DESIGN, DEVELOPMENT AND RECENT EXPERIMENTS AT THE CIMPLE-PSI DEVICE

M. KAKATI
CIMPLE-PSI Laboratory, Centre of Plasma Physics-Institute for Plasma Research, Sonapur 782 402, Assam, India
E-mail: mayur@cppipr.res.in

TRINAYAN SARMAH*, NGANGOM AOMOA*, J. GHOSH*, B. SATPATI*, GAGAN SHARMAa, AJAY GUPTAa and G. DE TEMMERMANa

aCIMPLE-PSI Laboratory, Centre of Plasma Physics-Institute for Plasma Research, Sonapur, Assam, India
bInstitute for Plasma Research, Gandhinagar, Gujarat, India
cSaha Institute of Nuclear Physics, Kolkata, West Bengal, India
dAmity Centre for Spintronic Materials, Amity University, Noida, Uttar Pradesh, India
eITER Organisation, Route de Vinon-sur-Verdon, Cedex, France

Abstract

The CIMPLE-PSI laboratory at India’s northeast corner, has been engaged over the last decade on the development of advanced experimental systems for fusion-relevant plasma surface interaction (PSI) studies and material testing. A segmented arc assisted high heat flux (HHF) device was developed that could deposit ITER-like extreme plasma heat flux (10 MWm⁻²) uniformly over an external target simply by supersonic expansion of a plasma jet. HHF was used to study the condensation of tokamak relevant tungsten dust particles, as it may happen after plasma-induced melting of tungsten inside a fusion device. The second device is called CIMPLE-PSI that was commissioned more recently, which is a complete tokamak divertor simulator that can reproduce both heat and ion flux parameters while operated with fusion like gases, at ITER divertor like extreme limits (ion flux ~10²⁵ m⁻²s⁻¹ and heat flux ~1-10 MW/m²). The paper reports the design principles behind the major sub-systems of this device, their individual performance and that of the integrated system as a whole. A detailed characterization of the plasma beam in terms of the plasma temperature, plasma density, plasma jet velocity etc. for different experimental conditions will be also reported in the paper. Bulk tungsten samples were exposed in this device under helium plasma, with formation of tungsten fibre foam structures on the plasma-exposure surface of the target. Glancing incidence small angle x-ray scattering (GISAXS) was used for studies on the helium bubbles that remain embedded under the sub-surface areas of the helium plasma exposed tungsten samples. W-fuzz grown in this system was found to be better crystalline compared to most other reported results.

1. INTRODUCTION

It is essential to understand how the plasma in the divertor region of the ITER tokamak with its extreme ion (~10²⁴ m⁻²s⁻¹) and heat (~10 MWm⁻²) flux, will interact with the tungsten wall once it becomes fully operational in the next decade [1]. Several linear plasma devices (LPD) facilities have been built worldwide to address this issue, where controlled fusion-relevant plasma-material interaction (PSI) issues could be explored under ITER-like simulated plasma conditions. LPDs provide excellent access for different diagnostics and for frequent PSI experiments with robust control on the exposure conditions. Some leading such devices in the world include MAGNUM-PSI and PILOT-PSI at DIFFER, the Netherlands, PSI-2 (Julich), NAGDIS-II (Nagoya University, Japan), DIONISOS (MIT, USA), GyM (IFP-CNR, Italy), LENTA (Kurchatov Institute, Russia), Linear Plasma Generator (JAEA, Japan) and MAGPIE (Australian National University) [2].

