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)

The first plasma had been successfully obtained on June 20, 2013 with a plasma current in excess of 12 kA in SST-1 at a loop voltage of ~ 0.35 V/m with ECH in second harmonic modes, which is close to the intended mode of operation in the ITER Tokamak also. With this achievement, now India has joined the elite club of countries having superconducting Tokamaks capable of conducting steady state experiments. India has thus become the sixth country after Russia, France, Japan, Korea and China to achieve this significant milestone. Post Engineering Validations of the assembled and refurbished SST-1, systematic experimental plans have been persuaded towards obtaining the First Plasma. Even prior to the first plasma, focussed experiments on break-down and plasma null had to be carried out. The plasma break-down in SST-1 have been successful with Electron Cyclotron Resonance assisted pre-ionizations both at second harmonic mode as well as at fundamental modes. A 42 GHz, 500 W rated pulsed gyrotron had been used for this purposes. The second harmonic mode experiments had been carried out at 0.75 T of Toroidal Field at SST-1 plasma major radius whereas the fundamental mode experiments had been carried out at 1.5 T of Toroidal field with superconducting TF magnets. Post First Plasma experimental efforts have been initiated at boosting the plasma currents in excess of 50000 Amps and electron core temperature in excess of 50 keV by increasing the loop voltages in ECH fundamental pre-ionization mode. On the engineering fronts, efforts have been made at increasing the Toroidal Field at the major axis beyond 1.5 T. Presently, SST-1 has achieved 1.8 T of operation plasma currents of the order of 15000 A at 1.5 T with ECH fundamental mode. More advanced diagnostics such as Thomson Scattering diagnostics, Far Infrared diagnostics etc are also getting integrated with the machine along with auxiliary sub-systems such as Lower Hybrid Current Drives. In parallel, experimental schemes are also being evolved at operating the SST-1 with higher loop voltage respecting the insulation limitations of the superconducting Poloidal Field magnets. Smart gas feeding system and advanced wall conditioning techniques have also been adopted into SST-1. With SST-1 experimentally demonstrating as a rugged distributed thermo-mechanical, electro-magnetic working assembly and device towards advanced plasma experiments, several sequential up-gradations have also been initiated SST-1. Augmenting a 22 K cooling system for the SST-1 current leads,

up-grading the integrated flow distribution system aimed at cooling the superconducting Poloidal Field Magnets of SST-1, up-grading the current leads to magnesium diboride (MgB2) brass based overloaded current leads and installations of the first wall components have been initiated.

SST-1 Diagnostics

Spectroscopy diagnostics: In SST1 tokamak, it consists of eight fiberscope system, made of eight optical fiber, interference filter and PMT, and 3 channel broadband low resolution spectrometer based impurity survey spectroscopy system. These diagnostics are in regular operation during SST1 campaign to monitor the main ion and impurity behaviour by recoding the spectral lines of hydrogen, carbon, oxygen and visible continuum in visible range from the various lines of sight through the plasma. Spectroscopy signal were recorded and analysed to characterize the wall and also the plasma formation with ECR assisted tokamak start-up experiments during recent campaign.

Aditya Tokamak

A total of 863 APPS discharges and 234 Capacitor bank discharges have been carried out in the Aditya tokamak in the report period. In these discharges electron density ~ 1 - 2 x 10^{13} cm^{-3} and electron temperature ~ 300 - 400 eV were achieved. The pre-ionisation experiments with Electron Cyclotron Resonance had been very successful. Long repeatable discharges (~ 80 - 100 ms) with plasma current ~ 70 - 90 kA were achieved with loop voltage of ~ 7 V (one third of the normal loop voltage) using ECR pre-ionisation had been obtained. This reduction in loop voltage for plasma production and sustenance of plasma is very helpful in reducing the hard X-ray production and also for elongating the plasma pulse. The plasma heating with ECR had also been carried out with limited success. Further, non-inductive current drive experiments using lower hybrid waves was also carried out during this period. Apart from these following other experiments were carried out. (1) Gas puff induced disruption experiments to determine long wavelength contribution to the radiation power loss during disruptions. Preliminary analysis shows increase in long wavelength contribution during disruptions. (2) In neon gas puff experiments up to Ne VIII ionization stage of neon has been observed during Neon gas puff into the Aditya plasma during current flat top. The amount of Neon has been optimized so as not to disrupt the plasma. (3) Break down location identification experiment had been carried out and it was observed in Aditya tokamak that plasma mainly forms in the inboard region (high-field side) at ~ - 9.9 cm to -16.6 cm from the plasma centre. Break down time changes with variation of charging of Vertical Field coils. (4) All the major diagnostics worked well during this period and several new diagnostics such as Hard X-ray measurements using silicon diode detector (SDD) along with Hard X-ray flux measurements are introduced. (5) Contributions made to the international tokamak physics assembly

(ITPA) disruption data base by analysing the disruptive discharges of Aditya tokamak, which matches quite well with the data from other tokamaks. During this report period, work has also been carried out towards preparing conceptual design report of the Aditya-U. The new vacuum vessel design is finished and work is going on for designing the buckling cylinder and power supplies.

Aditya Diagnostics

Spectroscopy diagnostics: Photomultiplier tube array based space resolved measurement system with good spatial (2.5 cm) and temporal resolution (100 micro-seconds) has been developed to measure the H-alpha and H-beta emission for studying the plasma breakdown phase of tokamak plasma. This diagnostic is having two 8 channel PMT arrays and 16 optical fibres transport light from plasma to interferences filter for wavelength selection before feeding to PMT arrays. It has been installed on Aditya tokamak and breakdown experiment was carried out to understand breakdown location and its movement with changing input parameter, such as magnetic field for error field correction. It was found that plasma forms in the inboard high magnetic field region in Aditya tokamak. Considering space resolved measurement of tokamak plasma the conceptual design of space resolved crystal spectroscopy system, which will view the plasma tangentially has been finished. Considering Aditya tokamak plasma parameters, spectral lines at 13.4474 Angstrom of He-like neon ion (i.e. Ne^{8+}) is chosen to be monitored by spherically bent mica 200 crystal under Johann geometry. This system will enable the space resolved measurement of X-ray emission from neon for estimating toroidal rotation velocity and to study core impurity transport of Aditya plasma.

Fundamental Plasma Sciences

Large Volume Plasma Device: The experimental investigations in LVPD during this period were primarily focused on three major physics programs. Firstly, we further carried out investigations on 1) ETG turbulence and initiated work on plasma transport, secondly investigations on understanding plasma in the near Electron Energy Filter (EEF) region from the perspective of understanding the working of EEF and its role in the evolution of ETG suitable profiles in the target plasma of LVPD and thirdly in understanding the role of energetic electrons and physics of energetic belts formed in source plasma of LVPD having similarity to Van Allen belts of earth's atmosphere. As proposed last year, investigations on understanding the non-linear aspects of ETG turbulence in the ETG dominated region, limited to a band (10cm x 40 cm) was carried out, initial results are obtained; they provide preliminary information but are otherwise not sufficient to

