using genetic, chemo-genetic, optical and magnetic systems to study the mechanistic underpinnings of normal physiological processes and behaviour and use this to decipher specific cellular and circuit dysfunction evoked pathophysiological states. We intend to study the signalling mechanisms and their ncRNA-mediated molecular regulations through the establishment of a 3D co-culture of glioma cells with neurons.

In the next phase, we will work for large-scale efforts towards a) an atlas for synaptic signalling, b) catalogue for subpopulation level identity & function of brain cells, c) neuro-glia interactome for brain function and resilience, and d) consortia projects for longitudinal human data. To leverage the knowledge acquired through the above programs, we will explore translational opportunities through collaborative and consortium projects between basic researchers in the DAE system and clinicians. New methodologies will be developed to achieve such readouts for basic, translational and diagnostic applications. Integrating this research with the proposed new pipelines for big data and AI/Modelling, new pharmacological targets and combinatorial therapies will be proposed.

Three significant developments have converged to make this an exciting time for neuroscience research. First, the tools for recording, imaging, controlling, and analysing brain activity have recently leapt forward with new genetic reporters, optogenetics, and high-throughput omics. Second, AI brings new concepts to the field and vastly increases analysis capacity. Third, mental health and neurodegeneration are now forefront concerns, and the latest tools provide untapped opportunities to treat them, especially in the context of the Indian spectrum of disease. The next few decades hold unprecedented promise for making significant breakthroughs in understanding of the brain to figure out how the brain works. In this regard, DAE is uniquely positioned within the scientific ecosystem in our country to lead the effort with the power of interdisciplinary expertise and the ability to capitalize on high-precision, big-data pipelines to drive quantum leaps in understanding the brain. The above-mentioned scientific goals and the roadmap can potentially develop "RNA therapeutics" modalities in the long run.

9.2.3 Decoding genetic landscape and genetic underpinning of diseases Indian context

It is proposed to undertake functional underpinning of the susceptibility of the Indian population to metabolic, cardio-vascular and rare-genetic diseases and cancers of young adults by mapping the mutational landscape of selected inbred populations. We propose integrating our efforts across DAE institutions and hospitals, and in collaboration with clinical geneticists, to generate a comprehensive reference genetic map of these populations through a large-scale WGS to identify mutations causing undiagnosed rare and orphan diseases using a consortial-based approach. It is also important identifying epigenomic alterations and epidemiologic and clinical factors associated with cancers in young adults and age-related metabolic diseases. In the first phase, the focus will be on ciliopathy, mitochondrial-metabolic disease, brain and eye development disorders, blood-related disorders, aging and cancer and the burden of pre-disposition/emerging comorbidity – for young who live long and the elderly.

The outcome of this programme would be followed up with patients with the help of clinical partners in this study. Further, using a subset of candidate genes, characterizing the function of genes to understand basic biology and pathogenic mechanisms will be carried out. India should be a leader in human genetics and rare disease diagnosis, as we will also be a most populated nation. We would like to develop a comprehensive knowledge of genotype and phenotype relations using WES and fundamental and clinical investigations. The understanding generated by these goals can also lead to the design of an assay for drug screening geared towards therapy or prevention.

9.3 BUILD – *New technology development*

9.3.1 Engineering Biology and Designing Living Systems

Governments and the public worldwide, including India are advocating for replacing and minimizing animal testing for investigational drugs and encouraging researchers to innovate effective non-animal methods. Such effective non-animal methods could increase the speed and success of drug discovery and acceptance. In cancer research, the existing organoid models cannot truly mimic the tumour microenvironment and surrounding physiology and, hence, cannot be used as alternatives to animal models for studying or drug testing. To bridge this gap in this thematic area, incorporation of bioengineering approaches with novel synthetic platforms to enhance the possibility of learning new biology by exploring living organisms in biomimetic 3D settings and building new technologies including complex 3D tumour models as an alternative to animal drug testing and cell-based computers is envisioned.

This thematic area will enable pushing the boundaries of 3D culturing capabilities and probe cells with unprecedented resolution using biomimetic in vitro platforms. By precisely tuning the systemic properties and accurately recreating in vivo parameters, the use of animal models will be minimized. Further, scaling up these systems for high-throughput applications such as drug screening will be undertaken. Overall, this thematic area would provide new methods to investigate various fundamental questions in biology and build new technologies using 3D systems.

9.3.2 Integrative imaging and therapeutic modulation across large length scales:

The aim is to spearhead a paradigm shift in biomedical microscopy and biomodulation in India by indigenously developing cutting-edge imaging techniques across length scales, from single molecules to whole organisms. Central to our initiative is the design and development of novel imaging solutions, focusing on tool development using chemical and synthetic biology approaches to democratize advanced imaging technologies across the country, particularly super-resolution microscopy, through innovative AI and ML approaches for pathologists.

Pioneering the development and implementation of advanced non-linear optical imaging technologies, bridging the gap between conventional microscopy and IR-based imaging modalities, development of new imaging tools and drugs based on peptides, small molecules, and designer cells for precision imaging and correction of cellular pathology, developing and refining AI/ML algorithms to enhance conventional microscopes' resolution, making super-resolution imaging accessible for pathologists and researchers alike are the goals to achieve. This proposal represents a bold and ambitious endeavour to redefine the landscape of biomedical imaging and research.

In summary, this proposal on health reflects a broad spectrum of scientific research directions, each aiming to address critical challenges in public health, environmental sustainability, and technological innovation such as:

1. **Microbial Biology and Antimicrobial Resistance:** The proposed research emphasises understanding microbial biology and mechanisms of antimicrobial resistance. These studies aim to develop effective infection prevention and treatment strategies, contributing to significant healthcare cost savings and better public health outcomes.

2. **Biodiversity and Ecosystem Resilience**: The study aims to generate knowledge on biodiversity and ecosystems in the Indian subcontinent, focusing on how habitat changes and climate change impact biodiversity. The proposed research seeks to foster sustainable urban development in India.

3. **Climate-Resilient Agriculture:** This proposed initiative targets food security in a changing climate by developing climate-resilient and disease-resistant plants. The proposed research involves using AI to enhance farm management and sustainability, identifying genes and epigenetic factors that regulate crop traits, and improving major Indian crops like rice, banana, tomato, and mung bean.

4. **Developmental Biology and Regenerative Medicine:** The proposed research aims to advance the understanding of morphogenesis, paving the way for innovations in regenerative medicine and biotechnology. It aspires to make transformative contributions to scientific knowledge and societal well-being by unlocking the potential of developmental biology to address healthcare challenges and drive economic growth.

5. **Neuroscience Research:** This proposed research highlights the convergence of new tools in neuroscience, such as genetic reporters, optogenetics, and AI, to advance the understanding of the brain. It focuses on treating mental health and neurodegenerative diseases, particularly in the Indian context. The proposal aims to inspire technological advancements in neural networks and robotics and understand the molecular mechanisms behind conditions like "Chemo Brain."

6. **Cell Biology:** This proposal involves using cryo-tomography and other advanced techniques to study cellular macromolecular assemblies, aiming to develop detailed cellular atlases. This research provides insights into cancer progression and aids in developing disease therapies by understanding the altered ultrastructure of cancer cells.

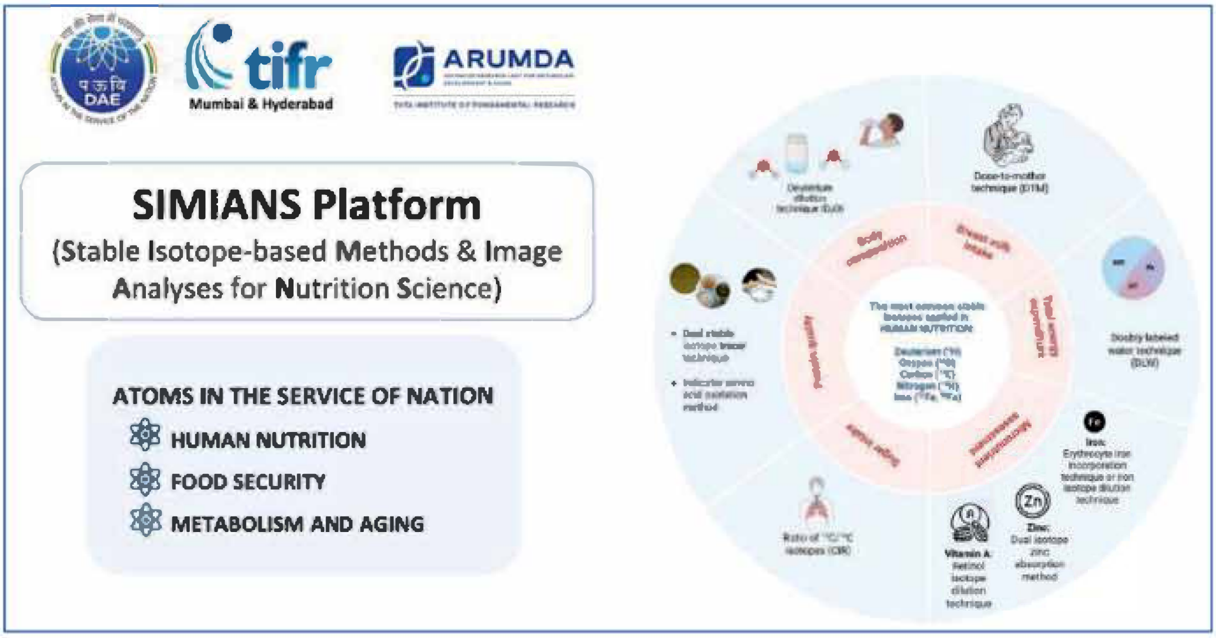
7. **Rare Diseases and Genetic Research:** The proposed research addresses the burden of genetic diseases and rare diseases in India. It aligns with the National Health Mission to improve diagnostics, treatment, and precision medicine strategies through interdisciplinary research and advanced molecular techniques.

8. **3D Culturing and In Vitro Platforms:** The thematic area explores pushing the boundaries of 3D culturing capabilities, allowing for precise cell probing and minimising animal model use. This research has potential applications in drug screening and fundamental biological investigations, aiming to develop new technologies using 3D systems.

9. **Biomedical Imaging and Research:** The proposal seeks to revolutionise biomedical imaging by making advanced microscopy techniques accessible and pioneering innovative imaging methodologies. The research envisions establishing an Advanced Bioimaging Centre as a hub for interdisciplinary collaboration, driving advancements in healthcare and contributing to national innovation and self-reliance.

9.4 Enhancing National Capacity in Stable Isotope Applications

India faces high prevalence of double and triple burdens of malnutrition, compounded by rising lifestyle diseases such as diabetes, obesity, and metabolic syndromes. These challenges are exacerbated by socio-economic disparities, genetic diversity, and rapidly changing dietary habits. The Advanced Research Unit on Metabolism, Development and Ageing (ARUMDA) at the Tata Institute of Fundamental Research (TIFR) represents a ground-breaking initiative aimed at addressing India's complex nutritional health challenges. By integrating stable isotope technologies with multidisciplinary research, ARUMDA seeks to revolutionize the understanding, management and alleviation of malnutrition, metabolic disorders, and aging-related diseases. This vision document outlines TIFR-ARUMDA's strategic roadmap for leveraging nuclear science in collaboration with other DAE organisations, to achieve transformative nutritional health outcomes using stable isotopes by 2030 and 2047. Stable isotopes offer a unique advantage as non-invasive, precise, and safe tools for studying nutrient metabolism, body composition, and energy expenditure. As India approaches the centenary of its independence in 2047, this TIFR-ARUMDA initiative under the DAE umbrella should aim to redefine the country's position in global health and scientific innovation.



The vision for Amritkaal Bharat should include India as a pioneer in stable isotope applications, transforming healthcare, nutrition, and aging research through cutting-edge nuclear science, primarily a resultant of interactions between ARUMDA and DAE units. By 2047, India should not only achieve self-reliance in stable-isotope production but also emerge as a global leader, exporting knowledge, technologies, and solutions to address pressing health challenges worldwide, driven by TIFR-ARUMDA in partnership with the other DAE units.

Foundational Infrastructure and Achievements: ARUMDA has established state-of-the-art facilities to support its mission. The National Analytical Facility for Nutrition and Metabolism Research, equipped with state-of-the-art metabolomics platform and Isotope Ratio Mass Spectrometry (IRMS), enables advanced metabolic studies. The SIMIANS Platform, embedded within the National Facility, is dedicated to using stable isotope-based methods and imaging analytics for addressing nutritional health challenges. Additionally, the ongoing installation of India's first human metabolic chambers at CMC-Vellore marks a significant milestone in controlled metabolic research. Ongoing collaborations with DAE institutions, such as the Heavy Water Board (HWB) and BARC, ensure a steady supply of critical stable isotopes like deuterium oxide (D_2O), doubly labelled water (DLW), Iron and others for research and interventions.

Strategic Goals and Future Initiatives: The vision for 2030 and 2047 is anchored in five key pillars: scaling stable-isotope production and utilisation in nutritional health, advancing research and innovation, building human capital, integrating findings into public health policy, and enabling the Global South to mitigate nutritional crises (initiatives like 'Nutrisotope Maitri').

To enhance isotope accessibility, ARUMDA with DAE organisation like BARC and HWB will focus on enriching stable isotopes of iron, carbon, and nitrogen while strengthening supply chains of these isotopes and D2O and DLW. Grassroots-level implementation of D_2O and DLW techniques will enable large-scale studies on assessing body composition and total energy expenditure across diverse populations.

Research and innovation will prioritize the development of new stable-isotope techniques for studying metabolic diseases such as diabetes and metabolic dysfunction-associated steatotic liver disease (MASLD). The procurement of advanced GC-MS systems will expand lipid metabolism research, while pilot cohort studies will generate data to refine national nutrition programs.

Capacity building is critical to sustaining the progress. An M.Sc. Program in Isotope and Nuclear Imaging Techniques will be launched to train the next generation of professionals, drawing expertise from TIFR, DAE and the International Atomic Energy Agency (IAEA) network of experts. Workshops and fellowships in collaboration with DAE institutions will further enhance expertise among researchers and clinicians.

Policy integration will ensure that stable-isotope-based evidence informs national health strategies. By collaborating with ICMR, MoHFW, and NITI Aayog, ARUMDA aims to refine programs like Anaemia Mukt Bharat and help develop dietary guidelines grounded in robust scientific data.

9.4.1 Roadmap to 2030 & 2047

The journey to 2030 is structured into two phases. From 2025 to 2028, the focus will be on scaling infrastructure, formalizing isotope supply chains, and launching pilot studies. Key milestones include completing the human metabolic chambers at CMC-Vellore, initiating the design of the M.Sc. Program, and deploying iron isotope techniques in high-anemia-burden states/populations.

> **Strategic Significance for DAE**
>
> - **Adding a new dimension to its mandate** to apply nuclear science for societal welfare.
> - **Positioning India as a global hub** for stable isotope research.
> - **Supporting SDGs** (e.g., Zero Hunger, Good Health) through innovation.
> - **Global health diplomacy** through the **"Isotope Maitri"** initiative
>
> ***Atomic Precision for Nutritional Security***

Between 2028 and 2030, the emphasis will shift to human capital development and policy integration. The M.Sc. program will be rolled out, and the DAE-TIFR/ARUMDA Centre for Metabolic Innovations will be established to prototype new diagnostic tools. Isotope techniques would be integrated into national health programs, and domestic production of critical stable isotopes would reduce reliance on imports.

