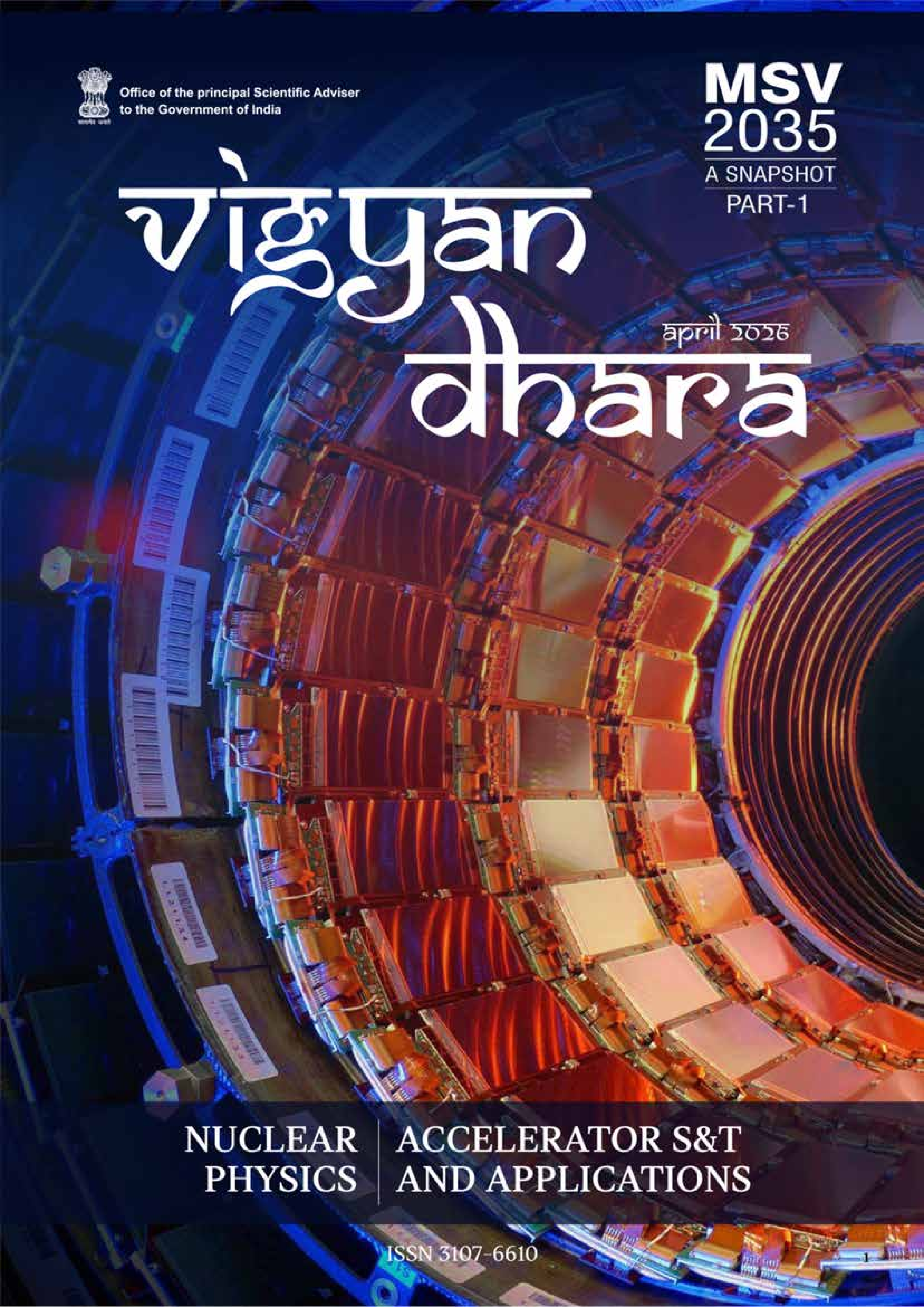

Office of the principal Scientific Adviser
to the Government of India

vigyan dhara

april 2026

MSV
2035
A SNAPSHOT
PART-1

NUCLEAR PHYSICS | ACCELERATOR S&T AND APPLICATIONS

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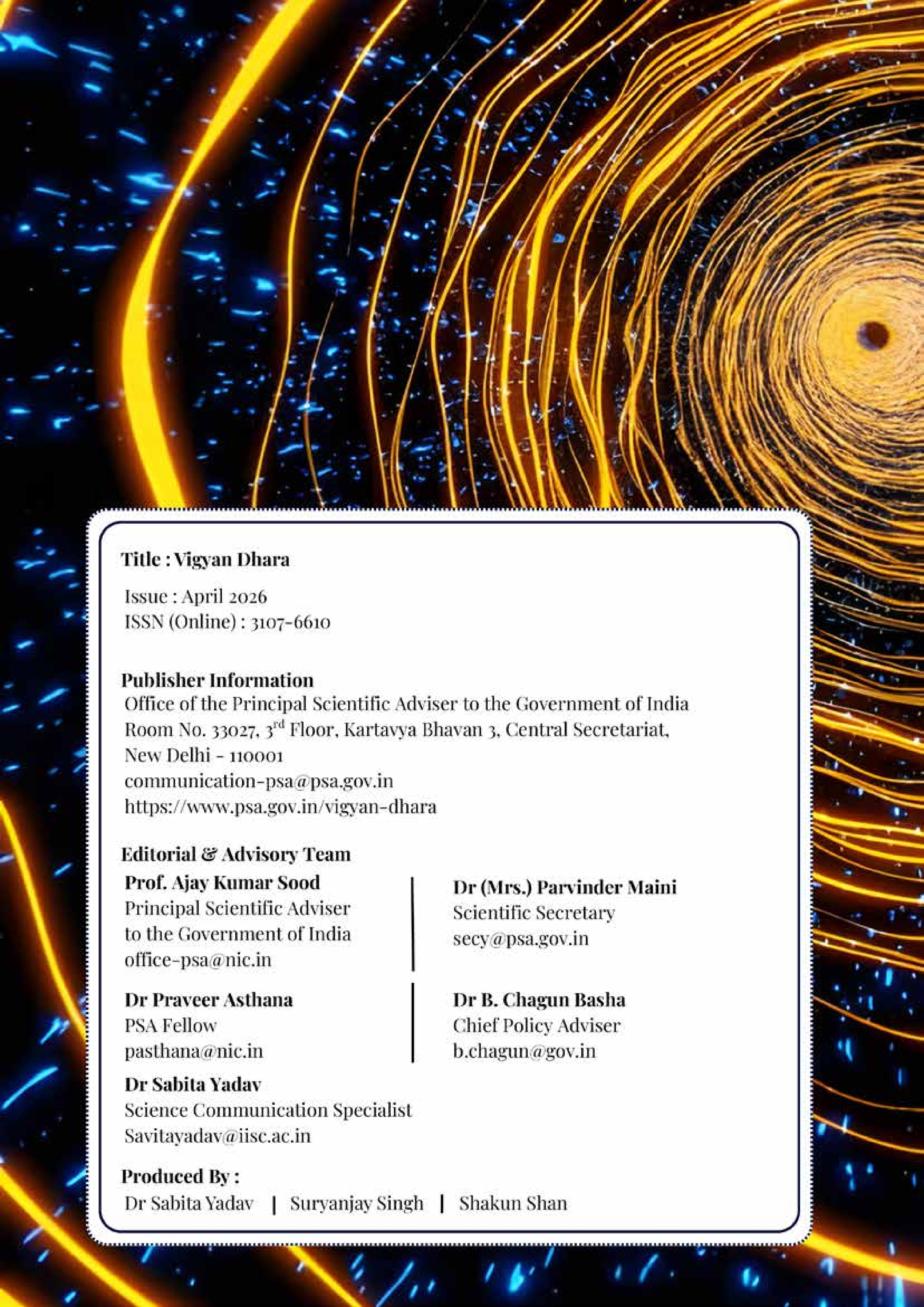

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Prof. Ajay Kumar Sood

Principal Scientific Adviser to the
Government of India

Foreword

Mega Science Projects (MSPs) constitute what is colloquially referred to as "Mega Science". These are technologically complex and large collaborative projects that aim to unravel some of the greatest mysteries of Nature that appeal to the curiosity of large sections (and at times the whole) of humankind. MSPs also advance the very frontiers of technology on the way, as they march towards unravelling yet unknown riddles of Nature. Such projects usually require very large resources – capital, human and financial. To put things in perspective, the Large Hadron Collider (LHC) at CERN, Geneva is a quintessential example of Mega Science Project – a multi-billion dollar scientific facility with about 2500 staff members where over 12000 researchers work from more than 70 countries across the world.

Given their complex and resource-intensive nature, it is natural that only a few such projects can be taken up nationally, and even internationally, at any given time. The decision about which project/s to undertake is thus a very well-considered decision taken by the concerned scientific communities and the governments/funding agencies. As these are also very long-term projects, typically taking 10 years to plan, 10 years to build and remaining in operation from 30-50 years, the planning for such projects has to necessarily rely on drawing decadal or multi-decadal roadmaps. Such roadmaps are drawn by all scientifically mature nations, either individually or through bilateral and/or multi-lateral forums. India too, has been carrying out such exercises, which are now known as Mega Science Vision (MSV) Exercises.

The earlier MSV Exercises (last being in 2014) were spearheaded by DAE and DST in Nuclear Physics (NP), High Energy Physics (HEP) and Accelerator S&T and Applications (ASTA), as these disciplines rely most heavily on MSPs for carrying out research. This time round, the MSV-2035 Exercise covering the 2020-35 period is being spearheaded by the Office of PSA (OPSA) to the GoI. The catchment area for the Exercise has also been enlarged by including three other disciplines, viz. Astronomy & Astrophysics (A&A), Climate Research (CR) and Ecology & Environmental Science (E&ES). Four of the six MSV-2035 Reports, on NP, HEP, A&A and ASTA, have been released and are available on the OPSA website.

The OPSA thought it would be useful to carry the highlights of these detailed reports in the OPSA Magazine, Vigyan Dhara, so that it could be disseminated to a wider and more diverse scientific community. This issue of Vigyan Dhara brings for you the highlights of two of the reports, viz. those on NP and ASTA.

This issue starts with an introduction to the MSV-2035 Exercises in NP and ASTA by Dr Praveer Asthana, PSA Fellow, who has been anchoring these activities in OPSA. Having been with the national journey in Mega Science for more than three decades, first in DST and then in OPSA, he has put this Exercise in its historical perspective. We follow this up with overviews of the MSV-2035-NP and MSV-2035-ASTA reports by some members of the respective Working Groups (Dr Amol Dighe, TIFR and Dr Bedanga Mohanty, NISER in case of NP, and Dr Vinit Kumar in case of ASTA) chosen by the nodal institutions (TIFR and RRCAT). Drs Dighe, Mohanty and Vinit Kumar are all eminent active members of the community and we are happy that they agreed to summarize these reports for our readers.

For our general readers, we bring in this issue a highly readable article "Nuclear Science and Accelerators in the Service of the Nation" by Dr Amit Roy, Former Director, Inter-University Accelerator Centre, himself an accomplished nuclear physicist and accelerator scientist. The article tries to convey how the discipline of nuclear physics, a fundamental science probing the structure of and interactions within nuclei, assisted by ever more powerful development of accelerators and detectors, has found applications in a large number of areas – from nuclear energy to materials science and engineering to healthcare. Only someone like Dr Roy, who has been with the national nuclear science journey for many decades, could have done justice to this task, and I am glad that he agreed to do this for us.

We thought that it would be useful for the readers at large to hear about various facets of the Mega Science enterprise in the country from two of the founding figures, Prof. VS Ramamurthy, Former Secretary, DST and Dr Anil Kakodkar, Former Chairman-AEC. It was under the stewardship of these eminent people (along with Dr R. Chidambaram, also Former Chairman-AEC and Former PSA, who unfortunately is no more) that the edifice of Mega Science got laid in India. Some of the guiding principles and management structures laid down by them have stood the test of time and are still serving the cause of Mega Science in the country. Prof. Ramamurthy and Dr Kakodkar were quite generous with their time and shared their comprehensive vision about mega science during the interviews that the OPSA organized. We are not being able to carry the transcript of full-length interview because of their sheer length in printed form. We are bringing for you a part of those highly illuminating interviews as part of the feature "Mega Science Projects – the National Dimension". The full interviews are available on Youtube. To complete the national picture, we have brought for you written views of Dr A.K. Mohanty, Chairman-AEC and Prof. Abhay Karandikar, Secretary-DST about the national Mega Science ecosystem. DAE and DST have been jointly spearheading mega science efforts in nuclear physics and accelerators, and it was important to have the perspective from the heads of these two premier agencies.

I sincerely hope that with the information presented in this issue of Vigyan Dhara, we would have convinced you of the importance of nuclear science and accelerators in advancing scientific knowledge, the necessity of MSPs in these fields of research, the considerable thought and effort invested in setting up the national mega science enterprise and establishing its foundational structures and principles, and most importantly, the importance of nuclear science and accelerators in promoting national development and prosperity.

I am glad that the OPSA has been able to set up a protocol and structure for carrying out MSV exercises this time. These have really been mammoth nation-wide consultative exercises, producing roadmap reports of impressive quality. Focusing on the NP and ASTA Reports, let me mention two specific items that got included especially at the prodding of OPSA. A special section was added to one of the Appendices of the NP Report on “Participation of Indian Industry in the Global Supply-Chain for MSPs” highlighting the fact that MSPs in NP had started enabling the Indian industry in this regard. In case of the ASTA Report, a special Appendix was added entitled “Return on Investment (RoI) for Accelerator Projects” where a quantitative analysis was attempted based on available information regarding various accelerator projects in the country. This first-of-its-kind analysis seems to indicate that the accelerator projects, in the long run, do return back the investments even in monetary terms, apart from making other substantial societal contributions by way of strengthening the research and high-tech industrial eco-system in the country.

I am sure that these Reports will be found useful by the concerned scientific communities in planning their ongoing and future mega science activities, by the government departments and agencies while deliberating on such projects for funding or otherwise, by the Indian industry while looking for high-tech opportunities, and by the general reader in appreciating the importance of these fields.

I sincerely hope that these detailed and structured roadmap reports will serve as benchmarks for the next such exercise, perhaps after another five years.

01

Mega Science and MSV-2035

An Introduction

Dr Praveer Asthana

PSA Fellow, OPSA

Mega Science deals with Mega Science Projects (MSPs). The very name suggests that there is something “large” about such projects. Images of the Large Hadron Collider (LHC) or the upcoming International Thermonuclear Experimental Reactor (ITER) flash before our minds. While the large physical size remains a feature of such projects in many cases, what is true of such projects, in general, is their “extreme technical complexity”, requiring “large collaborations” for their establishment and subsequent use. Such projects thus require large financial, human, and capital resources. Quite often, this makes it necessary for several nations (and institutions therein) to join hands together to turn them into a reality. A number of such projects today are thus international in character.

One may wonder as to why we construct such large scientific projects. The answer is simple. To understand the mysteries of nature and the way it operates has been an inherent desire of human civilization. One can very well imagine the wonder early human beings would have felt looking at the sun, the moon, the innumerable stars in the nighttime sky, the rivers, mountains, erupting volcanoes, rich flora and fauna around them and so on. From very early days of human civilization, there has been a systematic attempt to understand the working of nature. This has led to development of instruments of ever-increasing sophistication to expand the horizons of experimental and theoretical understanding of nature and accumulate large body of scientific knowledge. This quest for knowledge goes on! There are some areas of such human enquiry where the related instrumentation becomes technically complex and often acquires a large size. Let us take the case of Nuclear Physics, one of the disciplines being covered in this issue of Vigyan Dhara. It was Rutherford and his students, whose experiments using alpha particles as projectiles established the nuclear model of atom, with a tiny positively charged nucleus surrounded by electrons. In order to explore deeper and to find out what made the nucleus, one needed projectiles of higher energies. This progressively growing scientific need led to the invention of accelerators where one could produce beams of highly energetic charged particles to probe deeper into the structure of nuclei. As a result of these attempts, we know today that nuclei are themselves made of neutrons and protons, which in turn are made of quarks interacting via gluons. Much of this would not have been possible without development of the ever more powerful accelerators producing beams of charged particles of higher and higher energies. This progress in accelerator-size and related technologies has now brought us to the LHC. This example from Nuclear Physics, thus, clearly illustrates that it is the need posed by scientific enquiries at the very frontiers of human knowledge that lead us to launch Mega Science Projects. Nuclear Physics also happens to be perhaps the first discipline where such a need was felt. In that sense, Nuclear Physics may aptly be called the progenitor of Mega Science Projects. ITER, the biggest MSP in the history of mankind so far, tells us a similar story. One needs to confine plasma, heat it up to very high temperatures (about 10 times the temperature of Sun’s core in case of ITER), and sustain the resulting nuclear fusion reactions for sufficiently long durations to be able to gainfully harness nuclear fusion energy for power generation purposes for humankind’s use. Even establishing the feasibility of such a process on a scale, has led us to building a physically large and complex facility like ITER, with all its scientific, technological, and engineering complexities. It is clear that MSPs become necessary in some areas of science to push the very frontiers of human knowledge, pushing along with them the technological and engineering frontiers too.