explain the complete phenomenon taking place in the region. We are now planning to undertake measurements over the entire cross-section of LVPD. In this regard a 1.8m diameter rotatable probe drive is developed and is installed in LVPD. We have also made some progress in understanding physics of largest ever-made Electron Energy Filter (EEF). The physical presence of EEF divides LVPD plasma into three regions namely, the source, EEF and target regions. The source lies between the cathode and the first wall of EEF and is rich with energetic electrons, the EEF region is primarily the region between the two boundaries of EEF whereas the target region comprises of the space between the second surface of EEF and the end plate. These three regions are different from each other as they offer different plasma conditions. The source plasma in LVPD excites region of energetic electrons, confined in the form of a belt, having similarity to the Van Allen belts of earth's atmosphere. Understanding the role of energetic electrons and dissipation of energy through turbulence are among many interesting physical phenomenon taking place in Van Allen Belts, which are still unexplored. During this period, significant progress is made in the field of understanding the physics of near EEF plasma, also called as sandwiched plasma. Efforts will now be focused on carrying out turbulence study in the near EEF region. The region assumes significance as it mimics the SOL plasma of a tokamak. The LVPD is contributing towards understanding plasma transport because of ETG turbulence in the target region, turbulence in the near EEF region and the role of energetic electrons and physics of belts, similar to Van Allen belts. Theoretical predictions made in the past, supports the presence of temperature anisotropy in Van Allen belts. We have initiated work on the measurements of electron temperature anisotropy in the source plasma of LVPD. This requires careful measurement and proper usage of diagnostics because of the sensitive nature of measurements. We are also exploring different diagnostics for validating these measurements. The preliminary investigations are carried out on fluctuation induced ETG transport in the target plasma of LVPD. In our endeavor of understanding plasma transport in LVPD, we measured fluctuation induced particle flux for two configurations in LVPD, one suitable for ETG and another unsuitable for ETG. The initial results are supportive for the cause that particle transport enhances when ETG suitable conditions are excited in the plasma. This needs detailed investigations before any scaling to plasma transport can be provided. During this time, efforts are also made towards increasing the pulse duration of plasma from its present duration of 9 ms to 50ms. We have successfully tested the present source for 50ms duration of plasma discharge. But for carrying out turbulence study during these long pulse durations, we need to modify the existing EEF and discharge power supplies. Work on these areas is initiated. In both plasma diagnostic and device developmental front, the following efforts are initiated in LVPD. They are

summarized as follows, 1) Microwave interferometer diagnostic is successfully designed and tested in LVPD and experiments are carried out for its use in validation of Langmuir probe measurements. This diagnostics will soon be developed as a resident diagnostic for density measurements in LVPD, 2) The large rotatable probe drive, a circular ring with ring diameter (ID=1.6m, OD=1.8m) is made operational, remotely by making use of stepper motor and is now ready for mounting of probes for carrying out investigations on non-linear structures in LVPD. A vacuum interface coupling is developed for this purpose, 3) the provision for accommodating a high current, low voltage power supply (10kA/20V) is worked out in the laboratory and this supply will soon become a part of LVPD and, 4) a major development work during this period was the execution of fast ramp Langmuir probe diagnostics ($\leq$ 500 kHz) ramp frequency. This will be of great use in estimating temperature fluctuations. Actual requirement is of 1MHz and work on it is in progress.

Interaction of Low Energy Ion and Neutral Beams with Surfaces: A new electromagnet was designed and got fabricated in a local company. The new electromagnet is energy efficient and more powerful compared to the earlier one. It has been designed to produce 3.2 times more magnetic field for the same electrical power (8 KW). Magnetic field was measured along the central axis from one end to the other. In the Helmholtz regime, i.e. from -5cm to 5cm a minimum of 1.2 kilo Gauss was obtained with a maximum of 5% variation at both ends (coil current=60A). It is expected that when tested at its full capacity, i.e. 70A coil current a minimum of 1.4KGauss magnetic field will be produced at the centre which will be 3.2 times the magnetic field (436 Gauss) obtained with the earlier electromagnet with a maximum of 200A coil current (electrical power 8KW). Since plasma density, hence the ion current varies as the square of the magnetic field for such plasma sources it is expected to increase ten-fold. Ion current to the biased plate has already been measured to be 500mA which is 8.33 times the previously measured ion current of 60mA. When tested at its full capacity, i.e. 70A coil current it can be extrapolated that ion current will see ten-fold increase to 600mA in line with the design of the new electromagnet. At present the electromagnet can be run for one hour uninterrupted after which it has to be turned off to cool it. To make the electromagnet run uninterrupted without any time limit, we are adding an extra cooling channel the work for which has already started. For the next three months (Jan-March 2014) we will test the electromagnet with the new cooling channels for long hours (more than six hours) and if it passes we will carry out some surface experiments as planned.

SYstem for Microwave PLasma Experiments (SYMPLE): This is a development of a plasma source and an HPM (high power microwave) source for

the investigation planned on HPM plasma interaction in SYMPLE (System for Microwave Plasma Experiments). The plasma opening switch incorporated in the VIRCATOR circuit has enhanced the input pulse power to ~15 GW, the efficiency of the device, in terms of conversion of electrical to microwave power, remain very poor and the microwave output is only a few hundreds of KW, and broadband. Efforts are on to improve the efficiency by optimizing the parameters with the help of simulation work carried out using MAGIC code. Negotiations are on with foreign vendors towards procurement of HPM source (~1 GW), for which several rounds of discussions have been held with France based and US based companies. As for the plasma source, the work carried out during this year includes additional diagnostic measurement using spectroscopy, to validate the Langmuir probe results. Analysis of the spectroscopy results, using LTE model show electron temperature about 5 times less compared to Langmuir probe measurements. Analysis using more accurate analysis techniques is presently on. Further, experiments were carried out by reversing the anode cathode configuration of the gun. Observations show reduced noise in the probe signals and enhanced density. Analysis is under way. A phase I study in SYMPLE is initiated to address weakly nonlinear wave plasma interaction using HPM source of ~3 MW power (3 GHz). For this, we have placed order for a magnetron based HPM source. A pulse power modulator has been designed using PSPICE simulation to give input electrical power to this magnetron source. An appropriate coupling scheme has been developed to couple this HPM with plasma. One salient feature of this scheme, apart from the gas flow requirement in all the components, in consideration of the high electric field, is the mode converter (to convert TE output of magnetron to TM) which had to be specially designed. Development of high frequency diagnostics is the other front where investigations are focussed. Efforts are on innovative designs and development of high frequency (up to 4 GHz) as well as plasma compatible miniature (PCB based) probes. Different types of probes have been developed. A calibration system is also developed based on a strip-line capable of high frequency current transmission, configured in such a manner that magnetic field can be estimated at different locations. Initial experiments have revealed linear (with frequency) probe pick up to 2 GHz.

Magnetized Beam Plasma Surface Interaction Studies: Demonstrating suitable wall materials that can withstand gigantic heat flux of 10- 20 MW/m^2 on plasma facing components at the PFC-DIVERTER and Limiters is considered as a major challenge towards successful demonstration of thermonuclear fusion reactor. Therefore worldwide research effort is focused towards developing test facilities for fusion wall materials that can provide well controlled synergistic

plasma heat flux conditions in the laboratory. The Linear Plasma Device is considered to be a valuable device due to its simplified geometry offering flexibility of target conditions and orientations. Besides, the device is useful for investigating different physics mechanism which will help towards better understanding of controlling plasma heat flux on the targets. Towards this effort, we have designed our Linear Plasma Device system called APEL-Device that stands for Applied Experiments on Linear Plasma Device. The experimental system will be commissioned at the new IPR-extension campus in GIDC, Gandhinagar. The device under steady state operation can produce a uniform axial magnetic field over a length of 1.5 m Tesla in the range of 0.5-0.8 within less than 10 % variation. Currently the prototype testing of the high density plasma source which based on the principle of magnetron discharge is currently under progress. The experimental validation of this source is being carried out in the basic experimental chamber at the new campus. The existing experimental facility offers number of exciting opportunities in various aspects of plasma physics including PIC and fluid simulation of the magnetron device, magnetized sheaths at the plasma boundary - an outstanding problem for any practical plasma systems that influence plasma production, transport and extraction of particle beams. In addition research on frontier areas such as diagnosing negative ions using resonance probe, fundamental properties of ion-ion plasma and the production and characterization of Cesium free negative ion source for its primary applications in fusion and plasma propulsion is being pursued in this project.

Plasma Torch Experiment: Experiments to investigate the dynamics of thermal plasma inside the plasma torch were carried forward. Specific experiments were performed in order to explore the role of return current closure in the force balance mechanism of the plasma torch. The class of plasma torches used had all the three: wall, gas and magnetic stabilization mechanisms incorporated in it. Different return current geometries were used to explore the above phenomena. In order to carry out a one-dimensional force balance analysis, experiments were first performed in the absence of external magnetic field. Force calculations indicate a very good match with experimental results, given the assumptions. In the presence of external magnetic field, interesting results emerge that point to a threshold flow at which electro-thermal efficiency is highest. Higher the applied field, lower the threshold flow. This in turn points to the fact that a purely one-dimensional force balance analysis may not be sufficient to account for forces arising out of application of an external magnetic field. A full three-dimensional analysis becomes imperative; detailed experiments and analysis are in progress. Magnetic probes were fabricated and garlands of such probes were installed on

the plasma torch in an attempt to explore magnetic tomography to investigate the physical processes. Preliminary results have emerged that throw some light on the arc root fluctuations. These activities are underway.

