An overview of key enabling technologies for DAE's nuclear programme

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Homi Jehangir Bhabha envisioned that the success of India's nuclear energy programme would depend upon how soon the country becomes self-reliant in the manufacturing of required essential technologies, e.g. ultra-high vacuum systems, cryogenics and associated technologies, precision electronics, control and instrumentation, robotics, particle accelerators, plasma, lasers, etc. He initiated R&D programmes at TIFR, Mumbai, on few of these technologies immediately after taking over as Director in 1945, and expanded them once DAE was formed in 1954. In this article, we present a brief overview of R&D carried out by DAE during the past seven decades in the areas of key enabling technologies needed for the advancement of our nuclear programme. The tremendous efforts of DAE resulted in achieving self-reliance in the nuclear power programme as well as in the development of necessary technologies for investigation of fundamental science and for facilitation of societal and industrial growth in the country. DAE led the nation to not only become a partner in several international science megaprojects, e.g. LHC, FAIR, Fermilab, ITER, etc. but also took a leadership position in national megaprojects, i.e. MACE, LIGO-India and ADS.

Keywords: Accelerators, fusion, lasers, plasma, mass spectrometers, nuclear programme.

Introduction

HOMI Jehangir Bhabha placed the national three-stage nuclear power programme on a firm footing to ensure a long-term clean energy demand as well as facilitation of science and technology growth in India. During Bhabha's stay at Cambridge (1927–1939) (ref. 1), Cavendish Laboratory was the epicentre for various scientific breakthroughs like the discovery of neutrons by James Chadwick, production of transmuted lithium by John Cockcroft and Ernest Walton using high-energy protons, production of electron pairs from gamma radiation by Patrick Blackett and Giuseppe Occhialini using a cloud chamber, etc. The investigations on nuclear reactions to discover the building blocks of matter were at the forefront of international research and were attracting the greatest minds of the world. Bhabha was no exception to this and he too developed an enduring passion for conducting experiments on accelerating particles that release radiation. As the world's first nuclear reactor Chicago Pile-1 (CP-1) based on a self-sustaining chain reaction was established by the US in 1942, Bhabha was quick to realize the significance of nuclear reactions for peaceful applications. In 1945, after taking over as the first Director of the Tata Institute of Fundamental Research (TIFR), Mumbai, Bhabha envisioned that setting up of experimental facilities for a robust national nuclear energy programme would require the indigenous development of several key technologies. As depicted in Figure 1, building-block technologies (e.g. vacuum systems, cryogenics, magnets, ion optics, precession electronics, control and instrumentation, robotics, nuclear detectors, radiation shielding, etc.), and enabling technologies (e.g. accelerators,

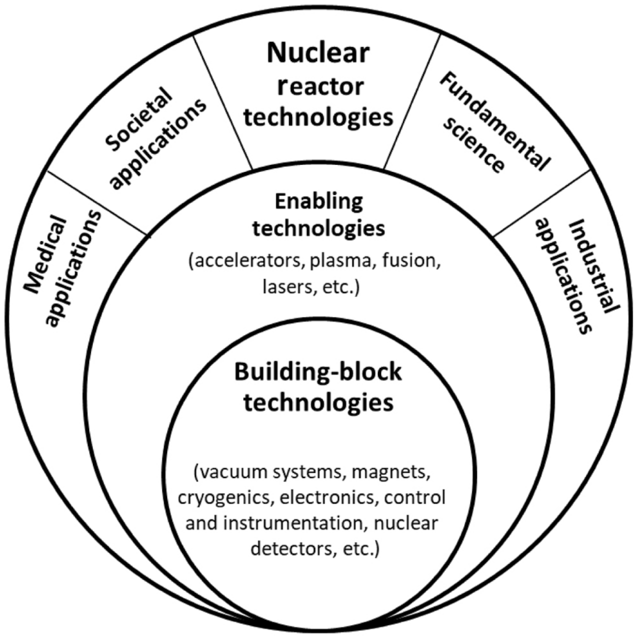

Figure 1. Schematic representation of various building-block and enabling technologies needed for the nuclear programme, facility creation for the investigation of deep fundamental science and applications in the areas of societal, medical and industrial growth.