Given the complexity, scale and resource-intensive nature of MSPs, it is obvious that not too many such projects will be built or operated at any given time, either nationally or internationally. The choice of which projects to undertake is therefore made through widespread consultations in the concerned scientific communities. Such consultations periodically take place in the most scientifically mature nations as well as other nations. These are known by various names in different nations, and over a period of time several international forums have also come into being. In the Indian context, such consultations have now come to be known as Vision Exercises. As expected, some of the fields where such exercises were first carried out were Nuclear Physics (NP), High Energy Physics (HEP or Particle Physics), and Accelerator S&T and Applications (ASTA). These were jointly conducted by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST) the last Exercise having been conducted in 2014.

By 2020, it was widely felt by the national scientific community that time had come to carry out the next Mega Science Vision (MSV) Exercise. There were several reasons for this:

(a) About six years had elapsed since the earlier such Exercise

(b) Most of the projects that had been identified in earlier Exercise in NP, HEP, and ASTA had moved towards implementation, along with few more that had emerged in the intervening period

(c) The Indian experimental community had become larger, more widely distributed among institutions, more confident, ambitious, and desirous of undertaking even larger number of projects with more complex and substantive hardware contributions

(d) Indian economy and industry had become globally competitive and were being noticed

(e) India was being actively approached by several nations or consortia of nations to participate in a number of ongoing and new projects

(f) There was a need to undertake several important national projects as well to ensure technological self-reliance in crucial areas

(g) There was a need to look at ways to nurture the entire eco-system for such projects to ensure a sustained pipeline of human resource and technological knowledge.

It was also noted that the need for, and culture of Mega Science, had acquired a wider reach and percolated to other areas of science too. After consultation between the OPSA, DAE and DST, it was decided that it would be better for the OPSA, with its predominant advisory and coordination role in the Government of India (GoI), to lead the MSV Exercise this time. Given the typical timeframe of such projects in general, and of those which were ongoing, 2035 was considered a reasonable timeframe to be covered under this new Exercise. Thus, the MSV-2035 Exercise was born to be led by the OPSA. For the sake of completeness, it may be mentioned that apart from NP, HEP, and ASTA, it was decided to carry out the Exercise in Astronomy & Astrophysics (A&A), Climate Research (CR), and Ecology & Environmental Science (E&ES)— the last two being entirely new additions under the Mega Science umbrella. The Exercise was to lead to six Roadmap Reports, one in each discipline, summarising the vision of the concerned scientific community for undertaking MSPs and other allied activities to nurture the required mega science eco-system. Four of these six Reports have now been released. In this issue of Vigyan Dhara, we are presenting the salient aspects of the MSV-2035-NP and MSV-2035-ASTA Reports. Similar issues on the remaining Reports will follow.

Coming back to the MSV-2035-NP and MSV-2035-ASTA Exercises, the OPSA started by requesting TIFR, Mumbai and RRCAT, Indore to lead these Exercises as Nodal Institutions and to nominate a Nodal Scientist in each case. TIFR and

RRCAT readily agreed and nominated Prof. Amol Dighe (from TIFR) and Shri Purushottam Shrivastava (from RRCAT) as the Nodal Scientists. In consultation with these institutions, a Working Group (WG) was constituted in each of these two areas, chaired by the Director of TIFR/RRCAT and Prof. Amol Dighe/Shri Purushottam Shrivastava as the Member-Secretary. A smaller sub-group of the WG acted as the Drafting Group (DG). Extreme care was taken to ensure that the WGs comprised eminent active scientists from across the country, with the best possible institutional and gender representation, and included nominees of the concerned government agencies. Compositions of the two WGs are given in the accompanying boxes (B1 and B2).

The OPSA also laid down the goals of this Exercise and a protocol for structured national and international consultations. Very large number of scientists were consulted while preparing the successive drafts of the NP and ASTA Reports (about 4000 researchers in case of NP, and around 6800 researchers in case of ASTA). Comments made by a number of eminent national and international experts and the OPSA during on-line meetings/off-line consultations were also accommodated to the maximum possible extent. A notable value-addition because of these consultations was the addition of "Annexure A.5: Return on Investment (RoI) for Accelerator Projects" to the ASTA Report. A first attempt of its kind in the history of such Exercises in the country, the analysis in this Appendix seems to indicate that if one were to wait for sufficiently long time, the investments made on accelerator projects do return back even in monetary terms, apart from giving other valuable societal returns like research publications, PhDs, etc. and enhancing nation's prestige internationally.

ALICE Collaboration/CERN

The MSV-2035-NP Working Group

Box 1

Chairperson	Director TIFR, Mumbai **Dr Jayaram Chengalur** / **Dr S. Ramakrishnan** / **Dr Sandip Trivedi**
Members from the Drafting Group	• **Dr Alphonsa Joseph Palakkel,** IPR, Gandhinagar • **Dr Aradhana Srivastava,** BARC, Mumbai • **Dr Bedangadas Mohanty,** NISER, Bhubaneswar • **Dr Rudrajyoti Palit,** TIFR, Mumbai
Other expert members	• **Dr Akhil Jhingan,** IUAC, New Delhi • **Dr Javed A. Sheikh,** Kashmir University, Srinagar • **Dr Lokesh Kumar,** Panjab University, Chandigarh • **Dr P. K. Atrey,** IPR, Gandhinagar • **Dr Rajdeep Chatterjee,** IIT-Roorkee • **Dr SadhanaDash,** IIT-Bombay • **Dr Subhasis Chattopadhyay,** VECC, Kolkata • **Dr Vaishali Naik,** VECC, Kolkata • **Dr Vandana Nanal,** TIFR, Mumbai • **Dr Vishwajit Jha,** BARC, Mumbai
Agency Representatives	• **Dr Purushottam Shrivastava,** RRCAT, Indore (Nominee of Secretary-DAE) • **Shri S. K. Varshney,** DST (Nominee of Secretary-DST)
Representatives of the O/o PSA	• **Dr Praveer Asthana,** National Coordinator • **Dr Arun Bhardwaj,** O/o PSA
Nodal Scientist	**Dr Amol Dighe,** TIFR, Mumbai

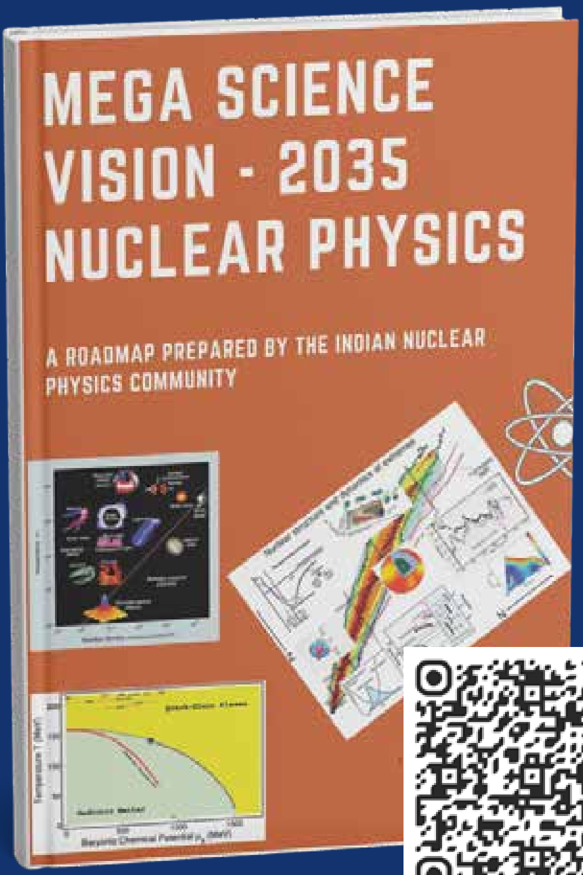
The MSV-2035-ASTA Working Group

Box 2

Chairperson	Director, RRCAT, Indore **Mr. Debashis Das** / **Dr S.V. Nakhe**/ **Mr. U. D. Malshe**
Members from the Drafting Group	• **Ms. Sudeshna Seth,** VECC, Kolkata • **Dr Puneet Jain,** IIT Roorkee • **Mr. Abhishek Rai,** IUAC, New Delhi
Other expert members	• **Dr Vinit Kumar,** RRCAT, Indore • **Dr S. M. Yusuf,** BARC, Mumbai • **Dr Malay Kanti Dey,** VECC, Kolkata • **Dr Tanuja Dixit,** SAMEER, Mumbai • **Dr Jaydeep Basu,** IISc, Bengaluru • **Dr Subhendu Ghosh,** IUAC, New Delhi
Agency Representatives	• **Dr Srinivas Krishnagopal,** Nominee of Secretary, DAE • **Dr M. C. Ramadevi,** Nominee of Secretary, DoS • **Mr. S. K. Varshney/ Dr Praveen Kumar S,** Nominee of Secretary, DST
Representatives of the O/o PSA	• **Dr Praveer Asthana,** National Coordinator • **Dr Arun Bhardwaj,** O/o PSA
Nodal Scientist	**Mr. Purushottam Shrivastava,** RRCAT, Indore

These Reports are “community documents”, the formulation of which has been facilitated by the OPSA. These documents summarize the Roadmaps for India’s engagements with MSPs in NP and ASTA in the 2020-35 timeframe, as best as the two scientific communities can visualize at this stage. Needless to say, if there are momentous developments in these fields in this period, those will have to be accommodated in the plans as and when they arise. Given the ever-increasing pace of scientific developments, it is difficult to foreclose such possibilities.

Finally, let us focus on the question usually asked of such Exercises and Reports. Of what use will be these Reports? Who will use these Reports? First, these Reports already list the ongoing MSPs in which Indian scientists are engaged and lay down their preferred trajectories. In addition, after careful SWOT analyses, some other (existing, upcoming, planned, or proposed) projects have also been listed in which India can possibly get involved. It is hoped that these Reports will help the Indian scientific community to self-organize and submit proposals to the funding agencies for continuation of, or for getting into, some of these projects. Once the proposals flow into the funding agencies, we expect that these Reports will also be useful for them while assessing those proposals. Many a times, proposals for India’s participation in international projects are received through diplomatic channels. In that event also, these Reports should help the government agencies to assess the value of those proposals and their relative priority as viewed by the concerned national scientific community. To conclude, one sincerely hopes that these Reports will play a valuable role in guiding and nurturing the mega science eco-system in Nuclear Physics and Accelerator S&T and Applications in the country, till they get updated again in the next MSV Exercise in future, hopefully after another 5 years.



MEGA SCIENCE VISION - 2035 NUCLEAR PHYSICS

A ROADMAP PREPARED BY THE INDIAN NUCLEAR PHYSICS COMMUNITY

Scan to Read
Mega Science Vision-2035: Nuclear Physics

MEGA SCIENCE VISION-2035 ACCELERATOR S&T AND APPLICATIONS

A ROADMAP PREPARED BY THE INDIAN ACCELERATOR S&T COMMUNITY

Scan to Read
Mega Science Vision-2035: Accelerator S&T And Applications

02

Mega Science Vision–2035: Nuclear Physics

Dr Amol Dighe
Professor, Department of
Theoretical Physics,
Tata Institute of Fundamental
Research

Dr Bedangadas Mohanty
Professor,
National Institute of Science
Education and Research

Laying the Foundations for Discovery, Technology, and National Capability

When we speak of nuclear physics, we often think of atomic nuclei or powerful reactors. Yet, nuclear physics today is far more than a specialised scientific discipline. It is a gateway to understanding the origin of matter, the evolution of the Universe, and the forces that shape nature at its most fundamental level. At the same time, it underpins technologies that affect everyday life, e.g, medical imaging and cancer therapy, clean energy, advanced materials, national security, and high-performance computing.

Recognising this unique blend of fundamental science and societal relevance, the Office of the Principal Scientific Adviser (PSA) to the Government of India initiated the Mega Science Vision-2035 (MSV-2035) Exercise. Conceived as a long-term national planning effort, MSV-2035 brings together scientific communities to articulate strategic roadmaps in areas where large-scale, coordinated investment is essential for global leadership.

"Nuclear physics sits at the intersection of curiosity-driven discovery and nation-building technology."

Source: Licensed Stock Visuals

The MSV-2035 (Nuclear Physics) Report — henceforth called MSV-2035-NP — prepared by the Indian nuclear physics community, with the Tata Institute of Fundamental Research (TIFR) as the nodal institution, sets out a coherent vision for the next decade. It identifies key scientific questions, the facilities required to address them, and the ecosystem needed to sustain excellence, innovation, and national capability.

How This Vision Was Shaped

The MSV-2035-NP document is the outcome of a nation-wide, community-driven planning exercise, rather than the product of a single institution or committee. It reflects extensive deliberations across India's nuclear physics ecosystem, spanning universities, national laboratories, accelerator centres, experimental facilities, and international collaborations.

A Working Group gathered inputs from the community on current activities, future aspirations, and emerging opportunities. A Drafting Group prepared an initial document, which underwent multiple rounds of scrutiny within the Working Group, through written feedback from the broader community, and via consultations with national and international experts. The revised document was reviewed by the Office of the PSA and further refined before finalisation.

This transparent process ensured that the report represents a consensus vision of the scientific community, informed by global best practices while remaining grounded in India's strengths, experience, and realistic future potential.

A Tradition of Big Science Participation

India's engagement with nuclear physics has a long and distinguished history. From early work on cosmic rays and nuclear structure to the establishment of accelerators, reactors, and national laboratories, Indian scientists have steadily expanded the country's scientific footprint. Over the past five decades, this engagement has increasingly taken the form of Mega Science Projects (MSPs): large, collaborative endeavours that demand sustained investment, sophisticated infrastructure, and international partnership.

> *"Mega Science is not a single experiment; it is a long-term national commitment."*

Through participation in global facilities spanning heavy-ion physics, rare-isotope research, fusion science, underground experiments, and large detector collaborations, Indian researchers have contributed to major discoveries while building domestic expertise and training highly skilled human resources.

Source: Licensed Stock Visuals

Scientific Achievements Underpinning the MSV-2035 Vision

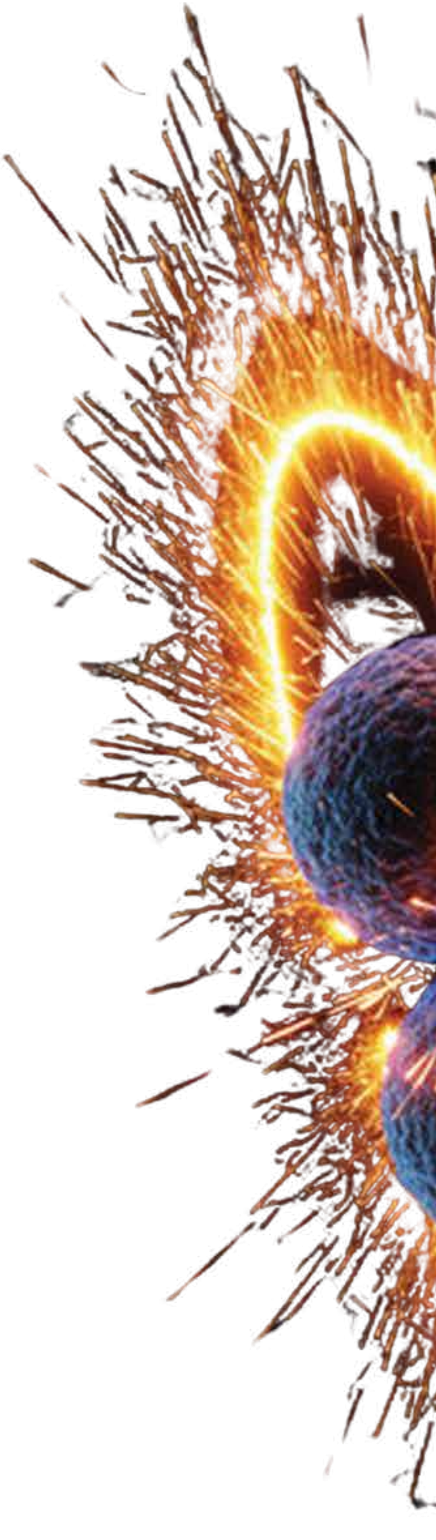
1 **Heavy-ion discoveries:** Indian scientists have made key contributions towards establishing the quark–gluon plasma as a strongly interacting perfect fluid, mapping collective behaviour in nuclear collisions, and advancing experimental searches for the critical point in the Quantum Chromodynamics (QCD) phase diagram at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC).

2 **Advances in nuclear structure and exotic nuclei:** India has played a significant role in advancing the understanding of nuclear structure, including studies of nuclei far from stability, helping refine models of nuclear forces, and element formation in astrophysical environments.