Plasma Wake-Field Accelerator Experiment: Experimental verification of the result of the finite volume modeling (FVM) studies on the heat pipe oven plasma source was successfully carried out. Extensive work to establish the interferometry diagnostic techniques resulted in the conclusion that in order to obtain stable interference patterns over the relatively long path length, reorientation of the experimental setup (excimer laser and the heat pipe system) so that both are vibration isolated. The lab space was reconfigured with the heavy optical tables newly laid out and the whole system has been repositioned to suit the interferometry experiment. The heat pipe oven main chamber has been replaced with a new one which will offer same 40 cm heater lithium vapour column but with extended cooled water sinks which also hold temperature sensors now. Design of this new section is based on earlier studies in FVA and experiments. The beam shaping of the excimer laser has been tried out and the most suited beam profile has now been chosen for plasma experiments. Procurement and acceptance tests for various optical and opto-mechanical components were carried out and a new indents have been raised to get the planned components which also include custom designed CO_2 laser interferometry related components. The 30 Watts CW and pulsed CO_2 laser has been procured and commissioned with in-house built controls. The excimer laser system also has been recalibrated. Some initial experiments in study of the photo-ionized plasma was also carried out in low resolution.

Basic Experiments in Toroidal Assembly (BETA): Fluctuations and intrinsic flow generation studies have been carried further exploring new fluctuation regimes with varying control parameters. The work includes experimental activities, data analysis using statistical techniques to reveal nonlinear phenomena. A collaborative work has been initiated with SINP, Kolkata for advanced studies to understand the nonlinear phenomena. In one set of experiments varying the toroidal field strength is varied with a better resolution (varied in smaller magnitude ~ 45 G) than that has been done in the recent past. In another set of experiments finite external vertical field is applied in steps of ~ 1.4 G. Both the experiments have produced interesting results in the phenomena of fluctuations and poloidal flows. Preliminary results of the data analysis using statistical techniques indicate intermittent or bursty features in the transport. Currently studies are in progress to unfold the possible existence of long-range correlations and self-similarity of the fluctuations. In addition to this a new source design is in progress to produce plasma with almost no residual primary electrons.

SMARTEX-C: A Cryopumping unit has been procured and integrated with the system resulting in a base pressure of 2.5 X 10^{-9} mbar. The same was recorded with the filament glowing @18A as 4.5X10^{-9} mbar. Trigger-box for controlling and operating the experimental timing parameters in SMARTEX-C is wired on GPB with Fault Indicators and tested successfully with system for designed parameters. The timing parameters can be controlled by potentiometers giving freedom of setting a minimum hold time of ~ 10 micro-s. Rise time of the output pulses is in the range of ~ 10-15 nano-s. As a part of comprehensive development of DAQ, a new LABVIEW code has been incorporated with features like safety against unauthorized execution of the code, online and offline analysis. The procurement of a high current DC power supply (5kA/100V/1.2s) is in progress. The baking system and the charge collector diagnostics have been upgraded. It is observed experimentally that growth rates of Diocotron modes do get affected by inner wall resistance and stays un-affected when capacitive probes are made resistive. Observed trend of the growth rate of the resistive wall destabilization closely matches with theoretically expected growth rates. An improved grounding schemes has been worked out and the same has been implemented after construction of two grounding pits involving pipe-in-pipe, ionic breathing technique, electrolytic type and maintenance free ground-pits. The two pits have been connected in parallel with Cu-bus bars.

Theory and Simulation

Study of Neoclassical Tearing Modes and Resonant Magnetic Perturbations in Tokamaks: Using CUTIE code authored by A Thyagaraja UKAEA, (2,1) tearing modes have been extensively studied and compared with analytical results for benchmarking. The effect of flow on Tearing modes has also been addressed. A variety of flow profiles and their effect on Tearing mode stability has been studied. Also the effect of equilibrium modification due to flow using TOQ code and its role in linear growth and saturation of tearing mode using NEAR code is also addressed. These results show that there is a change in q, <J.B> and P profile in presence of flow due to flow induced Shafranov shift. In the near future, two fluid effects will be addressed using CUTIE. Also the study of RMPs using COMPASS/CUTIE suite of codes has already started and will be addressed in the future.

Study of Blob dynamics in Edge-SOL region using multi-field drift fluid model: Plasma blob is a magnetic field aligned plasma structure that is considerably denser than the surrounding background plasma and highly localized in the directions perpendicular to equilibrium toroidal magnetic field. These structures are generally formed near the boundary between edge and scrape-off layer (SOL)

regions and become charge-polarized under the action of magnetic field curvature. These move in complicated trajectories due to ExB drifts. This work reviews theoretical results on the blob formation, dynamics and transport that are obtained since last two decades. Plasma blob formation in a low shear region has been investigated. It is found that blob forms mainly in the presence of low pressure/density regions near radially elongated streamer if poloidal particle flux is higher than the radial flux. Influence of ion temperature gradient in the SOL region has been studied. It is estimated that a critical ion temperature gradient where it generates a new type of instability. Plasma blob formation rate as a function of the ion temperature gradient has been also investigated. Presently Edge localized modes (ELM) in the presence of peeling-balloon modes are being investigated using different magnetic and toriodal current equilibriums. An open source code BOUT++ is being used for the numerical solution. Next step is to generate these equilibriums using TEQ/ELITE code and will be integrated (Integrated Tokamak Modeling [ITM] approach) into the framework of the BOUT++.

Fluid and Molecular Simulation - Physics of Strongly coupled Yukawa Liquids: First principles molecular dynamics simulations are used to study two dimensional strongly coupled Yukawa systems using the code MPMD-2D. The up gradation of the code is made to address the physics of gravitationally equilibrated Yukawa liquids. Upgraded the MPMD-2D with the addition of diagnostic of calculating the dynamic scattering function, longitudinal current correlation function and transverse current correlation function by both and mean-square diffusion followed by rigorous benchmarking. Velocity auto correlation calculations were included and clarified that Green-Kubo's formalism of diffusion coefficient matches well with that by Einstein's calculation for regular un-gravitated fluid. Using these newly added diagnostics, physics of gravitationally equilibrated Yukawa liquids studied. Several new and interesting findings have been recorded.

Phase transition studies - Pair ion strongly coupled Yukawa solids and liquids: Phase transition in multi-component mixtures is an interesting phenomena occurring in different systems, ranging from molecular fluids to colloidal suspension to Complex Plasmas. Hard / soft core Yukawa potentials with soft cores / tails, either repulsive or attractive, are used to model colloid-solvent and solvent-solvent interactions. During the above mentioned period, a comparative study has been made on the role of pure repulsive Yukawa and attractive soft Yukawa potential on phase transition. Extensive Molecular Dynamics simulations are performed on such systems at different temperatures to analyse the phase stability. To understand the physics of such systems different

equilibrium properties are studied by calculating pair-correlation function, self-diffusion coefficient, velocity autocorrelation function, shear viscosity correlation function and correlation for thermal conductivity. In this study, we have observed a vapour-solid equilibrium phase in case of attractive Yukawa soft core system. Homogeneous liquid is also found for a critical reduced temperature. Analysis of pair-ion plasmas has never been explored in strongly coupled regime in context of the study of the phase state. This study will be done in near future. The above mentioned comparative study of repulsive Yukawa and attractive soft Yukawa potential on phase transition may be helpful for our future study.

