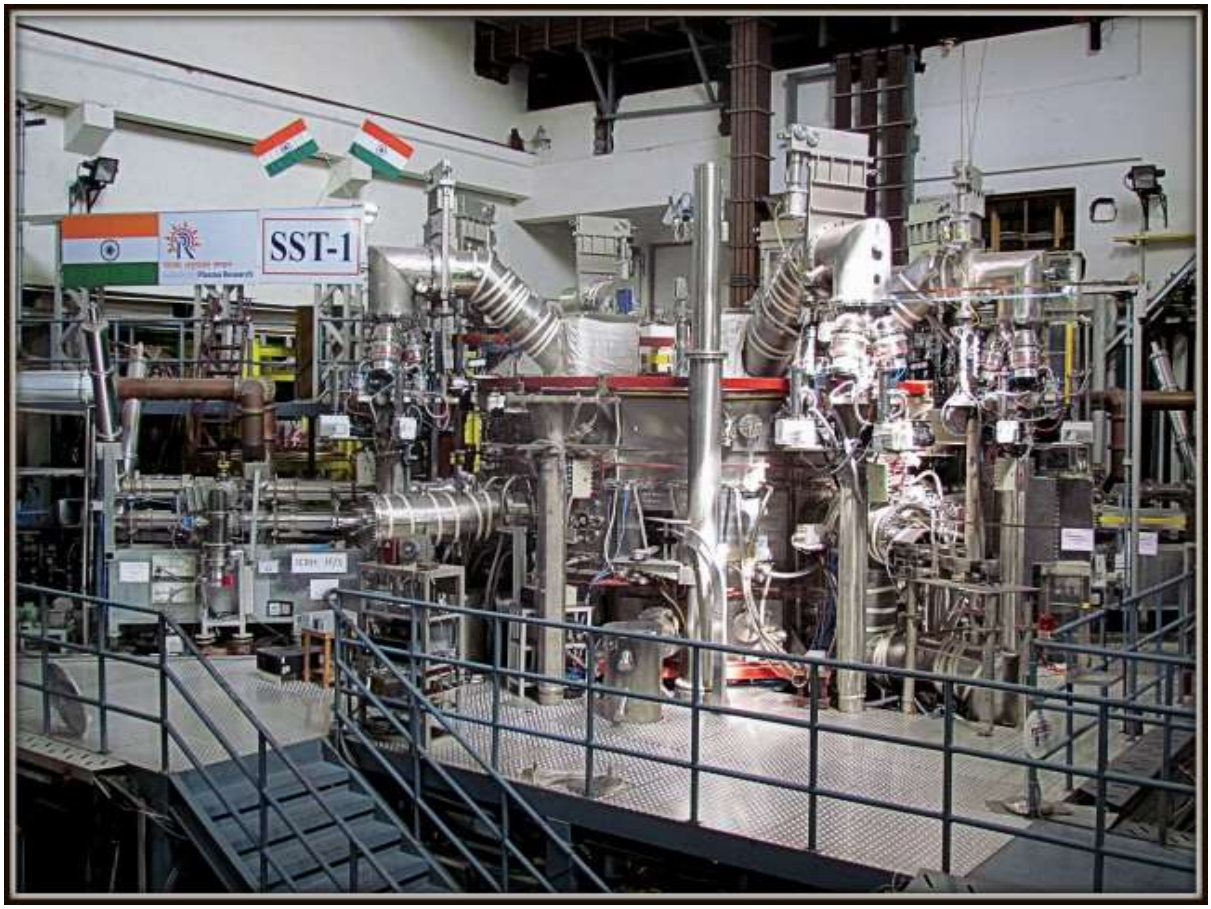
MP3-Nuclear Power Programme – Stage-3

3.07 Fusion Reactor

3.07-0100 Tokamak Research and Fundamental Plasma Studies

Steady-state Superconducting Tokamak -1 (SST-1): This machine has made spectacular milestone achievements since April 2014. SST-1 plasma durations have now been stretched up to ~ 500 ms, for the first time with maximum plasma currents achieved being ~ 75 kA at 1.5 T central field. SST-1 has also made several unique achievements in the meanwhile both in the areas of physics and engineering. In physics, SST-1 plasmas have demonstrated feasibilities of plasma start-ups with ITER relevant electric fields of 0.3 V/m, plasma formations with both second harmonic and fundamental electron cyclotron assisted pre-ionizations, non-linear interaction of the electrons with microwave fields leading to break-down of the plasmas and non-resonant heating of the plasmas, supra-thermal electron-cold plasma interaction dominated regimes on specific experimental parameters etc. On the technology fronts, SST-1 superconducting Toroidal Field magnets have been able to operate in a cryo-stable fashion in plasma experiments cooled with Two Phase helium in excess of 25000 seconds. SST-1 superconducting magnets are the only magnets in the world to operate in Two Phase cooling and have opened a new regime of operations of the superconducting Tokamak Magnets. SST-1 vapour cooled current leads heat exchanger sections also operate in a cryo-stable fashion during the plasma experiments with cold helium vapour instead of liquid helium for the first time. This has reduced the helium consumptions during the SST-1 operations significantly. After the 11^{th} campaign of SST-1, SST-1 has initiated the phase-1 up-gradation since Oct 01, 2014. Several core sub-systems of SST-1 will be up-graded during this phase. The first walls of SST-1 will be installed inside the SST-1 vacuum vessel by March 2015 after which SST-1 campaigns for longer plasma discharges would resume.



