Fusion and Plasma Research

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Preamble

Plasma physics is the science of ionized matter. Its importance has grown manifold due to its numerous fundamental contributions and diverse practical applications, including the prospect of developing a fusion reactor. The Institute for Plasma Research (IPR), with its main campus located in Gandhinagar, Gujarat, has the mission of R&D in Plasma Science & Technology, with special emphasis on Magnetic Confinement Fusion, Societal/industrial applications of plasmas, basic research in Plasma Science etc. This article presents an overview of development and progress in the field of plasma research at IPR.

I. Historical Perspective

Research in Plasma Physics started in India with Prof. M.N. Saha, known for the Saha-ionisation equation. Much of the early work was in the context of astrophysical and ionospheric plasmas. Although small-scale experimental studies of plasma processes continued to be carried out in various university departments, national laboratories and institutes of technology, plasma research in India majorly remained of theoretical nature. In the early 1970's, responding to a call by Dr. Vikram Sarabhai for starting a focused experimental plasma physics activity that would act as a precursor for a future fusion research program in the country, several noted scientists working in different Institutions in India and abroad joined the Physical Research Laboratory, (PRL) Ahmedabad. They included Prof. R. K. Varma, Prof. Bimla Buti – a former student of Prof. S. Chandrasekhar, Prof. R. Pratap, Prof. A.K. Sundaram, Prof. Predhiman Krishan Kaw, Prof. A.C. Das and Prof. A. Sen.

After the sudden demise of Dr. Sarabhai, Professor P.K. Kaw - who had earned his Ph.D. from IIT Delhi at the age of eighteen, took the lead in fulfilling Dr Sarabhai's dreams. An experimental plasma physics program had been launched under the guidance of Prof. Satya

Prakash, with Prof. P.I. John, a faculty member at Aligarh Muslim University and Prof. Y.C. Saxena, who had worked on cosmic ray research in the Kolar Gold Fields, joining the group. Prof. S.K. Mattoo, who had worked in solar physics, also joined the group. The plan was to establish an experimental program oriented towards the simulation of space plasma phenomena with the underlying purpose of eventually acquiring the skills necessary for fusion research.

In 1982, the Department of Science & Technology, realizing the importance of starting an indigenous fusion research activity, established the Plasma Physics Program (PPP) in PRL under its "Intensification of Research in High Priority Areas" initiative. PPP grew into the Institute for Plasma Research (IPR) in 1986, with Prof. P.K. Kaw as its founding director. The first indigenously built tokamak, ADITYA (meaning 'The Sun' in Sanskrit), was commissioned in 1989. Along with the tokamak project, a thriving plasma physics and plasma technology program was started. An essential objective of the program was to develop indigenous expertise in the construction of experimental devices for hot plasmas and to create infrastructure within the country that would pursue fusion power when it became viable. IPR quickly grew and became a premier institute conducting theoretical and experimental research in plasma sciences with the infusion of fresh talent from TIFR, IITs, several universities in the country and abroad.

India's tokamak research started with the building of ADITYA tokamak at the IPR. IPR indigenously built and operated the first Indian tokamak (ADITYA) and widened its scientific activities to include fundamental experiments in plasma physics. Another smaller tokamak, purchased from Toshiba, Japan, was installed at the Saha Institute of Nuclear Physics, Kolkata. At that time very few countries had tokamaks.

Along with the successful commissioning and operation of the ADITYA tokamak, several plasma technologies were developed for industrial and fusion applications. A significant jump in IPR's growth came in the mid-90s, when its proposal to build a state-of-the-art superconducting steady-state tokamak (SST-1) was approved by the Government. The construction and operation of SST-1 tokamak has led to several technological advancements in fusion technology in India. Furthermore, the ADITYA tokamak has been reconstructed with additional magnetic coils to produce shaped-plasmas. The progress made by IPR in designing, developing and operating conventional and superconducting tokamaks enabled India to become an equal partner in the biggest international fusion program – the International Thermonuclear Experimental Reactor (ITER), under construction in Cadarache, France. IPR has recently worked out a 25-year roadmap that includes the indigenous development of fusion technologies, building a series of progressively larger and more complex fusion machines, a focused and large-scale program for the societal applications of plasmas and new directions in basic plasma research.

Given its multidisciplinary, technology-intensive nature, plasma/fusion research has yielded numerous spin-offs in disciplines ranging from medical technology and environment to agriculture and material sciences to national security and Space. Several plasma-based technologies developed in IPR for meeting societal needs have been transferred to industries towards attaining an 'Aatmanirbhar Bharat'. The experimental plasma physics program has a strong synergy with theoretical and computational research, which has led to overall development of the field in India.

II. ADITYA Tokamak:

Nuclear fusion reactions power the sun and all of the stars of the universe. Reproducing these reactions on earth provides an attractive solution for meeting the ever-increasing demand of energy for the growing world population. It is quite well-known that when light nuclei fuse together, they liberate energy because the binding energy per nucleon of the resultant increases. As the nuclear forces dominate over the electrostatic forces at nuclear distances, bringing the lighter elements at nuclear distances is the key for realizing a nuclear fusion reaction. This can be achieved by subjecting the nuclei to very high energies through heating them to high temperatures $\sim 10^8$ K, so that they overcome the coulomb repulsion. At this temperature any mater will be in the plasma state. The most favorable reaction for achieving the controlled thermonuclear fusion on earth is the deuterium – tritium (D-T) reaction, which produce neutrons of 14.1 MeV.