India's battle against anemia and childhood stunting will reach its culmination, with iron-isotope-based interventions ensuring significant decrease in deficiency diseases by 2032-2035. Mitigation of diabetes, obesity & cardiovascular disease epidemics would be a reality through nationwide deployment of 13C/2H metabolic flux diagnostics, cutting incidence rates drastically. These achievements will position India as a model for other nations grappling with similar health challenges.

Expected Outcomes and Global Leadership: By 2030, ARUMDA with DAE organisation aims to achieve significant milestones, including the formulation of over ten evidence-based nutrition policies/publications and the training of 100 professionals in isotope applications. A 30% reduction in research costs through domestic isotope production will enhance affordability, while the establishment of a National Repository of Isotope Data will facilitate open-access research.

By 2047, stable isotopes would be deeply embedded in India's healthcare ecosystem. The widespread adoption of isotope-mapped metabolic profiles will allow for AI-driven dietary recommendations, tailored to individual genetic and lifestyle factors. This precision nutrition approach will significantly reduce the burden of diabetes, obesity, and micronutrient deficiencies. The National Metabolic Health Grid, powered by decentralized SIMIANS nodes, will provide real-time monitoring of population health, enabling timely interventions and policy adjustments.

India's leadership in stable isotope applications would be recognized globally, with frameworks exported to low- and middle-income countries through WHO partnerships. This vision underscores the transformative potential of the DAE-ARUMDA partnership in addressing India's health challenges and positioning the nation as a hub for metabolic health innovation.

Conclusion: The ARUMDA is DAE's bold step toward a healthier future. By investing in stable isotope technologies, fostering interdisciplinary collaboration, and aligning research with national health priorities, this initiative will pave the way for sustainable solutions to malnutrition, metabolic diseases, and aging. The vision for 2047 is not just about scientific advancement but also about ensuring equitable health outcomes for all, reinforcing India's role as a global leader in nuclear applications for societal welfare.

10. Computer Science

The Computer Science groups in the Department of Atomic Energy (DAE) aided institutes are located at Tata Institute of Fundamental Research (TIFR, Mumbai), The Institute of Mathematical Sciences (IMSc, Chennai), and National Institute of Science Education and Research (NISER, Bhubaneswar). The focus of CS groups at TIFR and IMSc is on understanding fundamental or foundational questions in algorithms and complexity, quantum computing, information and communication, machine learning, cryptography, formal methods and verification; equivalently, the mathematical underpinnings of computation. The vision of the school of computer sciences at NISER is to set up a Centre for Artificial Intelligence (CAI) that will attempt to create an indigenous “Make in India” large scale General Intelligence System as well as tackle problems such as bias, trustworthiness and privacy of machine learning models. Furthermore, the Centre for Artificial Intelligence will attempt to solve challenges across all sciences including biology, chemistry, physics along with earth & planetary sciences using AI. The worthy goal to aspire to for 2047 would be to create conditions in which the Computer Science groups at DAE aided institutes have the ability not only to keep the country abreast of latest scientific advances, but to also have a good chance of creating those advances right here.

Algorithms and Complexity: The Computer Science groups at TIFR and IMSc are currently engaged in developing conceptual and foundational ideas concerned with computing, communication and learning, in the tradition of Turing and Shannon. Just as exploiting and living harmoniously with nature would be impossible without grasping its basic laws, so is the case with these three areas. Basic laws manifest not only in what is possible, such as the construction of a steam engine or a supercomputer, but also, in perhaps a more profound way, in what is not possible, such as the second law of thermodynamics or the impossibility of building a universal debugger for computer programs.

Theoretical Computer Science (TCS) is centered around some of the deepest and most fascinating questions in Computer Science and Mathematics. TCS is expected to play a crucial role in various important areas such as data-driven computation, the algorithmic basis of the contemporary economy, secure computation, the utilization of quantum computing, and the study of deep learning. The core strength of the Computer Science faculty in DAE aided institutes lies in not only designing algorithms, communication protocols for basic problems, but also in discovering fundamental limitations of such algorithms if they are to be realized on models obeying the laws of physics.

Quantum computing, information and communication: The Computer Science groups in DAE aided institutes (in particular, TIFR) have been at the forefront of theoretical foundations of quantum information and communication complexity for the last two decades. TIFR provides an excellent environment for a healthy exchange of ideas between the physicists and computer scientists and is the testing ground for India's first digital computer, TIFRAC. It is by now widely believed that novel ideas from quantum information and quantum error-correction not only aid quantum computing but might also throw light on some unresolved questions in physics. We believe the Computer Science groups at DAE aided institutes are uniquely placed to play a larger role in this in the upcoming years.

The Computer Science group at IMSc seeks to look for practical applications of quantum computing and quantum information theory that are relevant to the current computing scenario such as learning theory, data analytics, and coding theory. Furthermore, the limitations of classical computation are etched in the area of computational complexity theory. Understanding the theoretical limitations of quantum algorithms is an essential and tangible goal towards analysing the applicability of quantum techniques to problems arising in computer science.

Machine learning: Advances in machine learning in the last few decades have prompted a revisit of several foundational notions in statistics and optimization. The School of Technology and Computer Science (TIFR) already has substantial research activity addressing questions of this sort: these include, for example, learning in changing environments, or learning in the presence of large noise when what is being learnt has some structure. Given the school's traditional strengths in algorithms, information theory and applied probability, the school is in a good position to grow further and emerge as a leading centre of research on these questions.

Cryptography: Cryptography, which provides the mathematical foundations and systems for securing digital communications, financial transactions, personal data, critical infrastructure, etc. by ensuring the confidentiality, integrity, and authenticity of information, fosters trust in online interactions and facilitates the widespread adoption of digital technologies that underpin modern society. Future research in the area will be driven by technological developments, emerging threats, and the need for more robust systems. The Computer Science groups at DAE aided institutes expect to build on their current strengths in other areas of computation such as complexity theory and algorithms to grow in this critical area.

Formal methods and verification: With the growing increase in computational power, we expect to see a surge in complex software and cyber physical systems which often work concurrently in parallel. These systems work in real-time and are also often stochastic in nature. It is imperative to ensure correctness of these systems since otherwise their failures can be catastrophic. Globally, formal methods tools are widely used in academia and in industry and there is an ever-increasing demand for their scalability due to increased complexity in software. Algorithmic verification aims to automate the process of ensuring correct behaviour of these complex systems. A fundamental research challenge is to consider mathematical models to capture systems that are stochastic and show real-time behaviour while also capturing corresponding requirements through logic. This can lead to automatic verification under these increased expressiveness scales for systems with huge state space. Over the years, the Computer Science groups at TIFR and IMSc have contributed fundamentally to specify real time requirements and establishing the decidability and complexity of these logics, and we expect it to further strengthen over the subsequent years leading to real-time verification of large and complex systems.

Algorithms with societal impact: These are algorithms taking societal considerations such as fairness, energy efficiency, and environmental considerations such as responsible scaling and sustainability of large computing infrastructures. The design of an algorithm that “minimizes the carbon footprint” is desirable. Heavy computing is energy-expensive, and thus explicit bounds on energy expenditure will become the norm. Given the proliferation of cloud computing, the general ideas that underlie distributed computing, such as scalability, fault tolerance, should be re-examined. Usually, these things come at a cost, and what exactly they are and what the adverse effects should/will be quantified. The Computer Science groups at DAE aided institutes will revisit and build new algorithms that are also socially efficient, i.e., that maximize social welfare.

Artificial Intelligence: The crucial aspects of artificial intelligence that will shape our medium and long-term goals.

- *Indigenous Large Scale General Intelligence System:* General intelligence would directly lead to solving problems with both decision and execution parts in the machine learning system. It is imperative that we move to future open instruction set architectures such as RISC-V.

- *Trustworthy and Private AI:* AI is shaping our world and will have a major impact on our daily lives in the near future. It is thus absolutely crucial to make sure that the AI is behaving as promised. Currently, we don't have any robust tools to validate the workings of these AI models.

- *Bias and Fairness in AI:* Artificial Intelligence technologies are revolutionizing various domains, but concerns about fairness in AI-generated results have surfaced. This problem revolves around understanding how biases are introduced, why they occur, and what consequences they entail. AI systems learn from data, and biased training data can perpetuate societal prejudices. The design and coding of algorithms may inadvertently introduce biases, leading to unfair outcomes.

10.1 Short and medium-term roadmap:

Algorithms, complexity, and verification: In these areas the goal would be to continue with the ongoing research programs in areas such as computational game theory, computational number theory and algebra, communication complexity, combinatorial, geometric and sampling algorithms, coding theory, reactive systems etc. Some of these results also overlap with areas such as machine learning and formal methods mentioned below. In particular, our short-term roadmap is to focus on the following sub-projects.

1. *Learning and optimization.*

Recent successes of large and successful neural networks have a far larger number of parameters than the number of data-points on which these networks are trained. This challenges the recommendation suggested by classical statistical theory that when fitting a function to a dataset, the number of parameters of the function to be estimated from the dataset should typically be much smaller than the number of samples in the dataset. We seek to obtain a theoretical understanding of this phenomenon of neural network models.

2. *Proof verification in the age of blockchain.*

We seek to use the recent advances in algebraic error-correcting codes, especially, the multiplicity variants of polynomial-based codes and high-dimensional expanders to obtain better proof- checkers both in theory and practice and to pursue various cryptographic applications of such checkers.

3. *Algorithmic coding theory.*

Several of the natural and fundamental problems related to codes based on polynomial evaluations (such as Reed-Solomon codes, Reed-Muller codes, Algebraic-Geometric codes) have continued to remain open. Our goal in this project is to investigate some of these problems.

4. *Algorithms for sampling.*

Sampling from subsets of n-dimensional Euclidean space that are defined by a set of constraints is an important primitive useful for applications such as volume estimation or (more generally) Monte Carlo integration. We seek to give sharper bounds on the number of steps a given random walk has to take before its distribution is sufficiently close to the uniform distribution on K.

5. *Computational algebra.*

Low degree polynomials are objects of central importance in discrete mathematics and computer science with numerous surprising applications to many sub-areas including, combinatorics, discrete geometry, complexity theory, coding theory, pseudo-randomness and algorithm design. The main focus would be on the design of faster and more efficient algorithms for fundamental computational questions about polynomials.

6. Fair division algorithms.

As algorithmic decision making becomes more prevalent, the issue of fairness of these algorithms becomes very important. In various fields such as clustering, advertising, resource allocation, and machine learning, there has been a significant amount of work on both defining relevant fairness objectives, as well as coming up with algorithms that achieve these objectives. Our work focuses on the foundational issue of fairness in particular, envy-freeness and equity in resource allocation. Our project aims to significantly extend the set of instances for which fair allocations can be obtained, as well as address the question of combining fairness and efficiency. While the literature so far has mostly addressed the case of additive goods, this class of valuations is highly restrictive, and we would like to extend existing results to more general valuations.

7. Secure computation in the quantum age and information theoretic limits.

Quantum computation has revolutionized Computer Science in general, and cryptography in particular. The leading agencies such as the National Institute of Standards (NIST) have already called for the standardization of cryptographic schemes such as public-key encryption and digital signatures that are believed to withstand quantum computers. The rise of near-term quantum devices (NISQ) also provides us with a fascinating opportunity to use the power of quantum information and computation to achieve tasks we believe to be impossible in the classical world. The main aim of this proposal is to explore the power of quantum computers in the area of secure computation and build new protocols that are provably, or believed to be impossible in the classical world and are resilient against the looming threat of quantum computers.

9. Stochastic reactive synthesis.

While traditionally reactive synthesis has focussed on qualitative objectives which require functional requirements to be satisfied, a more interesting, useful, and technically challenging problem is to consider specifications that combine both qualitative and quantitative objectives where the quantitative objectives are used to specify resource consumption, cost, energy among others which are important parameters in safety-critical embedded applications. Our focus will be on the study of solving Markov decision processes and stochastic games with a combination of objectives.

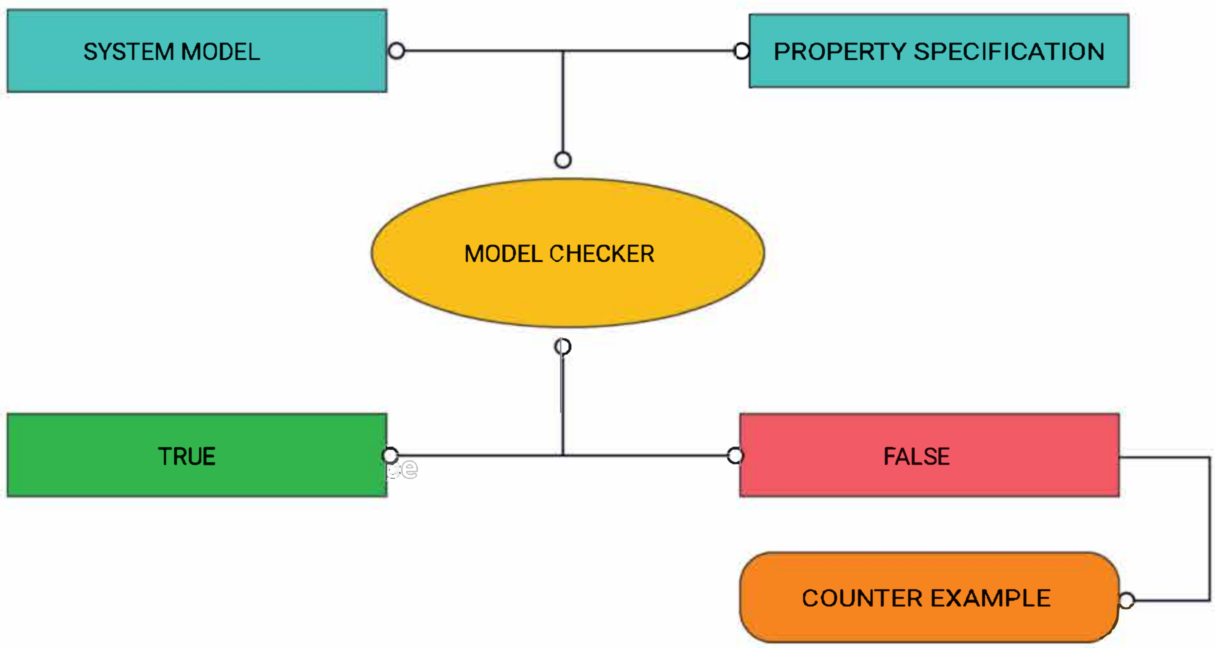
10. Communication complexity.

We seek to explore and find answers to some of these questions. What is the exact nature of communication complexity? Is it information theoretic, algebraic or combinatorial or all three?