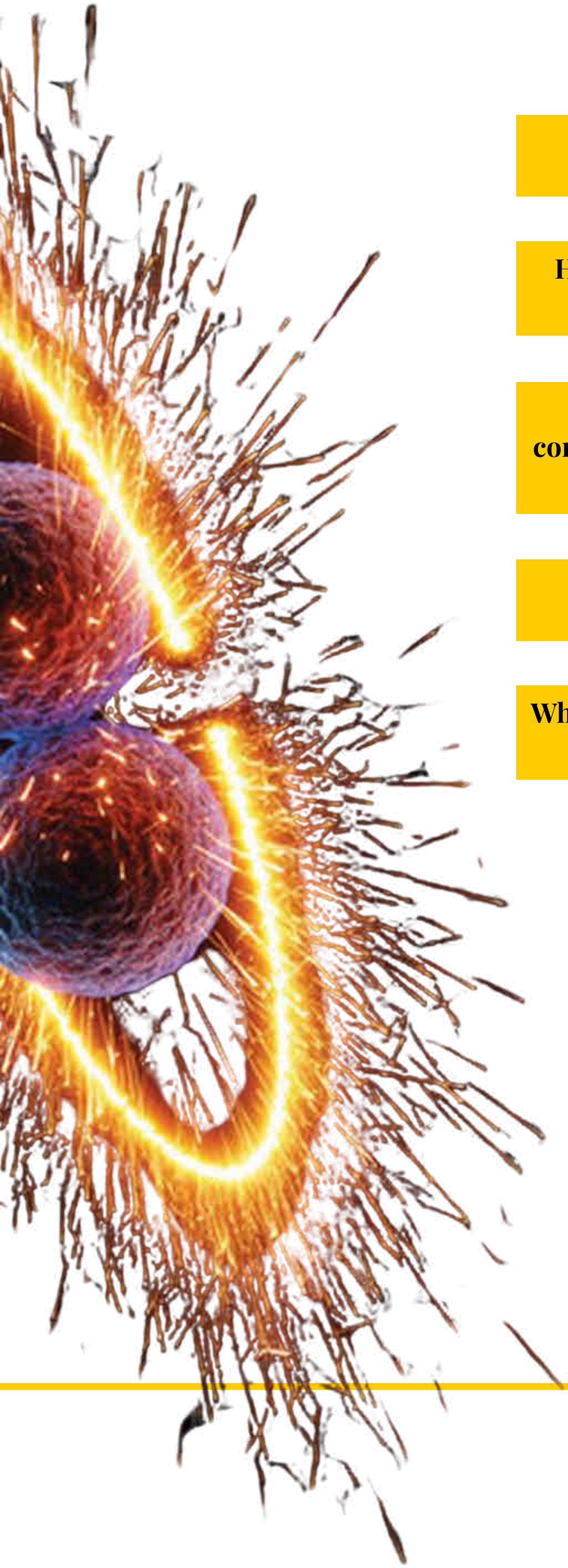
3 **Contributions to neutrino, astro-nuclear, and fusion science:** Indian researchers have contributed to neutrino physics and nuclear astrophysics through experiments and theory, while sustained engagement in fusion and plasma science, most notably through ITER, has strengthened India's position in long-term clean energy research.

4 **Detector, accelerator, and computing innovations:** The nuclear physics programme has driven indigenous development of advanced detectors, accelerator technologies, electronics, and large-scale data analysis capabilities, many of which have found applications beyond fundamental research.

5 **Training of skilled manpower:** Participation in Mega Science Projects has trained generations of scientists, engineers, and technologists in cutting-edge experimental techniques, computing, and project management, creating a highly skilled workforce for science, industry, and strategic sectors.



Proton Collision Forming Neon Rings (AI Generated)/Adobe



The Fundamental Questions

At its heart, nuclear physics addresses some of the deepest questions about nature.

What is matter made of?

How do the building blocks of visible matter acquire mass, structure, and stability?

How does matter behave under extreme conditions found in the early Universe or inside neutron stars?

How are the elements forged in stars?

What role do elusive particles such as neutrinos play?

> **"Every atom heavier than hydrogen carries a nuclear story written in the heart of stars."**

The MSV-2035-NP roadmap organises these questions into interconnected scientific themes, each requiring specialised facilities, theoretical advances, and sustained human capital.

Probing the Strong Force and the Early Universe

A central pillar of modern nuclear physics is the study of strong interactions, governed by QCD. Under extreme temperatures and densities, nuclear matter undergoes dramatic transformations, forming exotic states such as the quark–gluon plasma, believed to have filled the Universe microseconds after the Big Bang.

> *“By recreating the earliest moments of the Universe in the laboratory, nuclear physics turns cosmology into an experiment.”*

The vision emphasises India’s continued participation in complementary international facilities across different energy regimes, enabling a comprehensive exploration of the nuclear matter phase diagram.

Understanding the Architecture of Atomic Nuclei

Beyond extreme matter, nuclear physics seeks to understand how protons and neutrons organise themselves inside nuclei and how nuclei transforms. While stable nuclei are well studied, nuclei far from stability, with extreme neutron-to-proton ratios, remain largely unexplored.

Studying such systems informs stellar nucleosynthesis, constrains nuclear forces, deepens our understanding of neutron stars, and provides critical nuclear data for energy and medical applications. These nuclei serve as laboratories for extreme quantum systems, pushing theory and experiment alike.

Plasma Physics, Fusion, and Extreme States of Matter

An important component of the MSV-2035-NP is its emphasis on plasma physics and fusion science. Plasmas, the fourth state of matter, are central to both astrophysical environments and controlled fusion systems on Earth. Plasma physics bridges nuclear science, astrophysics, and future energy technologies.

India’s plasma programme, anchored at the Institute for Plasma Research (IPR) and strengthened by participation in the International Thermonuclear Experimental Reactor (ITER), provides a strong foundation. The roadmap recommends new plasma-based experimental systems, including ultracold plasma traps, laboratory astro-plasma simulators, and advanced pulsed-power and high-energy laser facilities. Beyond energy, plasma science contributes to materials processing, environmental technologies, and climate-related applications.

Nuclear Physics and the Story of the Cosmos

Nuclear astrophysics connects the microscopic world of nuclei to the macroscopic evolution of the cosmos. Precise nuclear data are essential for modelling stellar burning, supernova explosions, and neutron-star mergers.

Low-energy accelerators and underground laboratories, where rare reactions can be studied in ultra-low-background environments, are identified as critical future capabilities.

Neutrinos and Fundamental Symmetries

Neutrinos, among the most abundant particles in the Universe, are produced in nuclear reactions from the Sun to distant supernovae. Nuclear physics provides the tools to detect them and interpret their signals.

> *"Neutrinos allow us to see what light cannot."*

Research at the nuclear–neutrino interface addresses fundamental questions about particle masses, cosmic evolution, and the nature of matter itself.

From Discovery to Societal Benefit and Industry Partnership

Nuclear physics has repeatedly translated discovery into societal impact: from medical imaging and radiotherapy to energy systems, materials research, security technologies, and big-data computing.

> *"Mega Science transforms scientific ambition into national capability."*

The MSV-2035-NP places strong emphasis on early-stage and sustained participation of Indian industry in Mega Science Projects. Advanced manufacturing, precision engineering, electronics, cryogenics, and data infrastructure offer natural pathways for co-development, domestic capability building, and long-term economic benefit.

National Detector Capability and High-Performance Computing

Modern experimental science rests on two inseparable foundations: advanced detectors and high-performance computing (HPC).

> *"Detector capability and computing power together form the backbone of modern experimental science."*

The roadmap calls for national detector development and training centres, shared facilities supporting nuclear physics while also serving high-energy physics, astrophysics, medical imaging, and industry-facing applications. Equally critical is HPC infrastructure, enabling large-scale data analysis, detector simulations, nuclear theory, plasma modelling, and artificial-intelligence-driven discovery.

MSV-2035-NP places computing on equal footing with physical experimental infrastructure, recommending distributed national computing centres as shared assets across Mega Science domains.

Enabling Ease of Doing Science

Mega Science demands enabling institutional frameworks. It requires patience in funding, professionalism in management, and wisdom in evaluation.

The report advocates long-term, predictable funding aligned with project life cycles, professional project management to reduce procedural burden on scientists, and evaluation frameworks based on milestones and capability building rather than short-term metrics.

Outreach, Education, and Scientific Temper

Sustaining Mega Science requires the support of people, public understanding, and long-term trust. Mega Science must be visible, understandable, and inspiring to society.

Through national schools, student training, teacher engagement, and public communication, nuclear physics strengthens scientific temper and attracts the next generation of researchers and innovators.

Synergy with Other Mega Science Endeavours

Nuclear physics does not progress in isolation. Its goals and infrastructure overlap strongly with High Energy Physics, Astronomy and Astrophysics, and Accelerator S&T and Applications, three other areas in which the MSV documents have been written in parallel.

> *"Mega Science succeeds when disciplines move together, not in silos."*

Shared facilities, shared skill pipelines, and coordinated planning would improve cost-effectiveness and enhance India's ability to host and lead future Mega Science Projects.

How the Recommendations Function

The recommendations in the MSV-2035-NP report are woven throughout the document; closely linked to scientific themes, infrastructure needs, and system-level enablers. They articulate shared priorities and strategic directions, intended to guide policymakers, funding agencies, and the scientific community as future investments are planned.

A Phased and Prioritised Path Forward

The MSV-2035-NP roadmap follows a phased strategy. Near-term priorities emphasise strong participation in experiments at the RHIC (STAR), the LHC (ALICE), the FAIR (CBM, PANDA, NuSTAR), and ITER, alongside building national strengths in detectors, computing, and nuclear astrophysics. The medium-to-long term plan envisages leadership in radioactive-ion beams, plasma and neutrino facilities, Electron Ion Collider (EIC) experiments and new national accelerator and underground infrastructure, with flexibility for periodic review.

Looking Towards 2035

Scientific futures cannot be predicted with precision. The strength of Mega Science Vision – 2035 lies in its flexibility; providing strategic direction without rigidity.

> "Mega Science is strategic infrastructure for a knowledge-driven nation."

As India advances toward 2035, nuclear physics exemplifies how fundamental science strengthens national capability, global standing, and societal resilience.

The Envisioned Roadmap

Scientific field	Ongoing mega-science projects	New projects / activities
High-temperature QCD	• ALICE experiment at the Large Hadron Collider (LHC) • CERN Associateship	• Experiments at the Electron-Ion Collider (EIC)
Nuclear structure, reactions, high-density QCD	Experiments at: • Facility for Antiproton and Ion Research (FAIR) • Indian National Gamma-ray Array (INGA)	• Experiments at the Extreme Light Infrastructure - Nuclear Physics (ELI-NP) • Consortium for international facilities
Plasma	• International Thermonuclear Experimental Reactor (ITER)	• Plasma-related systems • Plasma Programme for people (P3)
New interdisciplinary ideas	• Reactor neutrino experiments (ISMRAN, CEvNS)	• Neutrino experiments with Deuterated Liquid Scintillator (DLS) • Neutrinoless double beta decay experiments
Ecosystem-building activities		• Detector Development and Training Centre • Underground Science Facility • High-Performance Computing

03

Mega Science Vision–2035:

Accelerator Science & Technology and Applications

Dr Vinit Kumar

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Particle accelerators are sophisticated machines that generate energetic beams of electrons, protons, or ions for applications in fundamental research, healthcare, industry, and national security.

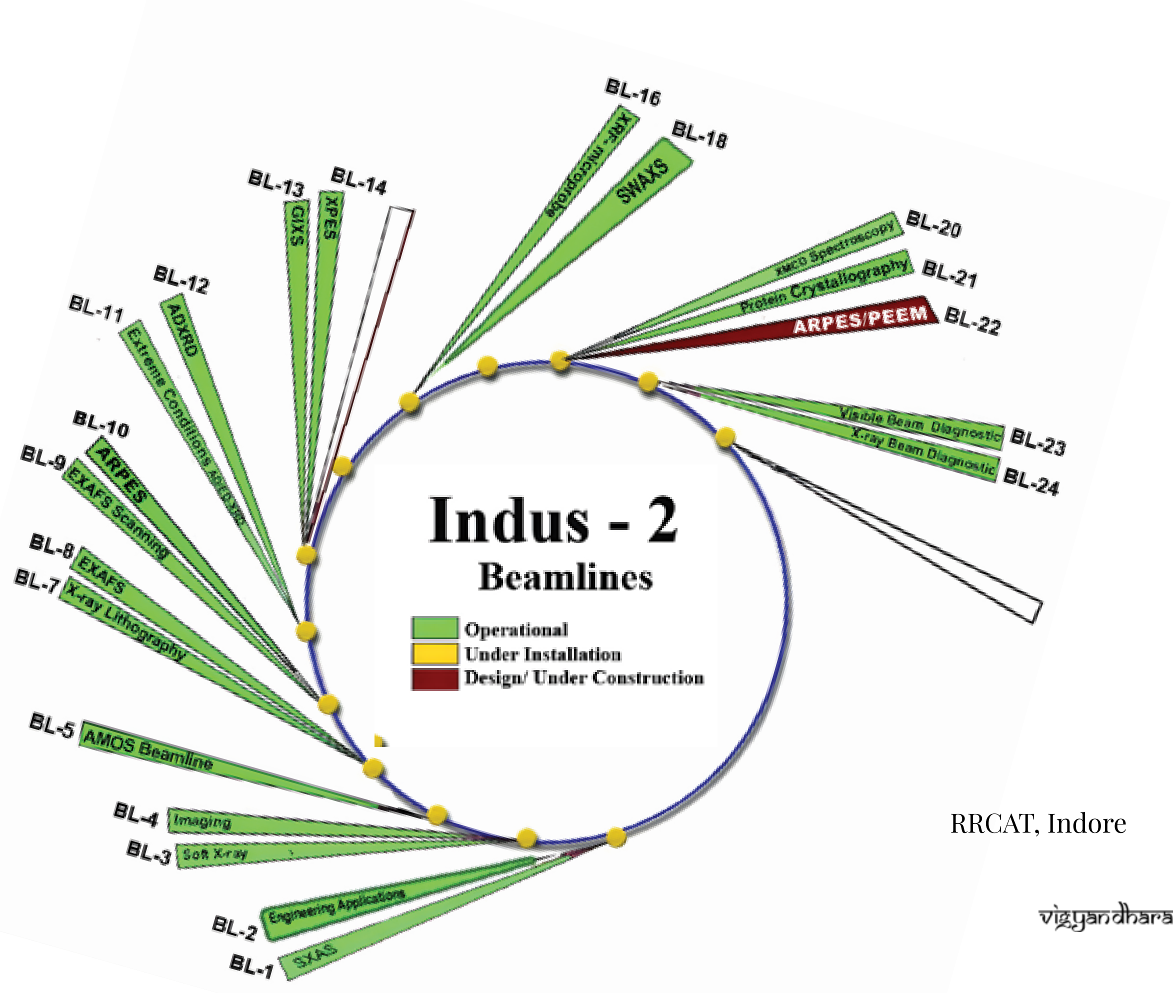
European Synchrotron Radiation Facility (ESRF), France

Journey of the Indian Particle Accelerator Program

India's accelerator Research and Development (R&D) began in 1940 at Saha Institute of Nuclear Physics (SINP) with an effort to build a 38-inch cyclotron, and has since progressed through major accelerator facilities established at centres such as BARC, VECC, TIFR, RRCAT, IUAC, and Society for Applied Microwave Electronics Engineering and Research (SAMEER).

During the last three decades, accelerator science and technology has expanded rapidly in the country. The focus has broadened beyond fundamental research through the development of medical cyclotrons, radiotherapy linacs, and industrial accelerators. Simultaneously, India has advanced into frontier accelerator technologies, including superconducting radio-frequency (SRF) ion linac, 3rd generation Synchrotron Radiation Sources (SRS), free-electron laser (FEL), superconducting cyclotron, rare isotope beam (RIB) accelerator, and laser plasma accelerator (LPA). Strong international partnerships with European Organization for Nuclear Research (CERN), Fermilab, TRI-University Meson Facility (TRIUMF), and FAIR have further strengthened India's integration into the global accelerator landscape.

The Report — henceforth called MSV-2035-ASTA — prepared by the community, with RRCAT as the nodal institution, sets out a coherent vision for the next decade. The final report presents a long-term strategic roadmap, identifying priority domains and projects with SWOT analysis, and recommendations regarding funding and monitoring mechanisms to position India as a competitive player by 2035.



RRCAT, Indore

Accelerators, Classification, and Technological Scope

Accelerators use electromagnetic fields to propel charged particles (like electrons or protons) to near-light speeds. Accelerated charged particles generate short-pulse intense photon beams (SRSs, FELs) and pulsed neutron beams (spallation neutron sources (SNS)), which serve large user communities across science, technology, and industry.

Accelerators are classified by geometry (linear or circular), power source (DC, RF, laser-plasma), and Radio Frequency (RF) cavity material (normal-conducting or superconducting). A particle accelerator comprises interlinked systems including electron/ion sources, RF cavities and systems (for RF accelerators), high-voltage systems, magnets, power converters, beam diagnostic instruments, cryogenic infrastructure (for superconducting cavities/magnets), vacuum systems, machine control, and interlock and protection systems. This signifies the complex and multidisciplinary nature of ASTA.

Condensed Matter and Materials Science: SRS, X-ray FEL (XFEL), and SNS are used to probe materials at atomic to mesoscopic scales. These have applications in healthcare, industry, energy storage and harvesting, advanced materials and devices.

Energy Applications: Accelerator Driven Systems (ADS) based on high-energy, high-power, superconducting proton accelerators can enable thorium utilization for energy production and facilitate transmutation of nuclear waste.

Healthcare and Biological Applications: Accelerators enable radiotherapy, medical isotope production, and medical sterilization. SRS and FEL facilities enable biomolecular structure determination, serial crystallography, real-time bio-imaging, drug discovery, and infectious disease research.

Industrial Applications: Electron accelerators support food irradiation for safety and shelf life, mutation breeding for crop improvement, water purification and waste treatment, radiography, polymer modification, material irradiation, and surface engineering.