(Fig 1: SST-1)

Aditya Tokamak : During this year special efforts are made to enhance the discharge performance as well as plasma parameters. Repeatable plasma discharges of maximum plasma current of ~ 145 kA and discharge duration beyond ~ 230 ms with plasma current flattop duration of ~ 140 ms with negative converter operation has been obtained for the first time in the first Indian tokamak ADITYA. The toroidal magnetic field is raised up to 1.125 T to maintain edge safety factor (q_{edge}) $\gtrsim$ 3. The best base vacuum of the order of ~ 3 x 10^{-8} torr has been achieved after successfully baking of Aditya vacuum vessel at 110° C leading to minimum loop voltage of ~ 1.7 V during plasma current plateau. Improved discharges are attempted over a wider parameter range as per requirements of different experiments such as lower-hybrid current drive (LHCD), electron and ion cyclotron heating (ECRH, ICRH) experiments etc. In these improved discharges, chord-averaged electron density ~ 3.0 – 4.0 x 10^{-19} m^{-3} using multiple hydrogen gas puffs, plasma temperature of the order of ~ 500 - 700 eV has been achieved and maintained till the end of the discharges. The measured confinement time matches quite well with Neo-ALCATOR scaling and most of discharges fall below L-mode

scaling barring a few. The discharge reproducibility has been improved with Lithium wall conditioning and much-improved plasma discharges are obtained by precisely controlling the plasma position. New experimental results in Aditya tokamak achieved during the report period include - Loop voltage reduction, plasma current extension and enhancements in count of low energy photons with LHCD, Disruption control and ion temperature increase with ICRH, Electron temperature enhancement with ECRH, Observation of Neon (Ne) Gas puff induced Radiative Improved (RI) modes, Runaway electron mitigation with local vertical magnetic field perturbation etc.

Aditya Diagnostics: LaBr Spectrometer to measure the full spectrum of x-ray emissions from bremsstrahlung and run away electrons is integrated and tested. One can measure the temperature of non thermal electrons by the slope of the spectrum. Flux of this high energies increase during Electron Cyclotron Resonance Heating experiments is observed. For Aditya plasma discharges peak flux or counts show in the energy range of 200-300 keV.

Aditya Upgrade: Substantial progress has been made in ADITYA Upgrade project with Conceptual Design Review being completed. Order for the new circular shaped vacuum vessel has been placed and delivery is expected by early next report period. Order has also been placed for the new buckling cylinder and delivery is expected soon. Vendor selection process for Dis-assembly of existing Aditya machine and re-assembly, installation and Installation testing of Upgraded Aditya machine is completed and order placement is in progress. Designing of new power supplies and divertor coils has also progressed well. Aditya Upgradation will be started soon by dismantling the old sub-system components.

Heating and Current Drive Systems

Lower Hybrid Current Drive (LHCD) System: The power launching capability of LHCD grill antenna at SST-1 with all of 32 elements has been enhanced. The conditioning of both the klystrons was carried out on water cooled dummy load. LHCD power was launched successfully in to SST1 machine to carry out experiments. The result clearly confirmed interaction of lower hybrid waves with plasma and generation of supra-thermal electrons with LHCD power. The high power source side is also modified to feed power to Aditya LHCD system. Each klystron feeds RF power to lower and upper row of the Aditya grill antenna. In Aditya, a drop in loop voltage is also observed in the presence of LHCD power.

Ion Cyclotron Resonance Heating (ICRH) System: The experiments are carried out on tokamak ADITYA using the developed ICRH system of 1 MW at 24.8 MHz frequency. The experiments are carried out to have plasma heating at second harmonic, disruption mitigation and also wall conditioning in presence of toroidal magnetic field. The wall conditioning experiments are carried out in presence of toroidal magnetic field under resonant (0.75T), non-resonant (0.45 T) conditions as well as with 20% He gas in a hydrogen plasma (0.45T). All three sets are found more effective in releasing wall impurities like water & methane as half an order (~ 5) of initial vacuum condition. The heating experiments at second harmonic are carried out using RF pulses of different magnitudes (5-100 *ms*) at different RF powers (40 kW-165 kW) in plasma duration of 100 ms. The soft X-ray data shows an electron temperature rise from 250 eV to maximum of 500 eV and NPA data as well data from Doppler broadening shows the ion temperature rise up to 350 eV. In order to carry out mitigation of disruptions induced by hydrogen gas puff, ICRH system was used in both fixed and real time feedback mode. After getting a normal plasma discharge of 100 kA and 100 ms duration, the plasma was deliberately disrupted with the help of gas puff and then after detecting the change in H alpha signal, the feedback was given to start RF power. It was observed that one can get back the original plasma current with the help of RF power after disruption.

*ICRH for SST-1 System***:** The integration of both the antenna and interfaces completed and both the lines are tested up to 150 kW power. One set of diagnostics on both the antennas are installed and Langmuir probe data is obtained during SST-1 experiments.

Positive Neutral Beam Injection: For the integration of neutral beam injector with the SST-1 tokamak, assembly and interface issues have been resolved. Procurement process is in progress for the components (fabrication) required for integration, namely the beam transmission duct and the shine through armour. Tendering process is in progress for the dis-assembly from test stand, transport of injector components and reassembly of the injector at the SST-1 radial port-1. Engineering design is completed for the support systems such as, thermal hydraulics, cryogenic transfer lines, electrical data acquisition & control layout. Up gradation of beam diagnostics and data acquisition are nearing completion. New electrical diagnostics and IR thermography are now included in the NBI system. During the operations on the test stand, the enhancement of the plasma discharge current in the ion source (PINI) from 200 A to 700 A , an increase of ion beam current from 8 Amp to 18 Amp has been achieved while raising the beam's energy from 25 to 38 KeV. Hydrogen cryo-pumping was also demonstrated successfully by using two cryo condensation pumps which is essential for integration of NBI

with SST-1. Further, operation of PINI was carried out in combination with the operation of cryo-pumps.

Fundamental Plasma Sciences

Large Volume Plasma Device (LVPD): Investigations on understanding the non-linear aspects of Electron Temperature Gradient (ETG) turbulence in the ETG dominated region is being realized now as 2m diameter rotatable probe drive has been employed. Data acquired using this drive will give an idea on how the evolution of non-linear structures in the background of ETG takes place and the role played by energetic electrons on their evolution when the ETG conditions are violated. Two of the major successes during this time is the successful installation and testing of computer-controlled stepper motor based linear motion probe drives and the tendering of 40 channels data acquisition system.