Multivariate Algorithmic Analysis: There is a real need for a mathematical framework that allows us to express the running time of algorithms in terms of both input size and the structural properties of the input instances. Such a framework would not only be a breakthrough in understanding the nature of computing, it would also drive the design of efficient algorithms in practice. A particularly successful attempt at creating such a mathematical model is the field of parameterized complexity. This field was created in order to improve over worst-case analysis for NP-hard problems; problems whose worst-case running time is conjectured to be at least exponential in the input size. However, so far, the success of fixed-parameter tractability has been limited to applications with NP-hard optimization problems, mostly on graphs and networks. There is no inherent reason why this should be the case. This idea of a multivariate algorithm analysis has the potential to address the need for a framework for refined algorithm analysis for all kinds of problems across all domains and subfields of computer science. Our ultimate goal is to unlock this potential. We will develop toolkits for designing and analysing multivariate algorithms for every relevant class of input instances, including, but not limited to set systems, matrices, matroids, polytopes, lattices, as well as algebraic, topological and geometric objects. We also aim to create a multivariate theory of approximation algorithms, of machine learning algorithms, of pre-processing heuristics, of dynamic algorithms, of distributed algorithms and even of polynomial time algorithms.

Machine learning: An important direction for future progress is suggested by the spectacular, and often baffling, recent successes of large machine learning models in a variety of application domains. The ultimate goal of a hypothetical "theory of large ML models" would of course be to predict reasonably precisely and accurately the expected performance of any proposed model architecture and learning procedure, but such a theory appears to be far away. Ongoing recent activities noticed in STCS (TIFR, Mumbai) in these directions in the setting of understanding what biases might be inherent in various learning algorithms and the school could attempt to further enhance activity in this and related directions over the coming decade.

Formal methods and Verification: Research in model checking aims at expanding the scope of automated techniques for program reasoning, both in the scale of programs handled and in the richness of system and properties that can be checked. We note here that though testing allows us to find bugs, it does not certify absence of bugs. Also, for most practical systems exhaustive testing may not be practically feasible.



Algorithmic model-checking

Formal verification is also used in the Electronic Design Automation (EDA) industry. Formal verification plays a significant role to boost productivity by an order of magnitude in the chip design and implementation cycles including functional, safety and security verification, logic optimization at various levels of design abstractions starting from architectural levels and up to implementation of both software and hardware models.

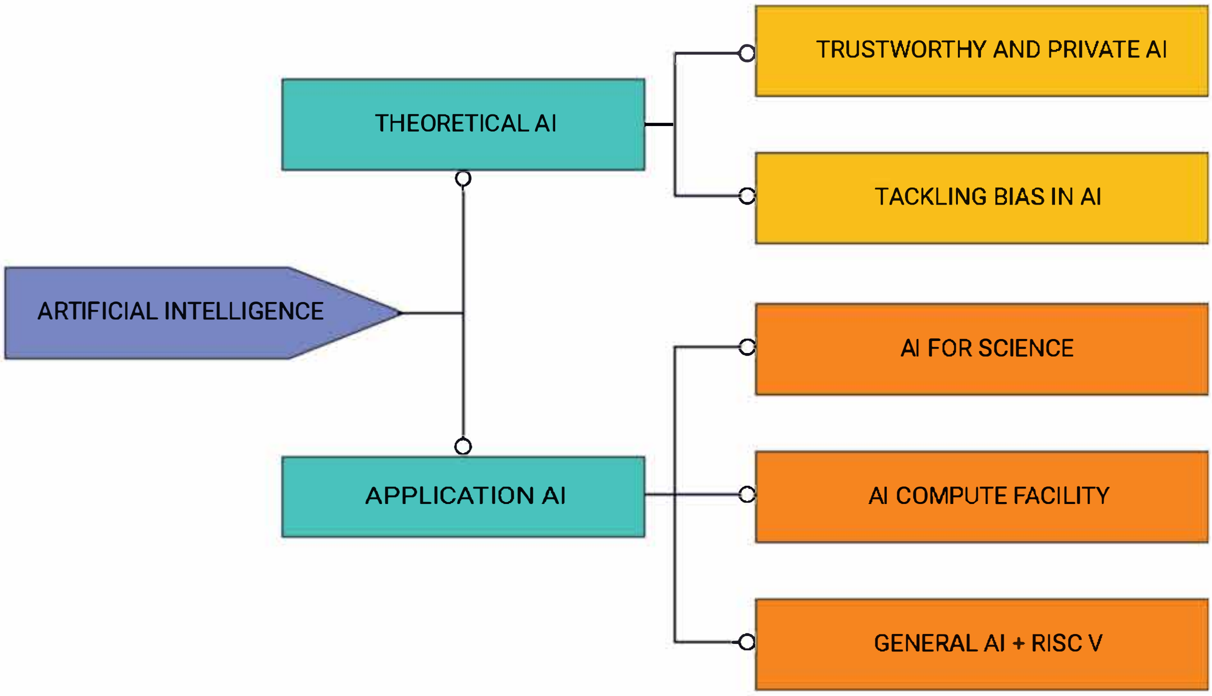
Artificial Intelligence:

- *Indigenous Large Scale General Intelligence System.*

  The goal is to set up a large-scale general intelligence system built on efficient and lower parameter custom models and integration into model operating systems to form the general intelligence system.

- *Bias and Fairness in AI.*

  We can envision a future in which AI systems develop algorithms, so any kind of quality control may not even be possible. Hence, we specifically want to develop algorithm design mechanisms where transparency and control are built in.



Centre for Artificial Intelligence @ NISER

- *Trustworthy and Private AI.*

  The focus of this line of work would be to build tools to check the validity of the output of AI models. Since the scope of this area will be enormous in the future, we aim to restrict our attention to the specific tasks for which the input and output behavior can be defined explicitly. This line of research falls at the intersection of property testing, sublinear algorithms and machine learning.

- *AI for Science*.

  One of the goals here is to address challenges in biology and predict intrinsic microbial metabolites that regulate host physiology. Other fields that we desire to explore include (i) Smart Agriculture; (ii) Early detection of eye diseases and hemoglobinopathies; (iii) Nucleic acid and Peptides-based therapeutic drugs for anticancer; (iv) Challenges in Chemistry - Clean, error free, easily interpretable NMR spectra, Machine Learning in Chemical Dynamics; (v) Challenges in Earth and Planetary Science - Earthquake detection; (vi) Challenges in Physics - Quantum many-body techniques, Weather and climate modeling, and Dynamic temperature evolution.

10.2 Long-term road map

Post-quantum cryptography: Much of current cryptography is based on problems which are believed to be difficult for classical computers to solve. However, quantum computers hold the potential for efficiently solving such problems and breaking the cryptography. Several new/additional problems which are expected to be resistant to quantum computers and on which post-quantum cryptography can be built are being considered with some of these being standardized. Given the need for cryptography which remains secure far into the future, post-quantum cryptography research and standardization efforts is an active area. As our understanding of the capabilities of quantum computing improves with time, this nascent area is expected to mature and remain highly relevant.

Quantum cryptography: It has been recognized from the early days of quantum computing that basing cryptography on quantum mechanical phenomena has the potential for delivering unconditional cryptography (i.e., cryptography which does not rely on assumptions of computational abilities of adversaries). Quantum cryptographic algorithms are expected to play important roles in a future Quantum Internet and is one of the fastest growing areas of research in quantum information science.

Formal methods and verification:

Most of the newer nuclear power plants have systems and equipment that are software controlled. The analog devices are being replaced by digital, software-based devices. Safety in these plants is of paramount importance and can include reactor protection or safety feature actuation. A conscious effort to deal with possible failures of these software systems and components operating on the nuclear power plants is necessary. Unlike some of the other domains where software is used, in nuclear reactors, the safety levels and requirements are very demanding.

Also as noted earlier, the soft landing of Chandrayaan-2 mission failed due to a software glitch. The Indian Space Research Organisation too can be keen on the use of formal methods to ensure correctness guarantees for the various software modules used in space research. The formal methods community in TIFR and IMSc would contribute in providing guidance to these requirements.

10.3 High Performance Computing Facilities – the next decade and beyond

High Performance Computing (HPC) related scientific research of DAE scientists spans over a very diverse range of sciences including: astrophysics and cosmology, biological sciences, chemical sciences, quantum many body physics, statistical physics, complex systems, nuclear and high energy physics, applicable mathematics, and even for string theory. In recent years, high performance computing has become an integral part of each of these subjects. For the fruitful implementation of big-science projects that Indian scientists are participating, one would anticipate a large demand for high performance computing. Moreover, recently Artificial Intelligence (AI) with Machine-Learning (ML) and Deep-Learning (DL) is becoming an important component in most of the above areas. It is highly anticipated that in the coming days there will be rapid expansion in computing intensive and data-driven field of research through these new directions.

Based on the experiences of peer institutions and R & D establishments worldwide, it appears that such allocation of individual resources is not necessarily optimal, since it misses out on the synergies that are derived from a unified computing resource centre. In view of this we envisage for a large data centre. This large data centre will be connected to all DAE institutes through dedicated fastest possible bandwidth lines.

Scientific areas that need HPC facilities:

Astrophysics and Cosmology

Astrophysics research in DAE is spread over almost all DAE-aided institutions including National Centre for Radio Astrophysics, Pune. The research areas also cover a broad spectrum-- from the nearby solar system to celestial objects in our Milky Way galaxy to the farthest corners of our Universe. This diversity in research topics has led to involvement in several observational mega-projects, such as Square Kilometre Array (SKA), LIGO India, and Thirty Meter Telescope (TMT).

Nuclear and Particle Physics:

Indian physicists are engaged in various nuclear and high energy physics experiments around the world including many inside India. These experiments collect a large amount of data that need to be analysed in the framework of numerical analysis utilizing a large computational resource. For example, often it is essential to have grid computing resources comprising a fast connection along with a large data-storage space and faster processors.

Theory: Strong Interactions Physics:

The computing usage of theoretical nuclear physics is mainly to investigate strong interaction physics. It has different components: first principles method of lattice gauge theory, hydrodynamical simulations, nuclear shell structure calculations, plasma simulations and the emerging field of machine learning. There is substantial presence of Indian physicists in these areas and they have made very important contributions to understand strong interactions physics.

Quantum many-body physics

Quantum Many-body Physics (QMP) encompasses the study of emergent phenomena in interacting quantum systems with a large number of degrees of freedom. Problems in quantum many-body physics require a wide range of tools, from analytical quantum field theory-based approaches, variational wavefunctions, large scale HPC with numerical methods like quantum Monte Carlo, exact diagonalization, DMFT, DMRG, Tensor Networks etc.

11. Fundamental Theoretical Physics

Traditionally, DAE has strongly supported fundamental theoretical physics, with its grant-in-aid institutions like

Harish-Chandra Research Institute, Institute of Mathematical Sciences,

Institute of Physics, National Institute of Science Education and Research, Saha Institute of Nuclear Physics, and Tata Institute of Fundamental Research

are carrying out theoretical research in many subareas of physics.

Fundamental theoretical physics plays a crucial role in understanding natural phenomena and contributes to various areas of science and technology. It studies Nature at widely different length scales, starting from sub-microscopic scales of femtometers to cosmological distances of gigaparsecs. It also spans time scales from beyond attoseconds to billions of years. Herein, some of the key visions of theoretical physicists in the DAE grant-in-aid institutions, for the next 25 years is presented.

- **Mega-scale:**
  - **Cosmology:** Deciphering the initial conditions of the Universe, discovering non-gravitational interactions of dark matter, nature of dark energy, formation of first stars and galaxies, testing the fundamental assumptions of the standard model of cosmology.
  - **Complex Flows and turbulence:** Analysing atmospheric and oceanic flows to understand the Indian monsoon and rainfall formation; understanding the role of turbulence in solar physics, supernova explosions and accretion disks.
- **Macroscale/Mesoscale:**
  - **Statistical Physics & Complex Systems:** Understanding the performance of living complex systems, e.g., enzymes, gene expression, active systems; designing new disordered and soft material functions via simulations and providing statistical physics tools to interdisciplinary applications.
  - **Quantum many-body physics:** Integrating quantum many body theory with computing tools, including quantum computing and AI-ML, for predicting the properties of interacting quantum systems.

- **Microscale:**
  - **High energy physics:** Establishing an end-to-end high energy physics program in India, focused on ``exploring the light hidden universe'' of weakly interacting particles.
  - **Strong interaction physics:** Simulating nuclear scattering processes from first principles, understanding dense matter such as neutron stars, phase transitions in the early Universe, controlling QCD uncertainties in high energy scatterings.
  - **Quantum gravity:** Understanding microstates of non-supersymmetric black holes, quantum dynamics of black holes, holography in AdS, flat and cosmological space times, reformulation of quantum field theory which makes the hidden global symmetries more manifest, string theory on cosmological space times.

The roadmap towards pursuing the above goals will include (i) generation of creative ideas and development of unified mathematical frameworks, (ii) analysing data from ongoing experiments efficiently and conceptualising future experiments, (iii) using large-scale numerical simulations for solving problems that are intractable by analytic means. In order to progress towards the fulfilment of the vision, one will need to facilitate the exchange of ideas within and across theoretical disciplines, close collaborations between theorists and experimentalists, availability of adequate computing resources, and training of next generation of young scientists. Investment in collaboration hubs, visitor programmes, high-performance computing data centres, and short-term advanced training schools is therefore crucial for achieving the goals stated in this document.

11.1 Scientific goals:

11.1.1 Cosmology:

Cosmology has seen tremendous breakthroughs and fundamental discoveries about the Universe over the last 100 years. The birth of modern cosmology can be traced to the *Great Debate* between Curtis and Shapley in 1920 about the scale or size of the Universe. The measurement of distances to the nearby galaxies by Hubble settled the debate and discovered the expansion of the Universe as predicted by Friedmann’s solutions to Einstein’s equations of general relativity. We have mapped the observable Universe in great detail from radio to X-ray wavelengths. The precise measurements of the cosmic microwave background, large scale structure in galaxy surveys, and measurement of distances to the distant galaxies using the Supernovae of type 1a has led to the establishment of the standard model of cosmology also called the ΛCDM model. The Λ and CDM (cold dark matter) in the name stand for two *confirmed* new constituents of the Universe (beyond the standard model of particle physics) discovered by cosmologists, namely dark energy and dark matter, respectively.

While we have made tremendous progress in understanding the origin and evolution of the Universe, Nature has also thrown up intriguing new questions about the Universe. There are numerous international experiments being planned in the next 25 years which should help in answering some of these questions. New theoretical understanding and data analysis tools would be needed to understand and interpret the deluge of data from the next generation of experiments. Some of the most important questions in cosmology are the following:

- **Early Universe:** What is the nature of the big bang? Was there Inflation in the beginning? The standard model of cosmology is consistent with the simplest models of inflation but details about the high energy theory of inflation and initial conditions before inflation remain elusive.

- **Dark Ages to Cosmic Dawn**: When and how did the First Stars form and ionize the Universe? How can we use the observations of this epoch to learn about fundamental physics?

- **Late-time Universe:** How do galaxies and the Cosmic Web form and evolve? What is the current accelerated expansion phase of the Universe telling us about fundamental physics? Is it due to the cosmological constant, a new fundamental particle field, or modification of gravity? Does Nature follow Einstein Gravity on large scales?

- **Cosmological Tensions:** There are many ways to measure the same cosmological parameters, e.g. using the cosmic microwave background, directly measuring the expansion history of the Universe, mapping the galaxy distribution in the Universe (large scale structure of the Universe), looking at absorption of light by intervening matter in the spectrum of distant quasars, etc. If the standard cosmological model is consistent and correct, all experiments should give the same values for these cosmological parameters. A disagreement between the different ways of measuring the same cosmological parameter then provides a clue to the physics and processes beyond the standard model of cosmology. Future experiments will also begin to test the fundamental assumptions of the Standard Model of Cosmology such as the cosmological principle.