Development of a nonlinear 2D Spectral code for studying memory dependent fluid models: Strongly coupled Yukawa liquids can be studied by both Molecular Dynamics as well as Fluid Models. Memory dependent visco-elastic models are used for such systems. A new 2D Pseudo spectral code is developed and benchmarked using some well-known flows and instabilities such as Kelvin Helmholtz instability. The following steps were completed: (i) Linear stability analysis of the viscoelastic fluid model for regime of K-H FLOW with unstable tanh-profile of velocity shear was completed using Matlab- eig code and spectral code. Growth rate were from both procedures for different modes with finite memory term matched reasonably for long wavelengths. Spectral code including the memory term or Frankel term for generalized hydrodynamics model was developed after extensive literature survey on strongly coupled viscoelastic Generalized Hydrodynamics models. (ii) Code was tested in the zero memory limit where it comes Navier Stokes equation for incompressible fluid. Both linear stability growth and growth obtained from Spectral code matched reasonably for long wavelengths. (iii) Diagnostics for gradient of vorticity and several other diagnostics were added and development for primary K-H instability and secondary instabilities due to memory term were observed. (iv)These studies were performed for a range of memory and Reynolds number and interesting physics were observed. A literature survey on correlation between memory and Reynolds number was completed.

Gyro-kinetic Simulation - Global Micro-tearing Modes and Alfven Ion Temperature Gradients (ITG): In the context of hot plasmas in Standard Tokamaks, gyro-kinetic studies of micro-instabilities such as ITG, AITG was performed using a 2D global gyro-kinetic electromagnetic stability code. New and interesting results showing the existence of collision-less Micro-tearing modes in large aspect ratio Tokamaks were found. Such plasmas can be characterized as collision-less due to the high temperatures (of the order of KeV) and are relevant for ITER-like scenario. Micro-tearing modes were previously thought to be non-existent in such plasmas, since collisions are necessary to

sustain parallel electron current but current studies indicate that electron inertia can also sustain such currents. Several characteristics of the mode have been obtained, such as the dependence on plasma beta, the spectrum, and electron temperature gradient. 2-D structures have also been obtained for the first time and comparative studies with another electromagnetic micro-instability, namely the Alfven-ITG have been carried out. Many more characteristics of the mode need to be studied, such as the effect of parallel magnetic field fluctuations, coupling to Trapped Electron Mode, ETG mode, Shafranov Shift, improvement of the 3-potential code etc.

Flux-tube Gyrokinetic Simulations of Hot Collisionless Tokamaks: The effects of finite ballooning angles on linear ion temperature gradient (ITG) driven mode and associated heat and momentum flux in Gyrokinetic flux tube simulation GENE was studied. It was found that zero ballooning angle is not always the one at which the linear growth rate is maximum. The ITG mode acquires a short wavelength (SW) branch when growth rates maximized over all ballooning angles are considered. However the SW branch disappears on reducing temperature gradient showing characteristics of zero ballooning angle SWITG in case of extremely high temperature gradient. Associated heat flux is even with respect to ballooning angle and maximizes at nonzero ballooning angle while the parallel momentum flux is odd with respect to the ballooning angle

Numerical experiments in pure electron plasmas: We have a unique special setup to perform controlled experiments in confining low density pure electron plasmas in tight aspect ratio toroidal magnetic fields. These traps routinely confine electron plasmas up to several 100s of rotation periods or Diocotron time scales. Similarly, experiments elsewhere continue to investigate the exciting physics of pure electron plasmas in low density limits, confined in large aspect ratio toroidal fields and in straight circular cylindrical traps. In this low density limit, several outstanding physics problems such as growth, saturation and damping of toroidal diocotron-like modes, role of aspect ratio in confining the plasma, effect of toroidal asymmetry etc. are yet to be understood. In the opposite limit of high density, where electron inertia becomes important, very little has been explored in pure electron plasmas either in uniform or toroidal traps. In this limit, as analytical methods become less tenable, to understand the physics at high density, a new 2D particle-in-cell based code including electron inertia has been developed. After rigorous and exhaustive bench marking of the code in low density limit, several new and interesting findings in the uniform magnetic field have been obtained in the high density limit.

Fusion Reactor Studies: The 1D reactor physics code is improved by adding self-consistent He fraction calculation, inclusion of multiple impurity fraction and line radiation. This has been used to participate in the IAEA-DEMO benchmarking system code session, Vienna, Dec. 2013. For this a typical 1 GWe fusion reactor is constructed with given physics constraints. The initial results are in agreement with other international codes and detailed comparison is underway. The 1D radial build up has to be converted into 2D reactor components and for this, the 2D profile of TF coil has to be obtained by solving bending moment zero curve for a thin coil, known as Princeton-D. This has been done for ITER TF magnet and compared with available data. This found to be in good agreement. The CATIA model of this coil is made and will be analysed for magnetic field produced by 16/18 coils placed toroidally. The profile of TF will decide profile of other reactor components. A 2D neutronic analysis will be carried out after designing the 2D reactor components. The plasma reconstruction code EFIT for ADITYA and SST1 has been installed and this will use the experimental data to reconstruct plasma MHD equilibrium. This will describe the quality and the shape of plasma formed in these devices. The interaction of EFIT with experimental data is in progress. A start-up modelling along with eddy current analysis is in progress. This has to be made available for analysing SST-1 experimental data obtained in the recent campaigns. The transport modelling using TSC for SST1 discharge is in progress. The preliminary plasma current control and radial position control simulations are carried out with ohmic and RCC coil. This has to be made to use the experimental data of ohmic to give more realistic output. The divertor equilibrium for ADITYA upgrade is obtained and the possibility of producing snowflake divertor is being examined.

Phase-mixing of electrostatic modes in a cold magnetized electron-positron plasma: Space-time evolution of electrostatic oscillations in a cold magnetized electron-positron plasma is studied using fluid description. Nonlinear equations up to third order, obtained by employing a simple perturbation technique, indicate phase mixing and eventual breaking of excited oscillations. The expression for phase mixing obtained using the above perturbation technique show that phase mixing time increases with the increase in the strength of ambient magnetic field.

Stabilization of Beam-Weibel instability by equilibrium density ripples: In this work we show that suppression/ complete stabilization of the transverse electromagnetic beam Weibel instability in counter streaming electron beams can be achieved by modifying the background plasma with an equilibrium density ripple, shorter than the skin depth; this weakening is more pronounced when thermal effects are included. On the basis of a linear two stream fluid model it is

further shown that the growth rate of transverse electromagnetic instabilities can be reduced to zero value provided certain threshold values for ripple parameters are exceeded. We point out the relevance of the work to recent experimental investigations on sustained (long length) collimation of fast electron beams and integral beam transport for laser induced fast ignition schemes, where beam divergence is suppressed with the assistance of carbon nano-tubes.

Electron acceleration by intense lasers in the presence of stochastic fields: Acceleration of plasma electrons subjected to an intense laser field in the presence of background stochastic fields have been observed in simulations as well as in experiments. The accelerated electrons are found to have a strong directionality along the wave vector of the laser, with peak energy gain significantly greater than the corresponding pondero-motive energy of the laser. In the present work, the mechanism of acceleration has been studied using single particle dynamics by subjecting the particle to combined field of laser and random forces. The interaction results in diffusion of momentum in the transverse direction and the energy gain is due to de-phasing of the particle from the laser field by the stochastic fields. The dependence of effective temperature of the quasi-thermal distributions have been studied as a function of laser intensity and pulse length. In all cases, two temperature distributions of electrons are observed.

Fluid simulation of Buneman instability: A fluid code based on LCPFCT subroutines has been written to simulate Buneman instability. The non-relativistic version of the code has reproduced the linear results for several initial conditions. The relativistic version of the code is presently being tested.

Nonlinear Dynamics of Relativistically intense waves in cylindrical and spherical geometry: Breaking of relativistically intense space charge oscillation/waves is presently being investigated analytically and numerically in cylindrical and spherical geometries, using Dawson sheet model. Using a perturbative method based on Lindstedt-Poincare technique, 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 an-harmonicity introduced by geometrical effects. A numerical code is presently being written to simulate and verify the dependence of phase mixing time on initial conditions.

Facilitation Center for Industrial Plasma Technology (FCIPT-IPR)

A. Sponsored Projects and Ongoing Activities

Development of Plasma Pyrolysis/Gasification system to dispose Solvent Mixture & Solid waste *(from Central Salt and Marine Chemicals Research Institute (CSMCRI), Bhavnagar, in May 2013):* This project is for developing a plasma pyrolysis/gasification system to dispose liquid and solid waste. Designing of the experimental system is completed and the purchase order was placed for its fabrication.