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plasma, fusion, lasers, etc.) are needed for the development of nuclear reactor technologies for basic research, radioisotope production and power generation. The know-how gained during the development of these indigenous technologies is also vital for the setting up of national facilities for the investigation of fundamental science as well as for strategic, medical, societal and industrial applications.

As India's nuclear programme was to be started from scratch, Bhabha took a visionary initiative by nucleating R&D activities on the development of a few building-block technologies at TIFR. In 1954, as the first Secretary of the Department of Atomic Energy (DAE), he expanded these R&D activities to a full scale at the Bhabha Atomic Research Centre (BARC), Mumbai to build a robust, self-reliant nuclear programme in the country. In due course of time, these R&D activities were further expanded to various other units of DAE, namely Raja Ramana Centre for Advanced Technology (RRCAT), Variable Energy Cyclotron Centre (VECC), Saha Institute of Nuclear Physics (SINP), Institute of Plasma Research (IPR), Indira Gandhi Centre for Atomic Research (IGCAR), etc. Due to the obstinate R&D efforts of DAE, India is now self-reliant in most of these enabling technologies required for nuclear industries. In this article, we present a brief overview of these achievements. Many offshoots of DAE's R&D activities are being gainfully utilized for medical, societal and industrial growth. We also briefly highlight DAE's contributions to international mega science and technology projects, and show that India is on a path to becoming a technologically advanced nation.

Particle accelerator technologies

During the past seven decades, DAE units have set up several modern particle accelerator facilities for their nuclear programme as well as for basic, applied and industrial applications. Both linear and circular type of accelerators have been developed/set up, including Cockroft–Walton, Van de Graaff, tandem Pelletron, linear accelerators (LINAC), cyclotron and synchrotron. Table 1 summarizes the major milestones of accelerator development in DAE. In the literature, DAE's accelerator programme has extensively been reviewed from time to time[2,3]. Therefore, here we will present only a brief overview. These accelerators play a vital role in a variety of scientific and societal applications, viz. basic nuclear physics research, materials processing and characterization, health and medicine (both for diagnostics and treatment), food, agriculture, strategic, nuclear power and industrial applications.

Accelerators for research, medical, societal and industrial applications

As summarized in Table 1, DAE's particle accelerator facilities are being routinely used for basic nuclear and condensed matter research as well as for medical, societal and industrial applications. In particular, electron beam and radioisotopes are making a big impact in the diagnostics and treatment of cancer. To cater the ever-increasing demand for medical radioisotopes, VECC is setting up an Advanced National facility for Unstable Rare Isotope Beam (ANURIB) in Kolkata. This facility will also be utilized for studies related to nuclear spectroscopy, materials science and radiobiology[4]. Indigenously developed electron accelerators are widely used for radiation processing of food commodities, mutation of seeds, development of bio-stimulators for different crops, sterilization of disposable medical products, etc.[5,6]. The irradiation of food items (fruits, vegetables, spices, cereals, etc.) enhances their shelf-life mainly by killing the microbes and sprout inhibition. Electron-beam facilities are also utilized by industries for polymer cross-linking which immensely improves their thermal and mechanical properties. The cross-linked polymers are utilized in the development of products like wires, cables, hydrogels, vulcanized rubber, plastic foam, composite materials, etc. In addition, electron beams find unique industrial applications in producing exotic colours in gemstones, semiconductor characteristics amendments, wastewater treatment, electron-beam welding for manufacturing special components, etc.[7]. Electron accelerators have been used for testing of nuclear waste depository materials, photoactivation and fission analysis, device performance enhancement and radiation sustainability studies[8,9]. DAE has recently developed a cargo scanning system for imaging of cargos to avoid the transport of contraband objects. Internal images of cargos with material discrimination features, are generated with X-rays which are produced by dual-energy (6 and 4 MeV) electron LINAC having a pulse-to-pulse energy variation flair.