Particle and Nuclear Physics: Colliders are large-scale, high-cost facilities requiring continuous upgrades in energy and luminosity, to test emerging fundamental particle physics models. Heavy ion accelerators and cyclotrons enable nuclear spectroscopy and reaction studies. Accelerators also support rare-isotope research, nuclear astrophysics, and Accelerator Mass Spectrometry (AMS) for geochronology and archaeology.

Security Applications: Accelerators can be used in cargo scanning, nuclear material detection, generation of high-power electromagnetic pulses, and fast X-ray bursts for strategic use.

Space Science and Aeronautics: Accelerator beams simulate space radiation environments for qualification of spacecraft components and sensors. SRS and accelerators also support payload spectral characterization and non-destructive testing of aerospace components.

Low Energy High Intensity Proton Accelerator (LEHIPA) developed at BARC, Mumbai

MeV Medical Cyclotron at VECC, Kolkata

Global Landscape of Accelerator R&D

High-energy physics has progressed through successive collider generations, culminating in the Higgs Boson discovery at the Large Hadron Collider. Upgrades and next-generation colliders aim to extend precision and energy frontiers. High-intensity proton accelerator, Proton Improvement Plan II (PIP-II), is under construction at Fermilab to support neutrino research.

Fourth-generation high-brilliance SRSs (HBSRS), such as ESRF-EBS, and APS-U, based on multi-bend achromat lattice, achieve diffraction-limited performance with 2-3 orders enhancement in photon brightness. Several new facilities and upgrades are planned worldwide along similar lines. XFELs such as LCLS, SACLA-XFEL, PAL-XFEL, SwissFEL, and European XFEL provide coherent, hard femtosecond X-ray pulses with peak brightness far exceeding that of SRSs.

Modern MW-class accelerator driven neutron facilities SNS in USA and J-PARC Materials and Life Science Experimental Facility in Japan deliver high peak flux of pulsed neutrons for advanced materials research. Modern heavy-ion accelerators such as FRIB at MSU, SPIRAL2 at GANIL, and ISAC at TRIUMF use advanced compact superconducting RF linacs to achieve higher intensities for frontier nuclear and rare-isotope research.

The ring cyclotrons at PSI (590 MeV) and TRIUMF (500 MeV) represent the beam-power frontier, while the superconducting ring cyclotron at RIKEN represents the high-energy frontier of heavy ion accelerators, supporting nuclear physics, rare-isotope, and neutrino-related research. Commercial ion accelerators (<400 keV, up to ~500 μA) and RF linacs (~MeV, ~mA) are widely used for semiconductor doping, implantation, and surface modification. Commercial 10 MeV RF electron linacs are deployed for irradiation, cargo scanning, flue-gas treatment, and wastewater processing.

Compact cyclotrons and high-current linacs support isotope production at centres at BNL and LANL, while commercial radiotherapy electron linacs are widely used for cancer treatment. Proton and carbon-ion commercial therapy systems represent the state-of-the-art in cancer therapy. Major ADS programmes are underway in Japan, Belgium, and China, based on a high-power superconducting proton linac. The multinational International Fusion Materials Irradiation Facility, an accelerator-based neutron facility for materials testing, is planned in Spain to support fusion R&D.

Major LPA programmes worldwide, including the BELLA facility at LBNL and the pan-European Extreme Light Infrastructure, have demonstrated multi-GeV electron acceleration using PetaWatt lasers and are progressing toward staged, high-repetition-rate plasma accelerators for next-generation research and medical applications.

National Landscape of Accelerator R&D

India's experimental nuclear physics infrastructure includes pelletrons with superconducting booster linacs at IUAC and TIFR, cyclotrons at VECC, and the low-energy, high-current FRENA facility at SINP. SRS facilities Indus-1 (450 MeV) and Indus-2 (2.5 GeV) at RRCAT, with 7 and 18 operational beamlines, respectively operate round-the-clock since 2010, supporting a wide national user base. Several activities, including capacity building and demonstration of indigenous manufacturing of some components for the proposed national HBSRS, Indus-3, are being pursued at RRCAT. An Infra-red FEL at RRCAT is operational as a user facility. A compact RF-photocathode-based THz-FEL is under commissioning at IUAC.

Superconducting accelerator development in India began at TIFR and IUAC with Quarter Wave Resonator-based heavy-ion linacs, and has since expanded to advanced SRF cavity fabrication and testing infrastructure at RRCAT, BARC and VECC, supported by international collaborations with Femilab and TRIUMF. With this capacity building and successful demonstration of the 20 MeV Low Energy High Intensity Accelerator at BARC, the development of the Indian ADS accelerator, requiring a 1 GeV, 10 mA proton beam is planned to be taken up in phases. Initial R&D efforts have been undertaken at RRCAT on the 1 GeV superconducting linac for the proposed Indian Facility for Spallation Research.

Industrial DC accelerator and RF electron linac systems (up to 15 kW) have been developed by BARC and RRCAT and deployed for medical sterilization and industrial processing applications. Work is in progress to develop accelerators for food irradiation, wastewater treatment, neutron generation and cargo scanning. India is expanding medical accelerator capabilities through high-current cyclotrons at VECC for isotope production, indigenous radiotherapy linacs developed by SAMEER, alongside the operational proton therapy facility at the Apollo Proton Cancer Centre in Chennai.

Experimental studies on laser–plasma interaction and laser plasma acceleration are being carried out at RRCAT, using 10–150 TW and 1 PW laser systems, achieving electron energies beyond 500 MeV and proton energies beyond 10 MeV. India's first AMS facility was established at IUAC, using an upgraded 15UD Pelletron; followed by the 500 kV eXtended Compact Accelerator Mass Spectrometer (XCAMS).

Assessing Needs, Technology Capabilities, and Future Pathways

India's accelerator user community has growing requirements across basic science, healthcare, industry, energy, and national security. Future programmes require HBSRS and FEL, SNS and RIB facilities spallation neutron and rare-isotope facilities, high-power ADS linac, medical cyclotrons and proton/carbon therapy systems, industrial electron linacs, and specialized ion accelerators with higher beam currents. To develop these accelerators, critical gaps need to be bridged in high-frequency RF sources, ultra-precision magnets, cryomodules, high-current proton systems, advanced digital controls, gantry-based hadron therapy, advanced cryoplants, strategic materials, and large-scale beam-dynamics computing.

A coordinated, mission-oriented approach is needed to strengthen indigenous R&D, deepen industry participation, and enhance the skilled workforce. Sustained international collaboration, coupled with focused domestic technology development is essential.

Strategic Directions and Priority Projects

Based on the considerations discussed, the Report recommends the following prioritized list of MSPs and programmes in six application areas to be pursued up to 2035:

Photon Science

- 6 GeV HBSRS
- Vacuum Ultraviolet (VUV)/Soft X-ray FEL (upgradeable to hard X-ray)

Neutron Science

- 200 MeV CW superconducting proton linac (ADS Phase I)
- 1 GeV pulsed superconducting proton linac and accumulator ring for spallation facility

Industrial Applications

- 7.5 – 10 MeV industrial electron linacs (10–30 kW class)
- 3 - 6 MeV electron linac for radiography/cargo scanning (tens of kW)
- 1 MeV 100s kW DC electron accelerator for flue gas and wastewater treatment
- 5-70 keV ≥ 500 of μA, tabletop ion sources for various applications

Medical Applications

- 6 MeV electron linacs for intensity modulated radiotherapy
- 6 MeV electron linac for precision radiotherapy
- 70–230 proton and 400 MeV/A carbon ion accelerator for therapy

Nuclear Physics

- RIB accelerator (~100 MeV/A) and upgrade of heavy-ion facilities
- Next-generation 10 – 20 MeV/A, 100s pnA heavy-ion accelerator

Laser Plasma Acceleration

- Basic R&D
- GeV-class electron and 30–70 MeV proton/ion LPA, femtosecond X-ray/γ source

A carefully crafted tentative phased implementation schedule, funding requirements, and human resource requirements for various phases of the projects are presented in the MSV-2035-ASTA Report. Two scenarios – one with modest funding and another one with aspirational funding have been considered. An increase in funding and human resources is recommended and justified, as the field has gained significant momentum in India and requires adequate support to effectively leverage recent advancements for national development.

The Report further covers the impact of accelerator projects on Indian industry and society; and a first-of-its-kind assessment of the long-term Return on Investment (RoI) from accelerator projects.

Implementation Framework and Enablers

The Report proposes a structured implementation framework, covering ecosystem development and project approval, funding, and monitoring mechanisms. It emphasizes enhancing industry participation, promoting academia–laboratory collaboration, strengthening supply chains, and fostering indigenous manufacturing.

Although Indian industry has contributed to accelerator projects, turnkey capability for large, complex systems remains limited. Early design-stage involvement and targeted technology transfer are recommended to build turnkey capabilities and global competitiveness.

Human resource development is central to the strategy. Dedicated academic programs in ASTA, structured training framework, international collaboration, national accelerator schools, and postdoctoral opportunities are needed, along with expanded outreach through internships, workshops, and lab visits.

MSPs should follow a structured lifecycle from conceptual design to operation stage, with stage-wise centralized proposal submission, inter-agency approval, and periodic reviews. IT-enabled project management, empowered young leadership, and international evaluation are essential for smooth execution.

Summary

This article presents a summary of the community vision contained in the MSV-2035-ASTA Report, including a recommended prioritised list of MSPs and programmes that will help policymakers, and guiding the community along a defined roadmap, strengthening India's position in this strategically important field, closely linked to the country's scientific and technological prowess.

04

Nuclear Science and Accelerators

in the Service of the Nation

Dr Amit Roy
Former Director, Inter-University Accelerator Centre;
and Ex-Raja Ramanna Fellow,
Variable Energy Cyclotron Centre

Study of Nuclear Sciences in India was pioneered by D.M. Bose and M.N. Saha in Calcutta University soon after the discovery of fission in 1939. Bose's student Shyamadas Chatterjee started fission studies with indigenously built detectors and found evidence of spontaneous fission but before he could publish Flerov and colleagues from Russia did it. M.N. Saha tried to build a cyclotron with the help of Lawrence in 1941 but his efforts were successful only after India became independent. The 37" cyclotron was functional in 1956. Around the same time, H.J. Bhabha established TIFR in Bombay in 1945 for nuclear studies and got a Phillips 1 MV Cockroft-Walton cascade generator in 1953 for neutron studies of relevance to reactor design, viz., fission, neutron diffusion studies, and neutron induced reactions. Cockroft-Walton generators for neutron-induced reaction cross-section measurements were installed at Bose Institute, SINP, Aligarh and Waltair. The first reactor, APSARA started functioning in 1956 and the CIRUS reactor was commissioned in July 1960 providing a copious source of neutrons as well as radioisotopes for nuclear decay studies.

It is clear that the pioneers of nuclear sciences in India initiated efforts right from the beginning to build all three major tools for research, viz., particle accelerators, reactors and detectors, and associated electronics, aimed mainly for fundamental research.

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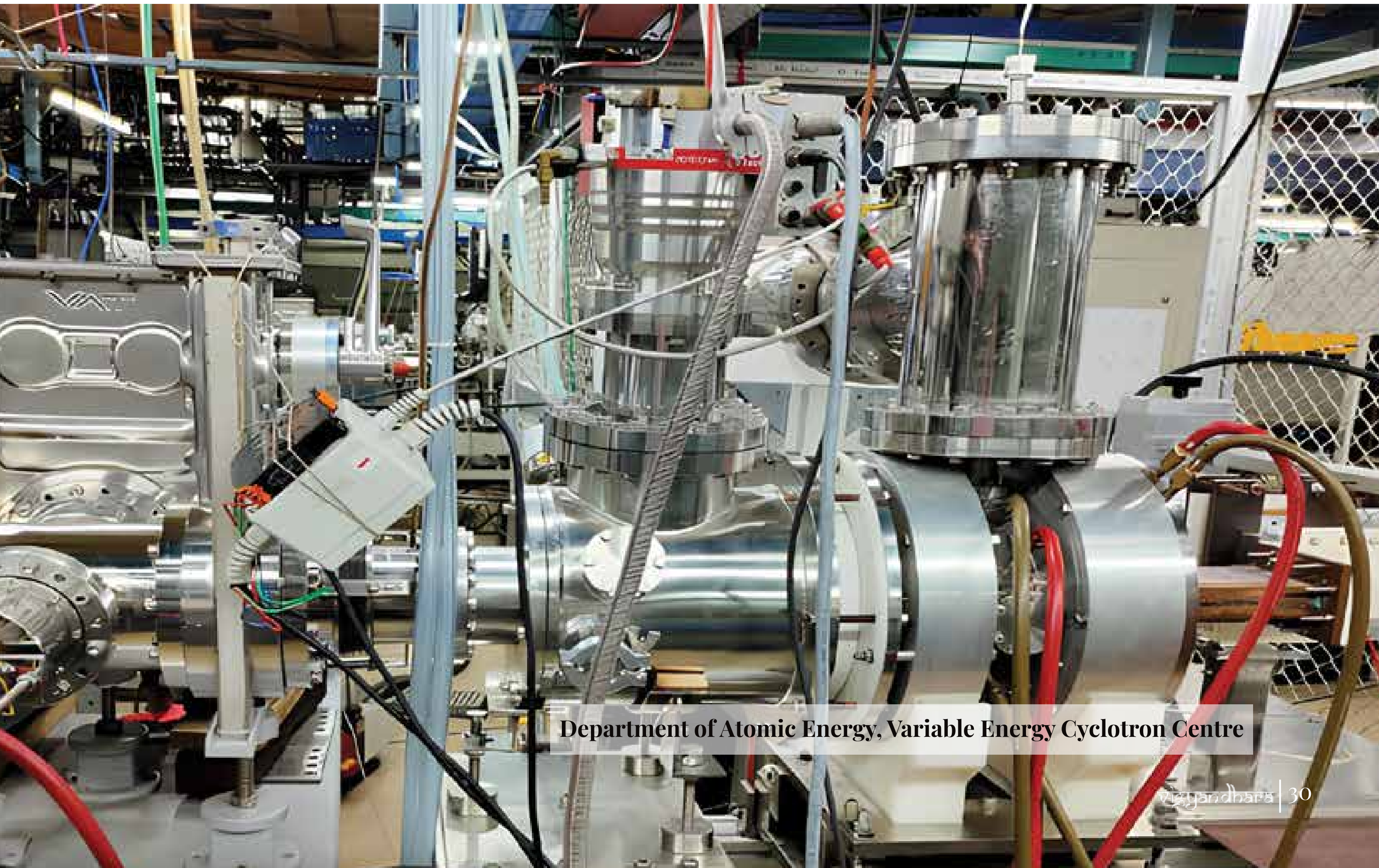
Expansion in the 1960s

By the 1960s, nuclear studies were in full flow at TIFR, BARC, SINP, the new Institute of Mathematical Sciences (IMSc), Physical Research Laboratory and various Universities such as those at Delhi, Calcutta, Aligarh, Chandigarh, Waltair, Calicut, and Bangalore. There was growth of a vibrant community in theoretical and experimental nuclear physics in Indian universities and institutes. PhD. programs were initiated, project funding and international interactions stepped up, and strong emphasis was laid on instrument building, nuclear electronics, and radiation detectors. The Electronics Corporation of India (ECIL) was set up to provide industrial support to the science programs. The major impetus for electronics development in the country came from the need to develop nuclear electronics for basic research.

Apart from neutron cross-section measurements, Beta decay spectroscopy studies were done using radioisotopes from the reactors accessible to all institutes and universities. These experiments provided stringent tests of nuclear models at low excitation energies of nuclei and significant contributions were made from India towards identifying the role of independent particle motion (i.e. shell-model), and that of collective motion of nucleons (vibration and rotation) in different nuclear mass regions. Detailed studies of fission of nuclei under neutron irradiation were done where the mass distributions of fission fragments and the multiplicity of neutrons accompanying the fission fragments were identified. With the 5.5 MeV van de Graaff generator at BARC, proton and alpha induced reaction cross sections were measured to derive the effective optical model for the nuclear potential.



Department of Atomic Energy, Variable Energy Cyclotron Centre

High Current Injector (HCI) project, IUAC

Accelerators and Reactors in 1970s-1980s

In the 1970s-1980s, a major effort was directed to build the first large particle accelerator in the country, the K140 Variable Energy Cyclotron at Kolkata. The first beam to be accelerated in this machine was of alpha particles in 1977 and this accelerator continues to be in full use with addition of heavy ions as a national facility. Two large Pelletron accelerators were bought and commissioned in this period, first at TIFR in 1989 and the second at Inter-University Accelerator Centre (earlier Nuclear Science Centre) in 1991.

First electron accelerator was a 4 MeV Standing Wave (SW) electron linac, built in the 1980s by TIFR, for radiography applications. Also, during that period, an 8 MeV race-track microtron was built and installed at Savitribai Phule Pune University.

New indigenous research reactors were set up at Indira Gandhi Center for Atomic Research, (earlier named Reactor Research Centre) at Kalpakkam and the Dhruva reactor at BARC for high flux neutron studies. Based on the success of the operation of the research reactors, a number of reactors were developed for energy generation at BARC. The Nuclear Power Corporation of India Limited (Nuclear Power Board) was established to harness nuclear power for societal needs.

