MP3-Nuclear Power Programme – Stage-3

3.07 Immediate Societal Benefit Programme and Long term Fusion Reactor Programme

3.07-0100 Immediate Societal Benefit Programme

I Facilitation Centre for Industrial Plasma Technology (FCIPT-IPR)

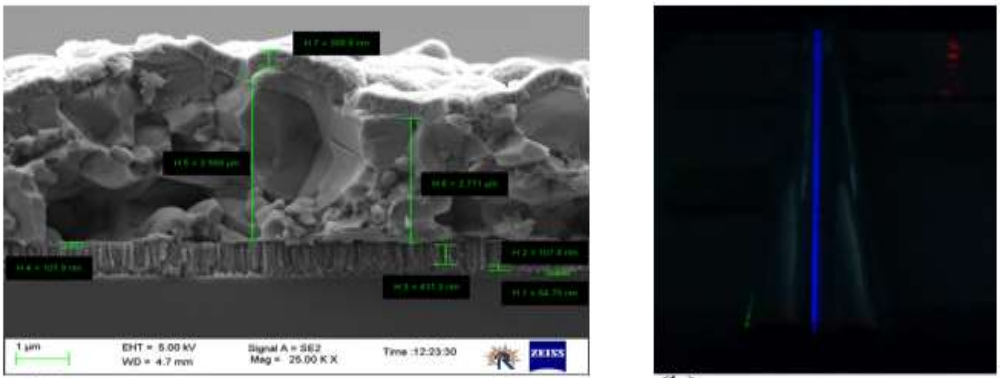
Sponsored Projects and Ongoing Activities

- DST has funded project on development of radical nitriding process for improving the life of cutting tools of agricultural implements. In this project, radical nitriding system has been developed and actual agricultural tools are nitrided. They have been sent to DST, Nagaland for field evaluation.

(a) (b)

Fig: (a) radical plasma nitriding system developed in FCIPT and (b) radical plasma nitrided agricultural tools.

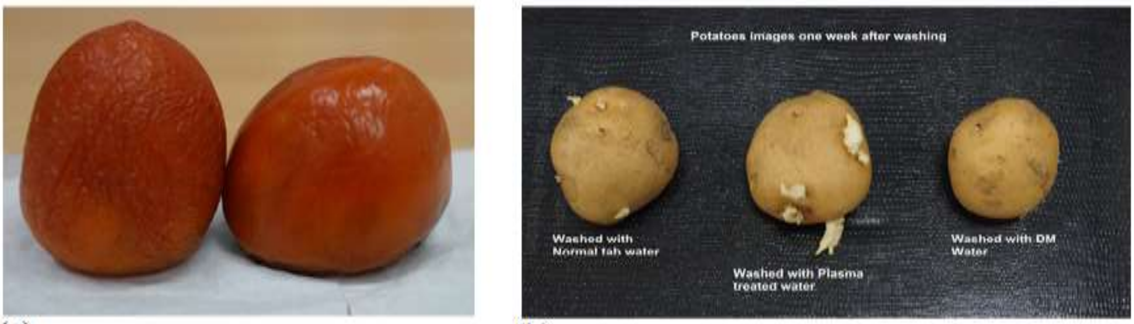
- ISRO sponsored project on design, manufacturing, testing and installation and commissioning of plasma nitriding system at IISU-ISRO, Trivandrum. Material procurement and testing of items have been initiated.
- DST funded project on development of CZTS based solar cell using magnetron sputtering involves preparation of CZTS (Cu_2ZnSnS_4) based solar cell using magnetron sputtering. First Mo deposited on soda lime glass using DC magnetron sputtering then Cu, Zn, Sn layer deposited by DC-Co-Sputtering Followed by sulfurization in a Sulphur and Nitrogen mixture environment. Studies on junction properties and optimization for improvement in efficiency are going on.
- Work on DST funded FCIPT-TEX project has been carried out. An MoU is signed between IPR Gandhinagar and MANTRA Surat for the scope of work. MANTA surat has contributed Rs. 20.0 Lacs in kind in equipment head. Designing of the mechanical reactor for treatment of 2.5 meter wide textile is over and procurement is under progress. This reactor has web guiding mechanism to control linear speed up to 60 meter per minute. Testing of DBD plasma generation across 2.5 meter wide electrode is completed for continuous operation of 12 hours.



(a) (b)

Fig: (a) SEM image of solar cell cross section for CZT+ Sulfurization and (b) DBD plasma across 2.5 meter electrode.

- In an Amrita University funded project on development and fabrication of plasma based TiN coating system, the system has been integrated and tested in FCIPT and its installation at Amrita University, Coimbatore is over.
- In a DST sanctioned project on development of novel biomedical implants with enhanced reliability, objective of developing plasma nitriding and Ti-TiN multilayer coating on prototype SS and Ti alloy implant samples is successfully completed.
- In an FCIPT based project, microwave coal gasification activity is initiated. Successful testing of 5kW power coupling to the reactor is demonstrated. Presence of hydrogen and carbon mono-oxide by microwave gasification has been tested using gas chromatography. There is an increase by 5 times in generation is observed. The powder feeder reactor is being redesigned to get more temperature for continuous gasification by using low grade Indian Coal.
- In an internal activity of FCIPT, work on water activation was initiated. The water was exposed to active species generated by DBD plasma and plasma jet. It was observed that chemical properties of water has improved to get better germination in food product and for better preservation. A clear indication of surface preservation of tomato and germination in potato using plasma treated water is observed.



(a) (b)

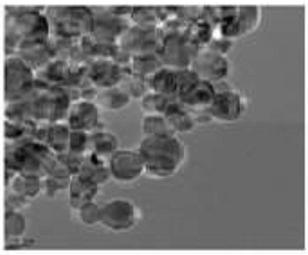
Fig: (a) the images of tomatoes after washing with untreated and plasma treated water are shown. The images are taken after 40 days of treatment and (b), the image of potatoes is shown taken after 7 days of treatment.

- An interesting internal project on which FCIPT has contributed significantly is the production of nano-particle. Work is carried out on cobalt and iron nanoparticles under various plasma parameters. A detailed study on the both atomic ordering and macroscopic morphological features were carried out. X-ray scattering analysis has estimated the size and shape diversity for various samples prepared.
- In pursuit of developing a 100kW plasma torch, FCIPT has successfully demonstrated a DC, non- transferred plasma torch (power ~ 85 kW across the electrodes and efficiency (>70%)) for steady-state operation. Role of gas flow configurations on the torch electro-thermal efficiency was also investigated. Numerical model of plasma torch was upgraded to include complex torch geometries; simulation was carried out and validated against experimental results. Studies were carried out to investigate the dynamical behaviour of the plasma in the torch using fast imaging and spectroscopy.
- A very significant societal benefit initiative of FCIPT is the plasma nitriding of Cut-tear-curl (CTC) tea roller to increase its service life and reduce the Chromium content in tea leaves. A plasma nitriding treatment of CTC roller in FCIPT is carried out and the facility is sent to Assam for field trials. Optimization of plasma nitriding experiments after field results will begin.

Technology Transfer

- "Atmospheric pressure plasma jet technology" transferred to M/s Aditya High Vacuum Pvt. Ltd., Ahmedabad on 23rd June 2016. FCIPT has developed state of art atmospheric pressure plasma jet using dielectric barrier discharge. Dermatologists at Institute of Post Graduate Medical Education and Research (IPGMER) Hospital, Kolkata have used this Plasma Jet for the treatment of fungal infection on human skin.
- " Metal oxide nano powder production technology" transferred to M/s Plasma & Vacuum Techniques, Ahmedabad on 8th July 2016. FCIPT has developed a plasma based instrument that can produce metal oxide nano powders in bulk quantities.

Plasma Jet on feet infected with Tinea Cruris



TiO2 nano particles 20-40nm

Dr Shashank Chaturvedi, Director, IPR(centre) and Mr Ashok Vora, Bhakti Energy(right), exchanging Technology transfer documents

- " Plasma Pyrolysis technology for organic waste" is transferred to M/s Bhakti Energy, Rajkot on 29th August 2016. FCIPT, IPR as a part of its contribution to Swatch Bharat Mission is expanding the use of Plasma Pyrolysis technology for the waste disposal. This technology is also transferred to M/s G P Green Energy Systems Pvt. Ltd., Kolkata on 7th December 2016.