- **Black Holes:** What is the origin of the stellar mass black holes in the universe observed in gravitational waves, and of the super massive black holes observed in radio, infra-red, x-ray and optical telescopes at high redshifts? How do the black holes evolve with time? Recent observations have shown that the supermassive black holes with masses higher than million solar masses exist at redshift $z \sim 10$, or when the age of the Universe was of order 100 million years. This poses an interesting problem of how such massive black holes are formed at such an early phase of the Universe. In particular, whether the existence of these black holes is consistent with the standard model of cosmology, or whether we need to invoke new physics is still an important open question.

- **The Local Universe:** What is the distribution of dark matter in the Milky Way and how does it affect the interpretation of data from the direct detection experiments? Since all efforts to detect dark matter have so far given negative results, we need to come up with new experiments for direct detection in laboratories and new signals for indirect detection of dark matter in astronomical observations. What role do neutrinos play in astronomical phenomena such as supernovae? How to use the next generation of neutrinos observatories to learn about the fundamental laws and astrophysical phenomena?

11.1.2 Complex Flows: atmospheric, oceanic and astrophysical:

Fluid flows drive physics at scales ranging from a few micrometres to galactic scales. The examples include atmospheric and geophysical flows as well as Astrophysical flows. Remarkably, in most cases, the governing equations are well-known but their solutions remain rather elusive. A key complication appears from the fact that when the inertial forces become dominant, the flow dynamics becomes turbulent wherein all length and timescales are excited. Thus, understanding turbulent flows in a variety of settings has been a central issue of interest in the last century. Thanks to recent advances in experimental techniques and the advent of high-performance computing, several questions of importance in this domain are now being addressed.

The expertise to tackle may of the above issues already exists in many parts of the DAE system. This may be brought together to address the following challenging questions:

- **Physics of droplet growth in warm clouds:** A warm tropical cloud is a turbulent suspension of aerosol and tiny water droplets in its simplest formulation. Rain initiation is an outcome of the dynamics of this suspension when the seed droplets grow to sizes of a 100 micron or so. Recent studies have underlined the importance of turbulence in accelerated growth of droplets in the coalescence phase. However, the bottleneck between the condensation (early phase) and the coalescence (late phase) growth is still poorly understood. This, along with the dynamics of ice crystals in higher latitude clouds, is a critical ingredient in not only understanding the microphysics of clouds but also in providing key inputs to large scale modelling of weather where the clouds form a building block. This is the right time to tackle this problem in all its complexity.

- **Interaction between turbulence and suspended micro-particles:** Typical studies of turbulent suspension focus on the one-way coupling of the effect of the flow on microparticles. With recent concerns on the fate of suspended micro-particles -- both in the ocean (marine snow and microplastics) and the atmosphere (pollutants) -- more detailed studies and predictions of their motion by factoring in every facet of their dynamics is critical. These would include the exploration of how such particles may affect flows, which in turn may lead to a different sampling of the flow by such particles. They would also address questions of transport of anisotropic particles, filaments and polymers.

- **Predicting the state of the atmosphere from sparse observations**: A mathematical framework may be built to address the question of state-estimation in dynamical systems associated with geophysical applications. In state-estimation, one tries to estimate the state of a system given (1) the dynamical equations, (2) observations of the system (functions of a trajectory). The latter nowadays includes high-resolution satellite imagery. This study will blend ideas from various disciplines including dynamical systems, control theory, machine learning and scientific computing.

- **Cyclone Diagnostics -- estimating the velocity-field from a cyclone track:** Cyclone-tracking methods often simulate the trajectory of a cyclone by assuming the state of the neighbouring air-ocean system (or some suitable approximation). Instead, we ask, to what extent does the trajectory of a cyclone determine the surrounding velocity field? This can be posed as a state-estimation problem which fits into the framework described above. The eventual goal is to infer the vertical vorticity distribution from other datasets (SST, cloud cover, etc.) and use these to drive the observer problem.

- **Bubbly flows:** Bubbles play a crucial role in mixing and heat transfer in various industrial and oceanic flows. Nevertheless, the fundamental understanding of the mechanisms governing mass and energy transfer in these systems remains elusive. The key challenge is to understand the turbulence generated in these flows and how it alters mass transfer.

- **Turbulent emulsions:** A catastrophic example of turbulent emulsions is the oil spills in oceans. How turbulent transport spreads oil, and what controls the size of oil droplets are some questions that have garnered the attention of scientists for the past few decades. However, with the advent of large-scale computing, the phenomenology of these processes is now being tested. A detailed understanding of the underlying multiphase flows remains elusive.

- **Jet formation in accretion disks:** Coherent magnetic fields in accretion disks facilitate angular momentum transport and formation of jets. They are thought to be generated and maintained by a turbulent dynamo, i.e. a mechanism that converts kinetic energy to magnetic energy. The open questions include how the dynamos operating in accretion disks help in jet formation and whether there are large-scale features that depict a correspondence between disk and jet mediated by dynamos. This will have a bearing on the interpretation of the observations from the Event Horizon Telescope.

- **Turbulent transport in weakly collisional plasmas like solar corona:** In spite of being extremely tenuous, hot and hence weakly collisional, the solar corona shows turbulent behaviour. The understanding of turbulent transport in such weakly collisional systems is one of the central problems in the field of plasma turbulence.

- **Turbulence in supernova explosions and neutrino physics:** After the shock wave formation and subsequent neutrino heating, the propagation of shock wave inside a core-collapse supernova leads to turbulence that can affect the explosion itself, as well as the flavour conversions of neutrinos that carry out almost 99% of the energy of the core collapse. Attacking this problem needs collaborations among astrophysicists and neutrino physicists.

11.1.3 Statistical Physics & Complex Systems:

At its core, statistical physics relies on the principles of probability theory and statistical analysis to study the collective behaviour of particles in systems that may contain trillions upon trillions of them. This approach allows us to tackle complex systems that would be otherwise impossible to analyse using traditional classical mechanics or quantum mechanics alone. Contemporary research on complex systems include the themes of emergence, complexity and organization that were mentioned by P. W. Andesron in his seminal paper ``More Is Different''. Over the years, there has been a paradigm shift from the traditional view to more towards neo-emergentism, a shift driven by the observations and phenomena from nature and largely made possible by innovative tools of empirical research and experimental design, as well as an impressive array of sophisticated mathematical and computational perspectives.

Some of the key questions in this area, that can help us identify the unifying principles and general truths in natural phenomena, are the following:

- **Fundamental nature of non-equilibrium phenomena:** While the formalism of equilibrium physics is established elegantly within the canonical Boltzmannian description, a unified understanding of non-equilibrium systems remains elusive although they appear ubiquitously in nature. For example, nonequilibrium processes are essential for fluid motions or sustaining life in a single cell, colloids, interacting particles, glasses to living systems such as bacteria, enzymes, macromolecules such as polymers and strongly interacting quantum matter. The major quest is for identifying universal physical and mathematical laws that may dictate fundamental limits and trade-offs governing the pattern and binding the performance of non-equilibrium systems. The questions to be addressed are how systems far from equilibrium approach their ordered steady state, or What the universality classes of non-equilibrium systems are?

- **Soft Condensed Matter, Chemical and Biological Systems:** The study of statistical mechanics of disordered and complex systems explores the emergent behaviours of systems with many interacting degrees of freedom, subjected to random interactions, or being immersed in a complex, chaotic or stochastic medium. These include aggregation, fragmentation, evaporation; diffusive and active transport phenomena; nonequilibrium thermodynamics of many body systems; dissipation in active matter and the living systems; charged polymers in solution, or polyelectrolytes; and structural & dynamical properties of water.

- **Disordered Systems and Amorphous Materials:** Understanding the dynamical and mechanical properties of amorphous materials, such as supercooled liquids, glasses, jammed materials, gels, and granular systems, is not only theoretically interesting, but also has applications in industry. Research on these materials involves studying the behaviour of glass-forming liquids, the structural relaxation and plastic response of a range of soft condensed materials, as well as granular materials and other amorphous solids in equilibrium and under external driving.

- **Emergent behaviour:** In some systems with a large number of components, the system-level properties cannot be predicted with knowledge of only the properties of its constituents; their emergence can only be understood with reference to interactions amongst the constituents. This emergent behaviour is observed in systems of interest in a wide range of disciplines: the cell, the brain, ecosystems, individual cognitive performance, markets, urban traffic flow, etc. the advent of affordable high-performance computing has made the exploration of such systems possible, with agent-based modelling having millions of interacting agents.

- **Synchrony:** Some networks of interacting systems with a range of frequencies are observed to undergo a transition to a state of synchronized behaviour. This emergent synchrony might help us to understand power-grid/communication-network failure and resilience, chimera states observed in neural/brain circuits, etc. From the point of view of statistical physics, the important questions is whether a unified framework can be developed by combining methods of non-equilibrium statistical physics and kinetic theory. Atomic ensembles interacting with the mode of a high-finesse resonator offer a unique platform to study the physics of long-range interacting systems, through the phenomena of optomechanical bistability, spontaneous spatial ordering, collective lasing, etc. Envisaged applications for these systems range from sensors to quantum enhanced metrology, quantum simulators and quantum optics.
- **Stochastic modelling of income dynamics:** Developing methods for studying the temporal properties of income dynamics, for example whether individuals can improve their income profiles within the socio-economic ladder in times comparable to their working life, is a fundamental question in the literature of economic inequality and mobility. This is where analytic frameworks built on stochastic modelling of income dynamics could be useful, for example, using the labour office data, one may try to answer questions such as: What is the time needed for a low-wage worker to spend in the

workforce in order to reach a reasonable income level? Which proportion of workers are able to reach the highest status during their working life? How easy it is for the workers to reach certain income targets? The methodology and the results emanating from such studies would be of wide interest to practitioners for developing policy interventions aimed at optimizing the time in the Indian economy. It would also motivate new multidisciplinary research focused on creating even more comprehensive methods that could be applied to economies all across the globe.

- **Interdisciplinary hub for complex systems:** The activities in the growing field of complex systems in India may be taken to the next level by establishing a key hub of research in complex systems. This unique centre is envisaged to carry out research on diverse topics such as intracellular signalling networks and their role during infection through pathogen invasion, social networks of individual contact and their role in the spreading of infectious diseases such as COVID, detecting rising systemic risk prior to a major financial crises or ecological catastrophe mediated by climate change, as well as, spatio-temporal pattern formation and its regulation that is crucial for development and functioning of many biological, ecological or social systems.

11.1.4 Quantum Many-body Physics

Quantum Many-body Physics (QMP) encompasses the study of emergent phenomena in interacting quantum systems with a large number of degrees of freedom. Historically QMP has been the birthplace of new ideas like symmetry breaking, Higgs-Anderson mechanism etc. which have impacted physics across scales. It has also been the generator of phenomena which have formed a crucial backbone of technology, from microprocessors to superconducting magnets to platforms for quantum computing. Traditionally phenomena in quantum materials have provided both the inspiration and the most versatile testing ground for new ideas in QMP. However, more recent platforms like ultracold atomic systems and quantum circuits have enlarged the ambit of the subject, bringing with them new phenomena and new paradigms.

Problems in QMP require a wide range of tools, from analytical quantum field theory-based approaches, variational wavefunctions, to numerical methods like quantum Monte Carlo, exact diagonalization, DMFT, DMRG, Tensor Network based methods etc. The DAE system has a versatile group of scientists with wide research interests and deep expertise in these areas. However, it is important to keep in mind that this is an arena where new phenomena are uncovered in experiments frequently. As a result, the “interesting” problems change, and this often requires new expertise. The quantum many-body theorists in DAE aided institutions would like to focus their future research on the following areas.

- **Topological Phases of Matter:** The traditional notion of classifying phases of matter by their symmetries has been updated with inclusion of their topological properties, leading to diverse topological phases of matter. These states are characterized by protected edge modes, robust quantized responses, fractionalized excitations with non-standard mutual statistics (in systems with topological order). In future, the research of DAE scientists would focus on

- o The interplay between symmetries and entanglement in topological phases of matter.
- o Analogues of topological order in classical systems using topological gauge theory.
- o Protocols for 'smoking-gun' detection of SPT phases (e.g. in curved space-time).
- o Non-hermiticity as a route to new topological phases in open quantum systems.

The long-term objective of this research would be to produce a complete framework for classification of phases of matter (even in strongly interacting systems) involving symmetry, topology and entanglement.

- **Heterostructures and Quantum Devices:** The experimental ability to create heterostructures, which creates boundaries between materials with different bulk properties, is the key to making devices for quantum technologies. It is thus imperative to study junctions of quantum many body systems in their own right. Some interesting heterostructures we propose to study are

  - o Junctions between recently discovered anomalous fractional quantum Hall systems (without magnetic field) and superconductors, which can exhibit parafermionic excitations.
  - o Interfaces of magnetic and non-magnetic materials leading to valleytronics, anomalous Hall effects etc.
  - o Interface of magnetic materials to enhance coercive fields and transition temperatures
  - o Interface of insulating materials (e.g. $LaAlO_3$-$SrTiO_3$) which shows metallic and even superconducting behaviour.

The goal of this research is to predict heterostructures with interesting properties relevant to quantum technologies, sometimes by mixing the properties of the materials forming the interface, sometimes by creating a junction with new properties not inherited from the parent materials.

- **Quantum Information:** A new paradigm is gradually evolving in quantum many-body physics where quantum information (QI) theoretic quantities like entanglement entropy, negativity etc. are used to characterize the many body states of matter. As the 2nd quantum revolution winds its way, we expect these connections to get deeper and provide a more fine-grained non-local description of states of matter. Some key issues of immediate interest are:

The connection between correlation functions and entanglement entropy, negativity etc; entanglement of excited states, and many-body localization in disordered systems; evolution of entanglement in closed and open quantum systems, driven floquet systems. This has implication for thermalization, dynamical phases of matter in ultracold atomic systems and NISQ computations; evolution of QI measures (entanglement, quantum magic etc.) in quantum circuits under hybrid dynamics involving unitary gates and projective measurements, relevant to preparation of quantum states with large resources; quantum error correction by storing information non-locally in states with large entanglement and entanglement phase transition.

- **Non-Equilibrium Quantum Dynamics** Non-equilibrium dynamics of quantum many body systems is a relatively virgin field with very few universal paradigms. Ultracold atoms, quantum materials in pump-probe setting and random circuits provide a versatile setup to study non equilibrium quantum dynamics. Our proposed research would use multiple techniques from large scale numeric to non-equilibrium field theories to
  - Classify dynamics where the system fails to thermalize at long times. What is the long-time fate of such a system? How does it depend on initial conditions?
  - Develop a general framework for understanding pump-probe spectroscopies. What are the signatures/features one should follow? How does one interpret these features?
  - Classify Floquet phases of matter in driven quantum systems.
  - Find general conditions for existence of long-lived prethermal phases of matter under quantum quenches. Classify non-equilibrium steady states which show larger versatility than equilibrium phases.
  - Study dynamics of open quantum systems. An important goal is to find sectors/properties of systems which are protected from runaway heating in these systems. This can be used for quantum state preparation in NISQs settings.