The methods to harness the fusion power on earth are diverse, each with its own advantages and disadvantages. Over the past few decades significant progress has been made around the world. The decades of research have led to good understanding of the physics of both inertial confinement fusion and magnetic fusion, and forms the base for big experiments like magnetic fusion based ITER, and inertial fusion based NIF and LMJ. The most promising and well-researched candidate for the magnetic-confinement based nuclear fusion reactor is 'Tokamak', a toroidal device where high temperature plasmas are confined with special arrangement of magnetic fields. Strong magnetic fields, produced by electromagnets, are used to confine the high-temperature plasma in a toroidal, doughnut-shaped vacuum chamber to physically isolate and thermally insulate the plasma from the solid surfaces surrounding it. The plasma in a tokamak is heated mainly by driving high-currents through it, by launching radiofrequency waves and/or injecting energetic neutral particle beams. The ITER is based on tokamak concept which envisages to demonstrate generation of efficient fusion power ($Q > 1$) using Deuterium - Tritium (D-T) reactions through fulfilling the Lawson criterion, the triple product of plasma density (n_e), temperature (T_e) and confinement time (τ_e), $n \times T \times \tau e \geq 3 \times 10^{21} m^{-3} keV\text{–}sec$ (deuterium-tritium fusion). A reliable and efficient fusion reactor producing electricity will also likely be a tokamak based reactor.

The design, fabrication and installation of the indigenously built ADITYA tokamak (Figure 1) took place during 1983-1988, and it was commissioned in 1989. It created the first hydrogen plasma discharge in September 1989. The medium-sized tokamak has a major radius of 0.75 m, a minor radius of 0.25 m, and a maximum toroidal field of ~1.5 T. The ADITYA tokamak had several electromagnetic coils, namely the toroidal field (TF) coils: 20 numbers, Ohmic (OT): 5 sets and Vertical field (VF): 2 sets, for producing different magnetic fields required for sustaining super-hot plasmas at several million degrees Centigrade. The successful operation of ADITYA realized technological advancements in pulsed-power, vacuum, electronics, diagnostic and data acquisition for the first time in the country. ADITYA, when commissioned, had the largest Ultra High Vacuum volume ~ 1 m^3, the largest pulsed power system drawing ~ 50 MW for 5 seconds, the first and the largest inductive energy storage system in the country. The notable contribution of ADITYA in nation-building lies in the fact that the machine was constructed

Figure 1: ADITYA-U tokamak

indigenously with major contributions from Indian industry. The data acquisition system for acquiring data from a pulsed discharge with high time resolution was developed in-house using Vax11/730, PDP11 and CAMAC based systems.

ADITYA operated for more than two decades, studying the magnetically confined hot plasmas using more than 30,000 plasma discharges, which validated its design and robust construction. Plasmas with maximum temperature ~7 million degrees Centigrade (~ 600 eV) was confined in ADITYA for quarter of a second (~ 250 ms) duration and with plasma currents up to 160 kilo-Amperes (kA). ADITYA achieved an energy confinement time of ~10 milliseconds.

Along with constantly improving plasma performance, several experiments have been carried out in ADITYA. A remarkable achievement of ADITYA was the discovery of `intermittency', i.e., the nature of the particle and energy transport in the tokamak edge region is bursty and not continuous. The probability distribution functions of broadband plasma density and potential fluctuations were non-Gaussian, a key feature depicting the intermittency in the tokamak edge region. This critical finding of the "BURSTY" nature of plasma transport obtained from careful and systematic experiments in ADITYA has substantially enriched the understanding of the transport of energy and particles from tokamak plasma. This discovery has opened up new avenues of research on this topic worldwide. A variety of other experiments were conducted on ADITYA, which led to significant progress in fusion research, such as the efficient control of plasma disruption and Runaway electrons in tokamaks.

III. ADITYA Upgrade Tokamak

ADITYA tokamak produced circular plasmas formed by a circular graphite ring, called a limiter, placed inside the vacuum vessel. Over the years, the technological advancement of tokamaks has shown better alternatives to the limiter-based circular shaped plasmas through defining the plasma boundary by means of magnetic fields. ADITYA tokamak was dismantled and rebuilt with new electromagnetic (divertor) coils to produce the magnetic fields defining plasma boundary and shaping the plasma. Complete up-gradation was carried out indigenously with the new divertor coils wound in-situ. An Indigenously developed equilibrium code, IPREQ, has been used to reconstruct the equilibrium of shaped plasmas (double-null configuration) for identifying the divertor coil locations. The ADITYA-U tokamak is now a part of an elite group of medium-sized tokamaks (HL-1M-China, COMPASS-Czech Republic, ASDEX-Germany, WEST-France, TCV-Switzerland, MAST-UK), capable of producing plasma in circular, single and double null divertor configurations.