- " Atmospheric pressure inline plasma processing technology" transferred to M/s Arshad Electronics Pvt. Ltd., Mumbai for treatment of textile and plastic film treatment on 9th November 2016.

Projects with International Collaboration

- CZTS based plasmonics solar cell (Indo-UK program): Experimental work carried out by Indian group was validated and understood by UK group in Loughborough University through theoretical simulations. This work presented a nice understanding of silver nanoparticle growth on patterned substrate for plasmonics solar cell application. Experimental results matches well with theory. This was the first time sticking behaviour of silver atoms were investigated both experimentally and in simulation.

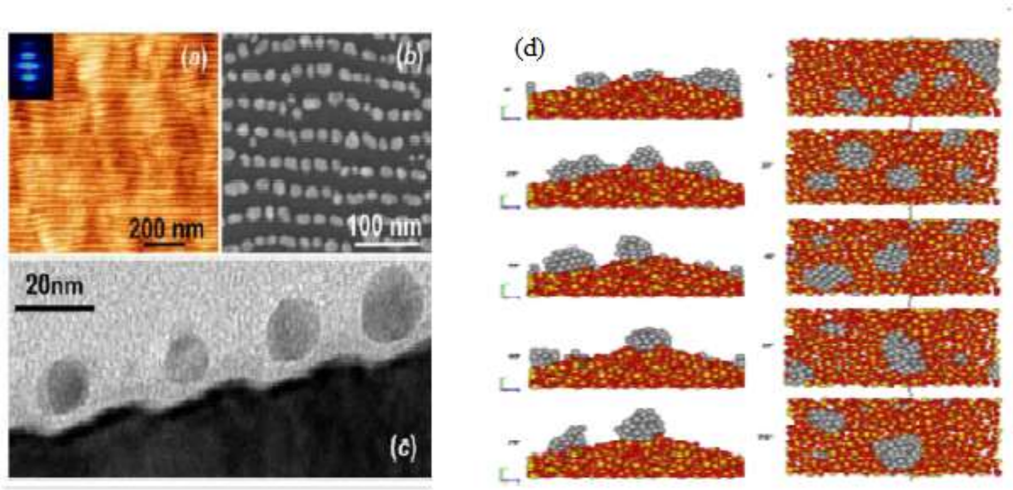


Fig: (a-c) AFM, SEM and TEM images of experimentally produced ripple like patterned (~ 30 nm), grown silver nanoparticles on ripple pattern and their cross-sectional images, showing the perfect alignment of nanoparticles chain. Subplot (d) on the right side shows final snapshots from the cumulative deposition of silver on the rippled silica surface at different AOI.

Patents

- Apparatus for water treatment to activate water using atmospheric pressure hybrid plasma system.
- Provisional patent on Nanoparticle generation by thermal plasma.

Awards

- Dr. S. Mukherjee elected as fellow by Gujarat Science Academy (GSA),Gujarat

Technology Awareness Workshops

- "Thermal Plasma & its Industrial Applications" on 29th April 2016.
- "Plasmas for Societal Benefit' on 21st October 2016.

II Remote Handling and Robotics Technology Development (RHRTD)

The scope of this project is to build a versatile Remote Handling System for Indian fusion devices and for short term societal beneficial programmes. The development of the technologies and subsystems required will be facilitated in collaborations with external agencies and institutions. The RHRTD division focuses on the virtual reality development, viewing applications, a higher payload (25Kg) articulated arm and RH control system applications development.

- **Development of Virtual and Augmented Reality Integrated Development Lab(VARID- LAB)**

A low cost solution for Virtual Reality facility has been conceptualized and work initiated in its realization at the remote handling and robotics division. This facility – VARID-Lab will be utilized to develop various virtual and augmented reality applications and will have the flexibility to integrate with remote handling equipment's. This facility will serve as a multi facet platform for various tasks namely, 1) rapid design reviews for RH equipment and schemes of existing and future tokamaks at IPR, 2) for application development of specialized VR applications that are not commercially available, 3) to integrate design and analysis tools (like finite element code, multi body dynamics, etc.) into VR, 4) to develop and integrate applications from other domains like haptic feedback, image processing and real time physics into VR, 5) for application development and testing for real-time robotic hardware linked virtual and augmented reality and 6) to work as centralized control facility with modular architecture for operator training and executing of RH operations.

Development of Various Virtual Reality Applications for Remote handling and Robotics

VARID-Lab, since its inception is consistently in use for various designs and control activities for RH systems at IPR. Some of the virtual reality (VR) based applications developed, integrated and tested in the VARID labs are briefly accounted here.

VR Based Control and Monitoring of RH Equipment Operation

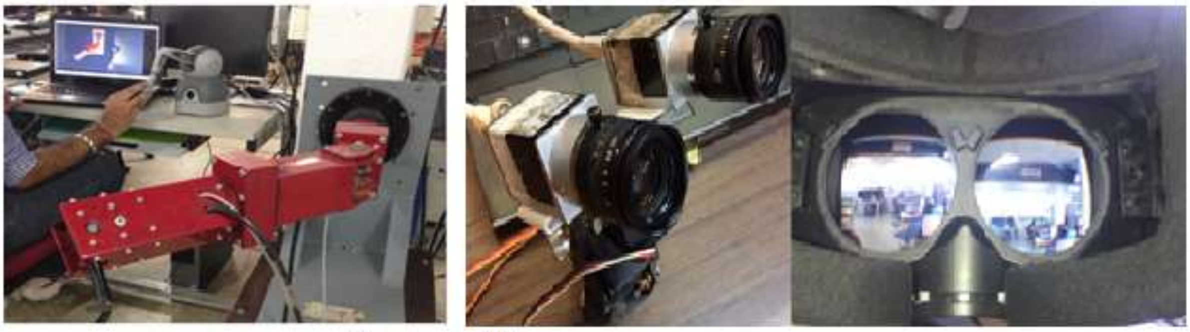
VR control and monitoring application is created for all available RH equipment at IPR. A specialized control network and application is created to receive the joint data from the equipment and constantly update a VR model at ~8Hz. The camera view and the VR monitoring give a comparison of the actual robot position and the VR model position. The VR monitoring for ABB Control from VARID Lab is as shown below.

(a) (b)

Fig: (a) VARID-Lab Setup under Operation and (b) VR monitoring for ABB Control from VARID Lab.

Bilateral Force-Feedback Control Mechanism Development

A comprehensive master-slave topology with active haptic and visual feedback to carry out remote handling operations in tokamak is realized. The master-slave topology is realized using commercial of the shelf (COTS) products. A virtual reality environment is developed using open source software for the purpose of operator training and tracking of live operations. A reasonable synchronization (time lag $\leq$ 20ms) between the master-slave angular displacement responses is achieved.



(a) (b)

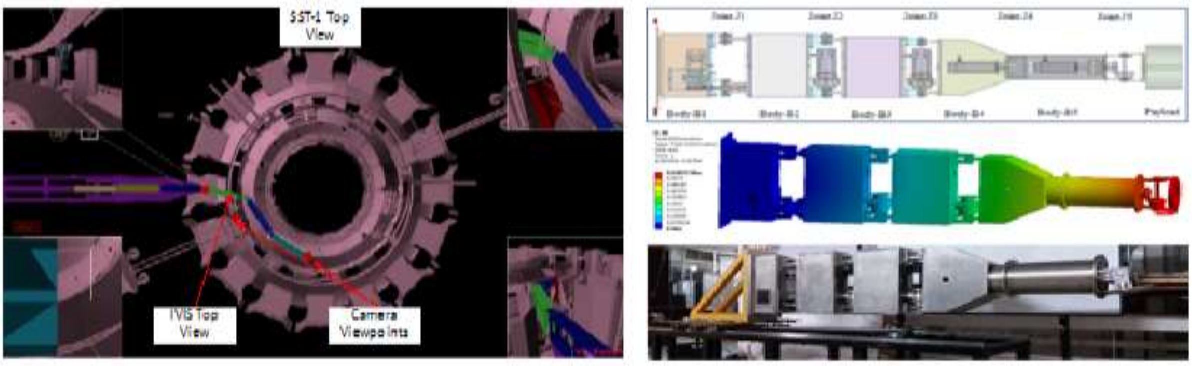
Fig: (a) Active master-slave force feedback development and (b) in-situ immersive viewing.