Accelerators for material characterization

Indus-1 and Indus-2 synchrotron radiation facilities are being profoundly utilized by researchers from universities, R&D organizations and industries for a deeper understanding of the internal structure of matter and its correlation with physical properties[10]. These facilities provide a wide range of techniques for materials characterization. Major techniques with Indus-1 are high-resolution ultraviolet spectroscopy, angle integrated photoelectron spectroscopy, angle-resolved photoelectron spectroscopy, X-ray reflectivity, infrared spectroscopy, etc. The major beamlines of Indus-2 are soft X-ray absorption, engineering applications beamline, soft X-ray reflectivity, X-ray imaging beamline, X-ray lithography beamline, dispersive and scanning EXAFS beamline, angle-resolved photoelectron spectroscopy, extreme conditions XRD, angle dispersive XRD, hard X-ray photoemission spectroscopy, X-ray fluorescence microprobe, small and wide-angle X-ray scattering, protein crystallography. These facilities have allowed researchers to explore the exciting developments in understanding of

Table 1. Major milestones of particle accelerator development at DAE in chronological order

Year	Accelerator	Beam	Maximum energy	Institution/ location	Purpose
1950	1 MV Cockroft–Walton	Proton	1 MeV	TIFR, Mumbai	Basic nuclear physics research
1957	Low-energy cascade generator	Proton	400 keV	SINP, Kolkata	Neutron generation
1960	38-inch cyclotron	Proton	4 MeV	SINP, Kolkata	Nuclear physics and spectroscopy experiments
1962	5.5 MV Van de Graaff	Proton	5.5 MeV	BARC, Mumbai	Nuclear physics experiments
1970	Cockroft–Walton	Proton	300 keV	BARC, Mumbai	Neutron generation
1977	K130 room-temperature cyclotron	Ion	$K = 130$*	VECC, Kolkata	Nuclear physics research, radiation damage study, isotope production and detector studies
1982	2 MV tandem Van de Graaff	Ion	2 MeV	BARC, Mumbai	Research in nuclear physics and atomic spectroscopy
1986	7 MeV linear accelerator (LINAC)	Electron	7 MeV	BARC, Mumbai	Research in chemistry and materials science
1988	14 UD Pelletron	Proton; ions ($A \leq 37$)	24 MeV; 10 MeV/$A^{\#}$	TIFR, Mumbai	Nuclear physics, condensed matter physics, atomic and molecular physics
1988	2 MeV ILU-6	Electron	2 MeV	BARC, BRIT, Navi Mumbai	Industrial irradiation applications for polymers, rubbers, cables, etc.
1989	KALI (Kilo Ampere linear injector)	Electron	1 MeV	BARC, Mumbai	Strategic and industrial applications
1995	3 MV tandem ion accelerator	Ions	3 MeV	NCCCM, Hyderabad	Material surface analysis
1998	500 keV Cockroft–Walton	Electron	500 keV	BARC, BRIT, Navi Mumbai	Surface treatment of polymers, textiles and rubber tiles
1999	450 MeV Synchrotron Indus 1	Electron	450 MeV	RRCAT, Indore	Basic research in physics, materials, chemistry, pharmaceuticals, environment, etc.
2000	5.5 MV folded tandem ion accelerator	Proton; ions ($A \leq 40$)	6 MeV; 66 MeV	BARC, Mumbai	Research in nuclear physics, radiation biology, materials science and ion implantation
2002	16.5 MeV medical cyclotron accelerator	H^- and D^- ions	16.5 MeV	RMC/BARC, Mumbai	Production of radiotracer ^{18}F for positron emission tomography
2002	1.7 MV tandem accelerator	Ion	2 MeV	IGCAR, Kalpakkam	Ion implantation, ion beam analysis and materials science
2004	10 MeV LINAC	Electron	10 Mev	RRCAT, Indore	Irradiation for sterilization of medical devices, irradiation of research samples for development of new crop varieties, colour modification of gemstones, development of novel materials, etc.
2005	2.5 GeV Synchrotron Indus 2	Electron	2.5 GeV	RRCAT, Indore	Basic research in physics, materials, chemistry, pharmaceuticals, environment, etc.
2006	750 keV Cockroft–Walton	Electron	750 keV	RRCAT, Indore	Surface treatments of rubber tiles, curing of paints and coated wood
2008	10 MeV LINAC	Electron	10 MeV	BARC, EBC, Navi Mumbai	Irradiation of various products like polymers, semiconductors, gemstone colour enhancements, seed mutation, food preservation, radiation hardening studies and basic research
2009	K500 superconducting cyclotron	Ion	$K = 500$*	VECC, Kolkata	Ion beam and nuclear physics research
2010	9 MeV LINAC	Electron	9 MeV	ECIL, Hyderabad	Cargo scanning and neutron radiography
2011	Compact Ultrafast Terahertz Free Electron Laser (CUTE-FEL)	Electron	10 MeV	RRCAT, Indore	Research and technology development (decommissioned in 2016)
2013	1–3 MeV Dynamitron	Electron	3 MeV	BARC, EBC, Navi Mumbai	Flue gas treatment, curing of rubber tiles and radiation hardening studies
2016	Infra-Red Free Electron Laser (IR-FEL)	Electron	24 MeV	RRCAT, Indore	Research, especially in condensed matter physics
2017	6 MeV LINAC	Electron	6 MeV	BARC, EBC, Navi Mumbai	Cargo scanning and radiography
2018	Proton cyclotron	Proton	30 MeV	VECC, Kolkata	Radioisotope production to treat cancer
2018	LEHIPA Facility	Proton	3 MeV	BARC, Mumbai	Nuclear physics and accelerator-driven sub-critical nuclear reactors
2019	10 MeV LINAC	Electron	10 MeV	RRCAT, Indore	Irradiation of different food and medical products
2022	6/4 MeV dual energy LINAC	Electron	6 MeV	BARC, EBC, Navi Mumbai	Cargo scanning with material discrimination facility
2022	High power Cockroft–Walton	Electron	1 MeV	BARC, EBC, Navi Mumbai	Wastewater treatment