In this paper, we will report design, development and commissioning of another magnetized plasma divertor simulator device at CPP-IPR, India, which was configured broadly in the line of the MAGNUM and PILOT-PSI devices mentioned above, but realized with a significantly smaller budget. This was named as “CPP-IPR magnetized plasma experiment for plasma surface interaction”, or CIMPLE-PSI in abbreviated form, which uses a segmented arc as the plasma source. Using the same plasma source, we had before established a high heat flux device which could reproduce ITER divertor-like heat flux (~10 MWm⁻²), but which could be operated effectively with argon only. Some remarkable plasma surface interaction experiments with tungsten was carried out in this device before [3, 4], a concise review of which is provided in this paper. In the longer time scale, CIMPLE-PSI will be utilized to understand the evolution of the micro-structure of tungsten and other plasma facing materials under steady-state exposure in this device. Surface microstructural changes will drastically influence the surface hardness, probability of dust release and gas retention properties of the metal, which are some of the most important issues relevant for controlled plasma fusion research. Studies have already been carried out in this direction, to quantify changes of surface mechanical properties of tungsten; but De Temmerman et al. have pointed out that measurements were made under relatively lower fluence (5×10²⁴ m⁻²), which may not be sufficient to
qualify the material from the perspective of ITER life time [5]. It was pointed out that the extremely high ion-flux in ITER combined with the long pulse plasma duration (10^2-10^3 seconds), may lead up to a maximum fluence of 10^{27} m^{-2} over just a single pulse operation of ITER [5]. Crystal microstructural changes are time-dependent phenomenon, and for meaningful qualification of tungsten for ITER use, it is essential to undergo particle loading equivalent to at least few hundreds of such pulses, which very few linear divertor simulator systems can provide at this moment. However, in case of CIMPLE-PSI, even at the highest field strength (0.45 T), the water-cooled electromagnet is designed to work in almost continuous fashion, which should allow CIMPLE-PSI to obtain ion fluences in excess of those reached in most experiments to date.

In CIMPLE-PSI, the arc source is connected at one end of the chamber and the plasma jet propagating in vacuum is collimated by an axial magnetic field produced by a water cooled copper electromagnet. This beam is finally made to interact with different material targets of relevance to the plasma fusion research, under controlled laboratory conditions. We here report on the characterization of the plasma beam under variation of plasma power and the magnetic field strength. We also report a PSI experiment, where tungsten was exposed under helium plasma that witnessed formation of tungsten-fuzz like nanostructures [6]. Advanced material characterization techniques including glancing incidence small angle x-ray scattering (GISAXS) were used for characterization of the tungsten nanotendrils and the helium nanobubbles embedded inside.

2. CPP-IPR HIGH HEAT-FLUX (HHF) DEVICE AND REVIEW OF PLASMA SURFACE EXPERIMENTS UNDERTAKEN WITH TUNGSTEN TARGETS

The CPP-IPR high heat flux (HHF) device is a simple, low-cost, indigenously developed, segmented plasma torch assisted, steady-state, high-heat flux device, which could reproduce the extreme heat flux expected in future fusion devices (Fig. 1a) [3]. A thermal plasma jet at atmospheric pressure interacts with an external surface usually in an uncontrolled fashion. Hence to deposit energy uniformly over a target, the plasma torch was coupled to a vacuum chamber, inside which the jet expanded with supersonic velocity. The initial expansion of the plasma continued until a shock was produced, after which the jet propagated with a constant cross-section, in the form of a stable, laminar beam, with a visible diameter of about 30 mm. For a 9-ring segmented torch, 43.7 kW input power (25 lpm argon, 350 A plasma current), through water calorimetry it was measured that the jet deposits more than 10 MWm^{-2} average power density over a 20 mm diameter copper calorimeter. Production of extreme plasma density of the order of 10^{21} m^{-3} was confirmed under most operating conditions with a relatively low plasma temperature of just 0.2 eV. The drawback is the high necessary operating pressure (few tens of mbars) which made it difficult to produce a collimated plasma beam with fusion relevant gases like hydrogen, deuterium or helium. A PSI experiment was performed in HHF to study the melting of tungsten. Bulk tungsten samples were exposed to the argon plasma under steady-state heat flux, which had led to the condensation of highly non-equilibrium skeletal and spherulitic crystals in micrometer sizes from tungsten melt, observed for the first time for this metal (Fig. 1b). The increase in the metal viscosity during high under-cooling, leading to a limited supply of atoms to the crystal surfaces compared to the corners, is understood to have resulted in these special crystal morphologies. It is interesting to note that fine dust particles with similar morphologies were observed in fusion machines, for example in the tokamak T10 for graphite materials [7]. The hydrogen retention characteristics of these tungsten dust particles was studied by Nuclear Reaction Analysis (NRA). To produce tungsten dust with even finer sizes, tungsten nanoparticles were synthesized with a segmented plasma assisted experimental nano-reactor system. The hydrogen retention of tungsten dusts in nano and micrometer sizes was found to be substantially higher than that of bulk tungsten. This is attributed to the presence of mesopores inside the aggregated nanoparticles and/or the larger surface area of the non-equilibrium crystals. It was pointed out that tungsten dust morphologies will tend to be more non-equilibrium in future tokamaks which will work at an even higher energy regime.
3. DESIGN, DEVELOPMENT AND COMMISSIONING OF CIMPLE-PSI