The main objective of ADITYA-U tokamak is to prepare the technological base for future Indian machines along with pronounced understanding the physics by conducting experiments focused on critical areas, such as generation and control of runaway electrons, disruption prediction and mitigation studies, and real-time plasma position control and confinement improvement studies with shaped plasmas. To date, in the ADITYA-U tokamak, a plasma with temperature ~7 million degrees C (~ 600 eV) has been confined for 0.4 seconds. Plasma-shaping experiments have been initiated in ADITYA-U by powering the new divertor coils and encouraging preliminary results are obtained. This is the first time that shaping of the plasma column has been attempted in an Indian tokamak. Till recent times only hydrogen (H) plasmas are produced in ADITYA and ADITYA-U tokamaks. For the very first time in an Indian tokamak, fully deuterium (D) plasmas have been produced successfully in the ADITYA-U, a significant step towards future developments in fusion research.

Plasma disruption event is a huge cause of concern for ITER as it can lead to considerable damage to the machine structure and plasma-facing components, and a search for a mitigation technique is still underway. An inductively driven pellet impurity injector, for the first time in any tokamak, has been fabricated, installed and operated in ADITYA-U tokamak in collaboration with BARC, Vishakhapatnam to inject micron-sized particles at high velocity (~220 m/s) as a plasma-disruption mitigation technique. The world tokamak community is also searching for a good strategy for mitigating high-energy electrons, called runaway electrons. Numerous experiments have been executed in ADITYA-U to effectively control the runaway electrons.

IV Superconducting Steady-State Tokamak (SST-1)

Until the late 1980s, all tokamaks used resistive copper magnets. However, use of resistive magnets is not viable for a reactor operating at steady-state, since it would consume a large amount of electrical power. The solution lies in using magnets made of superconductors. To acquire knowledge about technologies related to steady-state operation of tokamaks and to study the characteristics of tokamak plasmas under steady-state conditions, a steady-state superconducting tokamak (SST-1) has been designed and built in IPR to have plasma pulse length of several seconds. The Superconducting coils were fabricated by BHEL, Bhopal, whereas BHEL, Tiruchirappalli fabricated the vacuum vessel, cryostat and support structures. The conceptual design of the Helium Cryo-plant (1.3 kW at 4.5 K) for superconducting coils was also carried out by a group of IPR engineers and scientists. The Liquid nitrogen storage facility, consisting of large storage tanks, was fabricated and installed by INOX-India. Transfer lines and phase separators were developed with the help of Linde-India Ltd., Kolkata.

Figure 2 shows a recent picture of the SST-1 tokamak and its various subsystems. The major and minor radii of SST-1 tokamak are 1.1 m and 0.20 m respectively. The maximum toroidal magnetic field of 3.0 T can be produced at the machine centre. The SST-1 superconducting magnet system contains about 35 tons of cold mass at 4.5 K and is the largest cable-in-conduit-conductor (CICC) based forced-flow superconducting magnets in India. The CICCs are made up

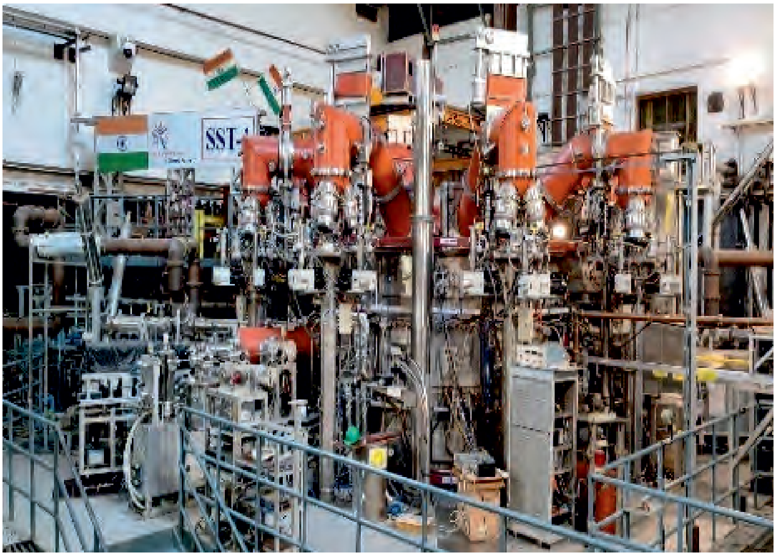


Figure 2: The SST-1 tokamak

of NbTi/Cu, which are successfully cooled down to 4.5 K using a helium cryogenics system. The cooling of the magnet system is achieved using a dedicated custom-designed helium cryogenic system, which is the largest helium cryogenics system in the country and has been operational for two decades. A 2.7 T main (toroidal) magnetic field has been generated in the SST-1 machine. The TF magnets have been operated for a record 15 days at a stretch during plasma operation in SST-1 with a single day maximum duration of ~ 7.5 hours.