The long-term goal of this research is twofold: a theoretical goal to develop a framework where interesting dynamics can be described systematically by a few variables/degrees of freedom (akin to renormalization in equilibrium systems), and a practical/technological goal of developing protocols to temporally control bulk properties of many body systems to perform particular tasks.

The melange of problems in quantum many body physics cover a broad range of topics with import on fundamental physics as well as new quantum technologies. These dual goals will drive the efforts of the quantum many-body physics community in the DAE aided institutions in the years to come.

11.1.5 Physics of Strong Interactions

Strong interactions between quarks and gluons is a fundamental force in our universe. It is behind the emergence of almost all of the visible mass in the universe, and may also hold clues to understanding of dark matter. Comprehension of subatomic particle properties including much of nuclear physics and its full potential hinges on a deep understanding of this force. From the deconfined quark-gluon-plasma during the universe's early stages to its transition into subatomic particles via complex dynamics, and from the nuclear force shaping all nuclei to matter under extreme densities in astrophysical objects like neutron stars, a thorough comprehension of strong interactions is essential. A large class of experiments at several high energy laboratories, including the Large Hadron Collider and the future Facility for Antiproton and Ion Research as well as future Electron-Ion-Collider are linked to various aspects of strong interactions physics.

Quantum chromodynamics (QCD), an asymptotically free local non-abelian quantum gauge field theory, is the theory of strong interactions of nature. The strength of the interactions of the strong force changes with the energy being probed which has implications in wide ranges of physics.

QCD at high energy:

In high energy domain, where the coupling constant of QCD is small, analytical calculations based on QCD have been proved to be accurate enough to explain numerous experimental data. However, inclusion of predictions of higher-order quantum effects at fixed order in a perturbative expansion, and re-summation to all orders of specific classes of corrections are necessary to reach an accuracy at the 1% level for many important measured observables. Use of improved predictions will allow to extract the value of several SM parameters, such as the masses of the W and Higgs bosons or the couplings of the Higgs boson to all the other elementary particles and also its self-coupling with higher precision. In turn, the value of these parameters will provide guidance to understand the mechanism of spontaneous breaking of the electroweak symmetry. In addition, these predictions will help to explore any new physics. Our physics goals in these areas involve:

- Interpreting high-precision data at the colliders
- Multi-loop gluonic processes, calculations at higher orders in the strong coupling constant.

- Higher order QCD corrections to differential cross-sections in Higgs, Drell-Yan, semi-inclusive Deep Inelastic Scattering.
- Precision Higgs measurement at current and future colliders (LH, HLLHC and FCC).
- Study of jets and their substructures.

QCD at Low energy:

QCD in its low energy domain is non-perturbative and so far, there is no first principle analytical solution. Euclidean formulation of quantum field theory on space-time lattices, so called lattice gauge theory, has emerged as a very powerful method to solve QCD by using large scale computation. Such numerical computations, assisted by formalism of effective field theory, has become integral to understand the physics of strong interactions.

Our future research will comprise of a judicious use of the theoretical tools, supplemented with insights from experiments in order to understand the strong interaction physics in its various aspects, starting from the early universe to constructing tomography of nucleons. Using large scale high-performance scientific computing, new algorithms and analysis techniques will be constructed and predictions on strong interactions physics as well as other quantum systems will be made. Some of the investigations will comprise machine learning. Moreover, development of algorithms for study of this physics on quantum computers is a part of our strategy in that. Below are some of our physics goals.

Physics of early universe, quark-gluon-plasma, and dense matter: Here key questions involve the study of high-density phase of the strongly interacting matter, in particular, the existence of a critical point in the phase diagram of hadronic matter, as well as the role of symmetry breaking at different phases of matter, their dynamical properties, through a synergy of large-scale numerical studies, exploration of new algorithms, and the formalism of effective field theory. The dense matter such as neutron star as well as the hypothesised colour-glass-condensate are also subject of interests. State-of-the-art hydrodynamical numerical codes including large scale ML utilities will be employed for the study of quark-gluon-plasma.

Nuclear astrophysics: A vast area of cosmology and astrophysics are deeply connected to nuclear physics. Starting from QGP at early universe, big-bang nucleosynthesis to star-burning and formation of neutron star requires deeper understanding in nuclear physics. Formation of exotic nuclei such as hyper-triton and their implications in astrophysics also need to be understood. A strong collaboration between nuclear physics, astrophysics and cosmology is expected in the next decades.

Nuclear Physics from first-principles: A first principles study of the first few nuclei is also crucial to understand the formation of nuclei in the early universe, particularly to understand the carbon cycle. Study of nuclear scatterings, particularly involving light nuclei, employing lattice QCD frameworks, will be of immense importance to understand the nuclear reactions of light as well higher nuclei. Information on polarized fusion using lattice QCD could be helpful for energy production in fusion processes. With current expertise in DAE institutes, an immense progress can be made provided adequate computing resources are available.

Emergence of mass and spin, and tomography of proton: The emergence of mass and spin in subatomic particles is a fundamental question in our understanding of nature. In fact, the future Electron-Ion-Collider will investigate these aspects. Detailed theoretical studies comprising lattice QCD calculations are very much necessary along with the EIC experiments to obtain the tomography of nucleons and other hadrons, which may also lead to new technological developments including their applications to medical sciences.

Heavy hadrons, exotics, and beyond the standard model: A large number of exotic subatomic particles have recently been discovered with the valence quark content beyond the normal mesons and baryons. Our focus will be predicting more such states aiding their discovery. A crucial step involves the understanding of their structures and bindings with a broader goal of deciphering strong interactions at multiple scales and unlocking its full potential. Likewise, precision studies based on lattice QCD are essential for investigating new physics phenomena, including lepton flavour violation, the anomalous magnetic moment of the muon, neutrino less double beta-decay, and dark matter, among others.

Sign problem, algorithmic developments for quantum computers: For systems where dynamics is involved (e.g., equilibration of the quark-gluon-plasma produced in the heavy ion colliders or at early universe), or at high densities (properties of the matter inside neutron stars), the numerical methods based on classical computers require an exponentially large time with increment of sizes. To solve the impasse, known as *sign problem*, novel conceptual works, in conjunction with the development of quantum algorithms, will be one of the main focuses of our research.

Computing Resources: The most essential part for carrying out calculations in this area is the access to large-scale high-performance computing of the order of 100s of Petaflops.

11.1.6 High Energy Theory

India boasts a strong and diverse community of particle physicists, who have made significant contributions in varied topics ranging from formal theoretical physics to collider physics, to flavour physics; from neutrino physics to astroparticle physics. Particle physics, however, was and remains a subject dominated by large experiments, big facilities, and often develops/shapes/utilizes the very frontier of technological developments. Even though India has a healthy population of physicists who are world experts in many corners of the field and contribute non-trivially to efforts led by mainly Americans, Europeans, and Japanese collaborations, we do not currently have the overarching depth or the breath in experimental, technical, and theoretical topics which would allow us to have one such major facility and lead the world of research in the fundamental physics of nature. The main goal of this program would be to pave the path forward so that by 2047 we generate such capabilities in all these frontiers. Clearly, in order to face the enormity of this challenge, we need to develop a multi-dimensional approach.

The overall programme has to seamlessly intertwine experiments and theory / phenomenology. The detailed vision of this ``Indian End2End HEP programme'' has been presented in the White Paper for the HEP vision 2047 that has emerged out of the Chintan Shivirs of the Department of Atomic Energy, Government of India. In this document, we include specific points relevant specifically to theory and phenomenology.

The physics goal: Exploring the light hidden universe

The visible matter contributes less than 5% to the energy of our universe. Finding and exploring light/ultralight hidden sectors, which are feebly connected to our visible universe, represents the new frontier in particle physics. One can envision building on the current expertise of Indian scientists in this area to tackle this issue along the experimental, theoretical, as well as in the computational frontiers.

The Theoretical Frontier

The theoretical exploration of the light and/or hidden (semi-visible) sector involves building models to solve non-trivial problems such as the strong CP problem of QCD, the observed discrepancies in measurements of neutron lifetime, the observed vs. estimated measurements of (g-2) of muon and electron, anomalies observed in collider experiments, the yet-to-be pinned down particle physics properties of the dark matter, etc., as well as studying phenomenological consequences of these scenarios in the myriad of low energy experiments and in various astrophysical measurements. The challenges in the theoretical domain that are crucial for the ``light hidden universe'' programme include:

- systematically charting the space of high energy theories to be explored at the experimental setup(s) constructed,
- developing effective field theory techniques to derive low-energy observables from these theories,
- bringing in the material science knowledge base needed for understanding and constructing novel detectors,
- collaborations with experts in nuclear and atomic-molecular physics where sources involve collisions, and with those in cosmology and astrophysics for understanding detectors facing the sky, for understanding the flux and the background.

Deepening the talent pool in HEP

One of the biggest efforts to be taken by the program in this regard would be to increase the depth of the talent pool in the Indian HEP community by means of providing training at various levels as summarized below:

- A HEP database: A database of pedagogical HEP resources will be built, which will include courses taught by various experts as well as supplementary materials/resources that can help prepare students.
- A regularly recurring school for beginning HEP graduate students in experiment as well as theory, based on the model of the highly successful SERC/SERB schools, will be re-initiated.
- Recurring schools for highly specialized training, which will provide advanced and focussed training aimed at postdocs and advanced graduate students, will be initiated.

The Indian end-to-end HEP Programme

The programme exploring the light hidden universe will rely on the expertise and talents of the current state-of-the-art facilities such as the BARC, RRCAT, IUAC, IMSC, SINP, RRI, TIFR etc., will bring together experimentalists, theorists, and engineers from varying fields of high energy physics, nuclear physics, astrophysics, condensed-matter and atomic-molecular physics, and even experts from industries. The programme will have a clear roadmap with incremental goals, which at every stage will identify niche areas of R&D, take steps to generate expertise aimed towards attaining the final objective, and will engage in verticals ranging from designing/developing table top experiments, to designing and developing specialized hardware including quantum sensors, to building specialized simulations and algorithms (particularly, AI and quantum machine learning), etc. The developments on the experimental fronts need to have an overarching theoretical support, which would require large roles to be carried out by phenomenologists and theorists. The culmination of these efforts would be in having a world-leading HEP experiment on Indian soil, spearheaded as well as implemented from beginning to end by Indian scientists (with possible international collaboration), which will also help nurture, build and focus the talent pool in the area of high energy physics.

11.1.7 Quantum Gravity and String Theory

A fundamental problem in theoretical physics is the unification of the two foundational theories of modern physics, namely general relativity and quantum mechanics. The problem of quantum gravity has important implications to a wide variety of subjects, ranging from black holes to cosmology. Over the years, research in string theory has led to significant progress on this longstanding question. The AdS/CFT correspondence -- a framework for quantum gravity in asymptotically Anti-de Sitter spacetimes, which grew out of string theory, has led to a paradigm shift, where spacetime and gravity are viewed not as fundamental, but as emergent phenomena from the dynamics of a dual, microscopic quantum system. The next few decades of research in string theory hold great promise in terms of solving the problem of quantum gravity, building a new quantum picture of spacetime and making contact with cosmology. Some of these promising directions are detailed below:

Black Holes and String Theory

The Bekenstein-Hawking formula -- a remarkable formula which assigns an entropy to a macroscopic black hole proportional to the geometric area of the black hole horizon -- is at the heart of quantum gravity. General relativity shows that this entropy satisfies the laws of thermodynamics, but does not explain its statistical origin in terms of underlying microstates. One of the success stories of string theory is an explanation of this Bekenstein-Hawking entropy in the special case of certain supersymmetric extremal black holes in terms of the underlying quantum degrees of freedom corresponding to branes and strings. The macroscopic calculation involves finding a (charged, extremal) black hole solution in supergravity/string theory and computing its area, while the microscopic calculation involves counting quantum states of a system of branes and strings in flat spacetime with the same charges as the black hole. Actually, more is true -- in string theory, the Bekenstein-Hawking formula receives classical stringy corrections, as well as quantum corrections, thus making the matching between the microscopic and macroscopic computations highly non-trivial. Nevertheless, in some special cases, this matching has been accomplished with great precision[2]. Furthermore, the AdS/CFT correspondence has led to a vast generalization of black hole entropy formula via the celebrated Ryu-Takayanagi formula. This has resulted in, among other things, a modern understanding of the structure of quantum information in gravity in terms of quantum error correction, and a resolution of the long-standing black hole information problem.

Black holes hold a lot of promise for important developments in the near future. The interplay between the mathematics of modular forms and the physics of supersymmetric black holes will remain a fertile subject in the coming years. Exact calculations in supergravity using localization and insights from low-dimensional quantum gravity on the one hand, and on the other hand precision-counting of microstates via the supersymmetric index are very active areas of research and will likely lead to an increasingly precise understanding of the microstructure of black holes in string theory in the near future. However, much of the progress in understanding black holes in string theory so far has been in the context of supersymmetric extremal black holes. The next few decades of research on black holes will have to include a major effort to understand non-extremal black holes. Finally, the interplay between quantum information, computational complexity theory and black hole physics within the AdS/CFT.

In such cases, the supersymmetric index can be obtained in terms of modular forms and related objects. The most well-known example of this are quarter BPS black holes in N=4 string theories. In this case, the index is given by Fourier coefficients of Siegel Modular forms. On the macroscopic side, classical higher derivative corrections can be taken into account using Wald's formula. Sen's Quantum Entropy function is a proposal to include the quantum corrections.

Correspondence is a very active area of research, with the goal of achieving an increasingly precise quantum picture of spacetime. So far, this effort has largely focused on semi-classical gravity; in the coming years, it needs to be extended to included stringy and non-perturbative quantum corrections, with the long-term goal of having a quantum resolution of the black hole singularity.

Scattering Amplitudes and bootstrap

Scattering amplitude is a basic quantity used to study properties of elementary particles in collider experiments. The method for computing these amplitudes was discovered by Richard Feynman more than seventy years ago and even today, this is the state-of-the-art. However, summing over Feynman diagrams is not a simple job in most cases. The number of diagrams for even six or seven gluon tree-level amplitudes grows dramatically, and so calculating these amplitudes in QCD is a daunting task. In spite of these physicists have computed such amplitudes and the final answer is amazingly simple! One of the reasons for this is that the Feynman diagram technique often hides the underlying symmetries of a theory. For example, the mysterious relation between the scattering amplitudes of gravitons and gluons, known as the KLT relation, does not have any simple explanation in terms of field theory Feynman diagrams. This has led many people to believe that perhaps Feynman diagrams is not the best way of organizing the perturbative expansion in quantum field theory, and that a more efficient reformulation must exist.