Advancements in Late 1980s-2000s

During the late 1980s and early 2000, superconducting linear accelerators were added to boost the beam energies obtained from the Pelletron accelerators at Mumbai and Delhi. This period also saw the development of the Synchrotron-based Storage Ring Facility at Raja Ramanna Centre for Advanced Technology. The era of industrial accelerators in India began with the setting up of an electron beam experimental facility in Trombay which later moved to the Board of Radiation and Isotope Technology (BRIT).

Many major experimental facilities and detector systems for nuclear studies were added in the past couple of decades. These are Indian National Gamma Array, Recoil Mass Spectrometers, Neutron arrays, Multi-layered Charged Particle arrays, Position sensitive detector arrays, Spin Spectrometers. High speed Data Acquisition systems and high performance Computing facilities were developed at the Kolkata, Mumbai and Delhi centres.

Major advances were made by Indian researchers in studies of structure of nuclei (interplay of single particle and collective modes, behaviour at high excitation energy, spin and isospin), nuclear reaction dynamics (different facets of direct, compound and pre-compound reactions, fusion and fission reactions, nucleosynthesis process).

India-International Collaboration Over the Years

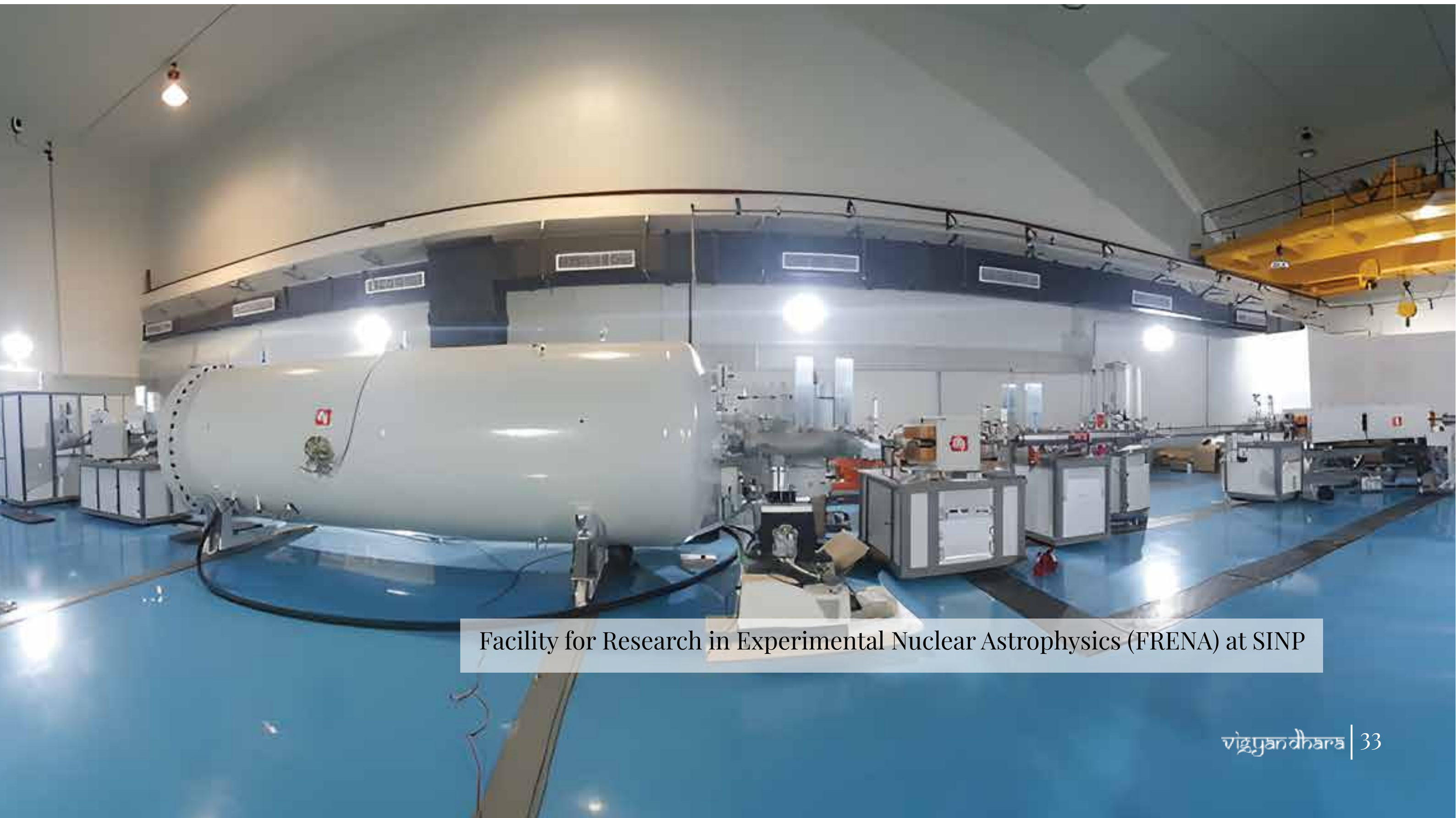
Indian researchers have been participating in experiments at large international facilities since the 1960s. It started with emulsion stacks being exposed to pion, kaon, and proton beams utilizing the CERN Proton Synchrotron. Around 1990, a team from national laboratories and universities started a collaboration for the WA93 experiment at the CERN Super Proton Synchrotron for the search and study of Quark-Gluon Plasma (QGP), which was followed up by joining the WA98 collaboration in 1993. The Indian team also joined the STAR collaboration at BNL during the 1990s. The Indian researchers were supported by DAE and DST jointly, building some sections of the detectors and signal processing electronics. Since then, the Indian nuclear physics community has been participating in many such mega science projects within India and abroad, e.g., Relativistic Heavy-Ion Collider (RHIC) facility, LHC facility, FAIR, ITER, and Indian National Gamma Array collaboration (INGA). The detector systems designed, developed, fabricated, and deployed at CERN and other international laboratories have enabled some of the most iconic fundamental discoveries of recent times.

Following the establishment of Superconducting Radio Frequency (SRF) technology in the centres at Delhi, Indore, Mumbai and Kolkata, a collaboration was established between Indian Laboratories (BARC, RRCAT, VECC, IUAC) and Fermilab for joint development of a high power high energy proton accelerator. This collaboration has facilitated the development of a project for 1 GeV high power proton accelerator by DAE laboratories that has among its goals, utilisation of Th, transmutation of fission products, production of radioisotopes, spallation neutron source, and medical therapy.

The plasma physics studies began in 1982 at the Institute of Plasma Research in the field of magnetically confined high-temperature plasma research by building a tokamak. In 1989, the tokamak, ADITYA, was commissioned and went into a phase of routine operation. This was followed by building a superconducting tokamak and joining the ITER project.

New accelerator facilities that have recently started operations are, the Superconducting Cyclotron at VECC, Facility for Research in Experimental Nuclear Astrophysics (FRENA) at SINP, High Current Injector at IUAC. The initial phase of the Advanced National facility for Unstable and Rare Ion Beams (ANURIB) has also been in operation.

Overall, the research conducted using these facilities in India resulted in many significant contributions to the understanding of nuclear interactions as well as nuclear structure. In plasma physics, important results have been obtained about the behaviour of plasma under confinement and participation in the ITER project has generated technical expertise for an indigenous demo fusion reactor design. It also generated invaluable nuclear data adding to the global pool for use in reactor technology and industry. A large number of students got trained, creating a reasonably large pool of experts, who can contribute to development of science and technology in the country.



Facility for Research in Experimental Nuclear Astrophysics (FRENA) at SINP

Societal Applications of Nuclear Technologies

During this process of pursuit of fundamental studies many of the tools required for nuclear science were developed. This process generated considerable technical expertise in the associated technologies. Many of these tools and techniques are already in use for societal applications in our country. Some of the examples of successful applications of nuclear technologies implemented in India are outlined here:

In the Medical field applications, radiation has been harnessed for both diagnostics and therapy. Diagnostics tools are radioisotopes that act as tracers and radiations for radiography. For Single Photon Emission Computerised Tomography (SPECT), radioisotopes used: 99mTc, 201Tl, 67Ga, 112In, 123I, are being produced either in our reactors or using accelerated high energy beams.

Positron Emission Tomography (PET) reveals tumours, dynamic effects such as blood flow using the isotopes, 15O, 13N, 11C, 18F, 68Ga. Although the majority of the hospitals are using imported isotopes, all these isotopes are now being produced at the 30 MeV medical cyclotron of VECC and supplied to local hospitals at a fraction of the imported cost. More indigenous facilities for PET isotope production are required to bring the cost of this procedure affordable to the majority of Indians. Towards this, an indigenous 18 MeV medical cyclotron project at VECC, Kolkata is approaching the assembly process this year at the VECC Bidhan Nagar campus. This will eventually reduce the cost of these isotopes further. Superconducting magnet for MRI, suitable for diagnostics, has been developed jointly by IUAC and SAMEER and is currently undergoing validation tests.

Medical Cyclotron Facility (MCF):, Kolkata

SIDDHARTH- the 6 MV Medical Linac developed under the Jai-Vigyan Mission.

For therapy, isotopes like 60Co and 192Ir used for Brachytherapy are being supplied by BRIT. It also supplies a host of therapeutic radio-pharmaceuticals using radionuclides (viz. 131I, 32P, 166Ho, 188Re, 177Lu, 90Y) designed to treat a variety of cancers.

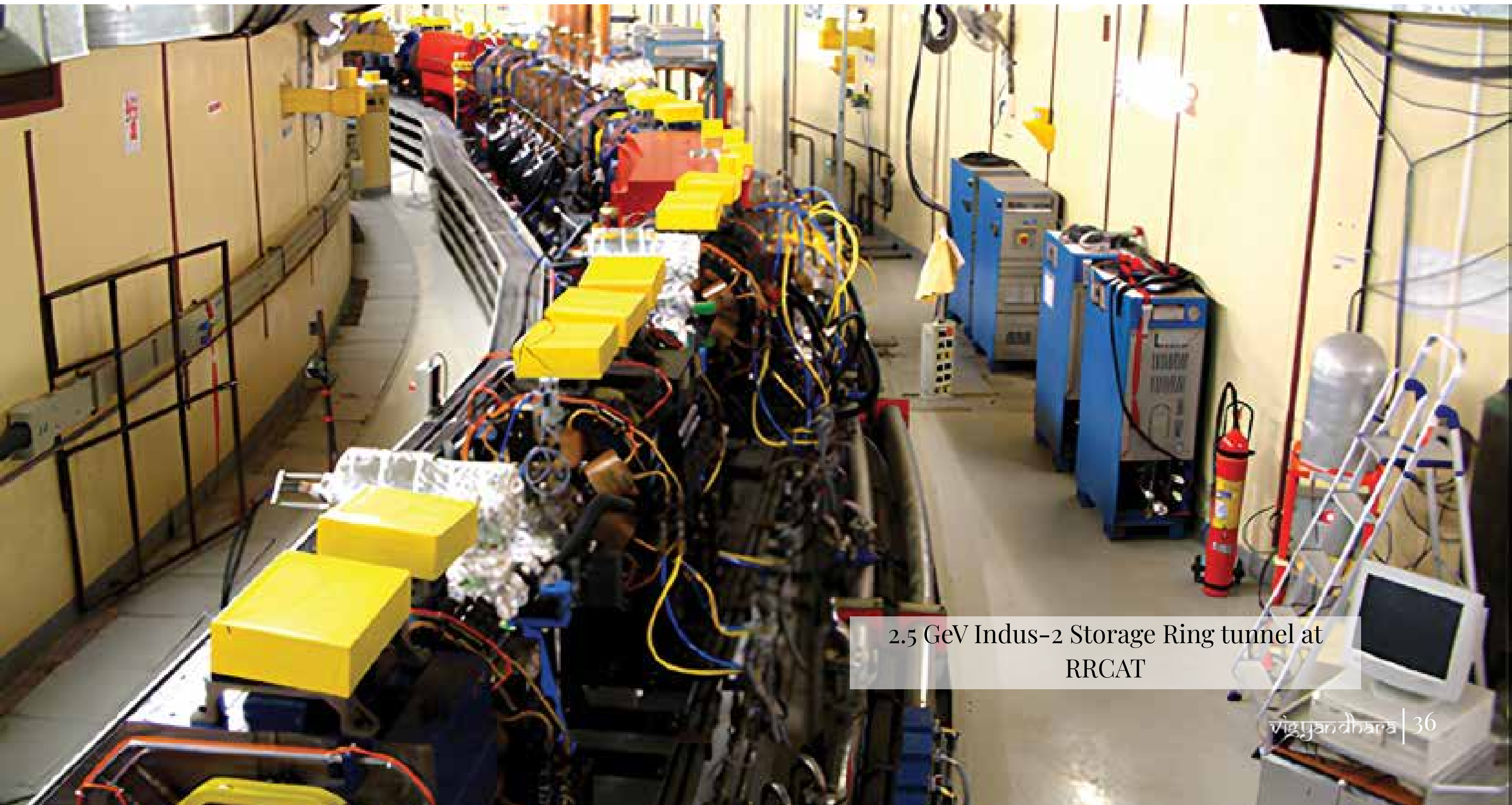
Linear accelerators are used to treat tumours and a large number of machines are imported at great cost making the treatment unavailable to many Indians. SAMEER has commissioned 2 radiotherapy machines, delivering 4 MV photons, and 5 machines delivering 6 MeV photons at various locations across India. As of now two machines are functional and treating patients.

6 MV radiotherapy machine technology has been transferred to two private companies. R & D for dual photon energy and dual mode (electron and photon) machine development is on-going. A 30 MeV and 5-10 kW beam power electron linac is under development at SAMEER for medical radio isotope generation. Currently, 20 MeV beam with 2.5 kW beam power is available for experimentation generating Mo-99 and Cu-67 isotopes to check their activity levels for medical use. A proposal to develop a Hadron Therapy machine is also under consideration at SAMEER. At present only two commercial 230 MeV proton cyclotrons for proton therapy are commissioned at Apollo, Chennai and at TMC, Mumbai.

Synchrotron radiation sources give high luminosity x-rays that can help decipher the structure of complex molecules that help in the understanding of protein structure & help in the discovery of specific drugs. The synchrotron radiation from INDUS-II electron storage ring at RRCAT is being used for this purpose.

Radiation induced modification of matter can give rise to many novel materials that can not be produced by any other technique. In addition, high-energy radiations generate highly reactive free radicals, ionic species or defects in matter that have been exploited to bring about changes in a wide variety of materials with increased toughness, adhesion, hardness and corrosion resistance. The radiation could be either from a radioisotope or it could be electrons or ions from an accelerator.

Some examples are: cross linking of polymers, curing of paints & varnishes, detoxification of wastes, purification of industrial gases, ion beam lithography for micro circuits, etc. Radiation is also used for sterilization of medical supplies. There are more than 25 radiation processing plants operating in India in Maharashtra, Bengal, Rajasthan, Gujarat, Delhi, Madhya Pradesh, Karnataka, Uttar Pradesh, Andhra Pradesh, and Haryana bringing in a lot of economic benefit. The radioIsotopes are being supplied by DAE units. Specific examples of such use are: Sewage Sludge hygienisation Facility at Vadodara using 60Co, Food Irradiation facilities at Defence Lab, Jodhpur, Trombay, Navi Mumbai, Lasalgaon, and Indore. An electron beam radiation processing facility (named ARPF) using a 10 MeV, 6kW electron linac is operating at Devi Ahilya Bai Holkar Fruit and Vegetable Mandi Complex, Indore. This facility is being used for development of new crop varieties, color modification of gem stones, development of novel materials, modification of semiconductor properties, sterilization of medical devices, etc. A twin 9.5 MeV, 15 kW linac in opposing beam configuration is also being developed for irradiation of samples at Indore. Another 10 MeV, 10 kW linac has been installed at a private company in Bengaluru for sterilization services.