Plasma formation in superconducting tokamaks requires strong pre-ionization, i.e., partial breakdown of hydrogen gas before applying the tokamak electric field for plasma current ramp-up. In SST-1, this is achieved by launching an electron-cyclotron (EC) wave using a 42 GHz Gyrotron source of 100–300 kW. As a result, a maximum plasma current of ~98 kA has been sustained for ~0.65 seconds in SST-1 assisted by Lower Hybrid Current Drive. The SST-1 tokamak is constantly improving its plasma performance and efforts are on to enhance the plasma duration beyond 1 second, with the help of the Ohmic, ECR pre-ionization and LH current drive in the coming experimental campaign.

V Fusion Plasma Diagnostics

Due to its high temperature, measuring devices cannot be inserted into a tokamak plasma. Hence it requires specialized diagnostic techniques and equipment for measuring its properties mostly from external measurements, such as density, temperature, magnetic and electric fields, radiations etc. Laser based diagnostics, such as the Thomson scattering system, based on collecting laser light scattered by thermal electrons are used to measure the electron-temperature and density. Tokamak plasmas radiate over the entire EM spectrum, covering hard X-rays, soft X-rays, UV, visible, IR and microwaves. These measurements are interpreted using sophisticated software to yield plasma parameters. The total radiated power is measured using bolometers. NaI-, CdTl-, LaB6-detector based systems have been used for hard X-ray measurements, whereas AXUV and surface barrier diode detectors are developed for soft X-ray measurements. Several spectroscopic systems in the visible and VUV regions have been designed and developed in-house for the measurements of emission from fuel and impurity ion/neutral species. Furthermore, for measuring the plasma density independently, heterodyne and homodyne microwave interferometer systems have been developed. The neutral particles coming out of the plasma are detected by a neutral particle analyzer (NPA) to obtain the ion temperature of the plasma. A fast visible camera gathers the images of the edge (low-temperature) region of the tokamak plasma, whereas an IR camera is used for measurement of temperature rise of the plasma-facing surfaces inside the tokamak. Numerous magnetic and Langmuir probes are deployed for magnetic and electric field measurements inside and outside the plasma.

VI Fusion Technologies

(a) High power RF systems:

Passage of a large toroidal current in a tokamak leads to joule heating. But this Ohmic process is very inefficient above a temperature of 30 million K, as the plasma resistance falls rapidly with rise in temperature. Therefore, auxiliary heating power is required to raise the plasma temperature beyond 30 million K. RF waves transfer electromagnetic energy to the plasma electrons and ions gyrating in the magnetic field through resonance processes. The RF waves are also required for maintaining the plasma current to provide plasma equilibrium in tokamaks.

Furthermore, in superconducting tokamaks like SST-1, RF waves are required to produce the seed plasma for initiating a tokamak discharge. Hence, simultaneously with tokamak development, several RF-based heating and current-drive technologies such as Electron Cyclotron Resonance Heating (ECRH) system, Ion Cyclotron Resonance Heating (ICRH) system and Lower Hybrid Current Drive (LHCD) system have been developed and used in IPR tokamaks. The plasma current in the SST-1 tokamak is driven using the LHCD system, which is based on klystrons and can deliver continuous wave (CW) power of ~1 MW at 3.7 GHz. A 42 GHz Gyrotron based ECRH system, which can deliver 500 kW power, caters to both the ADITYA-U and SST-1 tokamaks. The ECRH system is used for producing the seed plasma in both the tokamaks as well as for heating the plasma when it is fully formed. A tetrode-based ion cyclotron resonance heating (ICRH) system has been successfully tested at a maximum power of ~ 500 kW (CW) [maximum power ~1.5 MW (CW)] in the range of 20 - 47 MHz.

(b) Neutral Beam Systems:

The plasma in a tokamak can also be heated by injecting energetic neutral particles (NBI). An Indian Neutral-beam Test Facility (INTF), a R&D facility, is under development in IPR which will support IPR's negative ion beam based neutral beam injector (NBI) system development program. As part of the INTF system, an ultra-high-vacuum class stainless steel vacuum vessel that is 9 m long and 4.5 m in diameter with a top openable lid has been manufactured, tested, and installed at IPR to generate a diagnostic neutral beam. It is a first-of-its-kind facility in India, with a beam transport length of ~21 m. The IPR scientists designed the beam dump to absorb the ion beam power up to 6.1 MW using hyper-vapotron technology. Its construction is based on heat transfer elements made of CuCrZr material which has been developed under MoU with NFTDC, Hyderabad.

(c) Power Supplies:

Sophisticated Power supplies capable of delivering various power outputs (kW to MW) are the backbone of fusion research. Regulated High Voltage Power Supply (RHVPS), capable of delivering several megawatts of power are used for driving the RF and NBI systems at IPR and in ITER. RHV power supplies for diagnostic neutral beam (10 kV, 140 A extraction PS, 90 kV, 70 A acceleration PS), ICRH driver-stage / end-stage PS (8-18 kV, 250 kW / 27 kV, 2.8 MW) and ECRH PS (55 kV, 5.5 MW) towards India's commitment to ITER are under development. ITER India has already supplied a 100 kV, 70 A power supply to the RFX Consortium, Padua, Italy, to support the ion beam acceleration from the SPIDER beam source on the SPIDER testbed, which is under regular operation.