In-Situ Immersive Viewing

In many critical RH operations, the main requirement is to provide the operator the same unrestricted view of the task at the remote location as the operator would feel being present at the task location. A prototype has been developed for in-situ immersive viewing. The movement of the head is captured and sent to the gimbal mechanism to position the cameras as per the direction of view of the operator.

VR Based Operation Sequencing

Routine applications like deployment and retrieval of RH equipment from tokamak systems have used teach and play algorithms. In such algorithms a VR model of the RH equipment is trained to follow a particular path based on the available constraints. The cameras mounted on the actual system are simulated with the VR model to check the visibility range within the environment.



(a) (b)

Fig: (a) VR based path planning training of IVIS and (b) commissioned PRAS-II system.

Development of Prototype Articulated Robotic System –II (PRAS-II)

The RHRTD team has designed and commissioned PRAS-II system. This system is a 5+1 DOF equipment exhibiting snake like articulation for traversing a toroidal workspace. The system will be integrated to haptic controlled virtual reality setup for online control, tracking and monitoring of operations. The major achievements from this development are namely, 1) it can handle a payload of ~25kg at reach of 2m with positional accuracy of < 2mm, 2) the system proves the expertise of the IPR RHDTD Division to design and develop precise remote handling equipment with heavy payload capabilities, a major requirement for future tokamak devices, 3)the unique real time VR based control and monitoring system makes it easy to use the system in remote locations, and 4) the deployment of PRASII for tile inspection inside mock-up torus.

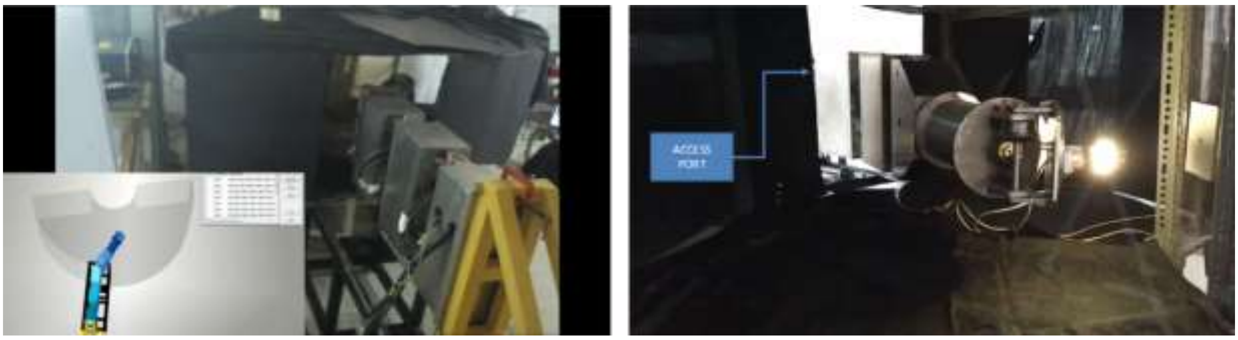


Fig: Deployment of PRASII for tile inspection inside mock-up torus

Development of Prototype Hyper-Redundant Inspection System (Hy-RIS)

Prototype 3-Axis tendon controlled Hyper-redundant robot for inspection in constrained spaces has been developed at the RHRTD Lab. Unlike conventional serial manipulator, where each joint has a motor mounted at its axis, the Hy-RIS has a universal joint. The motion of the universal joint is controlled using the plastic tendons which are connected to the motors mounted away from the robot body.

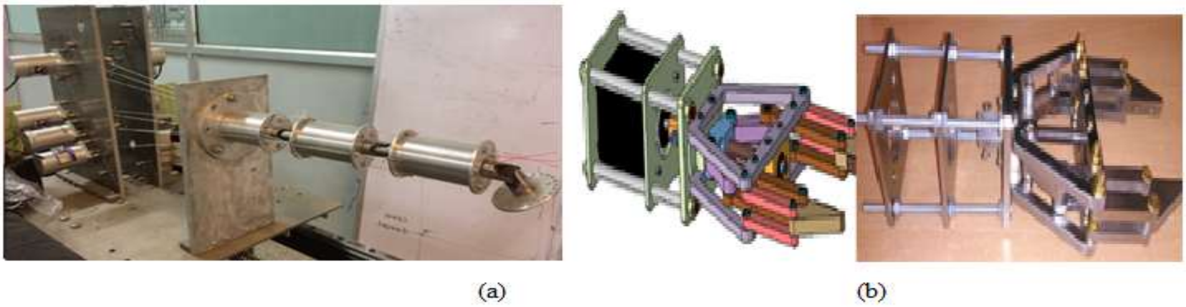


Fig: (a) Prototype Hyper-Redundant Inspection System (Hy-RIS) and (b) prototype gripper assembly.

Development of a Prototype Gripper Assembly

A Gripper Assembly was designed and developed at IPR. The gripper can lift up to 1kg of payload. The gripper has been integrated to ABB-industrial robot. It can handle a payload of 1 kg under gravity and payload of size 1-55mm.

Development of SST-1 Compatible In-Vessel Inspection System (IVIS)

An ultra-high vacuum (UHV) compatible (~1e-7mbar) and high temperature (~150^{o}C) visual inspection system, IVIS, is under development at RHRTD lab, IPR. It can be deployed in SST-1 like vacuum vessel during plasma campaign without breaking the vacuum. Presently, the system is under fabrication. The system is around 4.2m long and has a payload capacity of 1kg.

III Fundamental Plasma Sciences

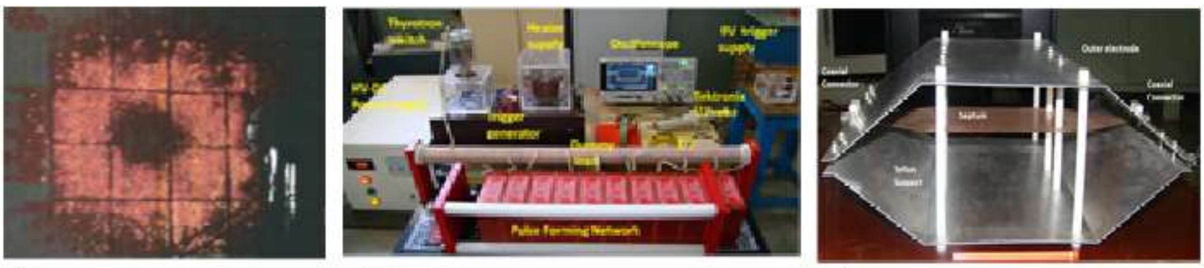
Large Volume Plasma Device (LVPD)

Focus of LVPD remains there on two fronts namely, 1) in carrying experimental investigations and 2) expanding for new developments. In order to understand anomalous plasma transport and loss in fusion devices due to electron temperature gradient (ETG) driven turbulence, considered as a major cause of plasma loss, we carried out investigations for particle transport by creating ETG suitable conditions in target plasma of LVPD. We report first observation of inward directed particle flux in ETG background from any linear device, which remains otherwise a subject matter of fusion plasma for theoretical investigations. Work on providing a theoretical explanation to these observations is underway. For developing complete understanding on plasma transport, energy flux needs to be addressed. Investigations on this are presently underway. In another significant experimental study concerning the earth’s atmosphere problem, the problem of loss mechanism of energetic electrons is addressed. In the source plasma (rich with energetic electrons) of LVPD, Quasi-Longitudinal Whistler turbulence is observed as an excited mode by the reflected energetic electrons. We consider that this may be the possible mechanism for the loss of energetic electrons in LVPD. In developmental front, the 40 channel, fast PXIe based data acquisition system is made operational in LVPD for actual data acquisition.