**K* value: In case of cyclotron, maximum possible energy of a particle with that particular accelerator is generalized in terms of the *K* value as K.E. = $K(Q^2/A)$; where *K* is a constant (reflects in 'MeV'), *Q* is the charge state of the particle and $^{\#}A$ is the number of nucleons.

materials in the areas of solar cells, nuclear materials, nanomaterials, thin films and interfaces, medicine, fuels, pharmaceuticals and the environment[11]. Typically, more than 900 user experiments are carried out annually at the Indus beamlines, with a total of about 175 publications in international journals each year. Users from about 150 different institutions and 10 different industries have used these beamlines at Indus-1 and Indus-2. DAE has also developed several state-of-the-art accelerator-based techniques such as accelerator mass spectrometry (AMS), Rutherford backscattering (RBS), proton-induced X-ray emission (PIXE), nuclear reaction analysis (NRA) and elastic recoil detection analysis (ERDA) for basic studies in material science[12].

Accelerators for strategic applications

Generation of pulsed, high-power (several gigawatts) relativistic electron beam is needed to produce flash X-rays, pulsed neutron sources, high-power microwaves and pulsed ion sources, which in turn are used for strategic as well as industrial applications, including futuristic use in thermonuclear fusion devices for energy generation. BARC has developed an intense pulsed electron accelerator named as Kilo Ampere Linear Injector (KALI) with its many versions like KALI 75, KALI 85, KALI 200, KALI 1000, and KALI 5000. It is capable of generating powerful pulsed electron beam of duration 50–100 ns with energies of 0.2–1 MeV and power up to 30 GW (ref. 13).