Interaction of Low Energy Ion and Neutral Beams with Surfaces: Additional cooling channels were incorporated in the new electromagnet which was earlier designed and got fabricated. We also replaced circular copper wires by rectangular copper strips of the same cross-section. With this slight modification we were able to have same number of turns of copper coils while adding extra cooling channels without changing the overall dimensions of the electromagnet. This new electromagnet helped to obtain ten times more ion current / plasma density compared to earlier (old) electromagnet continuously without any time restriction. With this increase in ion flux, we now expect the neutral flux has also increased by the same factor. Hence this increase in signal to noise ratio will make it easier for us to detect and diagnose the neutral beam.

SYstem for Microwave PLasma Experiments (SYMPLE): Towards the development of the phase 1 system aimed at interaction experiments on HPM (a few MW) and plasma, a magnetron tube has been procured. A line type pulsed modulator, to drive the magnetron, has been designed and the development is initiated. A coupling scheme has been designed and order is placed for the components. The plasma pulser is being upgraded to enable repetition of plasma shots at the rate, one pulse every 20 seconds. A mode converter is designed, to convert the TE10 mode of magnetron output to TM01 mode which will have electric field along the direction of the plasma density gradient. A yet another task undertaken is related to developing high frequency (~1-5 GHz) magnetic field diagnostics for SYMPLE. Probes were designed and fabricated on PCB's. In order to calibrate the system, strip line based circuits were made generating known fields of high frequency. Development of a backward wave

oscillator (BWO) of ~ 500 - 1000 GW HPM power has been taken up under a Memorandum of Understanding (MoU) between IPR and BARC.

Plasma Torch Experiment: Detailed theoretical investigation of the force balance mechanism in a dc non-transferred plasma torch was carried out. Spectral analysis of the data clearly showed that anode arc root shunting changes from random to magnetic field controlled shunting, with the power spectrum shifting from higher to lower frequencies. The experimental system was upgraded with the addition of a new 25 kW IGBT based power supply, digital flow controllers and magnetic coils. The power supply was interfaced with the flow controllers and torch using LabVIEW software for safe and controlled experiments.

Plasma Wake-Field Accelerator Experiment: Extensive experiments were carried out to redesign and optimize the oven for a uniform temperature profile along the axis of the oven. ANSYS/FLUENT simulation studies were also carried out in parallel to validate our oven design. The results of this simulation were in accordance with the results obtained experimentally. The thermal characterization of this oven has been carried out as a function of Buffer gas pressure and external heating temperature. An accurate determination of Li vapor density using Hooks method is being carried out, which employs white light dispersive Mach-Zehnder interferometry. Preliminary studies on the photo-ionized lithium plasma formed in the oven using 193 nm laser were carried out. The analysis of the emission data is being carried out to device a tool that can estimate the plasma density. A prototype 50 cm long CO_2 laser based Michelson interferometer was set up and the interference fringes were recorded. First stage documents for site clearance of IPR LINAC building was prepared and sent to AERB for approval. The AERB site inspection was carried out on 21st Oct 2014 and the inspection report is expected soon. The radiation and safety calculations for Bremsstrahlung radiations and neutron flux using empirical formulas are in progress.

SMARTEX-C: Capacitive probe signal has been modelled by finding induced charge on the capacitive probe using Green's Reciprocity Theorem. Signal can be modelled for a given input trajectory. Mounted array of probes in poloidal plane in order to carry out mode analysis. The mode analysis has been performed. Experiments on resistive wall destabilization of electron plasma had been carried out in a linear regime of the Diocotron mode. Confinement time scaling experiments were carried out and it has been observed that diocotron oscillations last beyond 1.2s duration. Effect of filament position on plasma confinement time, growth of the

instability has been observed. FPGA based trigger circuit was tested. The commissioning and installation of 5kA/100V power supply is underway. Constant current profile for 1.2 seconds at 5kA and for 4 seconds for currents up to 1.5 kA have been successfully obtained.

Theory and Simulation

Dusty plasma/ Complex plasma studies

Study of vapor-liquid (VL) phase transition phenomena in dusty plasmas: We have investigated this problem by performing extensive molecular dynamics (MD) simulations for the dusty plasma model given by Hamaguchi and Farouki (HF model). Our results indicate that the VL transition does not have a critical curve in the pressure versus volume diagram for a large range relevant parameters. Thus the VL phase transition is found to be a continuous transition in the HF model. We also provide an approximate analytic explanation of this finding by means of a simple model.

Lunar photoelectron sheath and levitation of dust particles: The decision to launch Luna Glob and Luna Resus satellites, carrying instrumentation to investigate the structure of photoelectron sheath and levitation of dust particles in the sheath, adjacent to the surface of the moon has intensified interest in this exciting area. A new analysis was done with more appropriate and parameters relevant to the lunar surface. The profiles of the electric potential, electric field, and electron density in the photoelectric sheath have been evaluated for typical lunar environment and used to obtain the profile of the radius of a dust particle for levitation.

Statistical charge distribution over dust particles in a non-Maxwellian Lorentzian Plasmas: On the basis of statistical mechanics and charging kinetics, the charge distribution over uniform size spherical dust particles in a non-Maxwellian Lorentzian plasma is investigated. Two specific situations, viz., (i) the plasma in thermal equilibrium and (ii) non-equilibrium state where the plasma is dark (no emission) or irradiated by laser light (including photoemission) are taken into account. It is shown that the charge distribution tends to results corresponding to Maxwellian plasma for large spectral index. The charge distribution predicts the opposite charging of the dust particles in certain cases.

*Kinetics of wet Sodium vapor complex plasma: W*e have investigated the kinetics of wet (partially condensed) Sodium vapor, which comprises of electrons, ions, neutral atoms, and Sodium droplets (i) in thermal equilibrium and (ii) when irradiated by light. The analysis has

been utilized to evaluate the steady state parameters of such complex plasmas (i) in thermal equilibrium and (ii) when irradiated. As a significant outcome irradiated, Sodium droplets are seen to acquire large positive potential, with consequent enhancement in the electron density.