3.1. The segmented plasma torch

A segmented torch was used as the plasma source, which operates in a similar fashion as the cascaded arc source in the Pilot-PSI or Magnum-PSI devices. This source configuration was introduced by Maecker in 1960’s, which was optimized further at Eindhoven University of Technology and DIFFER (the Netherlands) [3]. They typically operate at high-pressure which has the advantage of producing high-density plasma jets with excellent stability. The CPP-IPR laboratory has been using the segmented arc configuration for more than a decade for the production of different high temperature nanomaterials. The plasma source had a thoriated tungsten cathode and a stack of copper ring segments separated by Teflon gaskets and a copper anode, each of which were cooled-down by passing about eight litres per minute (lpm) of water at 2.5 bar pressure. For CIMPLE-PSI, a redesign of the source was done to allow operations with molecular gases and an axial magnetic field. Following the DIFFER design, this new source configuration had copper-tungsten alloy (25% copper and 75% tungsten) made inner segments and stainless-steel made outer jackets, which was fabricated at Excel Instruments, Vasai, India (Fig. 2a). The two dissimilar metals were joined by vacuum brazing at NFTDC, Hyderabad, India. In the new design, Viton O-rings are used for keeping vacuum, which is protected from the hot plasma by Boron-nitride made inner gaskets, and supported from outside by PVC made spacers (Fig. 2b). Individual segments had a straight central passage for plasma flow with 1 cm diameter and 1.5 cm thickness. With six segments the torch had a total length of 11 cm. A 7 bar system is used for the water cooling of the torch segments during plasma operation, which had produced individual water flow through each ring at about 16 litres per minute (lpm). The torch is operated with an Amtech, Gandhinagar made 150 kW (500 A, 300 V) DC power supply with an integrated high voltage, high frequency igniter for the initiation of the arc.

FIG. 1. a) schematic of the HHF device, b) SEM micrograph of the argon plasma exposed tungsten sample in HHF device that shows condensation of tungsten skeletal crystals.

FIG. 2. a) Drawing of the copper-tungsten and stainless-steel made segmented plasma torch, b) drawing of a single segment showing Boron-nitride inner segments, Viton O-rings and PVC spacers.
3.2. The water cooled copper electromagnet