Fig: a) probe positioning system, 2) data logger for PPS and 3) 40 channel data acquisition system comissioned in LVPD.

SYstem for Microwave PLasma Experiments (SYMPLE)

The experimental investigations in Phase-1 and Phase-2 systems of SYMPLE has resulted in 1) enhancement in the plasma characteristics, 2)measurement of ~ 500 MW pulsed HPM power from the Backward Wave Oscillator (BWO), being developed as a part of the joined effort with BARC, 3) development and testing of in-house developed pulsed modulator for Magnetron and 4)setting up of calibration system for high frequency diagnostics. The plasma density of ~$1x10^{18}/m^3$ and profiles (axial and radial), as required for the wave-plasma interaction studies have been achieved. The BWO tube developed at BARC, by the APPD team has been tested with the pulsed power unit (KALI) of BARC. Measurements are carried out by IPR team using B-dot and D-dot probes. The output HPM power of ~ 500 MW (3 GHz, 30 ns pulse width) has been estimated. A fast rise time (400 ns) pulsed modulator (50 KV, 100 A, 5μs flat top) has been developed in-house to drive the Magnetron (3 GW, 3 GHz). A TEM cell has been designed and developed for calibrating the fast diagnostic probes.



(a) (b) (c)

Fig: 1) Neon glow pattern showing TM_{01} mode HPM output from the BWO, 2) Pulsed modulator developed in-house and 3) TEM Cell designed and developed for high frequency (~ 1 GHz) e.m. excitation and calibration.

Interaction of Low Energy Ion and Neutral Beams with Surfaces

The new electromagnet in its final form is installed and plasma density exceeding by twenty times of old value is obtained. The maximum density obtained is 2.2 $x10^{13}$ cm^{-3}. We expect a similar increase in neutral flux. An inexpensive low energy neutral beam observation system based on micro channel plate and phosphor screen is procured and will be used to detect neutral beam in new UHV system.

BETA

In simple toroidal device like BETA, the plasma profiles and properties depend on toroidal magnetic field topology. Interestingly, for nearly closed field lines, which are characterized by large values of mean parallel correlation length, Lc, it is found that flute-like coherent structures dominates which are accompanied by large poloidal flows. For small values of Lc, the mean density on the high field side (HFS) is seen to increase and net poloidal flow reduces while at the same time a turbulent broad band in fluctuation spectrum is observed. A strong relationship is observed between Lc, flows and fluctuations. The observed imbalance between the mean flow, fluctuation driven flow and net flow is addressed.

Accelerator Division

Development of Li plasma source based on heat pipe oven configuration with extended uniform temperature profile is being carried out at IPR. A new wick with internal spring-load was designed, developed and tested successfully to avoid nucleation of Li vapor in the HPO system. Optical diagnostic techniques like UV and white light absorption, and spectral interferometry (Hook Method) have been used to measure the Li vapor column density as a function of external heating temperature and Helium buffer gas pressure. A new prototype Lithium HPO (40 cm long) with moveable heat sink on both the sides has been developed in IPR. For an accurate determination of Li vapor column density, spectral interferometry (Hook method) was implemented with the new HPO in one arm of the interferometer. Experiment on uniform Li plasma column production using 193 nm ArF excimer laser was initiated during this period.

Fig: A new HPO with movable heat sinks on either side. The inset shows the moveable heat sink in the system.

Dusty plasma

Dusty plasma experimental device is setup IPR to study flow induced excitations of linear and nonlinear waves/structures in a complex (or dusty) plasma. In this Π-shaped apparatus, a dusty plasma is created in DC glow discharge and micron sized dust particles are introduced.

A flow of dust particles/fluid is generated by additional gas injection from single or dual locations or by altering the dust confining potential and flow velocity is estimated by super particle identification code, particle image velocimetry analysis and the excitation of dust acoustic wave techniques. In this plasma environment, the nonlinear solitary dust acoustic waves (DAWs) are excited by the supersonic flow of the dust particles over an electrostatic potential hill. Also, high velocity dust acoustic shocks are excited.

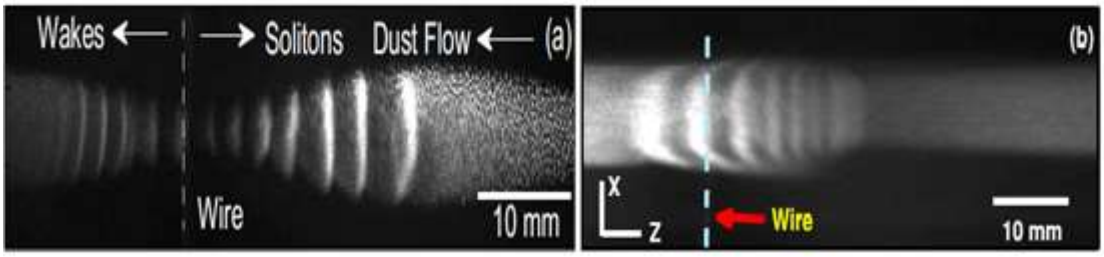


Fig: (a) Excitation of precursor solitons and small amplitudes wakes and (b) oscillatory shock wave fronts.

These experimental observations on shock formation can have potential value in understanding shock phenomena in space plasmas such as during solar wind interactions with the earth.

Magnetized Plasma Surface Interaction Experiments Division (MBPSI)

Magnetized Plasma Surface Interaction Experiments Division (MBPSI) is dedicated in carrying out research in the basic plasmas, plasma sources, and plasma sheath studies in magnetized plasmas. The relevance of these studies is useful for understanding plasma wall interaction in the fusion devices and development of plasma sources for industrial plasma applications. RF plasma sheath studies have relevance for ICRF antenna heating problem in tokamaks. The division has developed various subsystems namely, 1) Double Pulsed Nanosecond (DPN) Q-Switched Nd: YAG Laser system for negative plasma experiment, 2) Radio Frequency (RF) plasma system for study on ICRF antenna heating, 3) Applied Plasma Physics Experiments in Linear Device for understanding intensely magnetized plasma in the laboratory, 4) Pulsed Anodic glow plasma system (PAGPS) for studying the temporal characteristics of anodic glow plasma, 5) magnetically enhanced plasma discharges with hollow cathode for producing energetic particle beams, and 6) Inductive Coupled Plasma (ICP) for negative ion sheath studies.

Fig: Inductive Coupled Plasma (ICP) for negative ion sheath studies.

Non Neutral Plasma System (NNP)

The NNP system has undertaken long time confinement experiments. It was observed that the electron plasma in the system approaches magnetic pumping transport. The Toroidal Field (TF) coil is upgraded to produce magnetic field of 1.2 kG for time duration of ~ 3 seconds. In the up graded system, trap components and inner bore have been redesigned and fabricated. A query based database management system has been developed with protection circuits.

Basic Lab Facility

Several experiments dedicated towards developing better understanding of physical phenomenon's existing in atmospheric, astrophysical and fusion plasmas are developed. Inverse Mirror Plasma Experimental Device (IMPED) is one such facility dedicated for studying interaction of drift waves and Kelvin Helmholtz instability in a controlled manner. In dusty plasma investigations, the underlying physics behind the formation of rotating dust structures and vortices in dusty plasma is explored. In direct current glow discharge plasma, ionization waves are being studied.

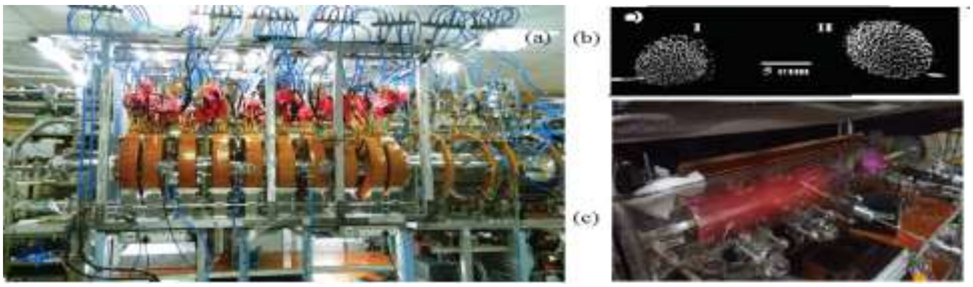


Fig: (a) indigenously developed IMPE device, (b) the images of the poloidal cross-sections of two counter rotating vortices and (c) picture of the direct current glow discharge plasma facility.