Laser Plasma interaction studies

Ion acceleration from laser-driven E-coli bacteria (with TIFR): Particle-in-cell simulations of laser interaction with a plane polished glass substrate and ellipsoidal particles (mimicking bacteria) in front of the substrate have been done to study ion acceleration. It is found that ion-acceleration energy is much higher for the case with bacteria than that with the solid substrate alone. Results were compared with TIFR experiments, and found to explain those results qualitatively.

Anomalous collisional absorption of light waves in under-dense plasma at low temperature: *We* now use quantum kinetic models and classical Dawson-Oberman model of collision frequency to study the anomalous nature of collisional absorption of laser-pulses. Anomalous growth of frequency and corresponding absorption is found with respect to laser intensity as well as electron temperature.

Propagation dynamics of laterally colliding plasma plumes in laser-blow -off of thin film: A systematic investigation of two plume interactions at different spatial separations (3-7 mm) in laser-blow-off (LBO) induced Li plasmas in ambient argon gas has been carried out. The transport of plasma species from the seed plasmas to the interaction zone is discussed in terms plume divergence, kinetic energy of particles and ion acoustic speed. An attempt is made to understand the formation and dynamics of the interaction zone in the colliding LBO seed plasmas.

Spatiotemporal focusing dynamics in plasmas at X-ray wavelength: Using a finite curvature beam, we investigate here the spatiotemporal focusing dynamics of a laser pulse in plasmas at X-ray wavelength. We trace the dependence of curvature parameter on the focusing of laser pulse and recognize that the self-focusing in plasma is more intense for the X-ray laser pulse with curved wave front than with flat wavefront. The simulation results demonstrate that spatiotemporal focusing dynamics in plasmas can be controlled with the appropriate choice of beam-plasma parameters to explore the high intensity effects in X-ray regime.

Nonlinear Plasma Theory

Fluid Simulation of wake field excited by a relativistic electron beam: A one dimensional fluid simulation of wake field excited by a relativistic electron beam propagating through a cold plasma has been carried out.

Nonlinear Dynamics of Relativistically intense waves in cylindrical and spherical geometry: Breaking of relativistically intense space charge oscillation/waves has been investigated analytically and numerically in cylindrical and spherical geometries. Using a perturbative method, it is found that oscillations/waves in these cases break via phase mixing at much lower amplitude compared to the slab geometry due to additional anharmonicity introduced by geometrical effects. A numerical code based on sheet model has been written to simulate and verify the scaling of phase mixing time on initial perturbation amplitude.

Observations of transient electric fields in PIC simulation of capacitively coupled discharges: We have used the semi-infinite particle-in-cell (PIC) simulation technique to verify the theoretical prediction for the existence of transient electric field in the linear regime; it is shown that the PIC simulation results are in good agreement with the results predicted by analytical model in this regime. It is also demonstrated that the linear theory overestimates the transient electric field as one move from linear to weakly nonlinear regime. The effect of applied RF current density and electron temperature on evolution of transition field and phase mixing regime has been explored.

Effect of mass and charge of ionic species on spatio-temporal evolution of transient electric field in CCP discharges: On the basis of *semi-infinite particle-in-cell* (*PIC*) *simulation* the effect of charge and mass of ionic species on the spatio-temporal evolution of the transient electric field and phase mixing phenomena in linear and weakly nonlinear regime has been explored. As an important feature, the simulation results predict that the maximum amplitude of the transient electric field decreases with increasing ionic mass and charge.

Investigation of wave emission phenomena in dual frequency capacitive discharges using particle-in-cell simulation: Dual frequency capacitively coupled discharges are widely used during fabrication of modern-day integrated circuits, because of low cost and robust uniformity over broad areas. At low pressure, stochastic or collisionless electron heating is important in such discharges. The present research discusses evidence of wave emission from the sheath in such discharges, with a frequency near the electron plasma frequency. In this work, the

occurrence of strong wave phenomena during the expanding and collapsing phase of the low frequency sheath has been investigated. Electron trapping near to the field reversal regions also occurs many times during a lower frequency period. The emission of waves is associated with these field reversal regions.

Fusion related studies

Electron emission induced cooling of boundary region in fusion devices: We have explored whether the electron emission from the boundary region surfaces can act as an efficient cooling mechanism for boundary region surfaces/dust electrons and hence the lattice. In order to estimate the contribution of this cooling process a simple kinetic model based on charge flux balance and associated energetics has been established. Along with some additional sophistication like suitable choice of material and modification in the work function via surface coating, the estimates show that it is possible to keep the temperature of the plate/particles well within melting/sublimation point for the desired regime of incident heat flux.

Kinetics of dust particles around SOL in fusion devices: A kinetic model based on the balance of charge and energy over the dust particle surface around the scrape off layer (SOL) region in fusion devices has been developed. The formulation has been utilized to determine the lifetime of cylindrical and spherical dust particles. A realistic situation in fusion devices, when the plasma exhibits meso-thermal flow, has been taken into account. It is seen that a large dust particle immersed in low temperature plasma can survive for long time; as an important outcome it is also noticed that the cylindrical particles of tungsten last longer than spherical particles. The findings are of relevance in characterizing and simulating the effects of a variety of dusts for experimental campaigns in large scale (ITER/Demo-like) fusion devices.