In the last two decades a lot of progress has been made in understanding the structure of this putative reformulation; no coherent picture has emerged so far, but this remains an active area of work. Research in string scattering amplitudes, and in particular construction of twistor strings or other ``toy string theories'' which capture a sub-sector of gauge theory or gravity is one promising avenue to be pursued. Secondly, flat-space holography is a very active area of research which seeks to reformulate gauge and gravitational amplitudes in flat spacetime as correlation functions in a lower-dimensional quantum theory. One of the lessons to come out of this effort is that these amplitudes are invariant under large (infinite-dimensional) symmetry algebras, a powerful tool which can be used to constrain these amplitudes significantly. A relatively short-term goal will be to find the complete set of symmetries of tree level scattering amplitudes in gauge theories and gravity, to understand their representation theory, and to then apply this technique to loop amplitudes. A long-term goal will be to reformulate gravity in flat space as a lower-dimensional quantum system, thus also solving the problem of quantum gravity in flat spacetime. Finally, significant recent progress has also been made by trying to solve for amplitudes from general principles such as analyticity, unitarity and crossing symmetry under the bootstrap program, which promises to yield increasingly precise results in the coming years.

Cosmology and String Theory

We are currently living in a golden age for cosmology. The precise measurements of the power spectrum of density perturbations of the cosmic microwave background and the distribution of galaxies over the past 25 years has revealed striking patterns. The surprising discovery of the accelerated expansion of the universe in the present epoch has given rise to one of the the biggest puzzle in physics: dark energy. The standard model of cosmology together with inflation has been successful in providing fits to the data. At the same time, many fundamental questions remain, such as for instance the resolution of the big bang singularity, an explanation for the initial state of the universe, the structure of quantum mechanics in an accelerating universe, etc. Quantum gravity lies at the heart of many of these questions. A large number of new experiments probing the very earliest epoch of the universe will become operational in the next 25 years, likely ushering in a new wave of progress in the subject.

The big open question in this field is to study phases of early universe in quantum gravity and understand implications for the big bang singularity. In the absence of a complete theory of quantum gravity, toy models will play an important role. Lessons from the study of black-holes will also likely be important. Inflation has emerged as the leading explanation for the nature of the inhomogeneities in our Universe. Since it is well-appreciated that inflationary physics is sensitive to quantum gravity, embedding inflationary models in quantum gravity and its implications will be pursued. String theory provides a concrete framework to address some of the puzzles in cosmology. Compactifications, de Sitter vacua in string theory (the KKLT and related constructions), symmetries, time dependence and the role of quantum entanglement are all active areas of research. Finally, the observation of gravitational waves by the LIGO experiment has given us a completely new tool to probe nature. There are proposed experiments in a wide range of frequencies which will allow us to probe the cosmic history of the universe. Gravitational wave production from inflation, phase transitions in the early universe, cosmic strings and exotic phases of the very early universe and their phenomenological implications are some directions of research along these lines.

11.1.8 Quantum Field Theories on Quantum Computers

Quantum computing is emerging as the next major frontier of research and development. An integral part of that involves the development of algorithms which can be executed on quantum hardware. DAE family has a large number of scientists, along with strong presence in computer science and mathematics, whose expertise can be utilized in this endeavour benefiting the nation in the long run and also in achieving the goals of National Quantum Mission.

As quantum technology worldwide is undergoing outstanding development, parallel efforts are underway to identify classes of problems that can benefit from the so-called Quantum advantage. Strongly interacting systems in particle and condensed matter physics are natural candidates in this class, necessary not only to understand how our Universe works but also in the design of novel technology for the benefit of the society. Analytical understanding of such theories is limited, while numerical studies using classical computers face roadblocks and impede progress, especially while exploring physics at finite densities or in real times. The new paradigm of quantum computation is known to be free of conceptual roadblocks faced with classical methods, and limited only by the corresponding technological development. Over the last decade, global efforts have been put towards developing quantum algorithms (for both near-term and far-term devices) for simulating gauge theories on quantum platforms. This includes developing novel frameworks for such theories, proposing and implementing system on analog quantum architecture, developing algorithms for universal quantum computers and benchmarking the same on NISQ era devices as well as developing algorithms for benchmarking the same on state-of-the-art classical computational tools such as tensor network methods and novel Monte Carlo methods.

Our initial aim will be to explore and exploit quantum algorithms for addressing relevant problems in the NISQ era . Simultaneously we will be developing algorithms which we intend to employ for technology development. In DAE family we have experts from different areas of the theoretical sciences, namely computer sciences, condensed matter and statistical physics, nuclear and high energy physics, mathematical physics and string theory. We will also closely collaborate with our experimental colleagues to establish a quantum hub within DAE.

The activities in our vision are designed to bring together the collective wisdom and advancements in diverse areas of the theoretical sciences to advance specific end goals. Some of the activities that we envisaged are described below:

Structure and complexity of quantum states, their preparation and measurement:

An important step that must precede any quantum computation is the understanding of the structure and complexity of different states. Here we plan to go beyond the commonly used measures based on bipartite entanglement entropies and develop new measures such as multipartite entanglement entropies and departure from stabilizer states. These tools will help construct a ``heat map'' of the Hilbert space showing the strength of the quantum resources (e.g. entanglement, coherence). This will be followed by exploration of different techniques based on projective measurements as well as unitary counterdiabatic evolution for accessing desirable states with greater quantum resources. This programme will be ultimately implemented with NISQ era processors with the goal of bettering entangled state preparation on classical simulators.

Error correcting codes from condensed matter, gravity and field theory:

A number of condensed matter systems such as those endowed with topological order (e.g., the Toric Code, quantum spin liquids) or others such as Sachdev-Ye-Kitaev model allow the realization of quantum qubits that are robust against local environmental perturbations. Lessons learnt from gravity and quantum field theories have enormously advanced our general understanding of quantum error correction and fault tolerant platforms. A key effort here is an interdisciplinary one of consolidating developments in these disparate areas and designing new robust error correcting codes.

Optimization strategies with quantum circuits:

Besides state characterization, preparation and measurement, the final ingredient in a quantum computation scheme concerns state manipulation. We will explore different strategies to optimize transport (with relevant constraints) of an initial state to a desired final one using local constraints and/or projections. This will include statistical inference schemes for learning random quantum circuits with specified end results.

Application - Quantum emulation:

The above proposed activities seek to advance our ability to study quantum states using ideas developed in different areas of physical sciences. Conversely, quantum processors will provide an ideal platform to advance the knowledge in the physical sciences. Some of the topics we will pursue are (a) simulation of entangled phases of matter, (b) study of string dynamics and topological qubits in gauge theory, (c) simulating scattering with quantum circuits, (d) simulating emergent spacetime with SYK model implementation, (e) studying measurement induced entanglement transitions, and (f) studies of topological states.

Commercialization - Quantum Linear Solvers:

One of our main goals would be to design and implement linear solvers on quantum processors and systematically scale up taking advantage of the progress we hope to make in state preparation, measurement and manipulation. Practical implementation on scale will require hybrid classical-quantum strategies whose relative proportions will be determined by the complexity of the linear system being studied. We will closely work with our industrial partner to commercialize the linear solver.

11.2 Proposed roadmap and expected outcomes

Though spanning across wide length and time scales, the study of theoretical physics uses many common techniques and mathematical frameworks. Indeed, questions at the cosmological scales often find their answers in the subatomic processes. The visions in different areas described in this document are therefore interwoven with each other and are interdependent in many instances.

12. Mathematical Sciences

The DAE mathematics portfolio has historical strengths in the areas of algebra, algebraic geometry, analysis, number theory, partial differential equations, representation theory, and Lie groups. Recently, we have added expertise in new subjects like probability and mathematical modelling. Several striking results and monumental achievements have been attained in the past decades. A very small sample of highlights include the study of vector bundles, algebraic groups including structural and arithmetic aspects, index theory for elliptic operators, and Diophantine questions innumber theory, especially Waring's problem. It is worth mentioning that India's strength in modern mathematics, especially in the early stages, has largely grown out of DAE AI's. In addition to forming the backbone of mathematical research in India, the DAE community has also been instrumental in the training of talented young people, across all levels of higher education. These efforts have already borne fruit a significant number of the mathematics faculty across the IIT's, IISER's and other leading institutions of the country have received their doctoral training at DAE institutions.

Our vision in this document, seeks to buttress, and amplify these two basic ideas. Namely, we wish to soar higher in our research aspirations and significantly increase our pedagogical footprint. Our research vision outlines some of the main themes and problems that will be pursued. We aim to add new areas of research to the DAE portfolio as well as engage with emerging technology such as Artificial Intelligence. Our training vision includes several new ideas, including a scaling up of 'Math Circles' as well as a new centre for women students, particularly from disadvantaged areas of the country.

12.1 Research Vision:

Algebra and Representation theory

The broad areas include Advanced Group theory, Infinite dimensional Lie algebras, Algebraic Combinatorics, (Galois) representation theory, and Langlands program

Advancing the theory of skew braces as a tool for classifying solutions of the Yang-Baxter equation, and as an independent subject encompassing several mathematical topics.

- Classification of irreducible integrable modules over infinite dimensional Lie algebras.
- Applying combinatorial methods to study problems in algebra, representation theory, and special functions.

The long-term goal is to understand different types of representation theories via a diverse set of methodologies along with several applications and interplay with different branches in Mathematics like Number theory, Geometry, etc.

Algebraic and Arithmetic Geometry

The broad Areas include Moduli Stacks, Algebraic K-theory, Motivic homotopy theory, Derived algebraic geometry, and enumerative geometry. Topics planned to study are: Period index problem over number fields; Understanding Brauer groups of algebraic stacks, Quiver varieties, and their moduli spaces Developments on Chern-Simons theory and their algebraic versions; Computing Gromov-Witten invariants of the quintic threefold by interpreting it as a relative Gromov-Witten invariant in enumerative geometry; A good theory of the Arithmetic cycles of a smooth open variety, Constructing mirrors of moduli spaces via cluster charts and applications to the Atiyah-Floer conjecture, and Constructing new homology theories for algebraic varieties using unstable motivic algebraic topology. Expertise to be developed are Algebraic K-theory, Algebraic stacks, Cohomological methods in algebraic geometry, Enumerative geometry, and Motivic homotopy theory

The long-term aim is to study fundamental questions and conjectures in algebraic and arithmetic geometry using homological and homotopical methods.

Analysis of Partial differential equations (PDE)

PDE arise in various models in engineering, natural sciences, and other branches of mathematics like geometry. Most of these equations are highly nonlinear and complex and finding an explicit solution to these problems is almost impossible. In view of this, the analysis of partial differential equations becomes extremely important especially due to their applications and various mathematical challenges it poses. There is no unified theory about PDEs and the mathematical tools needed to analyse equations vary quite a bit from one to the other. Based on the expertise available in DAE institutions at present some of the topics planned for study are:

- Fluid dynamics Equations, Fluid solid Interactions, and homogenization
- Elliptic and Parabolic equations, PDEs from Geometry
- Control Theory, Inverse Problems

The main focus of research will be to resolve major open questions in many of the subareas. The other focus will be to scale up the training and research programs to address the shortage of manpower for research in these areas.

Scientific computation and Applications

Scientific computation of PDEs addresses the issue of developing numerical schemes preserving the essential features of the model involved. It is also important to develop numerical schemes which are computationally less expensive. The aim is to develop novel, accurate, and robust algorithms for various non-linear PDE models that arise in modelling flow problems.

On the application front, we plan to focus on some of the relevant topics like Oceanic flows, weather, data problems, etc. Some of the future goals are:

- Developing models for oceanographic flows capturing turbulent multiscale flows in the ocean.
- Oceanic flows transfer energy from 1000 km scales to cm scales. This energy transfer is difficult to resolve with existing partial differential equation models. The plan is to develop stochastic reduced models using wave turbulence phenomenological understanding to decipher energy transfer across so many spatial scales.
- Develop a mathematical framework to combine observational data and dynamical systems to solve problems in state and parameter estimation. The broader goal of developing mathematics is to "learn dynamical systems from data"
- Establishing the mathematics of parameterizations used in weather and climate models using the Koopman operator framework.

Dynamics

The strengths include Ergodic theory, holomorphic dynamics, and homogeneous dynamics.

Research highlights and goals are:

- Investigation of Teichmüller spaces from several complex variable viewpoint.
- Developing a unified theory of various branches of conformal dynamics: rationalmaps, Kleinian groups, and algebraic correspondences.

- Studying geometric and ergodic-theoretic properties of thin subgroups of semi-simple Lie groups, enlarging on the class of lattice subgroups.
- Periodic tilings.
- Study of irreversible non-commutative dynamical systems with possible applications to quantum information theory, physics, and computer science.
- Classify q-Araki-Woods von Neumann algebras and study of the von Neumann algebras associated with locally compact groups.

Geometry

The strengths include Differential, Riemannian, symplectic, hyperbolic, complex,and geometric group theory.

Research highlights and goals are:

- Various topics in Riemannian and Finsler geometry.
- Questions in geometric analysis, gauge theory, and calibrated geometries, Existence and classification of symplectic structures, and their interactions with contact and symplectic topology, enumerative geometry, Gromov-Witteninvariants, etc.
- New areas at the interface of algebra and analysis including CAT (0) cube complexes, generalizations of hyperbolicity, and measured group theory.
- Automorphisms of free groups.
- Study of groups in low-dimensional topology using techniques from combinatorial group theory.
- Questions in complex geometry and Geometric PDEs

Number theory

The strengths include Algebraic, Analytic, Arithmetic, combinatorial Transcendence and Modular forms.

Ongoing/Upcoming research highlights are:

- Class number problem and its link to Artin's primitive root conjecture, Brauer-Siegel conjecture and Lenstra's work on Euclidean ideal classes.

- Growth, non-vanishing, periods as special values and distribution of zeros of L-functions in their various avatars.
- Studying arithmetic of Fourier-coefficients of modular functions through Atkin - Serre conjecture, Lehmer's conjecture, differential operators.
- Studying values of elliptic curves using quasi-periodic functions.
- Analytic methods like Poissonian correlations among various interesting arith-metic sequences or discrepancies in the prime number theorem.
- Exploring Diophantine geometry via the recent work of Pila-Tsimerman on Singular Moduli or via Lehmer's conjecture.
- Studying the Langlands programme in all its varied aspects (global, local and geometric).
- Exploring the Iwasawa theory of higher dimensional Galois representations.
- Studying (integral) p-adic Hodge theory and p-adic Galois representations using Prismatic co-homology and analytic geometry.

The long-term goal is to understand and explore the interplay between arithmetic,analytic and transcendental aspects of number theory to address some of the long-standing open problems as well as to strive for applications in real life.

Probability

The strengths include Percolation theory, random matrix theory, and stochasticanalysis.

Research highlights and goals are:

- Various topics in random geometry, random polynomials, rough path theory, Gaussian multiplicative chaos, and branching Brownian motion.
- Quantum field theories as continuum limits of lattice spin models from thepoint of view of probability theory.
- Understanding of stochastic processes on braided compact quantum groups; and potential connections between Anyonic quantum permutation groups andnon-local games.

One of the long-term goals is "Gender imbalance improvement". This is one of the major existing pressing issues inthe current mathematical community is gender imbalance. To address this complicated issue, we plan to implement several strategies in multiple fonts.The idea of having the program “Vigyan Vidushi” is a step towards this direction.

We also plan to approach the problem from the ground-root level by creating a center for women in Chennai to train underprivileged female students from rural and remote areas. The main focus will be to offer a 4-year BS program in Mathematics in cognizance of the new NEP.