IV. Theory and Simulation

The activities can be broadly divided into four categories namely, 1) dusty/ complex plasma studies, 2) laser plasma interaction studies, 3) study of fast time scale phenomena, 4) non-linear plasma theory and 5) fusion related studies.

Dusty plasma/ Complex plasma studies

Investigation of nonlinear regime of dust vortex flow dynamics in plasma

A non-uniformly driven 2D flow of the charged dust suspended in plasma follows special class of volumetrically driven hydrodynamic systems representing a range of natural flow set ups. In agreement with observations in the experiments, it is demonstrated that the nonlinear effects appear in the limit of small viscosity where the primary vortices form that scale with the most dominant spatial scales of the domain topology and develop separated virtual boundaries along their periphery.

Sub-and super-luminar propagation of structures depicting strongly coupled dusty plasma medium

The strongly coupled dusty plasma modelled by the Generalized Hydrodynamic (GHD) model suggests that dipole structures are observed to emit transverse shear waves in both the limits of sub- and super- luminar propagation. A Poynting like conservation law with radiative, convective, and dissipative terms being responsible for the evolution of W, which is similar to "enstrophy" like quantity in normal hydrodynamic fluid systems has also been constructed for the incompressible GHD equations.

Laser Plasma interaction studies

Ion acceleration using nano-pore solid surfaces (with TIFR)

In the laser-plasma based ion acceleration schemes, generally all ionic species of the same charge-to-mass ratio are equally accelerated in the transient longitudinal static electric field formed by the interaction of intense laser with solids. Here, acceleration is seldom mass-selective. The possibility of manipulating such ion acceleration schemes to enhance the energy of one ionic species (either proton or carbon) selectively over another is investigated experimentally in TIFR with nano-pore targets (targets with nano-holes). At IPR, 2D-PIC simulations have been carried out taking into the TIFR experimental conditions.

Molecular dynamics simulations of laser-driven atomic cluster

Anharmonic Resonance (AHR) absorption of laser light is known to occur when the time-dependent frequency of a laser driven electron in the anharmonic electrostatic potential of a cluster becomes equal to the laser frequency. However, this mechanism is still a matter of debate. To examine AHR a three dimensional Molecular Dynamics (MD) code has been developed. We have studied multi-particle dynamics of the ionized cluster with electrons (e) and ions (i) interacting (with e-e, e-i, i-i interactions) via Coulomb potential.

Effect of laser wavelength on the laser absorption and ionization of clusters

Laser-cluster interaction experiments earlier have demonstrated enhanced absorption of laser pulses when the Mie-plasma frequency of the expanding cluster resonates with the laser frequency. However, controversial result exists in the literature where role of above linear resonance was absent, thus violating the physical basis of the plasma resonance. In this work, we study the impact of laser wavelength on the absorption of short laser pulses irradiating a deuterium cluster by three dimensional molecular dynamics (MD) simulations. Detailed studies are being carried out to understand the simulation results.

The stability of 1-D soliton in transverse direction

In this work, with the help of 2-D fluid simulation, it is shown that single peak and paired solutions also get destabilized by the transverse filamentation instability. The growth rate of the filamentation instability being comparatively slower than the forward Raman instability and this phase comes quite late but is clearly distinguishable.

Study of Fast time scale Phenomena in Plasmas (EMHD)

Particle-in-cell simulation of two-dimensional electron velocity shear driven instability in relativistic domain

Particle-in-cell simulations have been carried out to study the instabilities associated with a 2-D sheared electron flow configuration against a neutralizing background of ions for both weak and strong relativistic flow velocities. In the nonlinear regime, both weak and strong relativistic cases lead to turbulence with broad power law spectrum.

Nonlinear Plasma Theory and Simulation

Kinetics of nonlinear plasma waves and coherent structures in collision less plasmas

Kinetic effects determine the structure of hot plasma turbulence and transport. The interaction between nonlinear solitary electron phase-space holes is studied in the electron acoustic regime of a collision less plasma using multiple scale Vlasov simulations.

Relativistic electron beam driven longitudinal wake-wave breaking in a cold plasma

Space-time evolution of a relativistic electron beam driven wake-field in a cold, homogeneous plasma is studied using 1D-fluid simulation techniques. It is observed that the wake wave gradually evolves and eventually breaks, exhibiting sharp spikes in the density profile and saw tooth like features in the electric field profile.

Phase mixing of relativistically intense longitudinal wave packets in a cold plasma

Phase mixing of relativistically intense longitudinal wave packets in cold homogeneous unmagnetized plasma has been studied analytically and numerically using the Dawson Sheet Model. It is found that the phase mixing time crucially depends on the relative magnitude of amplitude and the spectral width.

One dimensional PIC simulation of relativistic Buneman instability

Spatio-temporal evolution of the relativistic Buneman instability has been investigated in one dimension using an in-house developed particle-in-cell simulation code. The novel result on the scaling of energy densities has been found to be in quantitative agreement with the scaling derived using fluid theory

Effect of driving frequency on the electron energy distribution function and electron-sheath interaction in a low pressure capacitively coupled plasma

Using self-consistent particle-in-cell simulation, the effect of driving frequency (27.12–70 MHz) on the electron energy distribution function (EEDF) and electron-sheath interaction in a low pressure (5 mT) Ar Capacitively Coupled Plasma(CCP) discharge for a fixed discharge voltage is investigated. Mode transition with driving frequency, changes the shape of EEDF from a strongly bi-Maxwellian to convex type distribution before finally becomes a weak bi-Maxwellian.

Role of intermediate frequency on collision less sheath of CCP discharge operating with current driven triple frequency configuration

The CCP discharge features operating in current driven triple frequency configuration has been analytically investigated and outcome of this is verified by PIC simulation code. In this analysis the role of middle frequency component of the applied signal has precisely been explored. The middle frequency component is demonstrated to act as additional control over sheath potential, sheath heating and ion energy distribution function (IEDF) of the discharge; the effect of the middle frequency is seen to be pronounced as it approaches to lower frequency component.

Collective dynamics of coupled phase oscillators in a frustrated geometry

With a host of applications in physical and biological systems where frustrated configurations of nonlinear elements co-exist with a communication delay, its effects on the system of repulsively coupled nonlinear oscillators, configured a frustrated geometry, is studied. The time delay is observed in our study to remove the multi-stability that generally prevents repulsively coupled network to enter a stable synchronized ground state, achievable only in attractively coupled networks. The product of time delay and the collective frequency characterize the frustration over complete range of natural frequencies of the identical oscillators and their coupling strengths.

Role of neutral gas in Scrap-off Layer of Tokamaks and study of ELM-PB models

Role of neutral gas in Scrape-off Layer (SOL) region of tokamak plasma is important as it is expected to modify the plasma turbulence. This has been investigated using two models, namely strong interaction approximation where the neutrals are treated as diffusive fluid and weakly ionizing mono-energetic beam.

Strongly coupled plasmas subject to external "flow head" - a Molecular Dynamics study

Yukawa liquids in 2D when subject external flow head (or pressure head) in the presence of obstacle is shown to lead to formation of von Karman vortices for subsonic flows and blow shocks for supersonic flows. Several novel, but universal scaling laws have been obtained using Molecular Dynamics method.

Gyro kinetic simulations of micro tearing mode in large aspect ratio Tokamaks - Effect of external poloidal flows

Collision less micro tearing modes has been found linearly unstable in sharp temperature gradient regions of large aspect ratio tokamaks. The magnetic drift resonance of passing electrons has been found to be sufficient to destabilise these modes above threshold plasma.

A global gyro kinetic study, including, both passing electrons as well as trapped electrons, shows that the non-adiabatic contribution of the trapped electrons provides a resonant destabilization, especially at large toroidal mode numbers, for a given aspect ratio. In experiments, flows (whether self-consistent or external) are known to change the character of the linearly unstable modes as well as the nonlinear dynamics. The global stability code EMGLOGYSTO has been generalized to include external poloidal flows.