(d) Material Testing for Plasma Facing Components:

Material components which come in contact with the high-temperature plasma are subjected to very high heat loads of several MW/m^{2}and also the fusion-neutron flux. The suitability of the armor materials for fusion machines is tested in the High Heat Flux Test Facility (HHFTF) at IPR. In this facility, testing of heat removal capability and operational life time of plasma facing materials and components for tokamaks including ITER is carried out. A tokamak Divertor simulator device has also been developed indigenously for fusion relevant plasma surface interaction (PSI) research. This can reproduce ITER-like ion-flux (~10^{24} m^{-2}s^{-1}), heat-flux (~ 5×10^{6} Wm^{-2}) and ion-fluence (~3×10^{27} m^{-2}), under steady-state conditions at the CPP-IPR, Guwahati for testing and qualifying reactor-grade plasma-facing materials. An accelerator-based 14-MeV neutron generator facility (design yield ~5x10^{12}, present yield ~7 x 10^{11} neutrons/second) has recently been setup at IPR and will be made operational after regulatory approval.

(e) Remote Handling:

One of the challenges of a big machine like ITER is in-situ inspection and repairs and require advanced remote monitoring and handling of different systems and subsystems mounted inside the vacuum vessel. IPR scientists have developed an In-Vessel-Inspection System (IVIS) to perform remote in-service inspection inside a toroidal vacuum vessel. The IVIS can work in ultra-high vacuum and at 100 °C temperature in a noisy tokamak environment. IVIS is now being integrated with an Immersive Virtual Reality "Cave" facility at IPR.

(f) Tritium Permeation Barriers:

Indigenous development of tritium-permeation-barrier coating is another critical development infusion technology. Since tritium, a fuel gas of fusion reactors, is expensive and highly radioactive, a coating of the reactor walls with a Tritium Permeation Barrier reduces its leakage through metals. A magnetron-sputtering based coating system has been developed in-house, which coats Erbia (Er_2O_3) on stainless steel, obtaining a 100-fold reduction in the hydrogen permeation rate through stainless steel. Towards its tritium breeding blanket development program, a Pb-Li experimental loop has been fabricated and assembled at IPR, which has successfully demonstrated reduction in Pb-Li flow rate in the presence of magnetic field.

(g) Tokamak Fueling and Evacuation Systems:

Efficient fueling of a fusion reactor requires pellets of frozen fuel gas to be injected into the burning plasma. A single barrel pellet injection system has been developed and installed in the SST-1 tokamak. Cylindrical pellets (volume ~5 mm^3) made of hydrogen ice are formed in-situ in a barrel, for subsequent acceleration and launching into the tokamak. Another significant accomplishment towards attaining 'Atmanirbharta' in the field of vacuum technology is the indigenous development of liquid nitrogen cooled cryo-pumps for ultra-high vacuum applications in tokamak, defense and space sectors. These pumps are used in SST-1 tokamak and have also been delivered to the Space Applications Centre (SAC-ISRO), Ahmedabad.

(h) Cryoplant:

Recently, a prototype helium Cryo-plant, with a large indigenous content, has been developed and operated with encouraging results, boosting the 'Make in India' initiative.

VII India's Participation in ITER

The indigenous progress made by India in tokamak research paved the way for joining the ITER mega-project. The ITER is an experimental fusion reactor for realizing the scientific & technological feasibility of nuclear fusion as an abundant source of energy of future. The ITER facility is under construction in Cadarache in France. An agreement, known as ITER-agreement, between the seven partners was signed at the Elysée Palace in Paris on 21st November 2006 (Dr. Anil Kakodkar, the then Chairman, AEC signed on behalf of India). ITER partners are the European Union, China, India, Japan, South Korea, Russia and the USA.

The largest component of the ITER reactor, the cryostat, the giant vacuum vessel enclosing the entire tokamak, has been supplied by India. The cryostat, weighing over 3,800 tons, was made by M/s Larson & Toubro at its Hazira, Gujarat Unit. The Cryostat Base section has already been installed in the Tokamak pit at the ITER site on 28 May 2020, as shown in figure 3. The base structure, 29 m in diameter and 6 m tall, weighing ~ 1250 tons, has been placed with less than 3 mm positional accuracy. The 2nd of the 4 sections of the cryostat, the lower cylinder was also

Figure 3: Cryostat base of ITER at ITER site, manufactured in INDIA

successfully lowered onto the base section of the cryostat. Special welding techniques and weld inspection methods have been developed to meet the stringent dimensional control tolerance of 0.3% and sub-mm flatness control accuracy over 30 m size. The in-wall shielding, made up of borated steel (SS304B4, SS304B7) and ferritic steel are also been made in India by M/s Avasarala Technology Ltd. and M/s Larsen & Toubro, under the supervision of a team of IPR engineers. This in-wall shielding is required for shielding the fusion-neutron and also for reducing the ripple in toroidal field. ITER-India has also delivered and installed 4 km long cryo-lines and 7 km long warm-lines at the ITER site.