Development of CZTS based Solar Cells *(sanctioned by DST)***:** Purchase Orders for most of the equipment have been placed. Two numbers of 50 kHz bipolar pulsed power supplies have been developed in-house. Experimental trials are being carried out in the existing setup for depositing TCO (ZnO based) and absorber (CZTS based) layers.

Material Characterization of Hall Effect Thruster (*sanctioned by LPSC, ISRO in June 2012***):** Procurement of equipment have been successfully completed. Assembling and testing of the components is going on and very soon the actual experiments will be started. A surface flash over power source was also designed.

Development of a Magnetron based Ion Source for Nano-Patterning (*DST Fast track Young Scientist program***):** A diffusion pump based vacuum system with a provision to house multiple planar magnetrons is procured. Diagnostics of the developed ion source, using Langmuir probes, is being conducted.

Plasma Treatment system for improved adhesion of PVC coatings with Fabric (*Sanctioned by DST in 2011***):** A dielectric barrier discharge DBD based plasma treatment system has been successfully installed & commissioned at MANTRA, Surat of Gujarat. This system can perform plasma treatment of fabric at a speed of 0.4 to 4 meter/min.

Development of a Plasma based Nano-Titania Synthesis System (*Sanctioned by DST in 2011***):** A new system for large scale production of nanotitania has been fabricated and trial experiments are to start. As Market viability survey for nanotitania coated silk fabrics is being initiated.

Plasmonic Coupling Studies of Self-Assembly Nano-Partilces (*Sanctioned by DST-Nano Mission, in 2011***):** Variable angle Ellipsometer has been procured and installed successfully at FCIPT. Currently modelling of optical coefficients of ordered silver nanodots is going on.

Feasibility study to recover Phosphorus from Phosphoric Acid: The pyrolysis system was installed and commissioned at M/s. Excel Industries, Roha. Trial Experiments were conducted by feeding the mixture of charcoal and phosphoric

acid. Yellow Phosphorus was recovered successfully. Experiments, for optimization of the process, are being conducted at Roha.

SPIX - II (*ISAC, ISRO*): First phase of the project has been successfully completed. Project Steering and monitoring committee has evaluated the performance of the SPIX-II facility. Experiments were conducted on actual satellite solar coupons under LEO and GEO like space conditions.

Development of a HiPIMS system: 50 KW pulsed power has been successfully coupled with plasma load.

Development of a Plasma Carburizing System: The PDI of the plasma carburising system has been carried out and the system has arrived. Further, a 15 KW solid state pulsed power source has been developed in-house.

B. Material Characterization Activity

J.A.Wollam, USA make VASE Ellipsometer has been procured, installed and commissioned at FCIPT. A high temperature X-ray diffraction system supplied by Bruker AXS GmbH, Germany has been installed at FCIPT.

C. Projects with International Collaboration

Investigation of local structure and magnetism properties of Cobalt nano-structures (*Indo-Italian program*): Cobalt nano-particles of varying shape were synthesised and preliminary characterization was carried out. Magnetic susceptibility studies of these particles at 4^{o}K, at varying frequencies, are under way. Another magnetic material viz. iron oxide was also synthesised and studied for its morphology and local atomic ordering.

Low Energy Ion Beam for Nano Patterning and its Applications to Plasmonics (*DAE-BMBF program*): Nanodots were produced on GaSb surface using an ion beam and were used as a template to grow silver nanoparticles. These templates were later used as active SERS surfaces. Detailed investigation of the results is going on using FDTD simulations and ellipsometer.

A proposal was **submitted** to Department of Bio Technology, India, on **Bio relevant plasma treatment of chitosn nano-particle (PLATCHIP)**, under *Indo Danish proposals for strategic research cooperation within health science biotechnology*.

D. Proposals under consideration

The following proposals have been submitted to DST:

- Design and Development of Environment Friendly Plasma System for In-line Treatment of Textile at Moderate Speed.
- Development of Radical Nitriding system for improving the life of cutting tools.
- Using atmospheric pressure plasma, deposition of coating for barrier properties for packaging material

3.07-0200 Development of Auxiliary Technologies for Fusion

Magnets: Long lengths (in excess of 100 m in length) 30000 and 50000 A Nb3Sn based cable-in-conduit-conductors have been indigenously developed this year. This CICC has been room temperature characterized and is awaiting characterization at low temperatures with current the form of a wound magnet. A two turn double pancake consisting of indigenously developed NbTi/Cu based high field high current carrying CICC has also been moulded and impregnated inside a case structure. In parallel, high field operation compatible and high current carrying Nb3Al based strands development initiatives have begun in association with Indian industries. The novel intermediate MgB2 strand developments have also begun. A plan of making a superconducting solenoid from the Nb_3Sn strands appropriate for SST-1 application has also begun. No insulation impregnation schemes of the magnet winding packs in neutron radiation environment as well as for high temperature operations have also been developed completely with their chemical kinetics being experimentally established. A novel mechanical characterization facility at low temperatures i.e. at 77 K and 4.5 K has been conceptualized and is currently being attempted to be developed with Indian industries. Precision magnets of high homogenous category along with their housing cryostats appropriate for gyrotron applications has also been developed successfully along with a low loss cryostat around it for the first time in the country in association with an Indian industry. This system is also now ready for functional tests both at room temperature as well as at lower temperature in a gyrotron assembly. Under international collaborative initiatives a special purpose winding machine has been developed which is appropriate for fabricating Edge Localized Mode (ELM) Coils winding packs in intense collaboration with the Indian industries. Two 1:1 prototype winding packs suitable for Joint European Torus (JET) have also been fabricated. Two incoloy 625 cases suitable for these winding packs are currently being process developed and would be fabricated soon. Similarly, the R & D initiatives at high temperature

resin system based insulation vacuum pressure impregnation process and facility developments has begun. A power supply appropriate for testing the ELM magnets has been developed and is getting installed.

Cryo-pump and Pellet Injector: This program is aimed at research and development aspects for developing a cryo-adsorption pump providing high pumping speed. It involves research and development in the field of new sorbents, characterization of sorbents for adsorption isotherms of reactor relevant exhaust gases down to 4 K. Other important areas include design of components like cryo-panels, radiation shields, baffles, the Monte Carlo simulation for transmission probability, model dimensions of the pump, computational fluid dynamics for cryogen carrying components, experiments related to study with respect to different concepts etc. the progress and the results of various simulations, analysis and experiments carried out towards the technology demonstrated.

Valve technology: In order to developing valve technology for Cryo-pump a valve shaft, valve head, bellow assembly consisting various seals and actuator need to be developed. During operation the valve remains in opened condition and during regeneration the valve closes. Operation of the valve is done through pneumatic actuator. The role of metal bellow comes in isolating the pump environment from high pressure actuator environment. Therefore the metal bellow assembly has the following roles to play (i) Opening and closing of valve in working and standby condition of Cryopump respectively and (ii) Maintaining Ultra high vacuum inside the Cryopump. Design and analysis for the various components are completed and Experimental studies are ongoing for developing proof of concept for the valve technology and various Components of the Valve Assembly.

Extruder Type Pellet Injector: A key task of the injection is to develop a reliable pellet injector capable of injecting, in the steady state mode, an unlimited number of pellets into the plasma core. Several techniques for continuous pellet production have been proposed. One is an extrusion method using screw extruders is under developed. To demonstrate the performance of hydrogen pellet injection system with a prototype. The hydrogen gas is pre-cooled from 300K to 80K in pre-cooler by using LN_2 and liquefied from 80K to 20K by using cryo-cooler in two stages. It is solidified in screw extruder assembly. The pre-cooler consists of a Hydrogen gas filled copper coil suspended in a separate stainless steel vessel containing liquid nitrogen. The liquefier is consisting of a copper barrel connected to a cryo-cooler, which has a helical groove surrounded by a copper jacket, through which the pre-cooled Hydrogen condenses. Extruder barrel is connected to another cryo-cooler to solidify the Hydrogen before it is

forced through the extruder die. The die shape may be circular or rectangular and size is based on required pellet dimensions.