A water-cooled copper electromagnet configuration was preferred over a superconducting type, because of its lower cost and easier maintainability. To calculate the required number of coils, the number of turns per coil and the position of the coils, necessary to obtain a homogeneous 0.45 T field at the machine axis, we used a method based on the minimization of a weighted sum of the squared deviations from the desired field profile and the power dissipated in the coils for a given coil configuration [8]. Such a minimization, gives a set of linear simultaneous equations that can be solved to obtain the desired parameters. This analysis prescribed that three current carrying coils, having total 200, 160 and 200 turns respectively, may be placed spanning a total length of about one meter to produce a reasonably uniform field along the central axis. Square copper conductor with 10 mm sides and 5 mm through hole for passing water was procured from Luvata, Finland for development of the electromagnet. We opted for the double-pancake type individual coil units having two layers of ten-turn sections, with inner diameter 55 cm, outer diameter 75 cm and width approximately 2cm, so that total 28 units were required for erecting the complete electromagnet system [9]. The winding of the copper conductor into the pancake units was done using a motorized turn-table (R.B. Engineering, Howrah). Before that, the conductor was insulated with kapton and cotton tapes, and then the entire pancake was cast in epoxy for rigidity. Each coil had terminated in to pair of leads, to which copper connectors were brazed for electrical connections, and nozzles connected for passing cooling water. Each coil was tested for high voltage inter-layer insulation (2.5 kV) and unhindered flow of water along the through hole. Pancakes were placed along a raised platform, divided into three groups, having 10, 8 and 10 numbers of pancake units, with 190 mm separation in between the groups, at which vacuum chamber viewports were positioned for diagnostics and accessing inside the chamber. All pancakes were connected electrically in series. The vacuum chamber was placed concentrically with the magnet rings that could slide on a rail system. The length of the copper conductor in a single pancake was about 43 m and resistance 8.6 mΩ (R). For maximum current (10^3 A), 8.6 kW power will be released in each pancake, which has to be dissipated by cooling water. ANSYS analysis shows 6 bar pressure drop will create 2.25 liters/min water flow through each double-pancake, which should be sufficient to keep the raise in the temperature of the output water line under tolerable limit. A double loop water cooling system was developed: in the primary loop cold water flows into the individual magnet pancakes all in parallel (28 lines, maximum 300 lpm water flow and 7 bar water pump) and then dumps the heat collected from the magnet on a plate heat exchanger (PHE). This was measured to induce about 2.5 lpm of water in magnet pancakes. This heat is finally dissipated in to the atmosphere through a secondary circuit containing a cooling tower. The magnet is powered with an Amtech, Gandhinagar manufactured 350 kW (1000 A, 350 V) DC power supply. After commissioning of the magnet, field mapping was carried out along the axis of the chamber with a Gauss-meter (up to 850 A), which shows minor deviation of 2% compared with the theoretically calculated values. The Fig. 3 shows the maximum measured magnetic field along the chamber axis for 1000 A current through the electromagnet.

FIG. 3. Magnetic field as measured with a Gauss-meter along the central axis of the vacuum chamber, for 1000 Ampere DC current through the copper electromagnet.
3.3. The vacuum chamber, vacuum pumping scheme and the water-cooled target holder

The stainless-steel SS304 made vacuum chamber (38 cm inner diameter, 128 cm length) is installed on a rail system, so as to slide within the magnet rings (Fig. 4). The copper magnet and the rails together stand on a robust, raised platform, also made of SS304. The plasma torch is connected to one end of the vacuum chamber and the jet propagates in vacuum along the machine axis. To dissipate the plasma heat deposited on the chamber and avoid overheating, the chamber was made double walled that was further divided axially into four equal parts, through each of which water flows at 15 litres per minute (lpm). Two water lines go to the end flanges. A 2.5 bar closed water loop, with 5 TR refrigeration capacity, having 14 outlets was utilized for all these water cooling arrangements. The design consideration for the scheme of vacuum pumping for CIMPLE-PSI device was that about few pascal (10^{-2} mbar) pressure is to be maintained at the plasma material interaction region that corresponds to the possible situation at the ITER Divertor region. Moreover, the neutral density should be reduced to the minimum possible. The vacuum chamber was finally pumped down with two pairs of roots vacuum pumps, with pumping speeds of 2,600 m^3/h and 4,200 m^3/h respectively, each of which were backed by an individual Edwards 275 m^3/h (E2M 275) rotary vacuum pump. A relatively smaller pair of roots vacuum pumps (EH 2600) was connected symmetrically to the plasma torch end of the chamber, while the bigger pairs were coupled to the other extreme end of the system. To optimize the dimensions of the pumping lines connecting the vacuum pumps with the chamber and to estimate the respective conductance of the pipe work, we had assumed that the flow of gases will be in the viscous regime, although in many cases it approached the transition region. Separate vacuum pumping lines were used for connecting four pairs of roots and rotary vacuum pumps to the chamber, on each of which water cooling channels were welded on the surface, because roots vacuum pumps cannot tolerate temperature at more than 200˚C at the inlet. For 250 A plasma current (24 kW), 22.5 lpm helium flow and magnetic field of 0.4 Tesla, the ambient pressure at the vacuum chamber was measured by Baratron vacuum gauge as 3 Pascal. The target holder in CIMPLE-PSI device consists of a water-cooled copper substrate, with a small central hole to fix of thermocouples from below, above which sits the material target (Fig. 4, in the inset). The target is hard pressed against the substrate below, using six nuts and screws, by a stainless-steel holder from the top, which has a 2.2 cm opening at the centre. Tungsten targets of square shape, each side 2.5 cm long and 0.1 cm in thickness were procured from PLANSEE (99.97% purity). A good thermal contact between the target W plate and the water-cooled substrate below is ensured by putting graphoil layers at the interface. A ball and screw arrangement are provided for movement and positioning of the target inside the chamber, through an electrical motor located outside. Angle of incidence of the target plate with respect to the plasma beam may be adjusted.
manually, although normally it remains perpendicular with each other. Cooling of the target holder is accomplished through two individual water channels, the first one protects the top plate during direct exposure of plasma, while the second one controls the temperature of the target. The temperature of the W target could be measured using a K-type thermocouple, which had a thin insulating sheath at the sensing end. The exposed surface of the target is made floating, and can be biased with respect to the grounded chamber during a PSI experiment to control the incoming ion energy.