Several other in-kind components are under development and fabrication in ITER-India including 9 Ion Cyclotron Resonance Frequency sources of 2.5-3 MW; two Gyrotron sources, each having 1 MW power output at 170 GHz with a pulse length of 3600 seconds for the ECRH system of ITER, along with few advanced diagnostics. While the vacuum tubes for these systems are imported, there is a large indigenous component as well.

VIII Plasma Based Societal Technologies and spinoffs of Fusion research

Apart from Fusion Technology development, both for ITER and as part of the domestic program, IPR has a long-standing, focused program for developing plasma technologies for a variety of societal applications in the field of surface-engineering, Processing of Minerals, waste management, medical/health, agriculture, textile, industrial, space and defense. IPR has been actively involved with industries and external agencies on collaborations in the aforementioned fields to deliver technological solutions for the user. For facilitating need-based technology development for societal applications, a separate center named "Facilitation Centre for Industrial Plasma Technologies (FCIPT)" had been established in 1997 in a separate campus in the Gandhinagar industrial area. FCIPT takes up the development of plasma processing technologies from concept to commercialization, facilitates close interaction with entrepreneurs and organizations, and promotes awareness of the applications of plasma technologies. Over the years, the FCIPT has developed and transferred several plasma technologies to Indian and foreign industries. An overview of IPR's activities in these areas is shown in Figure 4.

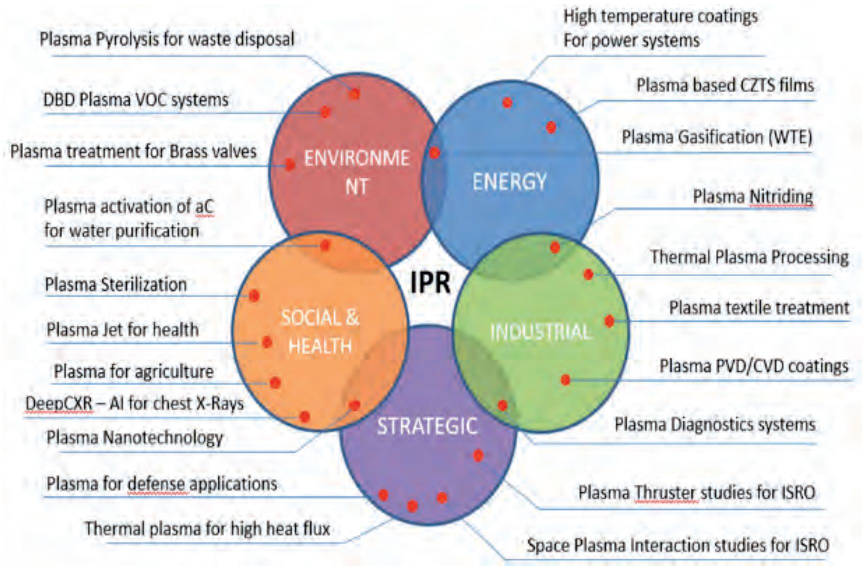


Figure 4: IPR's activity landscape on plasma technologies developed for various sectors of Industry/society

Incorporating atomic nitrogen on metal surfaces by immersing them in nitrogen-hydrogen plasma, known as plasma-nitriding, produces a hard, wear-resistant surface. FCIPT houses different sizes of plasma nitriding reactors to suit various industrial tools, gears, machine parts etc. FCIPT also houses the 3rd largest Plasma Immersion Ion Implantation (PIII) set up in the world for nitrogen incorporation in unique materials. Other surface treatment techniques include plasma surface treatment to produce improved adhesion of rubber to brass for the manufacturing of valves, CZTS-based solar cell production using sputtering, Teflon-coating for large-sized elastomer seal, plasma-based TiN coating system, plasma synthesis of advanced ceramics, plasma polymerization system to coat brass articles for Moradabad cottage industry. The coatings are characterized and tested with the state-of-art diagnostics including the SEM, XRD, XRD, XPS, AES, and SIMS etc.

Plasma pyrolysis is a process by which any organic mass can be thermally disintegrated into hydrogen, CO and lower hydrocarbons in an oxygen-starved environment. Plasma pyrolysis completely eliminates the formation of toxic molecules such as dioxins, furans, poly-aromatic hydrocarbons etc. unlike its conventional incinerators counterparts. Hence, it is an environmentally friendly process for the safe disposal of waste. The advantages of plasma pyrolysis are chemistry-independent heat generation, fast heating and fast quenching, pathogen-destruction by high ultraviolet radiation flux, high processing rates and compact reactors. It works equally well with dry or wet wastes, and most importantly recovers energy in the form of CO and H_2. Several Plasma pyrolysis systems have been developed, fabricated and delivered to different organizations by FCIPT-IPR for safe & eco-friendly disposal of biomedical waste (BMW), Municipal waste & Solvent waste, energy recovery from crude oil residue, ceramic catalyst for ozone treatment. For safe disposal of BMW, Plasma pyrolysis is approved under the Gazette of India.