Cryostats for Cryopump Regeneration Studies: The system will cater all the needs to carryout cryopump pumping speed studies for single and multi-panel assembly along with regeneration studies. Cool down tests of the cryostat with ultimate vacuum of ~5 X 10^{-8}mbar with the radiation shields were successfully carried out and final test assembly is ongoing.

Estimation of Gas Load during Cryopump Regeneration: The facility provides accurate and sensitive measurements of weight change, with one microgram sensitivity, for a various samples (Activated carbon granules of different mesh size, Activated carbon spheres, Activated carbon pellets & fabric i.e. Non-woven and Flat Knitted) exposed to controlled environmental conditions over an extended period of time.

Neutral Beam: In this programme the technologies related to a negative ion Neutral beam which would be used to heat and fuel the fusion plasma are being developed.

Experiments: Major achievement was the consolidation of operation in the volume operation mode of the Negative ion source with the following realizations: (i) Extraction of Hydrogen Negative ion beam up to 20 mA with extraction current densities up to 9 mA/cm^2 ; (ii) Installing and operating advanced diagnostics - Laser Photo Detachment, for the measurement of Negative ions ; (iii) Characterisation of the plasma in Robin for different levels of input RF power, operational pressures; (iv) The second phase of experiments on the study of Cesium distribution has been initiated.

Commissioning: A major achievement in commissioning, under the experimental programme was the demonstration of performance of the 11 kV/ 35 A power supply for 3600 S under full load conditions as a part of the FAT, the test demonstrated that all specifications of the power supplies have been met.

Procurement: (i) Placement of contract for the manufacturing of the 9 m long & ~5 m dia vacuum vessel for the IN-TF ; completion of design and initiation of manufacturing; (ii) PLCs for the control system for the Twin source have been procured and acceptance tested; (iii) Diagnostics design for IN-TF has been completed and procurement process initiated (iv) Contract for the Fabrication of 1 MHz, 180 kW RF Generator for the Twin Source has been placed, design process has been completed and fabrication has been initiated; (v) Completion of SAT for control hardware and initiation of software development for the Twin source.

Large Cryogenic Systems: This division works for the technology development to build helium refrigerator/liquefier (HRL) of large scale (cooling power capacity of few kW at temperature ~4 K) and associated other cryogenic technologies required for Fusion Reactors.

Conceptual Design of kW class Helium Refrigerator/Liquefier (HRL): A conceptual design of the HRL with main associated components have been worked out and based on that, the work break down structure for whole project, scheduling, R&D plans, have been worked out. The conceptual design documentation for HRL project has been completed. The conceptual design at the level of different systems and components are going on. The conceptual design of the compressor and oil removal system (3 compressors to provide total ~210 g/s at 14 bar helium flow) is finished and its detailed design is going on. A preliminary process analysis, for the main thermodynamic cycle of HRL, has been done.

Conceptual design of turbine and heat exchanger test facility: Considering that many components design and manufacturing will be done first time in India, it is necessary that all these components should be tested in the operational conditions before used in the HRL plant. Among these, heat exchangers and turbines need a dedicated test facility. As a part of this activity, the conceptual design of the cryostat and the helium compressor (for 75 g/s at 14 bar helium flow) and oil removal system for the test facility are going on. The conceptual design of the turbine break cooler and the external parts of the low temperature end of turbine have been done. The test cryostat has to be designed to be versatile to facilitate the testing of different sizes of heat exchangers and turbines.

Conceptual design of plate-fin heat exchangers: The Conceptual design of different heat exchangers of the main process cycle is being done and expected to be finished for all 8 heat exchangers shortly. The plate-fin counter-flow heat exchangers gives maximum heat duty with compact size, low pressure drop (about 10 to 50 mbar) and low approach temperature (down to ~0.3 K) which are necessary to have good efficiency of the HRL plant.

Prototyping and tests: The small size parts of R&D concern have been tried and among these the Al-SS304L and Cu-SS304L dissimilar metal friction weld joint for cryogenic application have been manufactured using 1/2 inch size tube as prototyping. The tests of helium leak test shows 80% joints to be successful. Further improvements with bigger sizes are planned. The prototyping and tests for different helium purifiers (for temperature 20 K, 80 K and 300K level purification) are expected to be done shortly.

Remote Handling and Robotics Technology: The environment inside the thermo-nuclear fusion reactor is hostile to human beings. In order to maintain and repair the reactor, as well as reconfigure it with new components before any new series of fusion experiments, a bespoke Remote Handling system is needed. The design and operation of the Remote Handling system requires a myriad of different technologies which includes design and modelling of RH systems, kinematics and inverse kinematics analysis, high fidelity communication and control system, imaging technologies, etc. The activities now are focussed towards the prototype development of the Inspection arm for SST-1.

Design Activities: The conceptual design of articulated inspection system is underway. A prototype articulated inspection system is being built. The system is 3 DOF robot with a payload capability of 5kg. A Preliminary kinematic assessment of the system was investigated to study the workable area. Each joint has been conceptualized indigenously to cater the system requirements. Further, optimization of link & joint structure will be planned to reduce the weight & torque and updating of design from testing data for more efficient design to achieve operational scenario.

Control System Development: The Control system architecture facilitates the control and monitoring of multiple RH Systems by separate operators and monitors. This system is especially important in environments wherein multiple RH systems work in coordination with each other. This control architecture also has an integrated virtual reality system. The Virtual Reality (VR) system shall 3d visualization of the RH operations. It will be used both for the planning of RH operation sequences and for providing an overview of operations during RH task execution. The ITER RH control system is taken as a baseline for this architecture. The VR must provide a very close corroboration with the behaviour in the real environment. The VR System must track both instrumented and non-instrumented operations. The operators will place a high reliance on the VR System, and so it must achieve high accuracy in modelling the RH equipment. To achieve this, the structural flexibilities under load must be modelled. The VR system shall have information regarding the remote environment, and this should be used to assist operations by performing collision avoidance and virtual guidance functions. The complete VR system shall be made up of three constituent components, namely: VR visualization front end system, CAT (Computer Assisted Tele-operation) system and Structural Simulator system. The VR system shall be able to run on many workstations in parallel, and to open the same or different models, and to connect to the same or different equipment controllers; to display the same scene (from different viewpoints) on different workstations.

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

Indian Test Blanket Module (TBM) Program: India is developing Lead-Lithium cooled Ceramic Breeder (LLCB) TBM for testing in one-half of ITER port no-2. The TBM design along with shield block module is under progress. Detail engineering design and analysis are in full swing. The Indian TBM team is involved in the R&D of TBM related technologies, such as, Liquid metal technologies,, helium cooling systems, Lithium titanate pebbles fabrication, Structural Materials, Fabrication Technologies for the TBM program. The LLCB TBM design activity is focused on the detail design of TBM first wall, back plate, coolant manifolds and support structure for TBM. Shield block engineering design and assembly sequence to form TBM Set is also under progress. Regarding LLCB TBS RPRS, after the comments and feedback from ITER for LLCB TBS RPRS version 2.0, IN TBM team has submitted new version of LLCB TBS Preliminary Safety Report (RPRS) version 3.0 to ITER which is presently under review. Safety experiment for Lead-Lithium and water experimental system has been assembled and experiments are under progress. The commercial melts of RAFMS has been delivered to IPR in the form of plates (6-30 mm) thickness. These plates are being used for weld joint developments. The fabricability of Indian RAFM steel using EBW, LASER, HIP and TIG welding for ITER-TBM program is under progress. Lithium titanate pellets has been produced at IPR (Lab scale) by solid-state reaction and Solution combustion process. Pebbles production by extrusion and spherodization is under progress. With reference to the interface between the Indian LLCB TBM system and ITER Central Interlock System (CIS) and Central Safety System (CSS), ITER team and Indian I&C team are working interactively to develop the safety functions. Indian team had submitted to host states check list input data LLCB TBS Rad-waste management and TBM transportation to CEA. Presently the preliminary classification of the rad-waste is on-going at CEA based on our input data. In TBM Transportation, there were no comments and in rad-waste input data there were few comments from CEA which are being addressed in detail by LLCB TBM team. In video conference IN team has clarified some points and working in the remaining queries. Based on the CEA comments IN team is planning to prepare revised rad-waste check list and transportation check list after the VC meeting with join rad-waste working group. As per the committed schedule for TBMA preparation for signature, IN team is working on the draft TBMA internally and plans to complete the first draft as soon as possible for sending to ITER organization for comments.