13. Health Science Research

Researchers from DAE-aided institutions working in the field of health sciences gathered at the DAE Chintan Shivir, to deliberate on a roadmap for health sciences. This initiative aims to contribute towards achieving the goal of a Swasth and Viksit Bharat by 2047. DAE-aided institutions are engaged in cutting-edge basic and translational research in the field of health sciences. Building on the achievements of the multidisciplinary expertise across other institutions, the health science theme proposes this roadmap towards a Viksit Bharat by 2047.

A major focus will remain on research, capacity building, and technology development to ensure affordable, high-quality, pan-India health particularly by leveraging digital technology. A central theme will be affordable, holistic healthcare based on the "One Health, One Solution" paradigm. In the health sector, DAE institutions have also proposed several other initiatives that can be developed to deliver affordable health outcomes for every resident of India. With the existing infrastructure and past achievements, we propose new programs, such as establishing centres for Infectious Diseases and Metabolic Syndromes (IDMS) and drug discovery.

The aforementioned vision is based on established national wisdom, expertise, and a robust knowledge base. Evolutionary or Darwinian medicine is a crucial aspect of medicine that should be incorporated into curricula. Many diseases and most physiological reactions we observe exist because of natural selection's role in protecting us. For example, responses like fever or vomiting are precautionary measures to clear infections or foreign objects. Similarly, possessing a single genetic variant for thalassemia may offer protection against malaria, making it advantageous. Furthermore, conditions such as insulin resistance, type-2 diabetes, or obesity may have emerged and become endemic due to rapid lifestyle changes and the inability of our physiology to adapt quickly. Addressing these diseases requires a different approach, one that can only be understood through the lens of natural selection. The dichotomy between traditional diagnostic and intervention strategies is counterproductive in light of natural selection. This programme has been developed by striking a balance between evolutionary medicine and traditional therapeutic approaches.

13.1 A Centre (IDMS) for Infectious Diseases (ID) and Metabolic Syndromes (MS)

Establishment of a clinical and therapeutic centre dedicated to research and treatment in Infectious Diseases (ID) and Metabolic Syndromes (MS) is proposed herein. The outbreak of COVID-19 highlighted the need for a more critical focus on infectious diseases beyond the traditionally recognized conditions like malaria, TB, and dengue. The pandemic also revealed that individuals with comorbidities such as lung conditions or cardiovascular diseases (CVD) were at a higher risk, underscoring the importance of addressing these factors.

Globally, CVD remains the leading cause of morbidity and mortality, and many of these conditions, including metabolic syndrome, play a crucial role in determining disease outcomes and mortality. Similarly, morbidity and mortality in cancer patients are often influenced by comorbidities like obesity and type 2 diabetes (T2D). A systematic analysis, supported by state-of-the-art facilities, is necessary to understand the aetiology of these conditions and develop effective interventions.

NISER is well-positioned with the technical know-how and facilities to undertake this initiative. Still, it will need to recruit clinicians specializing in ID and MS. Just as DAE pioneered the development of a robust system for cancer therapy, we now propose the establishment of an IDMS clinic and research centre. This centre will be staffed with world-renowned clinicians and researchers and will start with ten clinicians, 20 nurses, and other auxiliary staff members for a 200-bed facility. The centre will feature state-of-the-art diagnostic and care facilities.

13.2 Big Data and Digital Healthcare

In the rapidly evolving landscape of health research and treatment, harnessing the power of big data is essential for advancing our understanding of diseases and improving patient outcomes. Electronic Medical Records (EMR) are crucial for capturing and maintaining individuals' health and clinical treatment records over time. There is a pressing need for indigenous and advanced software-based management systems to systematically compile electronic records of patients in public hospitals. As these medical records are created, gathered, managed, and accessed by authorized clinicians and staff within or across healthcare organizations, EMR software must be designed to meet the specific needs of medical professionals. A cloud-based EMR system holds the potential to benefit patients, clinicians, and healthcare facilities within and across organizations, all while ensuring patient privacy and data security. This indigenous EMR solution could be commercialized to healthcare providers across India, generating revenue streams to support self-sufficiency. Simultaneously, the de-identified data collected could promote research and enable computational/AI projects to derive insights that improve cancer diagnosis, treatment, and outcomes. It is crucial that EMR data strictly adhere to the principles of being Findable, Accessible, Interoperable, and Reusable (FAIR). Significant effort will be needed to transform existing unstructured health records in government hospitals into FAIR-compliant EMR data. Researchers from ICTS-TIFR, IMSc, and IPR, who have experience handling Big Data and AI-ML, propose collaborating with TMC to create this comprehensive EMR database of cancer patients also. Once fully functional, the compiled data will be invaluable for AI-based health analytics research, helping to uncover genetic susceptibility, predict risk and prognosis, and prioritize healthcare resources.

13.3 Artificial Intelligence (AI) and Computational Biology

Artificial Intelligence (AI), Machine Learning (ML), and Computational Biology are poised to play increasingly critical roles in health sciences. Integrating AI into the Indian healthcare system is advantageous and essential to address the unique challenges posed by the country's diverse population, occupations, and regions. Specific areas where AI and Computational Biology will contribute include:

Data Entry and Documentation: AI-assisted tools can automate the manual entry process by extracting relevant patient information from printed documents.

Natural Language Processing (NLP): Large Language Models (LLMs) are increasingly used to extract and summarize texts/notes in various domains. Similarly, these models can extract valuable medical information from clinical notes, pathology reports, and other unstructured text data within EMRs.

Telemedicine: AI-assisted applications can enhance telemedicine services, particularly in situations where the patient and doctor do not share a common language, by facilitating communication and understanding.

Clinical Decision Support: AI-ML-powered tools can analyse real-time patient data, such as blood pressure, sugar levels, and other critical indicators, to provide clinical decision support to healthcare providers. For example, by leveraging patient EMRs, AI can alert clinicians to potential drug interactions.

Predictive Analytics: AI-ML tools can predict patient outcomes when trained on large EMR datasets. These tools can help identify individuals at risk of developing certain conditions, monitor disease progression, and more.

Image Analytics for Digital Pathology and Radiology: AI tools can assist in efficiently and accurately interpreting medical images. For instance, researchers at IPR have developed DeepCxR, an AI-based software in collaboration with ICMR Delhi that performs automated detection of pulmonary tuberculosis and other chest ailments using chest X-ray images. Soon, such predictive tools will be instrumental in screening and diagnosing cancer.

Drug Discovery: Computational methods, including AI, are expected to play an increasingly significant role in drug discovery, particularly in identifying new small molecules and peptides, as will be elaborated in a later section on drug discovery.

Researchers at IMSc, IPR, NISER, and TIFR possess Computational Biology and Data Science expertise, including AI-ML. We anticipate significant collaboration between these computational biologists, data scientists, chemists developing drugs and diagnostics, and clinicians at TMC in advancing this research area.

13.4 Accurate and Affordable Diagnostics

- **Biomolecular- and Microbiome-based diagnostics**

  Tumour-derived exosomes present a promising avenue for cancer diagnostics and therapeutics due to their numerous advantages. These include their high abundance, stability, diverse molecular cargo, and the ability to isolate them from any biological fluid multiple times during treatment in a non-invasive manner, thereby overcoming the limitations of traditional solid biopsies. Moreover, by leveraging the unique properties of exosomes—such as their structure and cargo—they can be further engineered for cancer theragnostic, offering high targeting specificity and efficacy.

  Researchers at NISER have developed a prototype test known as the **Gut Function Test (GFT)**, which requires only a single finger prick, like a glucometer test for diabetes, to provide a blood spot on a DBS card. The sample is then analysed using ultra-sensitive methodologies to generate a list of molecular markers that can reveal the status of various physiological functions and predict the entire gut microbiome. By employing an AI-ML-based training set, the results can categorize an individual for one or multiple diseases and recommend plausible interventions or supplemental strategies for clinical decision-making. This test is cost-effective and affordable for the general population in India and eliminates the need for faecal material collection.

- **Molecular probes for rapid diagnostics:** The development of multiplexed diagnostics will be a key focus area. Molecular scaffolds for multi-biomarker detection will be invaluable in diagnosing complex diseases where a single biomarker is insufficient for guiding therapeutic intervention. TIFR Chemical Science researchers are working on novel tools for multiplexed diagnostics within this context. Complex diseases like cancer, which exhibit numerous variants, also require companion diagnostics to assist clinicians in determining therapeutic routes, performing rapid and robust drug screening assays, and identifying the most relevant patient sub-groups during clinical trials. A diagnostic agent would rely on identifying metabolites and proteins; hence, computational tools for proteins can guide effective design.

- **Large-scale imaging-based early detection tools:** Over the coming years, we aim to develop and test prototypes of silicon (Si) and gaseous detectors for medical imaging applications. The long-term goal is to create indigenous, cost-effective imaging modalities that can be deployed in rural and urban hospitals across India. This initiative will be phased according to every five-year plan: (i) the research and development phase, (ii) the system optimization phase, (iii) the pre-clinical prototype development and testing phase, and (iv) the clinical prototype phase.

13.5 Drug Discovery and Repurposing

India has long been a global leader in producing affordable generic drugs and making medicines accessible worldwide. The COVID-19 pandemic demonstrated how inclusive programs that harness India's vast scientific community can unite industry and government to achieve formidable goals. For an AtmaNirbhar and Swasth Bharat in the face of emerging diseases, rising cancer incidence, and antimicrobial resistance, it is crucial to establish collaborative drug discovery initiatives that incorporate repurposing and intelligent design, leveraging traditional knowledge from Ayurveda and other Indian systems of medicine.

A primary approach will involve employing AI-ML-based de novo drug design methods. A Network Pharmacology approach across DAE institutions (e.g., TIFR, IMSc, CEBS) would collaboratively use computational biology and chemistry to screen natural products from traditional Indian medicinal formulations and laboratory-synthesized therapeutically active compounds. This approach not only facilitates the prediction of novel lead molecules or the repurposing of existing ones (including phytocompounds) to treat various diseases but also provides insights into the probable mechanisms of action and toxicity of drug candidates. IMSc has developed a comprehensive resource, IMPPAT, which compiles phytochemical constituents from over 4,000 Indian medicinal plants used in traditional medicine, serving as a precursor to these efforts. The predictions derived from these methods must be validated in disease models.

A key focus area in novel drug development will be creating multi-targeted drugs for managing diseases with complex pathologies, particularly cancers. Researchers at TIFR, Mumbai, are developing clinically viable novel candidate drugs to counter multiple pathological processes, overcome chemoresistance in cancers, and reduce the side effects of current cancer therapies. Multifactorial diseases like cancer are often resilient to single-target drugs due to resistance mechanisms that either pre-exist or are activated as a compensatory response. Drug resistance is responsible for most relapses and cancer-related deaths. The shift from mono-target therapy to multi-target therapy in cancer treatment represents a pivotal strategy for enhancing the efficacy of anticancer chemotherapy. TIFR, Mumbai, proposes to establish a rapid drug and diagnostics development and preclinical screening facility within its Chemical Sciences division to support the creation of indigenous and affordable drugs and diagnostics.

To effectively screen the vast diversity of natural products available through Indian knowledge systems, CEBS proposes a Networked Drug Discovery (NeDD) model. This model will merge efforts across the country's university ecosystems with DAE facilities. CEBS and NISER have already developed frugal, cost-effective disease models in organisms such as yeast, algae (Chlamydomonas), and Drosophila, using principles of sequence conservation or by humanizing simple transgenic models. These models, which are inexpensive to culture in common laboratory settings, could enable university-college laboratories and start-ups to participate in high-throughput drug screens, fostering a sense of ownership and national pride.

Additionally, SINP plans to develop complex, hierarchical, high-precision, and highly controllable 3D bioprinted tissue structures of tumours. These models aim to replace animal testing with more physiologically relevant in vitro models, allowing for the assessment of tumour invasiveness, metastatic potential, and the therapeutic efficacy of drugs. This approach will also aid in developing methods for biomarker identification and creating metabolic sensors for other cancer-related studies. ACTREC-TMC, through its Anti-Cancer Drug Screening Facility (ACDSF), has established a wide range of human tumour cell lines, murine tumour models, and xenograft models for small molecule screening. However, a critical limitation is the absence of Indian patient-derived cell lines. To address this gap, ACTREC-TMC plans to establish a state-of-the-art drug discovery centre, the 'Centre for Innovation in Emerging Medicines (CIEM).'

There are several existing inexpensive drugs (e.g., aspirin, metformin, propranolol, progesterone, statins) that exhibit potential anti-cancer activities in various common cancers, including breast, cervical, oral, lung, and gastrointestinal cancers. These drugs could contribute to a 4-5% improvement in eligible patients' long-term survival. If about 250,000 non-metastatic and 100,000 metastatic patients could benefit from 5-6 such drugs, there would be significant cost savings and an extension of lives. In addition to preclinical facilities, TMC units plan to establish highly sophisticated centres capable of planning, initiating, executing, and analysing large, definitive clinical trials.

13.6 Indigenous Technology for AtmaNirbhar Bharat

- **Biomedical waste management:** Plasma pyrolysis-based biomedical waste disposal plants will cover all 100 smart cities by 2047 through technology transfer partners. Plant capacity will be calculated at 5 TPD for a town the size of Varanasi (~50 lakhs population).

- **Plasma-based Air Sanitization:** The plasma application for air sanitization involves generating reactive species that can effectively deactivate or destroy airborne pathogens. IPR, in collaboration with the Centre for Cellular and Molecular Platforms (C-CAMP), has co-developed a cold atmospheric plasma (CAP) based air disinfection device.

- **Indigenous Nuclear radiation detectors**

  TMC will collaborate with TIFR to develop next-generation radiation detectors, leveraging TMC's clinical expertise and TIFR's cutting-edge research capabilities. The partnership is expected to yield innovative detectors with enhanced sensitivity and spatial resolution, potentially transforming cancer diagnostics and treatment monitoring at an affordable cost. Integrating artificial intelligence into detector systems could enable real-time data processing and adaptive imaging protocols.

- **Indigenous production of high-grade medical equipment**

  DAE may aim to revolutionize India's healthcare technology sector by focusing on the indigenous development of advanced medical equipment. This ambitious initiative aims to create indigenous radiotherapy machines, CT scanners, MRI systems, Surgical robots and ventilators, among other crucial devices (dual-energy linear accelerator costs around 25 crores, dual-energy CT scan costs around eight crores, and MRI machine costs around 16 crores). This will significantly reduce the cost of diagnosis and treatment, making advanced healthcare more accessible to our population. Customized solutions better suited to local needs and conditions will be developed, potentially improving patient outcomes while reducing healthcare costs across the board.

13.7 Environment and Health

- **Linking Exposome, including Air Pollution and Climate to Human Diseases:** With the significant increase in pollution and the effects of climate change, it has become essential to understand better the impact of environmental exposures—the "exposome"—on human health. The Institute of Mathematical Sciences (IMSc) has substantially contributed to compiling, curating, and exploring environmental chemical spaces implicated in endocrine disruption, cancer, neurotoxicity, and vitiligo. It is aimed to identify and characterize environmental factors specific to India that contribute to diseases such as cancer, diabetes, and reproductive disorders. By leveraging toxico-genomics and AI-ML, it is planned to develop adverse outcome pathways and predictive toxicity models for environmental chemicals (e.g., pesticides, heavy metals, microplastics) and non-chemical stressors such as viruses and radiation. Researchers from IMSc, TMC, NISER, and SINP will collaborate to advance this critical research.