3.4. Plasma diagnostics and material characterization techniques

The basic plasma diagnostics of CIMPLE-PSI comprise a reciprocating Langmuir probe drive system, optical emission spectroscopy (OES) and calorimeters. A retracting Langmuir probe drive system, consisting of a solenoid valve running in closed loop, was integrated to the CIMPLE-PSI device, to be used primarily when the magnetic field is off. Tungsten made double probe heads (5 mm long, 1.9 mm diameter with 6 mm separation) protrude through a quartz glass envelope, the other ends of which were brazed to copper wires inside the probe shaft. In presence of excessive heat, the shaft may be set to continuous sliding motion so that the probe-tips and the glass envelope are not damaged. About 300 msec is required for the probe to travel 50 mm radially in to the centre of the plasma jet and coming back to the rest position, during which the probe tips may be biased transiently with a pulse length of about 20 milli-seconds. A Techtronix oscilloscope is used for the display of the fast voltage signals (TDS 2024C). For OES, we used a McPherson made Czerny-turner monochromator based very high-resolution spectrometer with a focal length of 1.33 meter (Model 209). This spectrometer, when fitted with a grating of 1800 g/mm gave a resolution of 0.007 nm, which is essential for measurement of the plasma beam velocity. The spectrometer utilizes a Newton 940 spectroscopic CCD camera consisting of a 2048x512 array of 13.5 µm pixels with thremoelectric cooling down to -80°C to ensure negligible dark current. With a convex lens and a set of five optical fibres, the plasma light is delivered to the spectrometers kept at a distance. They are HOH (UV/Vis) silica cable with 400 µm core, having SMA connectors on both ends and stainless steel flexible sheaths for protection. For OES measurement of the plasma density and gas temperature, a small amount of hydrogen (0.3 lpm) is mixed with helium and injected in to the plasma. This produces atomic lines from the hydrogen Balmer series along with the helium emission lines. The Hα line from the Balmer series can be fitted with a Voigt profile, which may be de-convoluted in to Lorentzian and Gaussian parts. From the corresponding Lorentzian width, which is due to the Stark broadening, the plasma density can be calculated. If the Gaussian width is of the same order as the Gaussian width, the ion temperature also can be estimated simultaneously from the corresponding Doppler broadening [10]. The instrumental broadening should be subtracted from the Gaussian width. Furthermore, plasma jet velocity was calculated from Doppler shift of the 706.74 nm helium atomic line. The plasma emission for spectroscopic analysis was collected from the centre of the first viewport at a distance of 8 cm from the anode. The average heat flux that the collimated plasma beam may deliver on an external surface was measured with a 2 cm diameter, copper-tungsten alloy made calorimeter, which was placed at the centre of the first window, perpendicular to the laminar plasma beam [3]. While connected to a closed loop water circuit (7 bar), we can assume that under steady-state conditions, the cold water passing through the calorimeter removes the entire heat deposited on its surface. Therefore, power absorbed by the calorimeter may be estimated by measuring the temperature difference between the incoming and outgoing water (PT100) and from the corresponding water flow rate. Other basic operational diagnostics include pressure gauges (Baratron), thermocouples (K-type), simple IR hand-held thermometers, and basic voltage/current meters.