Study of Kolmogorov Flow In Strongly Coupled 2D Yukawa liquids

A large-scale molecular dynamics simulation of Kolmogorov shear flow reveals the shear heating at the shear location that decreases the average coupling parameter exponentially with time. To suppress heat and also to see the fluid-like behaviour from molecular dynamics simulation, we exploit properties of a configurational thermostat to address shear heating. We find the average coupling parameter becomes almost constant after superposition of shear flow and nonlinear vortex structures are sustained for a longer time as compared to the fluid model.

Studies in Pure Electron, Pure Ion and mixed species non-neutral plasmas

Using a newly developed PIC-MCC code in 2D, the physics of ionization driven resonances and the related instabilities in straight magnetized cylindrical Penning- Malmberg traps have been studied. The linear and nonlinear stages of the instability, its saturation etc. have been studied. It is shown that the presence of weak background neutrals - which can be expected in real devices - is shown to have important effects of the dynamics of the instability in non-neutral plasmas.

Driven phase-space vortices: 1D Vlasov-Poisson Studies

Using an external drive of small amplitude (which would otherwise Landau damp in an initial value problem) and chirped frequency, it is demonstrated that giant phase space vortices may be formed in steady state, long after the drive is turned-off. It is shown that using a newly developed 1D Vlasov- poisson solver that these features are common to both Maxwellian and non-Maxwellian plasmas. In this work, the drive frequency is so chosen that only electrons would respond but for lower frequencies, ion dynamics may also become important.

3D Magneto hydrodynamics in conducting fluids with finite angular momentum

A new work has been initiated to study the MHD of astrophysical plasmas. To this end, a 2D Navier Stokes spectral code is being developed in both stream function vorticity and velocity-pressure formulations. This will be generalized to 3D later followed by addition of magnetic variables.

2D Plasma Thrusters: Computer simulation and modelling

A new work has started to understand the discharge mechanism and optimization of plasma thrusters (also called Hall thrusters) using fluid and particle methods. To begin with, 1D PIC model and fluid models are being looked into.

Fusion related studies

Reactor design study

The earlier design of SST-2 with aspect ratio 3 is not satisfying the neutronic performance due to limited space available at the inboard side. Hence, it is necessary to increase the aspect ratio without changing the minor radius of the plasma. The SST-2 with 3.4 aspect ratio is analysed for TF ripple and neutronic performance. The present inboard side radial build with increased shield blanket thickness is found to provide a life time of more than 5 FPY and this satisfies the design criterion. The magnetic analysis of TF coil has shown that the ripple at the plasma edge is well within 1 %. However, the volt-second estimation is found to be less than the requirement. The inner radial build up is compared with other devices and found that the dependency of volt-seconds on inner radius of central solenoid (CS) goes as quadratic and cubic. This clearly indicates that inner radius of CS should be close to 1 m to maximize the volt-seconds. In the present case, the inner radius of CS is around 0.65 m. In the present radial build up, a gap of 8.5 cm assumed behind the blanket for vertical remote handling (RH) concept and the structural material thickness of TF is assumed to be 13 cm more than other devices even though the operational field is same. It is decided to have the RH concept similar to ITER because the expected dpa during operation of SST-2 is less than 8-10 dpa and this allows handling the blanket modules through the equatorial port. Hence, the inner radius of CS can now become almost close to 1 m. This case has to be analysed further.

Divertor study for SST-1

The SST-1 equilibrium with additional divertor coil behind the divertor plate has allowed to increase the divertor index (DI) above 10. The SOLPS study of equilibrium more than 10 has shown great reduction of heat flux at the outboard (~ 40 %) and the optimal DI is about 13. The experimental feasibility of such configuration has to be analysed.

Aditya Upgrade

Extension of 3D Monte-Carlo simulations of Scrape-off Layer (SOL) plasma transport to Aditya Upgrade tokamak, multiple block limiter configurations is planned as future study.

3.07-0200 <u>Long term Societal Benefit Programme: Tokamak Research</u>

Aditya Upgrade Tokamak and Auxiliary Systems (Diagnostics, RF heating and Electronics)

During the reported period, the assembly work of Aditya Upgrade (AU) tokamak has been completed. The Transformer coils (TR) and Toroidal (TF), Vertical (VF) magnetic field coils have been successfully tested during integrated power testing. The TF coil assembly has been tested ~ 1.5 Tesla, the Ohmic coil assembly for ~ 12.5 kA (Loop Voltage ~ 20 V), and the Vertical coil assembly for ~ 3 kA. The TF coils displacement and magnetic field measurements have also being carried out during current charging test. Further all the CTC conductor based coils (Main diverter, aux. diverter, outer diverter, FFB and single turn C.C) are cured as per specifications.

Following the integrated testing, the positions of all the coils are measured using ECDS. Error magnetic field, the unwanted Br and Bz components of magnetic fields due to transformer (Ohmic coils inside the vacuum vessel), have been measured at 2 different toroidal locations as a function of Radius, R and height, Z. It is observed that the error fields are reduced in magnitude as compared to previous Aditya machine. These measurements are also compared with the simulated error field obtained by incorporating the measured coil positions. The Aditya Upgrade Tokamak has been prepared for the first plasma discharge by installing namely, 1) PFC (Graphite limiter), toroidal, poloidal and safety limiter inside new vacuum vessel, 2) testing and operation of Glow Discharge Cleaning (GDC) system for AU, 3) testing and operation of Pulse Discharge Cleaning (PDC) system, 4) data acquisition system, 5) Aditya Pulsed Power Supply (APPS), and 6) Plasma diagnostics like Rogowski coils, internal/external loop voltage probes, magnetic probe garland, thermal imaging and diamagnetic loops for parameter measurements. The capacitor bank power supply has been made operational for calibration and required discharges are obtained for calibration.

Fig: Flush mounted Langmuir probes installed on the belt limiter on the inboard side of the Aditya-U tokamak.

Diagnostics required for the first phase of operation are primarily, Microwave, Soft and Hard X-rays, Langmuir probes, Bolometer, Visible spectroscopy and Video cameras are installed. The diagnostics for later stages (Charge exchange, Thomson scattering, UV and VUV etc.) will be coupled in the coming months. The electronics and data acquisition system for diagnostic channels are tested for their readiness. Gas fuelling and coil temperature monitoring systems are made operational. First plasma discharge of plasma current ~ 80kA and duration ~ 15ms is obtained in Aditya Upgrade tokamak using APPS operation. Different wall conditioning techniques such as ECR and PDC discharge cleaning will be made operational. The baking system for Aditya-U vacuum vessel (~ 150° C) will be made operational with temperature monitoring facility active for the coils and vacuum vessel. Plasma is characterized by using measurements of plasma position, electron temperature and plasma density respectively.

AU is supported with various heating schemes. For this, various developmental activities are in progress in LHCH system, which includes design of various rf components, design of

PAM antenna. In a collaborative effort with CEA, France and ENEA, Italy, the fabrication of oversized circular corrugated section of a LHCD transmission line, including a bend, is in progress. The development activity of 64 slot vacuum window (brazing of multiple ceramics on single titanium frame) is in progress with CEERI, Pilani.

ICRH system on Aditya had a capability of introducing 200 kW, RF power but for next phase of operations in Aditya Upgrade, ICRH power for 750 kW will be coupled for conducting experiments of second harmonic heating. The power will be introduced through two different ports using two antennas. A separate line for feeding power to ion Bernstein wave antenna will be used. Indigenously developed RF generator (100 kW, 45.6 MHz) will be used for feeding the power to it. Complete layout is finalized and all required components/equipment like RF switches, vacuum interface section, transmission line, and support structure is in the final stages of procurement. Under ICRH group activities, the following developmental activity is undertaken.

42 GHz, 200 kW DST Gyrotron Project

IPR is also involved with 42 GHz, 200 kW DST gyrotron project with IPR as end user as well as responsible organization for developing complete test set-up including magnets, power supplies, microwave characterization, DAC, water cooling system etc. The complete test set up is developed at IPR. The integration of the gyrotron on tank and magnets is completed. The alignment of magnetic and geometric axis is done. All magnets including the superconducting magnet are energized and field profile was obtained. The conditioning of the gyrotron was done up to 40 kV outside and up to 30 kV on the system. Beam current of 12 A for a short duration is obtained. Experiments for extracting microwave power will begin.