- **Nutrition and Health:** As globalization progresses, there is a renewed interest in plant-based protein sources, particularly sustainable and nutritious options like legumes. We are currently working on improving the mung bean for sustainability in the context of climate change, screening approximately 214 genotypes. Additionally, we aim to identify and assess the health benefits of under-recognized, nutritionally enriched legumes of tribal origin. Our expertise in this area will be further applied to manipulating light signalling to enhance nutrient content. Moreover, we plan to increase anthocyanins and vitamins in tomato fruits to promote human health.

- **Epidemiology:** The growing burden of cancer in India represents a significant healthcare challenge. According to the International Agency for Research on Cancer's GLOBOCAN project, the incidence of cancer in India is projected to rise from 1.3 million cases in 2018 to approximately 1.7 million by 2035. Although age-adjusted cancer rates in urban and rural India have remained constant over the decades, the absolute number of new cancer diagnoses continues to rise. This increase is primarily due to population growth, longer life expectancy, and lifestyle changes transforming rural populations into semi-urban and semi-urban populations into urban populations. Equally concerning is the projected rise in cancer deaths, expected to increase from 0.88 million in 2018 to 1.3 million by 2035. As a result, India must prepare itself to address the escalating cancer burden.

14. Cancer Care

Health is a crucial pillar for the maintenance and sustainable development of the country. A nation can only thrive if its population is healthy, which is a significant challenge for a country like India being the most populous in the world. Through the Tata Memorial Centre (TMC), DAE has substantially contributed in providing affordable, high-quality cancer care to the Indian population across various strata of the society.

14.1 High-Quality and Affordable Cancer Care Across Bharat

(a) National Cancer Control Program

In 2022, the projected number of new cancer cases in India was 1.46 million, with a crude incidence rate of 100.4 per 100,000 individuals. Cancer deaths are expected to rise from 0.88 million in 2018 to 1.83 million by 2047, making it imperative for India to prepare itself to address this significant healthcare challenge. The Tata Memorial Centre (TMC), India's oldest and largest cancer centre, has spearheaded the systematic National Cancer Control Program to ensure high-quality, affordable, and standardized cancer care across the country.

A key focus remains on preventing common cancers, particularly those affecting the oral cavity, cervix, and lungs. Tobacco usages and obesity are significant contributors to cancer, both of which are preventable. It is crucial to prioritize early cancer detection by raising awareness among the public and primary care physicians, including alternative medicine practitioners and traditional healers. Currently, the private sector provides over two-thirds of cancer care in India. To make quality cancer care accessible to all sections of society, it is important to expand cancer treatment facilities across different regions of India and establish additional government-run centres. Further attention is needed in palliative care, survivorship, and patient advocacy. A dual approach is required for planning a systematic national cancer control program. Firstly, there is a need to ensure uniform standards of cancer care across India by strengthening existing centres. Secondly, additional government-run cancer centres must be established to address gaps in access across various regions. TMC would lead the creation of a national network of palliative care departments within its hospitals and other institutions. This network will promote evidence-based practice, training, education, research, and access to services throughout India.

The National Cancer Grid (NCG), a DAE initiative launched in 2012, successfully implemented the first approach. NCG's broad vision includes establishing uniform standards of patient care for preventing, diagnosing, and treating cancer, creating adequately trained human resources, and facilitating collaborative basic, translational, and clinical research in cancer. NCG has revolutionized cancer care in India by establishing the world's largest cancer network, comprising over 200 cancer centres, research institutes, patient advocacy groups, charitable organizations, and professional societies. The organizations associated with NCG provide treatment to over 700,000 new cancer patients annually, which accounts for over 60% of India's cancer burden. Uniform standards of patient care are being implemented nationwide by adopting evidence-based treatment guidelines. NCG also evaluates adherence to these guidelines through institutional peer reviews of the participating centres. Quality assurance programs in surgical pathology and radiation oncology are also being planned. By incorporating all cancer care stakeholders in India, NCG has become a strong, unified, and powerful voice in the fight against cancer. Further expansion and deeper integration of the National Cancer Grid to ensure uniform standards of cancer care is being proposed, aiming to cover more than 90% of cancer patients across India

The second approach involves the Hub and Spoke healthcare delivery model, which ensures high-quality cancer care is accessible to people close to their homes. This model provides familiar and less complex cancer care at local centres ('spokes'), while uncommon cancers and those requiring complex treatment protocols are managed at expert centres of excellence ('hubs'). To avoid overburdening the hubs, the spokes must be adequately equipped to handle common and less complex cancer types prevalent in the region. This strategy effectively minimises costs and reduces inconvenience for patients and their families. Care delivery would be carried out at the spokes as much as possible, with treatment planning, even for uncommon cancers, done at the hubs and actual treatment delivered at the spokes. Hubs will be comprehensive cancer facilities with state-of-the-art equipment, infrastructure, and expert human resources capable of treating all types of cancer. Each hub is envisioned as a 300-bed facility, with an estimated cost of Rs. 750 crores and an annual recurring expenditure of Rs. 120 crores, covering a population of approximately 4 crores, i.e., an estimated cancer burden of around 40,000 new patients annually. A spoke is envisioned as a 100-bed facility, built at an estimated cost of Rs. 300 crores and an annual recurring expenditure of Rs. 40 crores, covering a population of approximately one crore, i.e., an estimated cancer burden of around 10,000 new patients annually. Highly complex treatments, such as bone marrow transplants, complex surgical interventions, and high-end radiation, will not be available at the spokes. All existing TMC centres should act as hubs, guiding neighbouring states in developing spokes.

The proposed Hub and Spoke model would ensure that the entire Indian population can access affordable, high-quality cancer care. This model will establish sufficient hubs in all Indian states equipped with advanced cancer treatment facilities. These facilities will be designed to handle approximately 2.1 to 2.5 million new cancer cases annually, with a prevalence of 3 to 4 times that number, which is the projected cancer incidence and prevalence in India over the next 15-25 years.

(b) Therapeutic Nuclear Medicine in Oncology

Significant gap exists between the demand for, and availability of dose isotope therapy beds, which are crucial for treating cancers such as neuroendocrine tumours, thyroid cancer, and neuroblastoma. Additionally, innovative radio-tagged monoclonal antibodies can potentially treat common cancers such as breast and head and neck cancers. If one-third of common cancers could benefit from this treatment, it is estimated that approximately 200,000 patients could be treated annually with these beds. Currently, only 75 beds are available across 30 centres in the country, with most centres having just 1-2 beds. Need for 25-30 large centres in ideal locations, each with 35-40 nuclear medicine beds and sufficient space to accommodate large delay tanks is envisioned. Another limitation of existing facilities is the inability to synthesize ready-to-use therapeutic radiopharmaceuticals. There is a pressing need for a large isotope therapy facility with a comprehensive hospital radio-pharmacy capable of producing ready-to-use therapeutic radiopharmaceuticals that meet Good Manufacturing Practice (GMP) standards. Additionally, these facilities require specialized medical support from oncologists and physicians. Establishment of 5-6 nuclear medicine centres across the TMC hubs is being proposed, each equipped with 35-40 nuclear medicine beds. These units would develop systems and processes to establish best practices that can be emulated by non-TMC healthcare institutions.

(c) Centres of excellence in cellular therapy, including immunotherapy, supported by GMP facilities

Recent advancements have shown that many cancers traditionally difficult to treat such as prostate cancer, acute leukaemia, chronic leukaemia, melanoma, and renal cancers, are now responsive to cellular therapy, including various forms of adoptive immunotherapy. These forms of cellular therapy require highly sophisticated, GMP-grade, scalable laboratory setups and highly trained multidisciplinary teams. In the next 15 years, there is need to build capacity in this frontier area of cancer treatment. Within the Tata Memorial Centre (TMC), 5-6 highly sophisticated and self-contained cellular therapy units may be established to produce tailored cellular therapy products ready for human use in treating 5-6 niche cancers. These public sector units will offer treatment at nominal costs to patients, ensuring access to cutting-edge therapies. It is being proposed to set up 4-5 highly sophisticated and self-contained cellular therapy units, including immunotherapy, in selected TMC hubs. These units will also enable research on novel technologies for next-generation CAR therapies, including nanotechnologies, NK-cell therapy, and oncolytic immune-virotherapy.

(d) State-of-science Biobanks in all TMC units

The cancer incidence rate in India is significantly lower compared to more developed countries, with a gradient in incidence observed from rural India to urban India to Western countries, approximately at a ratio of 1:3:9. This suggests that certain elements of the traditional Indian lifestyle may protect against cancer. However, these factors are not yet fully understood. These protective elements could be related to environmental factors (such as diet, exercise, and hygiene) as well as the genetic makeup of the Indian population. Following geographically well-defined population cohorts over time, with meticulous baseline characterization, will be crucial in identifying the specific protective and risk factors for various cancers in the Indian population. This will also help in devising appropriate primary and secondary preventive strategies. The establishment of state-of-the-art biobanks in all TMC units will enable such studies. TMC aims to set up and coordinate at least four well-defined and meticulously followed population cohorts across India's rural, semi-urban, and urban centres.

14.2 Prevention of Cancer

Cancer prevention is a critical component in the fight against this devastating disease. Cancer is a complex condition requiring a multifaceted approach that addresses various risk factors and promotes healthy behaviours to reduce its incidence and impact. At its core, cancer prevention involves a comprehensive strategy targeting multiple aspects: minimizing the risk of developing cancer, ensuring early detection, and improving outcomes for those affected. This holistic approach includes several key components: addressing obesity, promoting proper nutrition and hygiene, encouraging lifestyle changes, combating smoking and tobacco use, limiting alcohol consumption, raising awareness, and empowering individuals to take responsibility for their health. Comprehensive research to be undertaken to identify dietary patterns and nutrients that may modify cancer risk, thereby enabling the development of evidence-based guidelines for cancer prevention. Beyond addressing individual risk factors, cancer prevention efforts also focus on raising public awareness and empowering individuals to take proactive steps to protect their health. This includes educating the public about the importance of cancer screening and early detection and promoting healthy behaviours and lifestyle choices through community-based programs, public health campaigns, and school-based initiatives.

Early detection is a cornerstone of cancer prevention, as it allows for prompt diagnosis and treatment, significantly improving outcomes and reducing mortality rates. Screening tests, such as mammograms, Pap smears, and VIA tests, are instrumental in detecting cancer at an early, more treatable stage. Increasing access to screening services is essential for downstaging the disease. TMC, through all its centres, will ensure the development of preventive oncology departments to address these issues in their respective regions.

A key initiative would be the creation of a DAE cohort focused on understanding the environmental, genetic, and lifestyle factors contributing to cancer risk. This cohort could provide valuable insights into prevention strategies tailored to the Indian population.

Additionally, establishing an epidemiological long-term cohort across different TMC centres could shed light on geographical variations in cancer prevalence and the potential influence of regional factors such as environmental exposures, cultural practices, and socioeconomic determinants. The Department of Atomic Energy (DAE), through TMC, would provide technical assistance to state and central health agencies to develop cancer infrastructure following the Hub & Spoke model.

TMC's Centre for Cancer Epidemiology (CCE) is unique among Indian institutions, collecting population-level data, conducting interventions, and researching cancer incidence and burden. TMC proposes establishing a network of CCEs within its units and collaborating with non-TMC institutions to provide large-scale quantitative data to policymakers. Additionally, TMC will collaborate with ICMR to enhance complementary capacity in this domain.

14.3 Integrative medicine

Traditional AYUSH systems of medicine, particularly Ayurveda, take a holistic approach to healthcare, emphasizing disease prevention, personalized treatment, and addressing the root cause of disease rather than just the symptoms. Combining traditional and modern medical practices, integrative medicine offers a promising avenue for developing new and affordable treatments for various diseases, including emerging conditions. TMC has embarked on an ambitious project in Khopoli, where an integrative medicine approach will be employed to treat cancer. As part of this initiative, TMC plans to establish a facility for cultivating and conserving medicinal plants and developing herbal formulations for integrative medicine. For integrative medicine to succeed, there is a need for rigorous basic research in AYUSH systems for oncology, transforming experience- and reason-based traditional Indian medicine into an evidence-based science. In the coming years, TMC units will harness digital technologies to provide cancer care to a broader section of the population, potentially linking with Ayushman Arogya Mandirs. By utilizing these technologies, TMC would mitigate the impact of the shortage of healthcare professionals and ensure more equitable access to cancer care across India.

In coming few years, a 100-bed hospital-cum-research facility, ACTREC-TMC, will become operational in Khopoli, dedicated to treating cancer patients using integrative medicine approaches. Over the following decade and half, it is being proposed to establish ten state-of-art integrative medicine departments across selected TMC units.

15. HRD ecosystem of Aided Institutes of DAE

This white paper presents the vision on redesigning the education and the human resources development (HRD) ecosystem of the Aided Institutes (AIs) of DAE. The proposed redesign and revamping is necessitated by three ongoing changes; a) The rapidly changing nature of scientific research practices; b) The changing nature of the world, and c) Our changing aspirations as a nation.

DAE has affiliated institutes that work in most frontier areas, related UG programs, a research centre for science education (Homi Bhabha Centre for Science Education - HBCSE, TIFR), and a school system (Atomic Energy Education Society - AEES). DAE is the only establishment in the country with such range and diverse strengths. This ecosystem can be leveraged to address the practice-education gap. This unique braiding of research backgrounds would allow them to translate the frontier practices into educational models of compelling quality, for the country and the world to follow. Having identified the broad nature of the crisis and a potential way out of it, the aided institutions came up with a set of proposals. As a systematic investigation of frontier science and technology practices and human learning/education practices, in tandem, is a requirement for the proposed redesign, the need for establishing more centres of science education research (similar to HBCSE, TIFR) has been identified.

At the school level, the proposals were centred around AEES. Ongoing national and multi-AI programs, such as *Vigyan Pratibha* and the Science Olympiads, could be leveraged for wider nurture and dissemination. At the UG level, a world class 4-year program, with emphasis on advanced experimentation and instrumentation was proposed by Tata Institute of Fundamental Research (TIFR). Replication of the Centre for Excellence in Basic Sciences (CEBS) model, expansion of programs at NISER, CEBS and Homi Bhabha National Institute (HBNI) were among other highlights. Saha Institute of Nuclear Physics (SINP) proposed a research associateship and internship program for UG students and faculties. At the master's level, programs in cutting edge areas, involving a multi- institute collaboration, were outlined. The Tata Memorial Centre (TMC), in association with Institute of Mathematical Sciences (IMSc), proposed a program in data science, with a focus on health informatics. At the master's level, programs on bio-analytical sciences and sustainable energy (jointly by HRI, SINP, NISER, IMSc) were some highlights. At the Ph.D. level, targeted industrial collaboration and MD-Ph D programs to produce clinician researchers (TMC-SINP, other AIs) were proposed. Proposals on outreach, equity and inclusiveness include expansion of the *Vigyan Vidushi* model, and a regional focus by concerned AIs (for e. g. HRI catering to north India and SINP focusing on north east).

In summary, this proposal outlines an action plan in three broad phases: initiation/expansion, consolidation, and excellence. These denote short-term, medium-term and long-term plans, respectively.

परमाणु ऊर्जा विभाग
DEPARTMENT OF ATOMIC ENERGY