Divertors: Basic components of High Heat Flux Test Facility viz. Vacuum Chamber, Target Handling System, Electron Beam System, Water Circulation

System and Thermal Diagnostic Equipment are assembled, integrated and tested to make the facility operational. Vacuum chamber & target handling system for high heat flux test facility is installed & tested. Electron gun has been integrated with the horizontal port on vacuum chamber and tested to its full 200kW power of operation in steady-state as well as transient mode. During EB-System operation, X-ray leakage all around the high heat flux test facility is monitored. Two divertor target test mock-ups having tungsten alloy mono-blocks with straight copper-alloy tube developed under MOU with NFTDC (Hyderabad) are high heat flux tested with incident heat flux up to 20MW/m^2 over 30mm x 30mm area of the test mock-ups. HHF testing is being performed for more than 100 thermal cycles with typical duration for each cycle of 15s ON & 5s OFF. Ultrasonic Flaw Detection Experiments are being performed on both the divertor target tungsten alloy mono-block test mock-ups before and after the HHF tests. No appreciable degradation at the W-Cu and Cu-CuCrZr joint interface could be observed as a result of these HHF tests. The procurement of Data Acquisition & Control System (DACS) for High Heat Flux Test Facility (HHFTF) is in the ordering stage. Technical part of the draft of the MOU for collaboration on tungsten coating development for first wall application of ITER-like tokamak is prepared after discussions with ARCI (Hyderabad). Budget requirements for undertaking the R&D activities under this MOU are being finalized by ARCI. Another project for tungsten coating technology development for first wall application is also being discussed with IMMT (Bhubaneswar). Experiments on studies on simulation of irradiation damage to tungsten materials have been initiated using high energy ion beam facility at IUAC Delhi. Pure tungsten material has been irradiated with gold ion beam of energy (120MeV) up to affluence of $1.5x10^{14}$ ions/cm^2, which has provided efficient means for production of displacement radiation damage. This is confirmed from increases in electrical resistance of the irradiated tungsten specimen. Corresponding material damage level is estimated to be found to be 0.34dpa using TRIM simulations. Computational Fluid Dynamic (CFD) Analysis and Thermo-Structural Analysis for engineering design of the test mock-up for Helium Cooled Divertor studies are currently going on. Studies on optimization of various geometrical parameters of the test mock-up and operational parameters of coolant Helium gas are performed. The optimized model will be fabricated and tested for its operation in near future. The fabrication of ITER-like Divertor Cassette Body is in the discussion stage with the vendor. Studies on Heat Affected Zone simulations, Hot Deformation Testing and Tensile testing of various reactor grade steel materials of interest to IPR & IGCAR are being carried out using GLEEBLE 3800 Thermo-mechanical simulator system. Tensile testing of tungsten material is also performed using GLEEBLE at elevated (600^oC) temperature. Thermal

Diffusivity & Specific Heat Capacity measurements are performed on various tungsten & carbon based materials using FLASHLINE FL5000 Laser Flash Thermal Properties Analyzer System. Studies on copper deposition on CFC material using Laser Cladding Process is nearing completion. Copper deposition is achieved by casting on textured CFC surface with titanium coating. High Temperature Cavity Blackbody to be used for calibration of Infra-Red Pyrometers and Cameras over wide temperature range has been installed and tested up to maximum operational temperature of 3000 ^{o}C.

Centre of Plasma Physics-Institute for Plasma Research, Guwahati

Theory and Simulation Laboratory: The plasma-sheath equation for a collisionless plasma with a finite-temperature negative ion particle source in a non-uniform open magnetic field is formulated. Structure of electric potential in one dimension is investigated analytically with the effect of strong surface H- production. It is observed that the potential profile depends on the profile of the magnetic field strength, the production rate and the temperature of negative ions. As the production rate becomes large and the negative ion energy becomes small, the potential near the wall decreases. The study of divertor plasma has now been a great area of interest. The region in which we are interested is the collisionless quasi-neutral magnetic presheath and Debye sheath along with the energy flux on the divertor wall. XOOPIC (Object Oriented Particle in Cell on X-Windows) is used to simulate the scenario and to get the results to help in improving future plasma fusion devices. In the area of fusion neutronics, we are conducting neutronics assessment of advanced shield materials using metal hydrides and borohydride for Indian fusion reactor. Works towards shielding assessment in terms of various loads to TF magnet are in progress. We are also studying the tritium breeding efficiency of various blanket concepts with varying radial thicknesses.

Dusty Plasma Laboratory: The present works concern the production and extraction of negative hydrogen ions using a novel technique by spraying a cesium coated tungsten dust into the hydrogen plasma volume. To extract the negative hydrogen ion, a new extraction set up is designed to create a new possibility in the extraction, acceleration and neutralization of NINBI issues relevant to ITER like conditions. Experiment is going on simultaneously with the extraction experiment, to evaluate the optimum conditions for H- ion production. Additionally, experiments to evaluate the different techniques for controlling the dust charging in laboratory plasma are also being carried out in the view of efficient H- ion production.

Double Plasma Device Laboratory: Here two projects are underway; (i) the study on surface processes in a negative ion source and measurement of negative ion parameters and (ii) the other is the ion-ion plasma experiments in a helicon source. One of the basic disadvantages of a volume negative ion source is that the magnetic filter field reduces the electron population in the extraction region along with the electron temperature. The reduction in density of these cold electrons (<1 eV) is undesirable in order to produce a large amount of negative ions in the extraction region. Different experimental techniques have been adopted so far to increase the number density of cold electrons. Keeping this in view two experiments are being performed i) Experiment on effect of cage bias and discharge voltage on plasma parameters in the target region of a double plasma device ii) Auxiliary filament's influence on the plasma parameters in the extraction region of double plasma device. In the other project, the design of the quartz tube with various ports and the antenna drawing has been completed. The Quartz tube chamber length is 60 cm. Total length of the stainless steel chamber has been ~ 105 cm. The electromagnet design has also been completed. Using Poisson Superfish code, the magnetic field profile for the electromagnet's parameters was obtained for the quartz tube and the specifications for the power supply for the electromagnet have been determined.

Pulsed Power Technology Laboratory: The conceptual design of a linear neutron source that can produce ~10^8 DD neutron per sec has been completed. The dimension of the chamber such as the height (30cm), diameter (50cm) and volume (76 liters) is chosen in order to develop ~20 cm long neutron source that can be used for uniform exposure of neutron flux to fusion materials of different dimensions. Initially, the deuterium plasma will be created inside the chamber by creating glow discharge. Then, the ions are accelerated towards the cathode and subsequently, those ions fuses to produce neutrons. The aim is to achieve a plasma density ~ 10^{15} - 10^{16} m^{-3} which will generate neutron production rate (NPR) in the above mentioned range. A detailed theoretical estimation based on the cathode transparency, cathode current, ion cross section etc. to achieve the said range of NPR has been carried out. A neutron shielding scheme for the tolerable dose limit of human being (0.001rem/h) is theoretically estimated and it is found that 40 cm thick borated- water-SS jacket is suitable for neutron flux range supposed to be emitted from our device. A Plasma Focus experiment in which the neutron emission from the existing 2.2 kJ Mather-type plasma focus is also being investigated in deuterium medium by using different shaped anode tips namely oval, converging, diverging and cylindrical anode tip. A correlation between hard X-ray and neutron emission is observed. The detail analysis for these results is still going on.