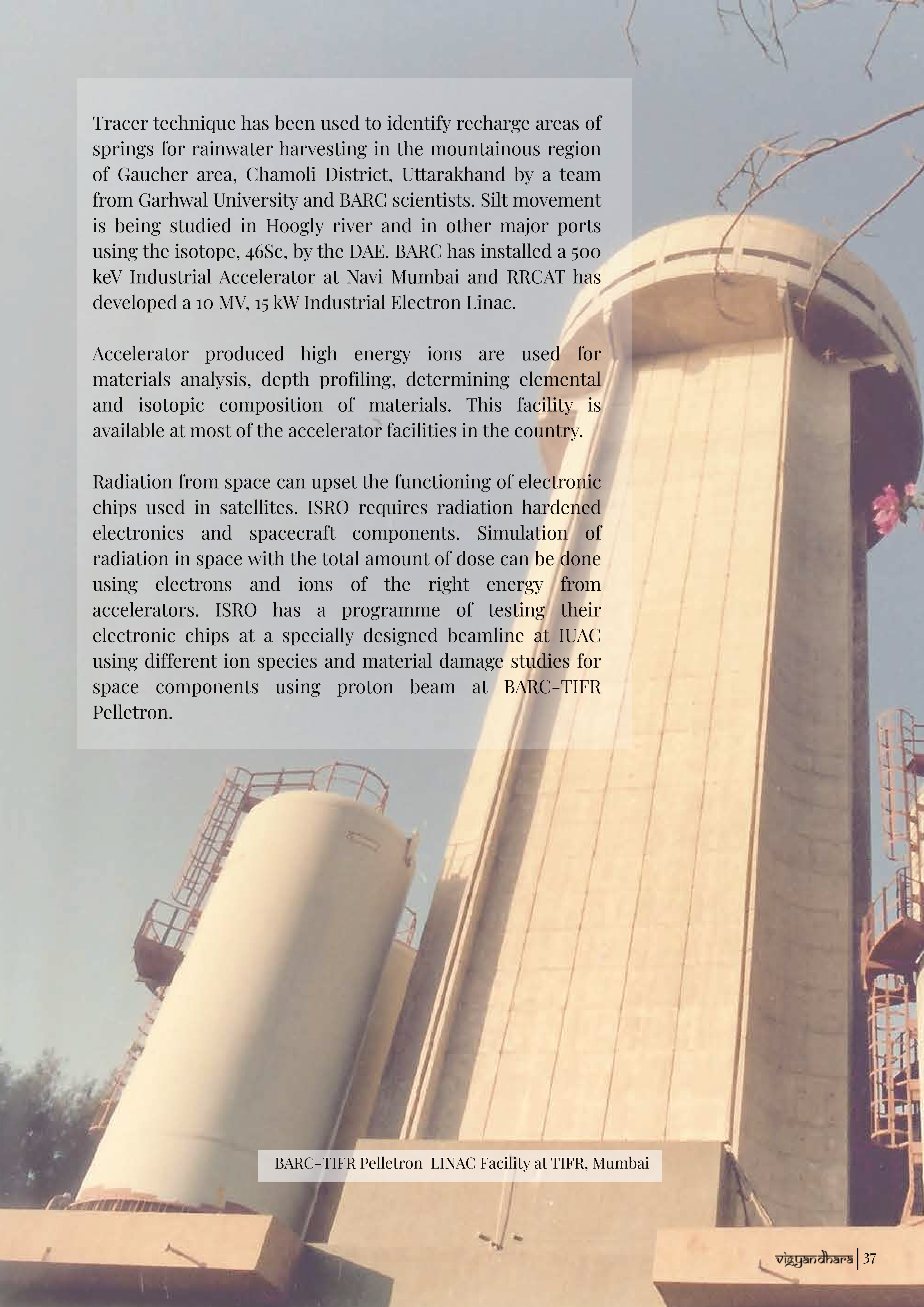


2.5 GeV Indus-2 Storage Ring tunnel at RRCAT

Tracer technique has been used to identify recharge areas of springs for rainwater harvesting in the mountainous region of Gaucher area, Chamoli District, Uttarakhand by a team from Garhwal University and BARC scientists. Silt movement is being studied in Hoogly river and in other major ports using the isotope, 46Sc, by the DAE. BARC has installed a 500 keV Industrial Accelerator at Navi Mumbai and RRCAT has developed a 10 MV, 15 kW Industrial Electron Linac.

Accelerator produced high energy ions are used for materials analysis, depth profiling, determining elemental and isotopic composition of materials. This facility is available at most of the accelerator facilities in the country.

Radiation from space can upset the functioning of electronic chips used in satellites. ISRO requires radiation hardened electronics and spacecraft components. Simulation of radiation in space with the total amount of dose can be done using electrons and ions of the right energy from accelerators. ISRO has a programme of testing their electronic chips at a specially designed beamline at IUAC using different ion species and material damage studies for space components using proton beam at BARC-TIFR Pelletron.



BARC-TIFR Pelletron LINAC Facility at TIFR, Mumbai

Accelerator Mass Spectrometry (AMS) is a technique that finds use in a variety of areas. e.g., geosciences, oceanography, climate change, atmospheric sciences, biomedicine, and forensic science. A world class AMS system has been running and serving many users at IUAC. A recent example of such a study is the radiocarbon dating of charcoal samples from Rakhigarhi, Haryana which were found to belong to the Harappan period of civilization in India. In another study, Tsunami records of the last 8000 years in the Andaman Island, India from mega and large earthquakes were identified.

Nuclear energy, being one of the cleanest of all energy sources, is essential for mitigating effects of climate change while fulfilling our energy needs along with other renewable sources. At the same time it can provide for energy security of our nation.

About 8 GW of power is currently being generated using fission reactors, majority of them indigenously designed and manufactured in the country.

The full technology of reactors from design to manufacturing, operation and control has been mastered by the DAE with the Pressurised Heavy Water Reactor (PHWR) going to be the workhorse. A new design using natural U with additional safety features and the Advanced Heavy Water Reactor (AHWR) has also been designed and is being developed. Recently, the Prototype Fast Breeder Reactor (PFBR) has reached criticality, a major technologically challenging milestone ushering in the beginning of the second stage of reactor development as envisaged by Homi Bhabha. This is an extremely important step as it opens up the utilisation of Th for energy generation. India has the largest reserve of Th and hence we do not have to depend on imported Uranium in future and be self-sufficient for nuclear energy.

Nuclear Energy is being used for propulsion in space and also at sea. For space applications, the techniques used are, radioisotope heating units, thermoelectric generators and Nuclear Thermal Propulsion rockets.

ISRO has used two Radioisotope Heating Units (RHUs) in Chandrayaan-3 and is developing a 100-watt Radioisotope Thermoelectric Generator (RTG) for future missions and a Nuclear Thermal Propulsion rocket engine in collaboration with the Bhabha Atomic Research Center (BARC) using isotopes like strontium-90 and plutonium-238.

For applications at sea, small reactors are used. Indian Navy's submarine, Arihant (Sub Surface Ballistic Nuclear) has an 82.5 MWe PWR using 40% enriched uranium driving the submarine. The reactor went critical in August 2013. Arighat, a variant of Arihant, has also joined the fleet. The third nuclear powered submarine to join the Indian Navy is Ardhiman. Further vessels in the class are expected to have a 100 MWt PWR reactor.

Conclusion and Future Vision

Nuclear Science and Technology has deeply impacted many aspects of our life and has been serving the nation in ways more than one. Fundamental contributions to the knowledge about nuclei have been made by Indian researchers and many ingenious nuclear technologies have been implemented in India bringing in great economic benefits with relatively modest investments. The Mega Science Vision for Nuclear Physics and Accelerators (MSV-2035) lays out ambitious plans for the development of new facilities requiring modest increase in funding, which when implemented would give back to the nation invaluable assets and contribute in a wholesome way to the well being and prosperity of our nation.

Narora Atomic Power Plant, Uttar Pradesh

Accelerators Over the Years and Support to Cutting Edge Research

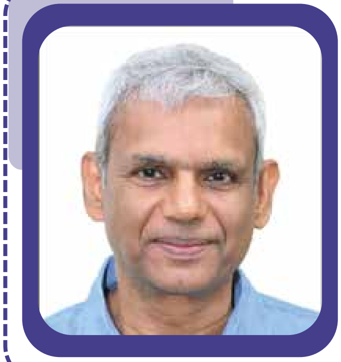
Shri Vivek Bhasin
Director,
Bhabha Atomic Research Centre (BARC)

Particle accelerators have been the backbone of nuclear science, driving both fundamental discoveries and technological advancement. BARC has a long-standing history of developing accelerator facilities that support cutting-edge research in various domains of basic sciences and applications.

In India, nuclear physics research took a significant leap in the sixties with the setting up of the 5.5 MV Van de Graaff accelerator at BARC. This facility enabled pursuit of research in several areas of nuclear physics of contemporary interest that were in the forefront during the 60's and 70's. In 90s, the Van de Graaff accelerator was replaced by the 6 MV Folded Tandem Ion Accelerator (FOTIA), to enable research across interdisciplinary fields. Over the years, it has produced very fruitful results, including past neutron induced R&D.

Accelerator-based R&D received a major boost with the commissioning of the 14 MV BARC-TIFR Pelletron in 1988, later augmented by an indigenously developed superconducting LINAC booster in 2007. Advanced experimental setups have led to pioneering research, including the identification of the origin of asymmetric fission in pre-actinide nuclei, highlighting the role of proton shell effects in low-energy fission. Application-driven R&D includes radio-pharmaceuticals, space component qualification, corrosion studies of reactor components, and induced mutation research in grains, demonstrating the versatility and scientific impact of the facility.

Looking ahead, an accelerator complex has been proposed at BARC-Vizag, comprising proton, electron, and heavy-ion accelerators. Major milestones are being achieved through commissioning of 20 MeV proton accelerator, LEHIPA, at BARC. The next milestone is the establishment of a 40 MeV proton accelerator, MEHIPA, at Vizag. Additionally, a versatile heavy-ion accelerator to deliver both stable and unstable isotopic beams (SUBHIR) are some future milestones. Together, these initiatives position India at the forefront of nuclear science, driving ground breaking research and innovation for the future.



The Mega Science Vision and Its Role in the Nuclear Physics Community

Prof. Jayaram N. Chengalur,
Director,
Tata Institute of Fundamental Research

The process of creation of the Mega Science Vision – 2035 (Nuclear Physics) document has been collaborative and inclusive. Inputs from the wider nuclear physics community have been taken and incorporated, while many national and international experts have provided important suggestions based on a critical reading of a draft version of the document.

The document details the plans of the Indian nuclear physics community for the next decade, in the areas of quantum chromodynamics, nuclear structure and dynamics, and plasma physics. It presents scientific questions that are important, urgent, and possible to address collectively given the experience, expertise, and resources available. It also discusses what needs to be done to build up the necessary infrastructure and ecosystem, and suggests ways to facilitate the inception and smooth functioning of future mega science projects.

In addition, this document also acts as a repository of information about the current mega-science projects that Indian nuclear physicists are involved in. The expertise gained by the community in implementing these projects provides a firm base on which the ambitious plans listed in this document were built. Informed by this experience, the mega-science vision 2035 also highlights the need for creating a national detector development and training centre. This would be an important initiative that would have a significant positive impact on all the proposed R&D programs. The programs identified here will place the country at the cutting edge of research in this field and I look forward to the community moving towards their implementation.

India’s has Progressed Significantly in the Field of Accelerators

Dr Viraj P. Bhanage
Director,
Raja Ramanna Centre for Advanced Technology

Raja Ramanna Centre for Advanced Technology (RRCAT), Indore had the privilege of serving as the nodal institution for the MSV-2035 Exercise in the area of Accelerator Science & Technology and Applications (ASTA), the first such comprehensive national exercise undertaken in this field. The MSV-2035-ASTA document reflects the collective aspiration of the scientific community to position India among the global leaders in accelerator science while addressing the country’s long-term scientific, technological, and societal needs.

Over the past three decades, India has made significant progress in development and utilization of various types of accelerators. At RRCAT, this includes the development and operation of synchrotron radiation sources Indus-1 and Indus-2, infra-red free-electron laser, industrial electron linacs and laser-plasma accelerators. RRCAT has established extensive infrastructure and gained significant expertise in various domains of accelerator technologies, including magnets, ultra-high vacuum, superconducting RF technologies, superconducting components, precision manufacturing, control and power electronics, etc.

RRCAT is now preparing to establish a 4th generation High Brilliance Synchrotron Radiation Source, to enhance capability of performing the synchrotron-based fundamental and applied research in India. Other institutes in the country are also gearing up to develop other types of accelerator-based facilities that will address emerging scientific and technological challenges as well as societal needs.

As the field of ASTA has gained considerable momentum, the MSV-2035-ASTA document suggests a well-prioritized national roadmap, funding modality and approval & monitoring framework. It also highlights the importance of development of the ecosystem by industry participation. I am confident that the document will serve as an important guiding framework for India’s future endeavours in accelerator science and technology.

Low Energy Nuclear Physics Research at IUAC

Prof. Avinash C Pandey
Director,
Inter University Accelerator Centre

IUAC has state of the art nuclear physics facilities which has been involved in the research of nuclear structure and reaction dynamics for three decades. These include facilities of electromagnetic recoil mass spectrometers, namely the Heavy Ion Recoil Analyzer (HIRA) and HYbrid Recoil Analyzer (HYRA), Indian National Gamma Array (INGA), National Array of Neutron Detectors (NAND), and the General Purpose Scattering Chamber (GPSC). The Nuclear Physics program covers almost all the current thrust areas (for instance, study of stable and unstable nuclei at extreme conditions of excitation energy (temperature), target deformation effects, role of transfer channels in enhancing sub-barrier fusion cross sections, nuclear spectroscopy, chirality, etc.) through studies of nuclear dynamics and nuclear structure at energies from well below to well above the Coulomb barrier of the various projectile-target systems. IUAC also has a detector development program for preparing detector systems based on proportional counters, ionization chambers, silicon and scintillator detectors.

This is further exalted by a strong front-end analog and digital electronics development program for detector signal processing. This has resulted in more than 400 research articles in prestigious international peer reviewed journals along with close to 100 PhDs across several universities from all over India. IUAC has provided detectors and allied instrumentation to other labs in the country, and is also involved in international collaborations of detector development programs such as NUSTAR-FAIR, Germany (NUclear STructure, Astrophysics and Reactions- Facility for Antiproton and Ion Research) and GANIL, France (Grand Accélérateur National d'Ions Lourds- French for "National Large Heavy Ion Accelerator"). Along with IUAC, other institutes involved in similar nuclear physics research activities are Tata Institute of Fundamental Research, Bhaba Atomic Research Centre, Saha Institute of Nuclear Physics, and Variable Energy Cyclotron Centre.

Low-energy nuclear physics research is the base of understanding fundamental interactions leading to the creation of the Universe by addressing synthesis of nuclei in stars, supernova explosions, and formation of heavy/super-heavy nuclei. It connects particle physics and astrophysics. With the availability of high intensity projectile species in the future, as part of mega science projects,

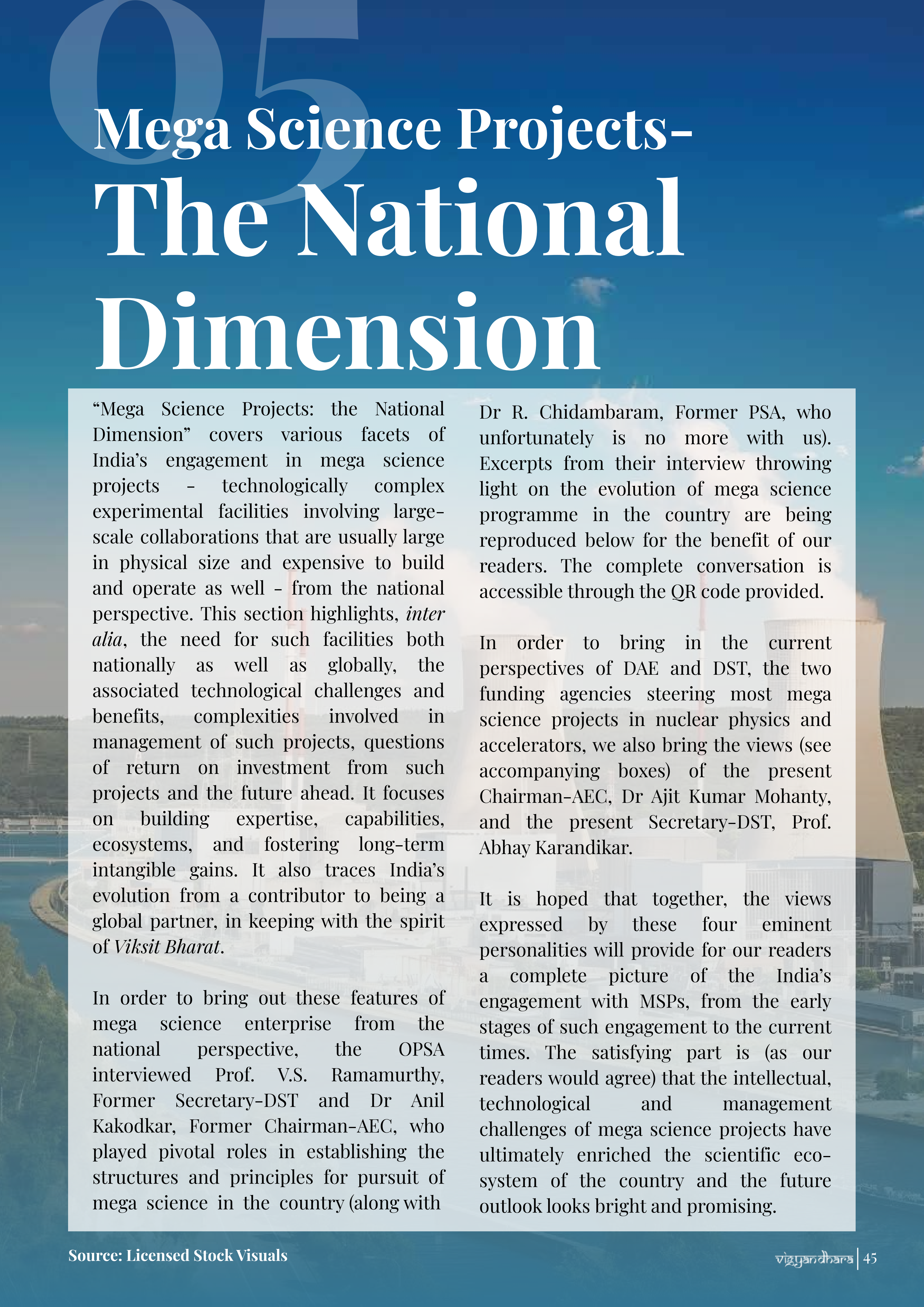
it is planned to study problems related to nuclear astrophysics (with stable as well as radioactive ion beams), reaction dynamics and structure studies of heavy nuclei with the facilities at IUAC. These are technological challenges in terms of nuclear instrumentation. Development in this area finds application in industries such as medical, homeland security, etc. Skilled manpower can be generated and participation from the industry along with extra funding needs to be encouraged.