Significant progress has been achieved in the application of plasma-based technologies in the medical & health sector with the development of Portable plasma-jet for sterilization of surfaces, Nano-coatings on PPEs for anti-viral and anti-bacterial properties, for treatment of fungal skin infections; for faster coagulation of blood; for cancer treatment; and a plasma-based air purification system. Preliminary results on a plasma-treated catheter surface have shown significant alteration of surface chemistry and morphology of catheter surface. 90% reduction in the bacterial adhesion on plasma-treated silicone catheter surface as compared to the untreated one, has been obtained. Automated detection of TB in chest X-rays has been carried out using an AI-based software, capable of running on mobile devices, by training it with chest X-rays from a large number of hospital/medical research centers.

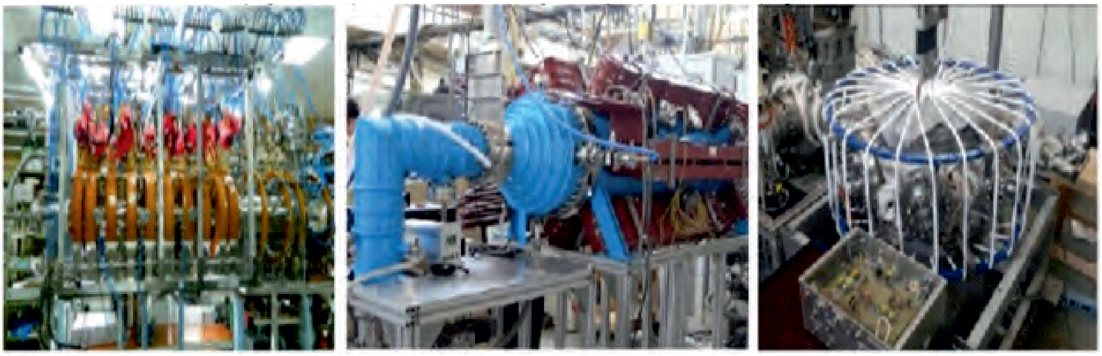
In the agriculture sector, several plasma-based systems are developed for increasing the life of agricultural implements using plasma nitriding, for pesticide removal from vegetables using plasma jets, plasma treatment of seeds for improved germination of seeds. Specialized plasma systems have been developed to process polyester fiber& Khadi for making them suitable for dying using natural dyes instead of synthetic dyes and to modify the surface properties of angora wool for commercial manufacturing of 100% Angora products. In a major thrust towards realizing the Make in India program, specialized electrodes for Plasma Spray systems, currently an import-item, are developed and delivered to Indian industry. These electrodes have yielded performance at par with imported electrodes.

Basic research in Helicon plasmas at IPR has led to the development of Plasma thrusters, which are one of the advanced means for satellite attitude control in space. A prototype helicon plasma thruster, designed, fabricated & operational at IPR, has successfully demonstrated a thrust of >90 mN with 5 kW RF power, using both electromagnets and permanent magnet-based operation with Ar gas. Upgrade to 10 kW is presently underway, and the existing system is equipped with a variety of advanced diagnostics for in-depth understanding.

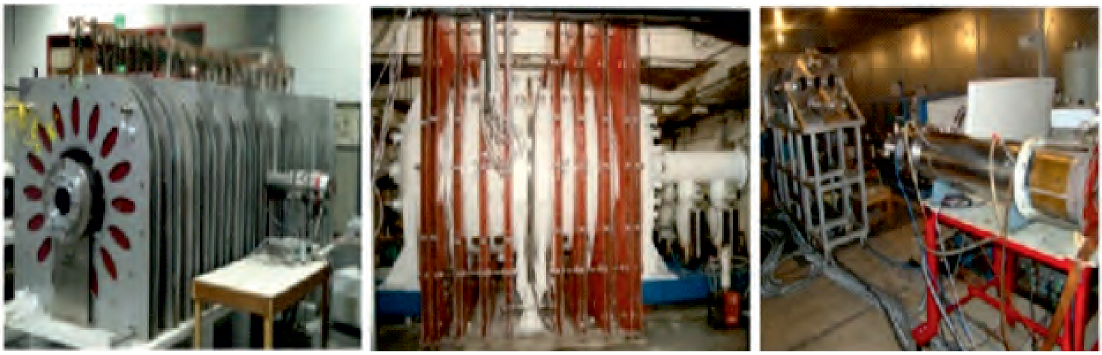
Based on its developmental capabilities in the area of large-volume vacuum systems, IPR has been chosen as a major contributor to the construction of the Laser Interferometer Gravitational-wave Observatory, LIGO-India project, the other partners being RRCAT Indore, DCSEM Mumbai and IUCAA Pune. The LIGO Division at IPR is responsible for designing, procurement, installation, and commissioning a vacuum system with a volume of ~ 10,000 m^3 operating in Ultra High Vacuum (~ 10^{-9} mbar) range. IPR is also designing and developing the Control and Data System (CDS) for the LIGO India project.