Nonlinear Dynamics

Time-delay effects on the aging transition in a population of coupled oscillators: A system of coupled oscillators can display a wide spectrum of collective behavior ranging from synchronization to spatiotemporal chaos and has therefore served as a useful paradigm to represent collective phenomena in a variety of applications in physical, chemical, biological, and social sciences. We investigated the influence of time-delayed coupling on the nature of the aging transition in a system of coupled oscillators that have a mix of active and inactive oscillators. A systematic numerical and analytic study has been done starting with a simple

model of two time-delay coupled oscillators that have identical frequencies but are located at different distances from the bifurcation point. We find that time delay can act to facilitate the aging transition by lowering the threshold coupling strength for amplitude death in the system. We then extend our study to larger systems of globally coupled active and inactive oscillators including an infinite system in the thermodynamic limit. Our model system and results can provide a useful paradigm for understanding the functional robustness of diverse physical and biological systems that are prone to aging transitions.

Facilitation Center for Industrial Plasma Technology (FCIPT-IPR)

A. Sponsored Projects and Ongoing Activities

Development of Bio-medical implants with enhanced reliability: DST has funded a project for the development of biomedical implants with enhanced reliability, to work in collaboration with CGCRI, Kolkata. In this project a combination of Plasma Nitriding & TiN coating will be used on SS and Ti alloy based knee and hip implants to improve their reliability as bio-compatible components.

Development of a 5 kw microwave source for coal gasification: This project is sanctioned by IPR and is meant for developing a microwave source which will be used for gasifying low grade Indian coal and for using these gases for thermal applications/ power generation.

Design and development of Environment friendly Plasma System for in-line treatment of Textile at moderate speed: The project has been started in the month of January 2015.

Development of Plasma Pyrolysis/Gasification system to dispose Solvent Mixture & Solid waste: The Plasma Pyrolysis/Gasification system was fabricated and delivered to CSMCRI, Bhavanagar, in Gujarat. The system will installed and commissioned shortly subject to availability of shed at CSMCRI.

Development of CZTS based Solar Cells (sanctioned by DST): The entire system with all accessories has been assembled, installed and commissioned. H_2S gas line installation will also be completed soon. Actual experiments to develop the CZTS based solar cell will start then after.

*Material Characterization of Hall Effect Thruster (sanctioned by LPSC, ISRO in June 2012)***:** An UHV based test facility to measure in-situ differential sputter yield has been setup. The actual experiments at various operating parameters are going on.

*Development of a Magnetron based Ion Source for Nano-Patterning (DST Fast track Young Scientist program)***:** The system has been installed and the experiments have started. Different plasma modes at different operating parameters were observed. Diagnostics of these plasmas is going on.

*Development of a Plasma based Nano-Titania Synthesis System (Sanctioned by DST in 2011)***:** Actual experiments were carried out in the newly installed system and nano-Titania could be produced at a rate of around 100 gm/day. Novel automated powder collection system was developed and found to be working as planned. Nalli Silks is carrying out the survey to find market potential of this technology.

*Plasmonic Coupling Studies of Self-Assembly Nano-Partilces (Sanctioned by DST-Nano Mission, in 2011)***:** In-situ Rutherford Back-Scattering (RBS) measurements have been performed to investigate the growth of nao-particles on patterned substrates.

*Feasibility study to recover Phosphorus from Phosphoric Acid***:** The pyrolysis system was installed and commissioned at M/s. Excel Industries, Roha. Optimization of the experimental parameters was completed and 80% of good quality elemental yellow phosphorous could be recovered successfully from the feed. Project was completed.

*SPIX – II (ISAC, ISRO)***:** As a part of the second phase of the project, ESD experiments were carried out on different types of solar satellite coupons (on different types of cells and in different configurations).

*25 kW Plasma Torch***:** Plasma torch was tested at approximately 30 kW for continuous use in a closed chamber. Semi-empirical scaling laws were formulated, which will be used to upgarde the plasma torch to higher powers ~ 50 – 100 kW. Miniature enthalpy probe was tested for high water cooling pressures. It was also tested for steady state survival inside the plasma torch plume. Experiments to estimate plasma enthalpy were performed. New plasma torch for 50 –

100 kW power range is being fabricated. This will be installed and tested for different conditions and scaling laws will be validated.

Development of a Plasma Carburizing System: The plasma carburising system has been installed and tested at FCIPT, IPR. Experiments have been carried out successfully.

B. Material Characterization Activity

- Installation of a Field Emission Scanning Electron Microscope (FESEM) from Carl-Zeiss is underway at FCIPT, IPR.
- LAICPMS (Laser Ablation Inductively Coupled Plasma Mass Spectroscopy) system of ThermoFisher is under installation at FCIPT, IPR.
- A lab building for housing the Transmission Electron Microscope (TEM) is being constructed. PDI of the TEM (FEI make) was carried out and the instrument is expected to be delivered at FCIPT, IPR, soon.

C. Projects with International Collaboration

Investigation of local structure and magnetism properties of Cobalt nano-structures (Indo-Italian program): Synthesis of Cobalt nano particles, under externally applied magnetic fields, is being carried out. Synthesis of Iron oxide particles, under externally applied magnetic fields, has been completed and their characterization and analysis is in progress.

Low Energy Ion Beam for Nano Patterning and its Applications to Plasmonics (DAE-BMBF program): The project has been successfully completed and the concerned report was submitted. And a follow-up project proposal has also been submitted.

Plasmonics based CZTS Solar Cells (Indo-UK DST program): A project proposal to develop plasmonics based CZTS Solar Cells and to demonstrate an improved solar cell efficiency, using Silver nano particles, has been submitted and sanctioned.

D. Proposals under consideration

- A Proposal was submitted to DST on "A feasibility study to improve oxygen diffusion barrier properties of polyethylene web by plasma treatment" and defended. The project is expected to be sanctioned soon.

- A proposal on “Pilot scale process development for the recovery of valuable materials from electronic waste and setting up of a demonstration plant for recycling of electronic waste in India” was submitted to DST, in collaboration with Shriram Institute of Industrial Research, Delhi; and National Metallurgical Laboratory, Jamshedpur.