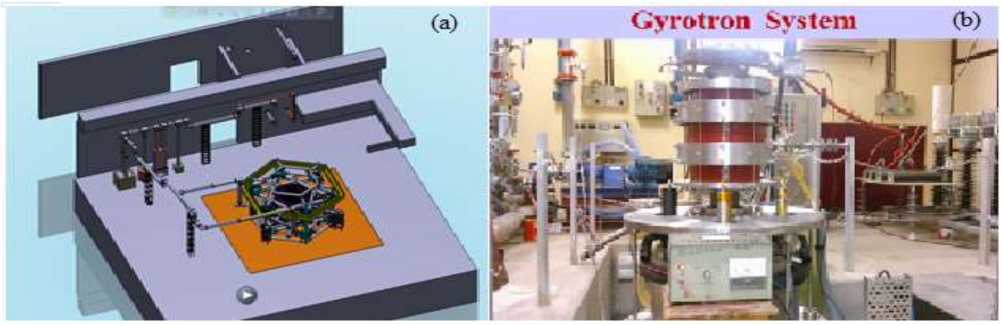


Fig: (a) Gyrotron, and (b) Gyrotron system.

Patents applied : Number of patents applied by the ICRH group are namely**,** 1) High power RF Hybrid Coupler, 2) Isolated power supply, 3) Jitter adjustment method: in progress, 4)IGBT based 7 kV solid state switch, 4)An electrical assembly for voltage balancing during turn-on of semiconductor devices(Applicant: IPR), 5) An electrical assembly to simultaneously limit current change rate in a semiconductor and fault energy in a microwave tube (Applicant: IPR), and 6) Protective device for the performance evaluation of crowbar (Applicant: IPR).

Steady-state Superconducting Tokamak-1(SST-1) and Auxiliary Systems (Diagnostics, RF heating and Electronics)

Post monsoon, a preparatory experimental campaign XIX had been undertaken in SST-1 in accordance with the mandate and projected deliverables of Steady State Superconducting Tokamak (SST-1) project. Experimental campaign XVIII in SST-1 had obtained Tokamak plasma discharges where plasma current in excess of 112.5 kA for a central field of 1.5T, plasma density ~ 0.8-1.0 x 10^{13} cm^{-3} and electron temperature in excess of 200 eV is obtained. With these Ohmic plasma parameters in SST-1, the phase-1 milestones of SST-1 was completed (110 KA of plasma current for 100 ms in 1.5 T of central field). Prior to the XIX campaign, the vacuum vessel of SST-1, equipped with plasma facing components was opened for additional in-vessel installations and inspections. The XIX campaign was a preparatory one confirming `quality vacuum', `reduced impurity states', `earlier cryogenic cooling of the magnet system and the cryogenic window', `basic feedback and controls required for the plasma shots', `long pulse data acquisition status' etc., apart from Electron Cyclotron pre-ionization and integrated operations of the associated subsystems. The campaign XIX held during Aug-Sep 2016 was dedicated for establishing all the engineering parameters and obtaining Ohmic plasmas ~ 80 kA for duration > 300 ms. Further detailed physics on magneto hydrodynamic aspects, magneto-static and electrostatic fluctuations and edge turbulences, mode rotation etc. have been planned to be studied subsequently apart from studies of lower hybrid coupling and further improvement of the core plasma parameters. The SST-1 up-gradation update has been presented in the IAEA Fusion Energy Conference in Kyoto, Japan on Oct 18, 2016.

In diagnostic front, contributions are reported from various diagnostics. The data from soft x-ray from SST1 operation has been analysed for different plasma discharges. There is not much variation of Te with increasing plasma current is observed. In Far Infrared interferometry/polarimeter for SST-1, optically pumped FIR laser is repaired by the replacement of faulty beam splitter coupling Carbon dioxide laser beam to FIR input, broken down Brewster window of Carbon dioxide laser and by carrying out realignment of circular waveguide inside the lab and in the SST-1 hall. In millimetre wave test facility, significant advances in technology has led to the development of a new generation of diagnostics methods that measures both density & temperature profiles and their fluctuation components in magnetically confined plasmas. The group has developed microwave system for 100 and 140GHz frequency sources for chord average density and Ka band (26.5-40GHz) FMCW reflectometry diagnostic to measure radial density profiles in SST-1 tokamak. An ECE radiometer system is also developed to obtain spatial and temporal evolution of plasma temperature.

Heating and Current Drive Systems

Lower Hybrid Current Drive (LHCD) System

The LHCD system is made available for experiments on SST1 during campaign-XVII to XIX. The LHCD power has been successfully launched into the SST1 machine during these campaigns and temporal elongation of plasma pulse is observed. Scintillating detector (CdTe) signal confirm generation of supra-thermal electrons responsible for non-inductive current drive due to LHCD. Spikes are also seen in loop voltage with LH power, which are the characteristics of LH power in low density discharges.

3.07-0300 Technologies for Fusion Reactor: Blankets, Divertor, Fuel Cycle, Fusion Reactor Material Development, and Large Cryogenic Plant and Cryo-systems (LCPC)

Indian Test Blanket Module (TBM) Program

Indian Lead Lithium Ceramic Breeder (LLCB) blanket concept will be tested in ITER through Test Blanket Module (TBM) program. TBM Division, IPR is engaged in the Design and Development of LLCB TBM and its associated ancillary systems. TBM systems design and related R & D activities such as development of blanket materials, Helium Cooling Systems, Lead Lithium technologies, Hydrogen isotope technologies and related diagnostics are in progress at IPR, India with the support from BARC Mumbai, IGCAR, Kalpakkam and various research centres and academic institutes within India.
Some of the major activities carried out by LLCB Test Blanket System are namely, 1) Development of IPR Interface Code for Shutdown dose rate estimation in Fusion system (IICSF), 2) nuclear analysis of neutron activation system for Indian TBM in ITER, 3) carried out joint benchmarking exercise with China TBM team to establish the common shutdown dose rate (SDDR) estimation methodology, 4) preliminary estimation of occupational radiation exposure during the Indian TBS maintenance activities in ITER, and 5) neutronic mock-up experiments for TBM shield module neutronic design validation. Under TBM fabrication technologies development activities, a 10 channel mock-up of TBM FW (U-shaped) has been fabricated indigenously at vendor site in Mumbai with technology support from BARC. In next phase, half size TBM first wall would be fabricated.

(a) (b)

Fig: (a) 10 channels U-shaped FW with ends welded and inlets & outlets of each circuit and (b) prototype demonstration of manufactured U-bent inner and outer plates with CNC C-shape grooved channels and curved ceramic cores.

Ceramic pebble development activities have taken a boost as Lithium Titanate Ceramic pebble production capacity has been upgraded to 5 kg of qualified pebble per month. These pebbles have been characterized in different international R & D laboratories. Experimental set up for measuring the effective thermal conductivities by steady state and hot wire method have been indigenously built at IPR. Besides this, an Experimental Helium Cooling Loop (EHCL) facility (450 C, 0.4 kg/s) is being set up at IPR. The performance tests of the circulators were conducted successfully. Development of a compact temperature-level measurement technique for liquid metal applications is undertaken. Long duration test (over 1200 hours) was performed to estimate the reliability and longevity of the sensor assembly in liquid Pb-16Li environment.

Divertor

The high heat flux test facility (HHFTF) setup for carrying out investigations for first wall materials has successfully taken up automation of High Pressure High Temperature Water Circulation System (HPHT-WCS) for feed-back control and data acquisition. Experimental study on high heat flux testing of tungsten coated test mock-ups is completed. The testing of high heat flux tested brazed tungsten mono-blocks and brazed joints between tungsten mono-block and copper-alloy tube are found to be intact. Thermal-hydraulic and CFD Analysis is performed for high heat flux experiments using Tungsten mono-block and Tungsten coatings. Experimental studies are conducted using HHFTF to verify heat transfer and on-set of critical heat flux. Studies continued using Gleeble 3800 thermo-mechanical simulator system at IPR for high temperature brazing & diffusion bonding of CuCrZr/SS316L with Tungsten materials and thermal fatigue testing of material joints. Magnetron sputter coating system is used to develop coatings of various materials e.g. Titanium, Carbon, Copper, etc. Carbon coating on material is needed for thermal diffusivity measurements using laser flash system. Titanium and Copper coatings are needed for material joining studies.