Thermal Plasma Processed Materials Laboratory : The development of the segmented plasma torch assisted Divertor Simulator system is progressing almost as scheduled; with roots/rotary vacuum pumps (total 12,000 m^3/h pumping speed) already delivered and vacuum chamber system in fabrication, the basic system is likely to be installed in the near future. As proposed before, the plasma jet assisted nanoparticle reactor in this laboratory has been upgraded by addition of mass flow controllers and injector systems for reactant material both in liquid and particulate form. In this period we had very interesting results in terms of synthesis of carbon encapsulated iron nanoparticles, particularly for biomedical and environmental applications. The sizes were nicely controlled through pressure in the sample collection chamber, which in turn could be correlated with smoothly varying magnetic properties. The low pressure synthesized samples were seen to approach super-paramagnet like behaviour (M_s=51.8 emu/g, M_r/M_s=4.9 and coercive-field H_c=52 Oe), which is likely to be most ideal for biomedical applications. The un-purified samples, although possessing smaller saturation magnetization may be more suitable for environmental engineering applications on the account of their faster, more economic processing by an essentially single step process.

MP-5 Basic Research

5.11 International Research Collaboration

5.11-0100 Participation in Other Large Tokamak Experiments

IPR-CCFE collaborations: Activities related to fabrication of Resonant Magnetic Perturbation (RMP) coils for Joint European Torus (JET) has been started by interacting closely with experts from Culham Center for Fusion Energy (CCFE). Material procurements and interactions with Indian Industries related to fabrication have been also initiated. The team for prototype ELM coil fabrication has made significant progress till date. They have carried out thermal and mechanical analysis along with the experiments related to impregnation and insulation. A parallel activity is also going on to make some mock-ups for coil winding and coil casing for the required shape-size and profile. Procurement of various items are also in progress. In other collaborative work, the JET neutron yield calibration was planned for two weeks to ensure direct measurements using a calibrated ^{252}Cf neutron source deployed inside the JET vacuum vessel. We have deputed 2 IPR staff members to participate in this calibration activities. This calibration has allowed direct confirmation of the calibration of the external fission chambers and also provided the first direct calibration of the JET activation system. The calibration of the neutron detectors was performed by

moving a standardized ^{252}Cf point neutron source inside the vacuum vessel through a large number of positions so as to map out the response to be expected for extended plasma and observing the detector response.

IPR-CEA collaborations: We have also signed an agreement to cooperate on tokamak WEST project (Tore Supra Upgrade) at CEA, France. This cooperation involve in-kind contribution of some hardware for Control, Data Access and Communication (CODAC) system and software development for Plasma Control System (PCS) and Wall Monitoring System (WMS). We are planning to depute 10+ personnel to CEA starting from Feb 2014 in batches.

A few other collaboration agreements with ENEA (ITALY) and KIT (Germany) are under discussions.

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

ITER-India : Till now total 14 out of 15 Procurement Arrangements (PA) (in terms of values 96% of total), have been signed. Till date ITER-India has signed three major contracts for the manufacturing of ITER components. Pre-procurement activities for remaining (one Procurement Arrangement) for ITER packages are going on towards the major milestone of signing the PA. Given below is the summary of activities.

Credit Received

- So far the earned value in terms of credit received from ITER Organization (IO) is 11543 IUA (ITER Units of Account).
- Task Agreement (TA) credit received from IO till date is 2776.864 IUA, 49.575 IUA credit request is in process and to be received soon, making a total of 2826.439 IUA.
- TA-I&CIPT-IN-01 for "I&C-IPT Plasma Control Group Working Plan IO-Scope Task for IN DA" has been successfully completed.

Design and Analysis

- IWS material received at site for bulk production of IWS blocks
- Manufacturing Drawings completed for welded Lower Bracket (LB) & of Support Ribs with LB for Poloidal Segments (PS)-1 of all Vessel Sectors
- Manufacturing design and manufacturing readiness report completed for Cryostat base section & its penetrations, Cryostat lower cylinder
- Final design, construction drawing and manufacturing readiness review completed for Cryostat Temporary workshop

- Final design review for DNB Asynchronous Grid Power Supply (AGPS) completed and contract has been awarded
- Completed preliminary design review of DNB Vessel, DNB Passive Magnetic Shield (PMS) and Exit Scraper
- Preliminary design completed for Main High Voltage Power Supply (MHVPS) for Electron Cyclotron power supplies and call for tender activities started
- The differences in the ECE spectrum from tokamak plasma between a direct line of site (normal to toroidal magnetic field) and a slightly oblique line of site have been modelled. Signatures of the presence of non-thermals from a comparison of normal view and oblique view is also calculated
- Development & Procurement of Auxiliary Systems & Services for IN-DA Gyrotron Test Facility is in progress
- Preparation and finalization of manufacturing drawing of remaining IWS blocks affected by PCRs
- Detail engineering & analysis of Component Cooling Water System (CCWS), Chilled Water System (CHWS) and Heat Rejection System (HRS) start of final design review for CCWS, CHWS & HRS
- Preparation and approval of manufacturing drawing of prototype cryolines
- Preliminary Design Review of DNB Fast Shutter Integration and DNB Active Correction and Compensation Coils (ACCC)
- Detailing design of components/subsystems of XRCS survey system
- Preliminary Engineering Design for Integration of XRCS (Edge High Resolution) into UP#09
- Dose analysis & shielding design for UP#09
- Neutronics analysis of XRCS Spectrometer Using ATTILA code

Tendering and Award of contract

- Contract Awarded for Cooling Water and Heat Rejection package and final design activities started
- Contract Awarded for Beam Source for Diagnostic Neutral Beam (DNB) and pre-manufacturing qualification completed
- Contract awarded for Test Bed for Ion Cyclotron Heating (ICRF) system package
- Tender activities are in advance stage for Cryo-Distribution system
- Price bid evaluation is in progress for prototype cryolines and all ITER cryolines. Contract award is expected by Jan-2014
- Tender released for procurement of Combiner for ICRF package
- Purchase Order (PO) placed for Fourier Transformed Spectrometer and indent raised for other lab components
- Award of contract for prototype cryolines and all ITER cryolines
- Technical and commercial bid evaluation for Cryodistribution system contract

- Technical evaluation of tender for ICRF combiner, preparation and review of tender document for ICRF local control unit (LCU)
- Tender evaluation and selection of bidders for ECRF high voltage power supply, DNB EGPS/RIDPS
- Start of call for tender activities for DNB RF generator
- Completion of evaluation of bid for prototype IC HVPS and award of contract
- Start of prequalification activities for Vacuum vessel Pressure Suppression System (VVPSS)

Manufacturing

- Bulk production started for IWS Support Ribs, Plates, Upper Bracket and Lower Bracket (Bolted) & Fasteners for various Poloidal Segments of Vessel Sectors
- Start of fabrication activities for cryostat base section, cryostat lower cylinder and completion of Mock-up of 40° Sector for base section
- Manufacturing activities are in progress for Source for the Production of Ions of Deuterium Extracted from Radiofrequency plasma (SPIDER) Beam Dump and SPIDER 100 kV power supply
- Manufacturing of support ribs, IWS plates, upper and lower brackets for Poloidal Segments of various vessel sectors
- Start of manufacturing of components for CCWS, CHWS and HRS systems
- Continuation of manufacturing activities for the DNB beam source and SPIDER beam dump
- Procurement and acceptance of materials for Jigs, Fixtures & assembly gadgets for magnet feeders & man access penetrations
- Continuation of fabrication activities for cryostat base section, cryostat lower cylinder and their penetrations
- Continuation of development & procurement of auxiliary systems & services for IN-DA Gyrotron Test Facility

Project Management, Quality & Safety and Infrastructure

- Studied various Design Change Requests (DCRs)/Project Change Requests (PCRs) & comments submitted to IO
- Networking activity for ITER-India LAB at IPR are in progress
- Completion of training of 1984 French Quality Order (INB order)
- Completed IO audit for five PAs
- Prepared component list for the categorization of CE marking and liaison with external agency
- Successful implementation of CADENAS for Mechanical standard parts in our ENOVIA data base
- Completed integration of ITER-India Lab building CAD data and Equipment in to ENOVIA data base and provision made for online interface management in design

- Implementation Agreement signed between IN-DA and DAHER for global transport
- Identification of new risks, mitigation plans and updating ITER-India risk register
- Work on intellectual property (IP) through ITER-India IP board
- Internal audits for all packages