E. MOUs signed

- A MoU was signed between IPR and Central Leather Research Institute (CLRI), Chennai, a CSIR lab; in September 2014. The objective is to carry out study on disposal of solid waste generated in leather industry.
- A MoU for research collaboration between IPR and RICMASS (Rome International Centre for Materials Science and Super Stripes), Italy has been signed in Feb/March 2014. Under this MoU it has been planned to carry out an in-depth study of defects and atomic level changes in materials exposed to fusion plasma.

3.07-0200 Development of Auxiliary Technologies for Fusion

Magnets: Fusion Relevant Magnet Technologies have made significant progresses since April 2014. Development of an appropriate ester based high temperature insulation for the ELM coils of the Joint European Torus (JET) Tokamak including the optimization of the vacuum pressure impregnation process parameters, validation of prototype radial plates suitable for fusion relevant prototype magnets, successful validations of 30 kA, 300 V power supply indigenously with the help of Indian industries, successful room temperature testing of a 8-turn single layer solenoid using 30 kA indigenously developed cable-in-conduit (CIC) superconductors, characterization of novel intermediate superconductor MgB2 based Edge Localized Magnets for Tokamak applications, experimental demonstration and validation of IGBT and mechanical DCCB based hybrid circuit breakers exceeding 1 KA and casing of the ELM coils are some of the milestone achievements. Indigenous Nb3Al multi filamentary high current high field strands fabrications are currently going on and centimetre long strands are expected by March 2015. Similarly, the conceptual validation of an indigenous material characterization facility at low temperature (MCFLT) is expected soon.

Figure 2. A 1:1 prototype of the ELM coil case after successful technology validation

Large Cryogenic Systems: A steering committee with national technical and administrative experts have been formed to discuss various ways to progress in this ambitious national project. The conceptual design of the different components have been completed which was necessary to decide the test facility. The conceptual designs of various prototypes to be tested also have been completed and presented in the steering committee. The thermodynamic process analysis and the study of the arrangements of components in the cold box have been done. Detailed design of prototype components to test and components of CORS are being done. The purchase of different components and elements are in process and major components are: Helium CORS, Turbines, test chamber with associated elements for turbine tests, test chamber with associated elements for plate-fin heat exchanger test and other laboratory equipment. The smaller scale helium purifier elements and oil removal system elements (adsorber beds, filters, automatic oil drainage valve, coalesce and its housing, etc) which can be made easily in-house are being tried and expected to get the desired results soon. The Al-SS304L and Cu-SS304L dissimilar metal friction weld joint for 1 inch size pipe for cryogenic application have been manufactured.

3.07-0300 Technologies for Fusion Reactor Materials, Blankets, Shields, Divertor and Fuel Cycle

Fusion Reactor Materials Development: Oxide Dispersion Strengthened (ODS) steel plate has been made using Reduced Activation Ferritic Martensitic (RAFM) steel powder

produced by Gas Atomiser and further processing such as mixing of powder with Yittria at ARCI and HIPing and Hot rolling at DMRL, Hyderabad. The characterization of the ODS steel plate has been done for the mechanical properties. Functional materials activities such as MgAl2O4 ceramic development activity for IR and RF windows is in progress with preliminary trials of synthesis with solid state route and required furnaces and equipment for such ceramics development are being procured. Tritium permeation barrier coating (Er2O3) development activity has been progressed with the improvement in the film structure using reactive sputtering and dip coating techniques. R.F. sputtering set up is now ready for Erbia film deposition. R & D of materials fabrication activity such as characterization of TIG, Electron beam and laser welded joints of SS316 L and SS316 LN plates for vacuum vessel applications has progressed well. Laser cladding of copper with SS has been done and characterization of the samples is being carried out. For the IAEA-CRP (Coordinated Research Project) entitled 'Radiation damage and H/D retention studies on ion-irradiated Tungsten and its alloys - Experiments and Modeling', work has been carried out using Accelerators at IUAC, Delhi, for heavy ions (Au and W) irradiation in Tungsten. The irradiated samples have been characterized at IPR. The structural and Microstructural changes such as preferred orientations, stress development and grain growth has been observed after irradiation in Tungsten. The modeling work for the CRP is also in progress.

Indian Test Blanket Module (TBM) Program: The TBM Division is developing Lead-Lithium Ceramic Breeder (LLCB) blanket module for testing in ITER. This program is in progress through collaboration with BARC, Mumbai, and IGCAR, Kalpakkam. Nuclear design and analyses has been carried out for the LLCB TBM set using the Monte Carlo radiation transport code MCNP and nuclear cross-section data Fendl-2.1. Various nuclear responses such as neutron flux, neutron spectrum, tritium production rates and nuclear heating rates were calculated. The materials of LLCB TBM will be activated during various

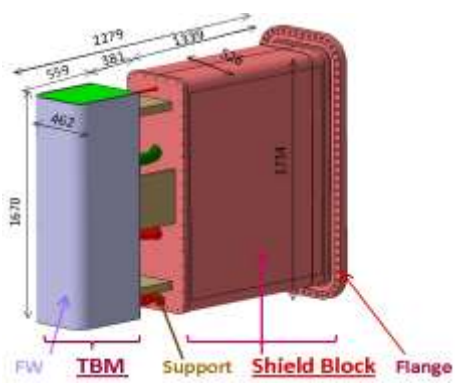


Figure -3: Test Blanket Module (TBM) set design

phases of ITER operations. Deterministic approach based code ATTILA has been used for calculating the neutron wall load, neutron flux profile in the equatorial port, nuclear heating at inner leg of TF coil, neutron flux at Divertor region. The results were compared with the published results and it was found that they are in good agreement with the published results. Engineering design of LLCB TBM set (as shown in *Figure -1*) and its performance analysis are in progress, which includes thermal, thermal-hydraulics, electromagnetic, structural etc. Preparation of Conceptual Design Report (CDR) is in progress. Lead Lithium-water reaction safety experiment is carried out for transient measurement of hydrogen production. Lead-Lithium loops are being designed, fabricated, commissioned and operated at IPR for testing and calibration of liquid metal diagnostics as well as to perform various experiments. Diaphragm based liquid metal pressure sensor and MHD flow meter have been successfully tested and calibrated in a hot liquid metal loop. R&D activities have been started to test the critical process sensors for the LLCS system which is one of the important ancillary systems of LLCB module. India-specific Reduced Activation Ferritic Martensitic (IN-RAFM) steel is being developed in collaboration with IGCAR, Kalpakkam and M/s MIDHANI, Hyderabad. Presently, the commercial melts are being produced for the mechanical and physical properties database generation. Tests have been completed for the thermo-physical properties of INRAFM steel. Synthesis of Lithium Titanate powder by solid-state reaction & solution combustion process have been established in laboratory scale. To study the corrosion of IN-RAFMS with Lead Lithium eutectic, a rotating disc experiment system is being developed in which sample coupons/disc made of sample material are rotated inside Lead Lithium, with the help of electromagnetic stirring arrangement.