Fuel Cycle

Activities toward development of hydrogen isotopes sensors to measure hydrogen isotopes dissolved in PbLi liquid are undertaken. Development of solid state proton conducting ceramic for electrochemical based hydrogen isotope sensor is initiated. Ceramic powder prepared at 1100 C of calcination temperature with 40 hours of ball milling and cylindrical pellets have been prepared from the SCY ceramic powder. These pellets are sintered at 900 C for 10 hours. Work is in progress for design, development and optimization of getter beds for hydrogen isotopes storage and transportation as a requirement for Indian-TBM programme.

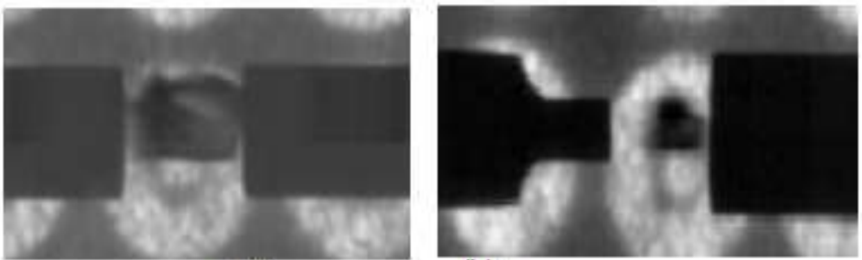
(a) (b)

Fig: (a) Prepared SCY ceramic powder and (b) A typical SCY ceramic pellet (diameter 15mm and thickness 3mm)

Fusion Reactor Materials Development and Characterization

Cryo-adsorption Cryo-pump and Pellet Injector Development

A single pellet injection system, SPINS-IND, based on pipe gun technique of propelling hydrogen pellets frozen in a specially designed sleeve cooled to 5 to 10 K using GM cryo-cooler is made operational with 95% reliability. For 2 mm cylindrical pellets velocity of 1.2 Km/sec and for 4 mm pellet velocity of 750 m/sec is achieved. The system is integrated to SST-1 and test runs made. In another major activity, an 80K helium gas supply system is commissioned.



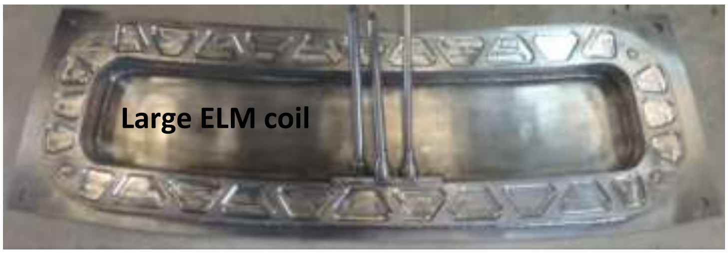
(a) (b)

Fig: 4mm and 2mm pellet in flight are shown in (a) and (b) respectively.

Magnet Technology Development Division

Material characterization facility at low temperature (MCFLT) is under final stages of development in India capable of tensile testing, fatigue testing and bend testing at 77 K and 5 K. Indigenously fabricated Nb3Sn and NbTi based large D- shaped toroidal field superconducting coils are to be validated using 30 kA, 30 V DC power supply having extremely low ripple. Installation and commissioning of this power supply at IPR Magnet Technology Lab has been successfully completed.

Under EU-Indo collaboration, MTDD has successfully develop and established technology for manufacturing of 1:1 of CuCrZr conductor based passively cooled 1:1 prototype for large as well as small ELM control coils appropriate for large Tokamaks such as Joint European Torus (JET) and SST-1.



Large Cryogenic Plant and Cryo system (LCPC)

The objective of LCPC is to develop a helium plant of 1 kW at 4.5 K. The group has developed prototype of plate-fin heat exchanger (PHE2) of 2-stream type.

(a) (b)

Fig: (a) Manufactured prototype plate-fin heat exchanger (PHE2) of 2-stream type (He to 2-phase N2.) and (b) Aluminium serrated fins used in making PHE2.

Continuing Schemes (Expected to continue beyond XII-Plan)

ITER-India

- Six segments of Base section of the Cryostat (a 30m dia and 30 m height vacuum vessel) manufactured by L&T, Hazira, is undergoing welding operations for final assembly at ITER site in France. About 600 neutron shielding block are delivered to Europe and Korea.

(a) (b)

Fig: a) base section of Cryostat, manufactured by L&T and b) neutron shielding blocks manufactured by Avasarala Technologies, Bangalore.

- A novel concept of “pipe-in-pipe” developed to accommodate thermal expansion in buried pipes is successfully accomplished. Pipe spools dispatched to ITER site in several batches.
- Prototype Cryoline manufactured at Inox India Ltd. is commissioned at ITER-India laboratory.
- Diacrode-based driver & final stage high power RF amplifiers are tested for 1.5 MW output in full 35-65 MHz frequency band in ITER-India lab. These RF amplifiers were manufactured by Thales, France as per specifications from ITER-India.

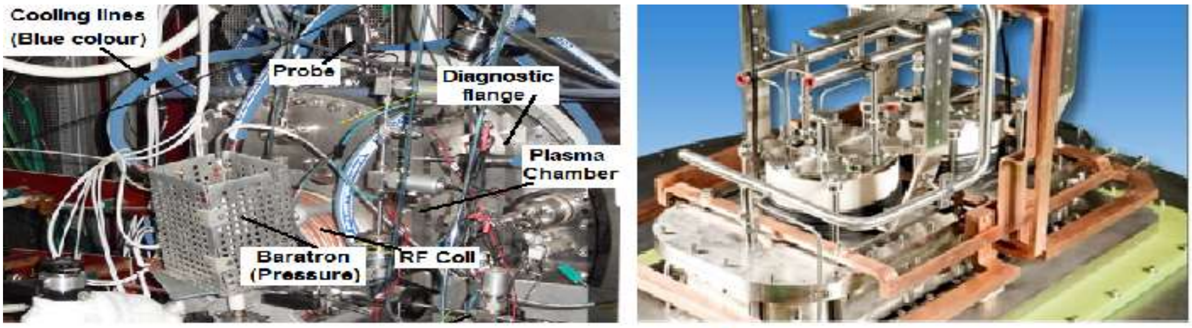
(a) (b) (c)

Fig: a) Prototype Cryoline manufactured at Inox India Limited, b) acceleration grid Power Supplies (AGPS) designed by ITER-India and manufactured by ECIL, and c) cold circulators.

- Dual output regulated high voltage power supply manufactured by ECIL on ITER-India specifications is operated continuously at ITER-India lab, delivering 2.8 MW of output power to drive 1.5 MW diacrode-based amplifiers on matched and mismatched loads is now being installed at the Neutral Beam Test facility in Padova, Italy
- Cold circulators successfully tested with highest mass flow rates. Their testing at JAEA also simulated all magnet operating conditions. The circulators were manufactured by BNI, USA and IHI, Japan as per specifications from ITER-India.

Negative Ion Source Development Group

ROBIN, the first step in the Indian R&D program on negative ion beams has reached an important milestone, with the production of negative ions in the surface conversion mode through Caesium (Cs) vapour injection effected using a specially designed oven. In the present set-up, negative hydrogen ion beam extraction is effected through an extraction area of 73.38 cm2 (146 apertures of 8mm diameter). The maximum negative ion current density ~13 mA/cm^2 at 60-70kW with 0.6Pa pressure is obtained in surface mode for 4 sec so far with beam divergence value in the range of 3° -6°. In continuation, Twin Source (TS) is manufactured in M/s HHV, Bangalore.



(a) (b)

Fig: (a) Robin and (b) Twin source assembly in IPR campus.