Accelerator-driven subcritical reactor system (ADS)

DAE has an undergoing project on ADS, which is likely to have a major impact on the nuclear energy scenario[14]. ADS relies on spallation neutrons, produced by a 1 GeV proton accelerator, driving a subcritical nuclear reactor. The system has increased safety and can use fuel with degraded neutronic properties. It can find applications in fuel breeding and incineration of the long-lived actinide and fission product waste. ADS can advantageously be used with thorium fuel, which though not fissile is fertile, i.e. can be converted into fissile material using a neutron source. The R&D activities of ADS have three major technologically distinct subsystems: (i) development of 1 GeV (10 mA CW) high-intensity proton accelerator (HIPA). For this, BARC has designed and established the LEHIPA (20 MeV, 10 mA) facility using indigenous radiofrequency quadrupole (RFQ), drift-tube LINAC, RF power supplies, etc. RRCAT is working on the design and development of a 1 GeV proton synchrotron for the generation of spallation neutrons. (ii) Heavy element targets that would produce spallation neutrons on bombarding with high energy proton, i.e. target materials taking a load of ~10 MW of heat energy. (iii) Sub-critical nuclear reactor for which BARC has taken up innovative interdisciplinary R&D programmes on power generation using ADS.

International collaborations

DAE's accelerator programme has led to the creation of core expertise on various aspects of accelerator development, i.e. design, fabrication, assembly, installation, integration, testing, commissioning and utilization. The manufacturing capabilities of sub-components of accelerator systems like different types of magnets, RF systems, power supplies, ultra-high vacuum systems, electron or ion sources, beam diagnostics, cryogenics, controls and instrumentation, radiological shielding and other utilities have been developed in the country. In addition, owing to the execution capabilities of numerous large projects, DAE is a strong collaborator in several mega international accelerator programmes.

One of the major international efforts is to develop accelerators with higher possible energies, which are aimed at probing the structure of matter as deep as possible. As a result, the Large Hadron Collider (LHC), the most powerful accelerator with proton energy of 8 TeV, has been built near Geneva, Switzerland[15]. DAE is an active partner in the LHC programme[16] and has contributed to the construction of LHC as well as its detectors – CMS (Compact Muon Solenoid) and ALICE (A Large Ion Collider Experiment). It has also contributed in almost all components of LHC such as superconducting magnets, vacuum systems, cryogenics, power supplies, control electronics, mechanical systems and so on. The experiments conducted using such powerful particle accelerators over time have explored the nucleus and shown scientifically that the basic building blocks of matter are the families of six quarks and six leptons. Such experiments have also enhanced our understanding of the basic operating forces in nature and led to the discovery of the Higgs boson – an elementary particle in the Standard Model of particle physics. The Pb–Pb collisions of LHC created very high-temperature matter, which was supposed to exist a few microseconds after the Big Bang, to understand the dynamics of fundamental particles in bulk. The futuristic investigation in particle physics is now to look into the unanswered questions of the origin of dark matter and dark energy, the matter/antimatter asymmetry in the universe, and the unification of electroweak, strong forces and gravity.

The Fermilab–DAE collaboration is aimed at the development of research facilities for proton accelerator projects in India. Under the Proton Improvement Plan II (PIP-II) project, Fermilab is supporting India in the development of a 1.2 MW proton beam for DUNE (Deep Underground Neutrino Experiment). Currently R&D work on the design, development and fabrication of various components such as room-temperature magnets, single-spoke resonator cavities, cryogenics, RF protection system, high beta superconducting radiofrequency (SRF) cavity, 650 MHz solid-state

RF amplifiers, etc. is being taken up at BARC, RRCAT, VECC and other national institutions.

DAE is also contributing to the Facility for Antiproton and Ion Research (FAIR), which is an under-construction accelerator complex in Darmstadt, Germany. RRCAT has supplied 127 power converters to the FAIR accelerator that were indigenously designed, developed, tested, and manufactured. Other technical support provided includes large superconducting magnets, beam stoppers, vacuum chambers and sophisticated detectors for experiments, which have demonstrated unique expertise developed by DAE in the areas of accelerators.