Divertors: In a fusion machine the plasma facing materials will be exposed to very high heat flux. To simulate this, a high heat flux facility (HHF) has been developed here and is in the final stages of integration. This HHF Facility has been used for testing tungsten materials for their performance under ELM-like thermal load conditions. Pure Tungsten (w) and Tungsten Alloy (W+1%La2O3) materials developed using Direct Sintering Press (DSP) has been tested. They could withstand 1000 cycles with energy density in the range 1.6-3.1 MJ/m2. Computer simulations followed by actual experiments are performed on two curved tungsten mono-block test mock-ups for thermal load testing. Effect of non-uniform heat load on tungsten mono-block is being studied using computational as well as experimental techniques. CNC Abrasive

Water-Jet Cutting System (OMAX 60120) has been installed & commissioned at IPR. It will be used for precision cutting of metals as well as non-metals such as tungsten, stainless steel, copper, graphite, alumina, etc. MOU is signed between IPR and ARCI for collaborative work on development of Tungsten Coating Technology for First wall and TBM applications. Samples are being studied by IPR for their physical & micro-structural properties as well as thermal cyclic testing. Electromagnetic Analysis of ITER-like Divertor are continued with to compute electromagnetic forces and resulting mechanical stresses under various plasma event scenarios. Meshing of the latest geometry of ITER Divertor cassette body is being done for thermal and structural finite element analysis. Experimental results of pressure drop across Helium cooled divertor test mock-up are compared with results of Computational Fluid Dynamic Analysis for various gas flow conditions. Deviation observed between experimental and computations results are being studied further. Tungsten irradiation damage simulation using energetic heavy ion beams is in progress. As a result of defect creation, micro-hardness of irradiated pure tungsten specimen is found to be higher than pristine material. Magnetron Sputter Coating System is in advanced stage of completion and is expected to be commissioned soon.

Fusion Fuel Cycle: We are in the process of developing a laboratory scale hydrogen isotope removal system (HIRS) for He purge gas to validate design concepts for tritium extraction. Different components of the system have been integrated and experiments are initiated. A couple of experiments have been performed using Gas Chromatograph. First experiment involved analysis of impurities in He gas at 303 K and the second one involved analysis of hydrogen isotopes in He gas at 77 K. Both these results are very encouraging and can be used for separating these species from He gas. Fabrication drawing for the packing column of hydrogen isotope extraction system (HIES) for liquid PbLi has been prepared and fabrication would start soon. Procurement of the off the shelf components are under progress. An experimental set up for determining solubility of hydrogen isotope in liquid PbLi is also under construction.

Centre of Plasma Physics-Institute for Plasma Research, Guwahati

Thermal Plasma Processed Materials Laboratory: A detailed study on the control of size, and hence their properties, of carbon encapsulated iron based magnetic nanoparticles was concluded with the publication of the results in the journal “Carbon”. Studies on the synthesis

of tungsten nanoparticles and tungsten coating have been started. Detailed study of the heat flux of plasma beam was conducted in High Heat Flux System. Preliminary experiments on Plasma Surface Interaction have been started which shows our plasma beam is capable of melting tungsten leading to the formation of interesting macrostructures on the surface. A 1.33 m spectrometer was successfully installed and used for plasma characterization.

Extraction of Negative Hydrogen Ions Produced by Caesium Coated Dust: Designing and installation of the new experimental set up to extract and accelerate the negative hydrogen ions produced by cesium coated tungsten dust particles are completed. Procurement of suitable TMP and rotary pump for evacuation, vacuum gauges, and different power supplies for plasma production and extraction, vacuum components for the new experimental set up are completed. The effect of external magnetic field on plasma parameters and dust charging is completed. This basic experiment will help us to find out the design parameters of the extraction grid to extract the negative hydrogen ions.

Development of a quasi-stationary type coaxial plasma gun to simulate plasma mater interaction of fusion reactor: In the development of this system, one of the important parts is its high power switch with triggering unit. The system comprises of Ignitron switch, High Voltage Trigger Generator, Multi-trigger Generator (Trigger splitter), Delay Pulse Generator and related optical fiber links. A high voltage (20 kV) capacitor has been charged and discharged through the ignitron to confirm the successful operation triggering units and the ignitron switch. The designing of electrode's assembly and vacuum chamber for pulsed plasma gun facility has been completed.

Development of Neutron Source based on Inertial Electrostatic Confinement Fusion Scheme and its Application in Damage Study of Fusion Materials: The objective of program is to develop portable neutron sources having linear and spherical geometry which will operate under continuous and repetitive burst mode and produce neutrons at the rate of 100 million to 10 billion per second. Such high flux neutron source is expected to provide the scope to examine the damage occurring in electronic components and in fusion materials. The cylindrical neutron source was designed on the basis of the theoretical estimations for the neutron production rate (NPR). Recently, cylindrical IECF chamber was installed and integrated. After coupling all the supporting units in the chamber, vacuum compatibility was checked. Meanwhile filamentary discharge plasma in H_2, He and Ar medium was produced in IECF device and plasma was characterized using an optical emission spectroscope. Monte-

Carlo N-particle simulation (MCNP) for estimating the neutron and gamma radiation mapping for the IECF experiment was done successfully.