The morphology of the helium plasma irradiated tungsten targets was investigated by a field-emission scanning electron microscope (FESEM, JEOL JSM-7100F). For detailed morphological analysis of the tungsten-fuzz samples at nanometer resolution, a FEI, Tecnai G2 F30, S-Twin TEM (300 kV) equipped with a Gatan imaging filter (model 963) was used, which had an Energy Dispersive X-ray (EDX) spectroscope attached for elemental analysis. In the present study, the depth dependent variation of the sizes of helium nano-bubbles in tungsten sample was investigated by glancing incidence small angle x-ray scattering (GISAXS) technique at the Micro- and Nanofocus X-ray Scattering Beamline at PETRA III, DESY, Hamburg [11]. Such measurement for investigation of the tungsten embedded helium bubbles was pioneered by the group at Australian National University [12]. The technique has the advantage that measurements are averaged over a larger volume of material compared to what becomes possible to study during usual HRTEM studies.

3.5. Commissioning of CIMPLE-PSI and characterization of the plasma beam

A 750-kVA diesel generator was procured exclusively for this device that provided uninterrupted DC electric power continuously to the experiments. For initiation of experiments in CIMPLE-PSI, continuous water cooling of all individual components including plasma torch, surface of vacuum chamber, vacuum pumping lines, electromagnet etc. are first ensured. Vacuum pumps started operation and base pressure of 4.2×10^{-2} Pascal was
registered in the plasma chamber. Helium was injected at 22.5 lpm at the cathode, and the six-ring torch was operated at 250 Ampere (20 kW), which produced a diffused plasma beam inside the vacuum chamber. The pressure at the vacuum chamber was measured with a Baratron gauge as 3 Pascal. Under this condition, plasma parameters were evaluated 8 cm away from the torch anode, with a double Langmuir probe. For 250 plasma current (20 kW), the probe could be still kept static inside the diffused plasma jet, and biased between -40 to 40 Volts. An ideal symmetric double Langmuir plot was obtained, from which the plasma density was estimated as 3.04x10^{18} m^{-3}, and plasma temperature as 1.0 eV. This plasma density corresponds to an ionization fraction of 0.1%. The magnet was then energized, and it was observed that the diffused plasma jet had collimated in to laminar beam under just 0.06 Tesla magnetic field, which extended beyond the second viewport of CIMPLE-PSI. The visual plasma intensity increased with field strength (maximum up to 0.45 Tesla) indicating enhancement of plasma temperature and density.

For characterization of plasma under different experimental conditions, the magnetic field was varied from 0.2 to maximum 0.4 Tesla, with 0.1 Tesla increment, for 200 A, 250 A and 300 A plasma current, results from the centre of the first viewport is presented in Fig. 5. As expected, peak plasma density is increasing with both magnetic field and the plasma current (Fig. 5a). The peak maximum plasma density for 250 A plasma current, 0.4 Tesla field was measured as 2.5x10^{20} m^{-3}, which shows density enhanced by almost two orders on introduction of the magnetic field, which is in the ITER divertor like regime. Radial variation of electron density and ion temperature for different magnetic fields are plotted in Fig. 5b and 5c respectively, for 250 A plasma current. This shows density and temperature were fairly uniform in the central portion of the plasma beam. The plasma density in the second viewport was about an order smaller, which we avoided measuring further in this report. CIMPLE-PSI was routinely operated continuously maximum up to 3x10^{3} seconds at 250 A plasma current, which witnessed stable plasma operation. The maximum rise in temperature of the magnet coils and the vacuum chamber surface was less than 15 °C, whereas vacuuming pumping lines were heated up much less than that.

The plasma beam velocity was measured at the first viewport from the Doppler shift of a helium emission line, for 250 A plasma current and with variation of the magnetic field (in Fig. 6a). The typical line shift was about 0.015 nm which was several times bigger than the resolution of the spectrometer that was 0.003 nm. Fig. 6b shows velocity is increasing with magnetic field, which is similar to the trend seen before in PILOT-PSI system [10]. From the product of peak plasma density at 250 A plasma current, 0.4 Tesla magnetic field (2.5x10^{20} m^{-3}), and the corresponding plasma jet velocity (4.03 x10^{3} m s^{-1}), the peak helium ion-flux at the first viewport of CIMPLE-PSI is estimated to be 1.01x10^{24} m^{-2}s^{-1}.