Particle accelerator science drives discovery, innovation, and societal progress

Dr Smt. Vaishali Naik,
Director,
Variable Energy Cyclotron Centre

The fundamental quest of nuclear physics is to investigate the structure of nuclear matter at the extremes of isospin/angular momentum, and to understand the various reaction mechanisms for the production of exotic nuclei, such as super-heavy elements. Another key focus is the production, research, and development of medical isotopes, as well as the study of advanced structural materials for nuclear reactors. India's particle accelerator ecosystem, built through national laboratories and academic institutions over the past decades, along with the development of state-of-the-art detector facilities provides a strong foundation for this goal.

Our future vision includes rare isotope beam facilities and GeV-scale particle accelerators. The VECC, led by the Department of Atomic Energy (DAE), is geared towards fulfilling the Atmanirbhar Bharat goals put forward by the Honorable Prime Minister through basic science and particle accelerator programmes. These efforts are aligned with the roadmap outlined in the Mega Science Vision (MSV-2035) document, prepared under the leadership of the Principal Scientific Advisor (PSA) to the Government of India. This reflects India's aspiration to enable frontier research in nuclear science and interdisciplinary applications.



05

Mega Science Projects- The National Dimension

"Mega Science Projects: the National Dimension" covers various facets of India's engagement in mega science projects – technologically complex experimental facilities involving large-scale collaborations that are usually large in physical size and expensive to build and operate as well – from the national perspective. This section highlights, *inter alia*, the need for such facilities both nationally as well as globally, the associated technological challenges and benefits, complexities involved in management of such projects, questions of return on investment from such projects and the future ahead. It focuses on building expertise, capabilities, ecosystems, and fostering long-term intangible gains. It also traces India's evolution from a contributor to being a global partner, in keeping with the spirit of *Viksit Bharat*.

In order to bring out these features of mega science enterprise from the national perspective, the OPSA interviewed Prof. V.S. Ramamurthy, Former Secretary-DST and Dr Anil Kakodkar, Former Chairman-AEC, who played pivotal roles in establishing the structures and principles for pursuit of mega science in the country (along with Dr R. Chidambaram, Former PSA, who unfortunately is no more with us). Excerpts from their interview throwing light on the evolution of mega science programme in the country are being reproduced below for the benefit of our readers. The complete conversation is accessible through the QR code provided.

In order to bring in the current perspectives of DAE and DST, the two funding agencies steering most mega science projects in nuclear physics and accelerators, we also bring the views (see accompanying boxes) of the present Chairman-AEC, Dr Ajit Kumar Mohanty, and the present Secretary-DST, Prof. Abhay Karandikar.

It is hoped that together, the views expressed by these four eminent personalities will provide for our readers a complete picture of the India's engagement with MSPs, from the early stages of such engagement to the current times. The satisfying part is (as our readers would agree) that the intellectual, technological and management challenges of mega science projects have ultimately enriched the scientific eco-system of the country and the future outlook looks bright and promising.

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Conversation with
Prof. V. S. Ramamurthy

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Q: With regard to mega science, whether as a project, an initiative, or a broader concept, how would you explain it to someone who is unfamiliar with the term?

Prof. Ramamurthy: We are not talking about "mega projects" in a generic sense; we are talking specifically about mega science projects. Today, we often see large infrastructure projects or other large-scale initiatives being called "mega projects," but my focus is only on mega science projects. In a mega science project, science comes first and "mega" comes second. That is what I want to emphasise.

The real questions are: What is the scientific problem being addressed? How many resources are required, including human resources? Are there people who understand the problem and are willing to contribute? And finally, is it something the country can afford to undertake?

Today, if you insist on doing everything entirely on your own, many scientific areas simply become unaffordable. However, if a project is sufficiently challenging, more people are willing to join and contribute. The important question is not whether you identify those hundred people at the outset. If the challenge is compelling enough, people come together naturally. That is how a mega project takes shape. It involves major investments; it is always a collective activity. The group may consist of 10, 100, or even 1,000 people, cutting across national borders and disciplinary boundaries.

What we have learned is that collaboration need not be confined within national borders. "Mega" does not necessarily mean multiple nations, but it also does not mean only Indians. Participation depends on expertise, willingness to take risks, and readiness to engage in challenging research. All research, by definition, is risky. If you already know the result, you do not need research. So, the question is: who is willing to take that risk, and why? These are the considerations that shape a mega science project.

Q: Could you give some simple examples of mega science projects for someone who may be unfamiliar with them?

Prof. Ramamurthy: There are certain research problems where you need a very large number of observers. Let me give one example. People talk about extraterrestrial intelligence. To explore this, people listen to signals and noise coming from space. Can one individual do this alone? No, it is not possible. There are individuals who keep a computer running in their homes continuously. When the computer is not in active use, they allow it to listen for extraterrestrial intelligence. To explore this, people listen to signals and noise coming from space. Can one individual do this alone? No, it is not possible. There are individuals who keep a computer running in their homes continuously. When the computer is not in active use, they allow it to listen for extraterrestrial signals. These efforts are not even organised research programmes; they are driven by individual curiosity. Yet, they constitute a mega science effort because no single person can solve the problem alone.

Another example is what is popularly referred to as the "God particle." I prefer to call it the Higgs boson, because there is a "Bose" in it, reflecting an Indian contribution. Such discoveries are not foreseeable in advance. What you see instead is enthusiasm and a deep desire to contribute. These are precisely the characteristics of mega science projects.

We understand very little about the universe. Some speculate about the existence of multiple universes or parallel universes, the multiverse. These are questions for which we currently have no answers. But that is precisely the spirit of science: what we do not understand far exceeds what we do.

Q: In the spirit of science, we understand the significance of advancing scientific frontiers. Could you elaborate on the importance of mega science for the scientific enterprise itself? Specifically, how do large-scale scientific infrastructure and accelerator-based experiments contribute to the overall progress of science?

Prof. Ramamurthy: If you want to observe anything, interfere with a system, or understand it deeply, you need investments. In that sense, mega science becomes an integral part of the scientific enterprise itself. Some may say that science is about sitting and thinking. There is a limit to how far that can take you. Even when you sit and think, you need inputs- observations, data, and evidence.

How are these observations made? Through telescopes, detectors, and various scientific instruments. All of these require investment. For the physical sciences in particular, it is difficult to progress without experimental tools and infrastructure. Perhaps in certain areas of knowledge, you can advance largely through theoretical thinking. But when it comes to understanding the physical universe around us, you need equipment, measurements, and observations. Mega science projects fall squarely into this category.

Q: India's participation in CERN experiments is often seen as a major milestone in collaboration. How do you view CERN and related experiments as a landmark in scientific progress?

Prof. Ramamurthy: Let us look at the 20th century. What was its defining scientific achievement? It was the understanding of the fundamental building blocks of the material universe. At one point, we believed that matter was composed of around 92 elements. Later, we learned that these elements themselves are made of nucleons, and nucleons are made of quarks. This understanding has emerged largely over the last 100 years. One of the major contributors to this progress was the development of particle accelerators. To probe deeply into nucleons and sub-nucleon structures, high-energy accelerators are essential. Accelerator technology played a crucial role in our understanding of the sub-nuclear world.

Over the course of a century, we learned a great deal. However, a key question remained: how many fundamental building blocks are there? Theoretical physicists proposed a model involving twelve basic building blocks- quarks, such as up, down, top, and others. This theoretical framework also required the existence of an additional particle: a boson. Scientists searched for this particle for decades, building increasingly powerful accelerators in the process. It took nearly 50 to 60 years. Along the way, The Large Hadron Collider (LHC) was developed with a very specific objective to address these fundamental questions. And it was the LHC that ultimately discovered the Higgs boson, around 2010–2012, after nearly six decades of global effort. Interestingly, shortly after this discovery was announced, laboratories in the United States reported that they had also observed similar signals. But in science, there is only a first there is no second. Decisions taken too early can fail. Decisions taken too late can also fail. In this case, the right decision was taken at the right time by CERN.

From India's perspective, our participation in CERN was crucial. We were collaborators and contributors. The credit for this decision belongs to the scientific leadership in our country, which recognised the opportunity and chose to engage. This decision was taken 20 to 30 years before the actual discovery. In science, such foresight makes a significant difference. Timing matters enormously.

Q: Within the broader accelerator and experimental ecosystem at CERN, could you elaborate on the expertise that India contributed and the expertise India gained in return?

Prof. Ramamurthy: At its core, an accelerator is conceptually simple- two electrodes, one at a lower potential and one at a higher potential. A charged particle accelerates between them. From a physics standpoint, there is nothing fundamentally new about that.

The science lies in what you do with the accelerated particles. The challenge is technological: how large a voltage difference you can create, how many accelerating stages you can couple together, and how reliably you can operate the system. Accelerator technology is therefore a technological challenge rather than a physics challenge. This is where CERN became a global benchmark. India was interested in accelerator technology, but the key question was: do we have the competence to contribute? The question was also about self-confidence. Could we assess our own capabilities honestly? Could we assert that we were competent to contribute? This is where scientific leadership matters.

Within the first decade of CERN's existence, Indian scientists approached the organisation seeking collaboration. CERN's response was direct: you are not a European country, what expertise do you bring? This is where the experience of Indian institutions, particularly TIFR, proved critical. . Indian scientists had deep expertise in cosmic ray studies using emulsion plates. While cosmic rays cannot be calibrated precisely, accelerators can. Indian scientists proposed using CERN's accelerators to calibrate their emulsion plates, which they would then use in their own experiments. This was a logical and scientifically sound proposal, and CERN agreed. Eventually, nearly 30 years later, an Indian scientist became the spokesperson for a CERN experiment. This progression from access to leadership was achieved purely on the basis of competence, not money or political influence. It stands as strong evidence that Indian scientists are fully competitive on the global stage.

Building on that experience, in the 1990s CERN upgraded its accelerators. By that time, India had already been participating in several experiments. We then asked whether it was possible to raise the level of our participation. CERN agreed that we could attempt this. As a result, Indian scientists proposed the development of a Photon Multiplicity Detector (PMD)- a modular detector consisting of several thousand individual detector elements. It is a large and complex system. The PMD was used extensively in early CERN experiments. Its performance was so impressive that laboratories in the United States requested it for use in their own accelerator experiments. The detector was sent to the US, used there, and later returned to CERN when the LHC became operational. The PMD has remained in continuous use and has always been in high demand. This demonstrates that quality is not determined by salary levels or national budgets, but by commitment, discipline, and attention to detail.

These experiences gave us confidence. When people ask whether we can do such things, we can now say, without hesitation, that yes, we can. The PMD experience reinforced that confidence.

Q: Moving to the administrative and management aspects of mega science, one model that is often cited is multi-agency funding. For example, the DST–DAE partnership during your tenure and during Dr Anil Kakodkar's and Dr R. Chidambaram's time enabled participation in several national and international programmes. Could you explain how this model evolved and why it was effective?

Prof. Ramamurthy: Multi-agency funding did not arise because a project demanded it. It arose because of the nature of participation. Many scientists working on these projects were from DAE institutions such as BARC, while others were from universities outside the DAE system. For instance, scientists from Delhi University were contributing alongside DAE scientists.

The question then arose: how do we fund such a collaborative effort? DAE's mandate does not include extramural funding in the same way that DST's does. DST, on the other hand, exists precisely to fund researchers in universities and non-DAE institutions. So the solution we arrived at was simple and practical: DAE would fund the DAE component of the work—equipment, manpower, travel, and other expenses—while DST would fund the university-based participants.

This arrangement required trust and professional respect: decisions taken by one department would not be questioned by the other. This collaborative model proved effective and created a framework that could, in principle, be replicated in other inter-departmental initiatives.

Q: From an administrative standpoint, one question that is often raised is the return on investment. As a scientist, you know that returns are not always immediate or tangible. How would you explain the value of investing in large-scale mega science initiatives, whether within India or internationally?

Prof. Ramamurthy: Return on investment in science should not be measured in terms of individual products. It should be measured in terms of expertise and capability. Take the World Wide Web as an example. Where did it originate? At CERN. Why did it emerge there? Because thousands of scientists were working across different countries and laboratories, generating enormous volumes of data that needed to be shared efficiently and reliably. That challenge led to the creation of the World Wide Web. Today, it is indispensable across every domain. Indian scientists had access to the Web long before much of the world understood its significance.

The true value lies not in the cost of discovering something like the Higgs boson, but in the broader knowledge ecosystem you become part of; what you learn by being at the table, by interacting informally, and by contributing continuously. These intangible benefits are substantial and long-lasting.

Q: There is an ongoing exercise titled Mega Science Vision-2035, in which you have also been involved as an advisor. How do you view this exercise as a roadmap for the country's mega science ambitions?

Prof. Ramamurthy: Such exercises are valuable. They signal that we are not satisfied with business as usual. However, identifying scientific priorities is only the first step.

What is currently missing is a broader debate. Mega science requires political understanding and support. Without that, initiatives risk facing the same fate as projects like the India Neutrino Observatory. We need to bring decision-makers, particularly political leaders, into the conversation early. Scientific deliberations must be linked to policy-level discussions. This is something we have not yet learned to do effectively. But if we want mega science projects to succeed, this linkage is essential.

Conversation with
Dr Anil Kakodkar

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Q: How would you describe what mega science is from your own perspective and how do you think mega science is important for the entire scientific enterprise in general?

Dr Kakodkar: Well, principally there is nothing like mega science and tabletop science. You can get earth-shaking discoveries from either side. Mega science usually involves very large outlays, and so some of them have become so big that it is beyond the budget of a single country. Of course, there are national mega science programs, but many of them tend to become international, essentially to elicit participation from multiple countries, both in terms of scientific contribution and financial contribution.

Some of the very key questions that are there before humanity—for example, where we came from, what are the origins of the universe—do require very large investments going into several billions of dollars. And they have contributed very significantly to our knowledge and understanding. For example, the Large Hadron Collider was built and it discovered the Higgs boson.

Q: Taking cue from what you just said in terms of the balance between a national project versus an international project; one recurring thought that the community sees is: should a country be doing both, or should a country focus on nationally sovereign mega science projects? How would you judge or comment on such a conversation? Should it be a mix of both?

Dr Kakodkar: Firstly, we should really create opportunities for people to get into science. Now, people certainly will pursue their own interest in science, and that should be allowed. But there is a lot of merit to group working.

Most of these mega science activities where you are building large experimental facilities- they involve technology of tomorrow or, for that matter, sometimes day after. You want to get into these technologies for other purposes or for the benefit of the needs of people.

For a large country like India, pursuit of science in itself is a requirement according to me. But even if you go purely from the kind of developmental perspective or application perspective, there is a lot of argument that a country like India should get into this. I will give you an example.

When India participated in LHC, we agreed to make in-kind contributions. Detectors were made and a lot of computing efforts were being done. So, in atomic energy we were working on grid computing because we contributed some bit to that technology, and in the process we benefited. These are all evolutions. If we do such things, you develop the technology and also bring in the application and commercial part of it. I think the country will advance at least by a couple of decades due to this. So it is very important that we participate in mega science projects.

Q: When it comes to India's participation in multiple mega science initiatives in the country as well as outside, predominantly outside with international partners, CERN partnership has always been a turning point. And you really played a major role where India became a formal participating member in many experiments as a chairman of Atomic Energy Commission at that point in time. How would you describe that moment as a turning point for India mega sciences and international partnership?

Dr Kakodkar: We had a long relationship with CERN. But it was only on the basis of individuals going there, carrying out the research and coming back. It was not a group activity of significant size. And there was not too much institutional partnerships. This was, I think, a major impetus to that mode of working. A lot of work for LHC was done in atomic energy, BARC, TIFR, VECC, but it was also done in a number of universities. So that is the major purpose- for Indian scientists to benefit from this new facility. Now, you must have a method of supporting Indian scientists visiting CERN. So what was worked out was collaboration between the DAE and DST. So the principle was that the university segment would be supported by DST, and the technology segment would be supported by DAE, as far as scientists participating in CERN is concerned.

We must look at this as a composite participation. This was the first time ever that we signed an MOU between two government departments- the DST-DAE MOU with Dr. V.S. Ramamurthy, who happened to be my batchmate. So all decisions which were to be taken at departmental level were being taken in a joint platform, common committee, where both of us used to sit. And then the further processing in which whatever was to be done in DAE, the Department of Atomic Energy would do; whatever was to be done in DST, the Department of Science and Technology will do. It was a new mode of functioning and it stood us in good stead.

Q: People usually ask questions in general on the amount of financial contribution or the in-kind efforts and contribution that we make as a country vis-à-vis what we get in return. I think some of the examples that you spoke about; it is also a technological return. How we encash it on our developmental journey is also something that we want to take out as an insight. Could you talk about the return on investment?