Ion-ion plasma experiments in a Helicon source : Design and commencement of fabrication of Helicon Plasma Source experimental chamber system and the electromagnet coil assembly has been completed.

Erosion due to ion sputtering in absence of Debye Sheath at Divertor plates: A 2D-3V Particle-in-Cell code with Monte Carlo Collision and a Plasma Surface Interaction Code is used to study the effect of grazing angle (α) on solid surface (divertor) erosion due to ion sputtering in magnetic fusion devices, where α is the angle between the magnetic field and the surface tangent. The ion distribution in front of an absorbing wall is computed using a kinetic model. Important factors like ion energy and impact angle for wall erosion and sputtering are highlighted. The dependence of these two parameters on grazing angle is investigated in detail. Physical sputtering for ion bombardment is strongly dependent on incident ion energy and this energy is mainly gained by the ions when they travel through the potential drop across the combined Chodura Sheath and Debye Sheath.

Interaction of dust acoustic waves with dust voids and their stability analysis: Detailed analytical theory for the system has been developed in 1-dimension ignoring the effect of ion-neutral collision. Numerical analysis of analytical equations currently underway is expected to provide the physical basis of dust void formation and also in explaining their stability. In another study the propagation of DA modes in linear and nonlinear regime in a four component thermal dusty plasma system under specific values of plasma parameters has been theoretically and computationally analysed. Validity of the theory has been tested with experimental data from Mars atmosphere and also with laboratory experimental data.

Continuing Schemes (Expected to continue beyond 2 years in XII-Plan)

ITER-India : From the beginning of the project in 2007, a total 14 out (of 15) Procurement Arrangements (PA) have been signed. Six major contracts for the manufacturing of ITER components have been signed till date. Pre-procurement activities for remaining PA are going on. The summary of activities is given below:

In-kind Credit Received

- So far the earned value in terms of credit received from ITER Organization (IO) is 15043 IUA (ITER Units of Account).
- Task Agreement (TA) credit received from IO till date is 2833.669 IUA.

Design and Analysis

- Completion of engineering drawing for Poloidal Segment-3 of Vessel Sector-3 and 2
- Completion of preliminary design assessment for XRCS Survey Spectrometer for Diagnostics
- Completion of neutronic analysis for Upper Port#09
- Completion of manufacturing drawings for Diagnostic Neutral Beam Source
- Final design of Diagnostic Neutral Beam Passive Magnetic Shield (PMS) and Exit Scraper is in progress
- Final design started for Main High Voltage Power Supply (MHVPS) for Electron Cyclotron power supplies
- Final design started for Chilled Water System-H2 components
- Development & Procurement of Auxiliary Systems & Services for IN-DA Gyrotron Test Facility is in progress

Tendering and Award of contract

- Contract awarded for Group Y Cryolines and for Cold Circulators
- Contract awarded for Test Auxiliary Cold Box and an MoU with JAEA has been signed for its testing
- Contract awarded for Cryodistribution components for ITER
- Tendering activities for group X cryolines are in progress
- Invitation of Bids for Diagnostic Neutral Beam EGPS from Shortlisted Bidders

Manufacturing

- Fabrication of Cryostat Base Section mock-up / prototype has been completed and for Lower Cylinder is in progress. Fabrication activities for Cryostat Base Section (Tier-1 & 2) are in progress and activity for Lower Cylinder (Tier-1) has started.
- Construction of Cryostat Temporary Workshop at ITER site has been completed and facility has been handed over to ITER-India

- Completion of Manufacturing and Inspection Plan for Cryostat Upper Cylinder and Top Lid components
- Manufacturing completion of Source for the Production of Ions of Deuterium Extracted from Radiofrequency plasma (SPIDER) Beam Dump and SPIDER Power Supply
- Machining of front side of Diagnostic Neutral Beam Accelerator Grid prototype has been completed
- Fabrication of In-wall shielding components – 322 Support Ribs and 192 Lower Brackets has been completed. Welding of 48 In-wall Shielding Support Ribs to Lower Brackets has been completed
- Manufacturing of first lot of pipes & fittings for Cooling Water Systems has started
- Casing manufacturing for cold circulators of Cryodistribution system has been completed. Fabrication of Test Auxiliary Cold Box has started
- Manufacturing of major components of the acceleration grid power supplies—60 kW water-cooled switched power supply modules and 2.8 MVA oil-cooled multi-secondary transformers has been completed and are presently being inspected at intermediate stages

R&D and ITER-India Lab activities

- Integration of prototype IC High Voltage Power Supply with transformers completed at ITER-India lab and satisfactory preliminary test results have been obtained
- Commissioning of 15 kW/3600s/35-65 MHz Solid State Power Amplifier for ITER R&D source completed
- Commissioning of 3MW Dummy Load with existing RF power successfully completed at ITER-India lab. Satisfactory preliminary test results have been obtained
- Fabrication of twin source vacuum vessel has been completed.
- Manufacturing of different metal parts for prototype HV bushing has been done
- Indigenous Prototype Production of Panels for Beam Line Components has been demonstrated
- Silicon Carbide plate with contour for ECE diagnostics Prototype Calibration Source has been fabricated

Project Management, Quality & Safety and Infrastructure

- Detailing of ITER-India schedules for the ITER detailed schedule monitoring

- Impact-coordination of the Project Change Requests (PCRs) from ITER-IO with ITER-India package members
- Networking activities for ITER-India LAB at IPR
- Annual ITER intellectual property meeting
- Identification of new risks, mitigation plans and updating ITER-India risk register

Figure 4 Cryostat Manufacturing process – bottom plate and horizontal plate

Figure 5 Manufacturing process of shell for cryo-distribution and cryo-lines

Figure 6 Assembly of left arm heat transfer elements for SPIDER beam dump for Diagnostic Neutral Bam for ITER