IX Basic Plasma Experiments

Basic research leads to new knowledge and provides scientific capital. IPR has continuously invested in many basic plasma physics experiments that verify new concepts and identify new paths for investigation. For example, research on a Helicon plasma device built by a PhD student in IPR has led to the development of a prototype Helicon plasma thruster system described in the previous section. At IPR, the major basic experiments are the BETA machine (a predecessor of ADITYA); Large-volume plasma device (LVPD): where space plasmas are experimentally simulated; Non-neutral toroidal plasma - applications of which include: precision atomic clocks, trapping of antimatter plasmas and antihydrogen production, quantum computers etc.; Dusty plasma experiments: throwing light on interplanetary space dust, comets, planetary rings, dusty surfaces in space, and aerosols in the atmosphere etc.; Experiments on negative-ion sources: for generating high power neutral beams, Inertial Electrostatic Confinement Fusion (IECF) Device: a neutron source with several applications, and so on. Pictures of a few devices are shown in Figure 5.



Inverse Mirror Plasma
Quiescent Plasma
Non Neutral Plasma



APPEL-Device
Large Volume Plasma Device
Microwave-Plasma interaction

Figure 5: Basic experimental devices at IPR

X Theoretical and Computational Research

Since the beginning, IPR has been pursuing a vibrant program on theoretical analysis and computer simulations in fundamental plasma science, fusion research; space and astrophysical plasmas; and plasma technology. As a result, several important discoveries have been made in the field of fusion and tokamak plasmas, Laser-matter interaction and inertial fusion, dusty plasmas, magnetohydrodynamics (MHD), electron-MHD, coupled limit-cycle oscillators and so on and are published in several renowned international scientific journals including, Physical Review Letters and Nature Communications.

It has been shown for the first time that plasma wave breaking leads to the generation of second harmonic and hard X-rays in ultra-intense ultrashort laser pulse-plasma interaction. Studying the dynamical behavior of two limit cycle oscillators that interact with each other via time-delayed coupling, it has been shown that even if they have the same frequency, the time delay can lead to amplitude death of the oscillators. An important application of this concept is in the assembly of cardiac pacemaker cells where cessation of rhythmicity can lead to a disaster.

A plasma with suspended nanometer or micrometer-sized particles in it, is known as dusty plasma (or complex plasma). Dusty plasmas are found in comets, planetary rings, dust in interplanetary space, interstellar and circumstellar clouds, laboratory plasmas and even in the tokamak edge region. The dusty plasmas are of particular interest as they can form liquid and crystalline states, plasma crystals. Notably, one can view the dynamics of the charged dust grains even with the naked eye. IPR scientists have pioneered the modelling of the dust dynamics using the generalized hydrodynamics description to show the influence of strong correlations on low frequency collective modes in a dusty plasma.

Towards a noted contribution to the 'Atmanirbhar Bharat', a faster and superior state-of-art computer code, ACTYS has been indigenously developed by IPR scientists to carry out nuclear activation analysis of fusion system. The code has been approved by ITER for its usage in ITER. Furthermore, continuing with its long-standing focus on high-performance computing facilities, IPR now hosts a 1-Petaflop HPC facility, which is ranked 11th in the country (as on July 2020) in terms of its computing power. This HPC system is named 'ANTYA' (meaning 10^{15} in Sanskrit) and has more than 10,000 cores that can perform 10^{15} Floating-point Operations per Second (FLOPS). ANTYA has been used extensively for fusion and basic plasma research in IPR. An example of simulations carried out in ANTYA on tokamak plasma and basic plasma is shown in figure 6. The figure shows the interaction of the magnetic islands in a plasma.

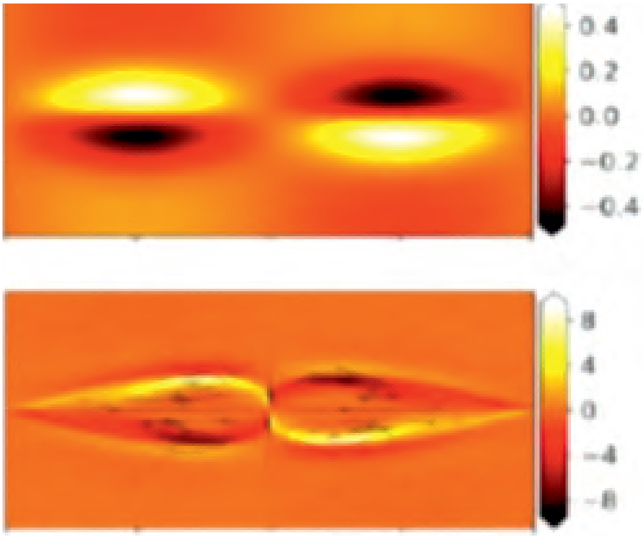


Figure 6: Interaction of magnetic islands

XI Summary and Future Directions

IPR is the main repository of plasma/fusion science and technology in India, having produced 159 PhDs and published more than 3500 research articles in national/international journals and conferences. Simultaneously, 60 patents have been filed from IPR on technological innovations. IPR has nurtured strong collaborations with various R&D organizations, the corporate sector, research institutions, IITs/Universities and colleges to develop user-specific technologies through contract research, equipment development and supply, technology transfer & consultancy, feasibility study investigations etc. A recently-drafted 25-year roadmap envisages the indigenous development of fusion technologies, the construction of a spherical tokamak-based Fusion Neutron Source and later of SST-2, a national program linking societal technology development in IPR with domain experts in medicine/health, waste disposal, agriculture, industry, defense, aerospace etc., and new directions in basic plasma research.