Dr Kakodkar: Return on investment is an important concept. But it is very restrictive when we tend to calculate that in financial terms alone. For example, one of the statements with respect to mega science projects is, "No, these are all very big projects, we cannot afford." Look at it the other way. We have a fairly large population, so we must have a scientific community in proportion to our population. If you want to engage in a mega science project, you have tremendous ability to support it without enhancing expenditure per scientist. If you do that, then you have several benefits. You could have spent a lot of money on our scientists going to such facilities abroad, and you would have supported them with fellowships. We should still continue to do that. But a good part of that can happen at home. So I think all these have to be considered as returns.

Even simple things like jacks that support the accelerator, superconducting magnets of different types, were made in Indian industry at their cost. But while India made a contribution, Indian industryv went to a different level. When the LHC project was being implemented, they certainly wanted India's participation. It was more by way of the capability of Indian scientists and technologists rather than monetary contribution.

For the financial aspect, a very creative formula was worked out. And that formula was that whatever we supply to CERN, regardless of how much it costs us to make, it will be valued at European cost. If you supply some equipment, its cost will be worked out on the basis of European cost. Eventually, there was zero investment. Now you calculate how much the return on investment is: it will almost come to infinity.

Q: From a management point of view, would you be able to share some lessons that one should consider when such large-scale, multi-agency partnership is taken up?

Dr Kakodkar: If you are talking about a project which has an outlay of 1000 crores, then if the project gets delayed by two years and if it is made available to users two years behind time, that means you have suffered a penalty of two years' interest of that value. So even if you take a nominal 10% interest, and if you talk about simple interest, that means there is a penalty of 200 crores. There is a lot of merit in terms of doing projects in time.

The LHC project did not get delayed nor did it get into cost overrun. And as an example of good project management, the LHC project in itself is a great example.

I have not seen equivalent projects even in non-scientific areas doing so well. And this project involved close to 1,000 people from many countries. So there is a lot of learning there.

Q: Is there any one, let us say, human resource management lesson or insight that you would like to convey from that experience?

Dr Kakodkar: In large projects, there are two types of human resources. Firstly, the users and researchers for whom this is meant. Being a part of a large research project is an important thing. You will have several papers; there are hundred authors, and your name is there. But within that, there is a lot of discussion that goes on. So how Indian scientists provide leadership to this whole movement is important. That is as far as the research management part is concerned.

On the technology side, you want to internalize all those technologies which have been built in contribution. There must be an equivalent domestic program at home so that you are building some, to absorb the capacity, otherwise people will move and after that everything will vanish. So there is importance to continuity of work, because without continuity of work, you cannot have continuity of knowledge or technology.

There must be parallel programs back home which help to internalize all that learning. And I think we suffered on that count; we have not done well in that part. India imports roughly 40 to 50 thousand crores worth of medical equipment, and of course they are of all kinds. But the real cost is in this high-end imaging equipment which has nuclear technology. We do not really make any Indian equivalent of those imaging equipment at that level.

Q: My last question is on the Mega Science Vision exercises that the country has been undertaking in repeated cycles. The current cycle, conducted by the Office of the Principal Scientific Adviser (PSA), focuses on the Mega Science Vision 2035, covering six areas. In this cycle, the focus is on nuclear physics and accelerator applications. What are your thoughts or suggestions on such exercises for a country like India?

Dr Kakodkar: There are two parts to this. We have already discussed the impact such initiatives can have on the larger scientific community by involving a greater number of people, providing access to cutting-edge technologies, and expanding overall participation. However, I would personally look forward to the day when a mega science project proposed by India attracts significant global traction. That would be the day I would say that India has truly arrived.

For this to happen, we must be able to identify a challenge that is both important and intellectually compelling, and then create a clear pathway showing how it can be addressed. If we can instill confidence that this is the challenge, this is the approach, and India will deliver, then others will join. That, to me, is one important measure of success.

The second important aspect relates to accelerator programmes, which are also a component of mega science initiatives. Consider India's nuclear programme, particularly the well-known three-stage nuclear power programme- comprising thermal reactors, fast reactors, and thorium reactors. At present, we are in the second stage with fast reactors. An alternative—or rather, a complementary—approach involves accelerators. If we develop high-current, gigavolt (GeV)-scale accelerators, they can produce large numbers of neutrons through spallation. These fast neutrons can be used for nuclear waste transmutation, which is an important challenge, and also for converting thorium into uranium-233. In this way, accelerator-driven systems can help breed fissile material required for the expansion of third-stage reactors. This approach is complementary to fast reactors, not a replacement. Therefore, in my view, accelerator-technology-based mega science is extremely well aligned—not only with scientific and research objectives, but also with India's long-term energy programme.

Q: I think that is a very important point for our concluding note as well. I have noted four or five key messages emerging from this discussion- building internal capacity, institutionalising partnerships, and the translational impact not only of the core scientific problem, but also of the ancillary technologies that emerge alongside it. Is there one concluding message you would like to leave us with, so that we may end this conversation on that note?

Dr Kakodkar : Often, when we talk about mega science projects, the focus tends to be on the financial aspect, and to some extent on the technological complexity as well. At times, these projects appear too distant or too difficult. As a result, we develop a tendency to do what others have already done, we become followers. This follower mindset is something we must consciously move away from. Novelty and disruptive thinking have to emerge from within. We need to graduate from imitation to imagination and bold decision-making, because by definition, a follower can never become a leader.

Even if the path appears difficult, such efforts invariably prove valuable in the long run. Mega science projects repeatedly confront us with these challenges, and that is precisely why they serve as an excellent learning ground for the country.

Dr Ajit Kumar Mohanty

Secretary,
Department of Atomic Energy

Q. DAE has led the way in building critical components for international projects like LHC, ITER, PIP-II (Fermilab), etc. How do you think the know-how gained from these international projects has benefited various national nuclear and accelerator projects?

Dr Mohanty: India's participation in global mega science projects such as CERN (LHC), FAIR, ITER, LIGO, and SKA has significantly strengthened its domestic capabilities in nuclear science, accelerator technology, and advanced engineering.

Through contributions to CERN's LHC, Indian institutions and industries have developed high-precision technologies such as superconducting magnets, RF systems, quench protection systems, and advanced detectors. These technologies have directly fed into indigenous accelerator programmes at BARC and RRCAT, enabling the development of proton accelerators and associated subsystems.

Similarly, India's involvement in FAIR has enhanced capabilities in ultra-high vacuum systems, superconducting magnet design, power converters, and particle detector technologies like GEM-based systems. These competencies are directly relevant to national accelerator facilities and nuclear instrumentation.

Participation in ITER has enabled India to master large-scale cryogenic systems, high heat flux components, precision fabrication, and fusion-relevant materials, areas critical for future nuclear energy systems.

Beyond hardware, these collaborations have strengthened:

- Systems engineering capabilities
- Advanced manufacturing ecosystem
- High-performance computing and GRID technologies
- Human resource development through global exposure

Overall, international collaborations have acted as technology accelerators, enabling India to leapfrog in strategic sectors and build strong foundations for self-reliant national programmes.

Q. While accelerators are often associated with basic research, they find applications in a large number of areas, from materials engineering, food preservation, healthcare to nuclear energy. How do you think the roadmap outlined in the MSV-2035 Accelerator S&T and Applications Report will help in systematically increasing the use of accelerators for useful applications in the country?

Dr Mohanty: The MSV-2035 roadmap provides a structured vision to transition accelerators from predominantly research tools to multi-sectoral national assets. Accelerators already have wide applications in:

- Healthcare (radiotherapy, isotope production)
- Food preservation and irradiation
- Materials research and semiconductor processing
- Environmental applications

The roadmap is expected to drive:

- Decentralised deployment of accelerator facilities across regions
- Standardisation and indigenisation of accelerator components
- Stronger industry participation and technology transfer
- Integration with national missions such as healthcare access, food security, and clean energy

Importantly, the experience gained from projects like CERN and FAIR—where Indian industries manufactured high-end components—will enable scaling up of domestic production ecosystems.

Thus, MSV-2035 will act as a bridge between high science and societal applications, ensuring that accelerator technologies contribute directly to national development priorities.

Q. India has consistently followed the model of making in-kind contributions to various international projects instead of just cash. As the head of the Atomic Energy Commission, how do you view this model's role in advancing our technological and strategic interests while remaining a core partner in global scientific pursuits and breakthroughs?

Dr Mohanty: India's approach of making in-kind contributions rather than purely financial commitments has proven to be a highly effective strategic model. This model ensures:

- Deep technological participation, not just financial involvement
- Development of indigenous manufacturing capabilities
- Integration of Indian industry into global supply chains
- Creation of long-term intellectual and technological assets.

For example:

- At CERN, India supplied critical components such as superconducting magnets, electronics, and detector systems
- At FAIR, Indian industries are delivering power converters, vacuum chambers, and magnet systems
- At ITER, India is responsible for major systems including the cryostat, cooling systems, and RF heating systems

This approach aligns strongly with **Atmanirbhar Bharat**, as it:

- Builds domestic expertise

- Enhances export potential of high-technology products
- Positions India as a reliable global technology partner

In-kind contributions thus ensure that India remains a co-creator of global science, not merely a participant.

Q. Mega Science Projects push the boundaries of what is possible, which often brings risks in terms of time and cost. What are the most important "Project Management" lessons the DAE has learned from such ventures that are found useful for planning future involvement in such projects, nationally as well as internationally?

Dr Mohanty: Participation in complex mega science projects has provided DAE with valuable project management insights:

a) Systems Engineering & Integration: Large projects like ITER and LHC require seamless integration of thousands of components across countries. This has strengthened India's expertise in systems-level thinking.

b) Precision Planning and Risk Management: Mega projects involve long timelines and high uncertainties. Experience has led to improved:

- Risk mitigation strategies
- Cost and schedule control mechanisms

c) Industry Collaboration Models: Engagement with Indian industries in CERN, FAIR, and ITER has demonstrated the importance of:

- Early industry involvement
- Quality assurance frameworks
- Technology absorption pathways

d) International Coordination: Working across multiple countries has enhanced India's ability to:

- Operate in complex governance structures
- Manage multi-institutional collaborations

e) Capacity Building

Continuous involvement has built a strong pool of skilled scientists, engineers, and project managers.

These lessons are now being applied in national projects, improving efficiency, reliability, and scalability.

Q. From a mere user of large accelerator facilities, India today is either a partner in global accelerator projects or has built a few large facilities on its soil. Do you think that India's increasing involvement with Mega Science Projects is in keeping with its long tradition of scientific research as well as its growing scientific, technological, and financial prowess in the world?

Dr Mohanty: India's increasing participation in mega science projects is a natural extension of its long-standing scientific tradition and its expanding technological and economic capabilities. Historically, India has been a strong contributor to fundamental science. Today, this legacy is complemented by:

- Advanced engineering capabilities
- A growing industrial base
- Increased financial commitment to large-scale science

India is now:

- A key partner in CERN experiments (ALICE, CMS)
- The third-largest contributor to FAIR
- A major contributor to ITER
- An active participant in LIGO and SKA

These engagements reflect a transition of India's position:

- From user of global facilities
- To builder and partner in global scientific infrastructure

Moreover, these projects generate:

- Scientific discoveries (e.g., Higgs boson at CERN)
- Technology spin-offs
- Industrial growth
- Skilled human capital

Thus, India's role in mega science is fully aligned with its vision of Viksit Bharat, positioning the country as a global leader in science, technology, and innovation.

Prof. Abhay Karandikar
Secretary,
Department of Science and Technology

Q: The partnership between DST and DAE is often cited as an early, and still shining, example of multi-agency cooperation in India. How has this joint approach specifically helped India manage the complexities of Mega Science projects more effectively than a single-department approach?

Prof. Karandikar: The Department of Science and Technology (DST) and the Department of Atomic Energy (DAE) jointly drive India's participation in major international Mega Science projects such as the Square Kilometre Array (SKA), Facility for Antiproton and Ion Research (FAIR). This partnership represents a unique and effective model of multi-agency collaboration, combining complementary strengths to manage the complexities of large-scale scientific initiatives.

DST primarily focuses on national science policy, science diplomacy, and strengthening the innovation and R&D ecosystem, with academic institutions and universities as key stakeholders. In contrast, DAE brings deep technical expertise through its network of large-scale facilities and premier institutions such as Bhabha Atomic Research Centre (BARC) and Tata Institute of Fundamental Research (TIFR), along with its experience in operating complex scientific infrastructure.

This collaboration enables a strategic blending of policy direction, international engagement, and technological capability, positioning India strongly in the global "Big Science" landscape. This has led to the creation of a distributed national talent pool with global-standard expertise.

Q: How has DST's participation helped in enlarging the human resource base involved in such projects by bringing in groups from higher educational institutions in the country at large? Do you think this has helped create a "talent pipeline" of young scientists who would be builders and/or users of future facilities?

Prof. Karandikar: As mentioned, the DAE primarily focuses on specialized institutions such as BARC, TIFR, and VECC.

In this context, the DST has played a pivotal role in enlarging the human resource base for India's Mega Science Programme through capacity-building efforts.

DST actively engages colleges, universities, and higher educational institutions across the country through its long-standing collaborative framework, which effectively democratizes access to global science. This has not only expanded the scale of researcher participation but has also ensured inclusiveness by enabling wider exposure to frontier areas of science and technology.

DST also supports the programme through training and workshops that bring together students and faculty from diverse disciplines such as physics, chemistry, biology, computing, and materials science. These initiatives not only generate awareness but also provide hands-on experience with advanced technologies, thereby strengthening the national talent pool.

The Mega Science Programme provides a platform for young doctoral and postdoctoral researchers to be trained in high-performance computing, advanced instrumentation, and large-scale data handling skills that are aligned with global standards. Most importantly, these researchers are directly involved in design, simulation, experimentation, and data analysis within major projects. This comprehensive exposure has helped in creating a strong and sustainable talent pipeline.

Q: Experiments at the LHC have considerably enhanced the horizons of fundamental knowledge in nuclear and particle physics and have already led to landmark discoveries. Do you think that DST's involvement in the LHC-CMS and ALICE experiments helped our academic community to be a part of these momentous discoveries? The FAIR Project, funded again by DST and DAE and led by DST, promises something similar in future in nuclear and particle physics.

Prof. Karandikar: Participation of Indian researchers in the CMS Experiment and ALICE Experiment at CERN has played a crucial role in enabling them to contribute to landmark discoveries such as the Higgs boson. This involvement has not only enhanced India's visibility on the global scientific stage but has also ensured that the contributions of Indian researchers are well recognized and documented in leading international journals.

During these experiments, Indian researchers are actively engaged in detector design, data analysis, and high-performance computing thereby contributing across the full scientific and technological spectrum. As mentioned earlier, DST as per its mandate, provides the opportunity to the young researchers from universities and higher educational institutes like IITs/IISERs in the specified activities which make them efficient enough to train the next generation in India.

Much like the Large Hadron Collider has provided opportunities for the particle physics researchers, it is expected thatFAIR may open a new arena for the Indian researchers in nuclear physics, heavy-ion collisions, and astrophysics. As the nodal agency from India, DST ensures broad-based participation from academic institutions across the country.

More precisely, DST will ensure the development of pool of scientists by nurturing the researchers in the field of accelerator-based nuclear science, detector technologies, and large-scale data analysis through FAIR program. This effort is also expected to prepare Indian researchers to take on leadership roles in future national facilities such as the proposed India-based Neutrino Observatory (INO), thereby strengthening India's long-term scientific capabilities.

Q: The Mega Science Vision Reports (including the present 2035 Reports) contain the roadmap drawn by the concerned scientific communities about India's involvement in Mega Science Projects. From DST's perspective, how do such well thought-out and considered Reports help in planning the nation's involvement in such major long-term projects?

Prof. Karandikar: The Mega Science Vision Reports, including the present 2035 Reports, play an instrumental role in guiding the DST during the critical planning of India's long-term engagement in global Mega Science projects. The roadmaps articulated by the scientific community in these reports enable DST to align national priorities with emerging global opportunities in a coherent and strategic manner.

They provide a clear perspective on which frontier areas such as astronomy, particle physics, fusion energy, and advanced materials require focused investment. This, in turn, supports informed decision-making and helps ensure that resources are allocated to domains with the greatest potential to advance both science and societal benefit.

As Mega-science initiatives can take decades to complete, these reports leverage DST to plan strategically for funding in the capacity of infrastructure and human resource development in a phase-wise manner to create a sustainable talent pool for India's own facility in future. Overall, they serve as a vital framework for structured, forward-looking, and globally aligned planning.

Q: From a mere user of large accelerator facilities, India today is either a partner in global accelerator projects or has built a few large facilities on its soil. Do you think that India's increasing involvement with Mega Science Projects is in keeping with its long tradition of scientific research as well as its growing scientific, technological and financial prowess in the world?

Prof. Karandikar: India has offered many high-end technologies in the past, even before the establishment of modern science.

It will lead us to be an equal knowledge and technology partner rather than being an end-user.

Indian scientists are making significant contributions to projects such as CERN's Large Hadron Collider, ITER, and SKA. Their involvement extends beyond manpower to include expertise in instrumentation and data analysis. Furthermore, India's participation in facilities such as the TMT and FAIR as a co-builder demonstrates its growing capability as a core partner in shaping global science, rather than being a peripheral participant.

Through these activities and the in-built ecosystem supported by the DST, industries, researchers, and a strong knowledge base are being developed. This will support the creation of indigenous facilities in India, such as synchrotron radiation sources, nuclear research reactors, etc.

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