Plasma and fusion technologies

Plasma medium exhibits exotic properties, including high enthalpy and energy density, high temperature and steep temperature gradient and the presence of reactive species. This makes plasma adaptable for a wide variety of materials synthesis and surface engineering. DAE had initiated a comprehensive R&D programme at BARC on plasma physics and technology during its formative years with a focus on the development of plasma formation devices, plasma diagnostics and instrumentation, plasma processing of materials, etc.[17]. The plasma and fusion research grew further when IPR (a research centre of DST) was moved to DAE in 1995 (ref. 18). Some of the developed plasma technologies include air and underwater plasma cutting systems, microwave plasma processing systems, plasma nitriding systems, plasma-enhanced chemical vapour deposition systems, plasma surface etching and cleaning techniques, plasma pyrolysis, plasma jets, etc. These plasma technologies are being deployed for solving many surface engineering and processing-related issues of the nuclear programme as well as for societal and industrial applications, including medical waste disposal.

IPR is carrying out fusion research based on a Tokamak device that has a magnetically confined hot plasma. ADITYA, India's first Tokamak, was commissioned in 1989. All the components of tokamak devices, namely ultra-high vacuum vessel ($\sim 10^{-8}$ torr vacuum in a vessel having $\sim 16\ m^3$ volume with $\sim 75\ m^2$ surface area), pulsed power system (a peak power level of 50 MW), magnetic field coils and the ohmic transformer were developed indigenously. ADITYA has a plasma of circular cross-section with a major and minor radius of 0.75 and 0.25 m respectively. A 100 kA plasma current is sustained for about 100 ms, to confine and heat the plasma. Plasma is further heated using an auxiliary RF system. Several diagnostics are deployed to measure various plasma parameters. ADITYA has been upgraded recently to obtain improved performance. For this, a 28 GHz, 200 kW gyrotron-based electron cyclotron resonance heating (ECRH) system has been integrated.

IPR has also established a state-of-the-art Steady State Superconducting Tokamak (SST-1), which is a large aspect ratio Tokamak and configured to run an elongated plasma current of 200 kA with a pulse duration of 1000 s. Various highly specialized and sophisticated components of SST-1 are indigenously manufactured in association with Indian industries, including copper and NbTi superconducting magnets, cryogenic technology, ultra-high vacuum systems, high heat flux removal technology, high-power RF technology and energetic neutral beam production and injection technologies.

Since 2005, DAE is a partner to ITER (International Thermonuclear Experimental Reactor), which is an international nuclear megaproject aimed at carrying out research and engineering on fusion processes to produce clean energy. Other partners of ITER are the European Union, China, Japan, Russia, South Korea and USA. ITER will be the world's largest tokamak nuclear fusion reactor which is being built in Cadarache, France. ITER-India is a special project under IPR and serves as the Indian Domestic Agency to design, build and deliver the Indian in-kind technological contribution to ITER. Some of the components delivered to ITER include 30 m high and 30 m diameter outer vacuum shell of ITER, several kilometres long cryolines for ITER cryo-plants, blocks and plates of borated steel (SS304B4, SS304B7), and ferritic steel for neutron shielding and reducing toroidal field ripple, RF sources, beam diagnostic system, power supplies, gyrotron sources, special materials like composition controlled CuCrZr, etc. These components are the first of their kind and are of high quality meeting the stringent nuclear safety norms of the Regulatory Board of France.

Laser technologies

In early sixties, DAE initiated a programme on the development of lasers, recognizing their importance as a tool of great power and precision for various nuclear programmes. BARC succeeded in the development of a semiconductor laser and demonstrated an optical communication link over a distance of 20 km. The laser programme was expanded with the establishment of dedicated R&D activities at RRCAT in 1986. RRCAT has developed a wide range of lasers, e.g. CO_2, nitrogen, Nd : glass, dye, etc. and utilized them for the investigation of materials processing, laser–plasma interactions, resonance ionization spectroscopy, nonlinear optics, etc.[19].

High-power pulsed lasers are needed for highly specialized tasks in nuclear and other industries, e.g. laser cutting, drilling and milling; laser cleaning; laser welding and soldering; laser marking and engraving; laser cladding or coating; laser surface modification and laser hardening; laser sintering, etc. RRCAT has indigenously developed 500 Hz pulsed TEA (transversely excited atmospheric pressure) CO_2 lasers with average power up to 500 W and pulsed Nd : YAG lasers of 250 W average power (5 kW peak power with multi-port time-shared fibre optic beam delivery). A few examples of classic applications of lasers in nuclear power plants are: (i) laser cutting of bellow lips during en masse coolant channel replacement (EMCCR) in nuclear reactors that substantially reduced the downtime. (ii) Laser-based technique for removal of any selected coolant channel in pressurized heavy water reactors (PHWRs) as well as for life assessment of pressure tubes. (iii) Underwater laser cutting of pressure tube stubs. These laser-based applications have enormously reduced radiation dose consumption, time and cost[20]. The developed lasers were also deployed for societal applications, e.g. welding of heart pacemaker, micro-welding of low dose I^{125} brachytherapy encapsulation for eye and prostate cancer, micro-welding of Ir^{192} high dose rate brachytherapy assemblies for treatment of internal organ cancer, etc.[21]. The developed high-performance copper vapour laser systems are used for the fabrication of fibre-based sensors, which are finding applications in areas like railway safety, temperature monitoring in high radiation fields, structural health monitoring, etc.[22]. A monolithic single-mode, 1 kW CW Yb-doped fibre laser has been developed for additive manufacturing of niche components which have a graded material structure or complicated structures that cannot be manufactured by conventional techniques[23,24].

Mass spectrometer technologies

The success of various stages of the nuclear fuel cycle requires mass spectrometers for the measurement of elements at the ultra-trace level along with isotope ratios in samples of hydrogen, lithium, boron, uranium, plutonium, etc. Thus, mass spectrometry is a crucial analytical tool for the determination of burn-up of fuel, nuclear materials accounting, nuclear environmental monitoring, migration studies, dating and radioactive waste control. BARC has indigenously developed various types of highly sophisticated mass spectrometers having a quality of international equivalence[25]. These include: (i) Thermal ionization mass spectrometer (TIMS) utilized for the determination of isotopic abundances of Li, B, U and Pu isotopes in solid samples. (ii) Inductively coupled plasma source mass spectrometer (ICPMS) used for trace, ultra-trace, isotope ratio analysis of elements in aqueous samples. The detection limit of ICPMS is parts per trillion for most of the elements. (iii) Process gas mass spectrometer used for the measurement of isotopic abundance of uranium isotopes 234, 235 and 238 corresponding to natural, enriched and depleted respectively, (iv) D/H mass spectrometer used for the determination of deuterium (D) to hydrogen (H) ratio and essential for the production of high-quality heavy water. (v) Time-of-flight mass spectrometer (TOF MS) which is sensitive to femtomole amounts of a sample. Apart from the nuclear industry, these mass spectrometers find applications in basic research, forensics, environmental science and geology as well as in various industries like petroleum, pharmaceutical, chemical, petrochemical, etc.

Radiation monitoring systems

Another hallmark of Bhabha's vision was to safeguard radiation workers and the environment from any harmful effects of radiation. For this, BARC indigenously developed various types of radiation detectors, e.g. gas-filled, solid-state, scintillation detectors, chemical dosimeters, thermoluminescence dosimeters, neutron detectors, etc. as well as radiation monitoring and surveillance network. In addition, for national nuclear and radiological safety, technologies for radiation monitoring and surveillance were developed and deployed countrywide. These are: (i) IERMON (Indian Environmental Radiation Monitoring Network) consisting of standalone GM tube-based gamma-ray monitoring stations and solar-powered, battery-operated systems with global system for mobile (GSM) and/or satellite-based direct communication systems[26]. To detect fallout radionuclides in the atmosphere from any nuclear/radiological events, IERMON is supported by the Environmental Gamma Spectrometry System (EGSS), which consists of scintillator-based gamma spectrometers. IERMON is compact, rugged, meant for open-field deployment and has successfully withstood the varying environmental conditions across the country. Over 500 IERMON systems have been deployed countrywide for 24×7 unattended monitoring of natural background radioactivity, detection of possible transboundary migration, surveillance around nuclear facilities (mining, nuclear power plants, etc.), detection of any nuclear/radiological events in metropolitan cities, etc. (ii) For radiation surveillance underwater, special environmental radiation monitors (ERM) integrated with an autonomous vertical profiler (AVP) have been developed, which are battery-operated, store the data and communicate them using RF once they come to the surface. These systems are capable of diving up to 200 m underwater and can monitor radiation levels at multiple preset depths. They are useful for underwater monitoring of radiation around the coast, discharge points, monitoring of ships/boats, etc. They also find applications in sediment transport monitoring/modelling and in the detection of a lost radiation source in water.

Technologies for fundamental science

Major Atmospheric Cerenkov Experiment Telescope (MACE)

In 2021, BARC had established MACE at Ladakh, which is located at the highest altitude (4270 m amsl) in the world[27]. A marvel of DAE's R&D efforts, the 28 m diameter MACE is the world's second largest gamma-ray telescope having 356 mirror panels and an integrated imaging camera (consisting of 1088 photomultiplier-based pixels along with a signal processing and data acquisition system). It has a wheel and track design with two axes movement capability of ±270° in azimuth and –26° to +165° in elevation. Through the detection of very high energy (VHE), i.e. >20 GeV, MACE is likely to provide unique opportunities to study exotic objects like pulsars, binary star systems, pulsar wind nebulae, gamma-ray bursts, supernova remnants, micro-quasars, giant molecular clouds, active galactic nuclei, etc. The MACE telescope is also expected to address a range of cosmological topics such as constraining the intensity of extragalactic background light, cosmic-ray electron spectrum, dark matter particles, the strength of the intergalactic magnetic field, etc.

Laser Interferometer Gravitational-Wave Observatory (LIGO) – India

DAE has taken a leadership position in LIGO-India project in association with the Department of Science and Technology, Government of India, National Science Foundation, USA; and several international and national research and academic organizations[28]. LIGO detects the squeezing and stretching of space when gravitational waves pass by the Earth. LIGO-India is an advanced gravitational-wave observatory having a long, *L*-shaped, ultra-high vacuum system (~4 km on each side) that will house several laser interferometers. It is a multidisciplinary mega-science project and therefore, the expertise of DAE generated over past seven decades in the areas of ultra-high vacuum, lasers, optics, electronics and instrumentation, control systems, computers, etc., will ensure its success.

Summary

DAE, through its intense R&D activities, has been successful in establishing the basic infrastructure and methodologies in India for converting knowledge base in the areas of vacuum, electronics and instrumentation, accelerators, plasma, lasers, mass spectrometry and radiation monitoring networks into state-of-the-art technologies required for nuclear, strategic programmes as well as for societal applications. For example, indigenously developed Nd : YAG laser was utilized to cut bellow lips during en masse coolant channel replacement in nuclear reactors, which substantially reduced the downtime; development of electron beam and radioisotopes for diagnosis and treatment of cancer; development of KALI for generation of high-power pulsed relativistic electron beam which in turn produce flash X-rays and microwaves needed for strategic applications; development of mass spectrometers for measurement of ultra-trace level elements (viz. hydrogen, lithium, boron, uranium, plutonium) along with isotope ratios, which are needed at almost every step of the nuclear fuel cycle; development and deployment of IERMON systems across the country for national nuclear and radiological safety, etc. These technologies have also helped in our understanding of fundamental science, and provided a further boost to the range of ancillary technologies and have benefited society by their vast applications.

DAE's expertise in the construction and management of mega-science projects has given it a leadership position not only in India but also at the international level. Consequently, today DAE is executing its own megaprojects such as MACE, LIGO-India and ADS MACE is expected to provide new knowledge in the areas of astrophysics, dark matter, etc. In addition, DAE represents India as a major partner in several collaborative international projects like LHC, FAIR, Fermilab, ITER, etc. It has contributed to these megaprojects by providing knowledge and know-how along with supply of various indigenously developed key components.

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