**FIG. 5.** a) OES measured electron density at the first viewport with variation of plasma current and magnetic fields, b) graph shows radial variation of beam density with variation of fields (250 A), c) graph shows radial variation of electron temperature (250 A).
For estimation of the heat that may be delivered on an external substrate by this plasma beam, one should consider contributions from electrons, ions, and neutral atoms, all together. For every electron-ion pair in the plasma beam arriving on the target, an energy equivalent to helium ionization potential is transferred to the surface upon their recombination, while their kinetic energy may be assumed as being partially absorbed at 40% [10]. For a Maxwellian velocity distribution, the total energy delivered by one pair of electron-ion may be written as:

$$\text{Total energy} = \frac{1}{2} E_{\text{diss}} + E_{\text{ion}} + \frac{1}{2} m v_a^2 + \frac{3}{2} k_B (T_e + T_i)$$  \hfill (1)

Where, $E_{\text{diss}}$ = molecular dissociation energy, $E_{\text{ion}}$ = ionization energy, $v_a$ = axial velocity of the plasma jet, $m$= mass of the ion, $k_B$ = Boltzmann constant, $T_e$=Temperature of the electron, $T_i$=Temperature of the ion. Putting ionization energy for helium as 24.6 eV and other numerical values in the above equation, the energy deposited by one pair of electron-helium-ion, at 250 A plasma current, 0.4 Tesla magnetic field and 2.4 eV ion temperature is estimated as 31.93 eV, where we have considered $T_i = T_e$. By multiplying with the corresponding ion flux, one can estimate the peak heat flux that the plasma beam may deposit as 5.1 MWm$^{-2}$. This was experimentally verified by water calorimetry, that measured heat flux averaged over the surface of the 20 mm diameter calorimeter as 3.34 MWm$^{-2}$. This shows CIMPLE-PSI could successfully reproduce both extreme ion and heat-flux parameters in the ITER divertor like order.

4. STEADY STATE EXPOSURE OF TUNGSTEN TARGET UNDER HELIUM PLASMA IN CIMPLE-PSI, CHARACTERIZATION OF MATERIALS GROWN ON THE EXPOSED SURFACE

A tungsten target is mounted perpendicularly at the axis of the vacuum chamber, at a distance of 26 cm from the torch anode (as shown in Fig. 7). The metal plates were first mechanically polished with silicon carbide paper (120 to 2500 grit size) to a mirror finish and then sonicated in both acetone and ethanol. The target was exposed to helium plasma at 250A plasma current, for total of 900 seconds, under 0.2 Tesla magnetic field. Moreover, the target was biased with respect to the grounded chamber at -45 Volt all throughout this PSI experiment, the current
through the target was 7.5 A. The target temperature was 930 K as measured with a thermocouple. It may be noted here that the ion energy is still much below the ion sputtering threshold, which is around several hundreds of eVs for this combination of helium ion and tungsten. After exposure, the sample surface appeared black. The powdered structure could be easily wiped off with a tissue paper, after which the shiny metal surface becomes visible again. Examination of the material under a FESEM confirms growth of tungsten fibre foam structures or tubular tendrils of nanometer level diameters (Fig. 8a). This is similar to tungsten-fuzz which was observed under similar exposure conditions in divertor simulator devices as well as in tokamak devices. The nano-tendrils do not have a uniform cross-section along their length. FESEM gives a range of diameters roughly between 15-35 nanometers. However, detached tendrils were examined under a HRTEM that demonstrated tendril diameters bigger than that (Fig. 8b).

With FESEM only the top of the W-fuzz is observed, while with HRTEM also the bottom of the fuzz is seen. It is known that the fuzz diameter decreases with thickness and is therefore higher at the base of the tendril than at the top. HRTEM also shows that bubbles are embedded inside the tendrils, which is understood to contain helium inside. Bubbles are considered also to be the precursors for the growth of the nano tendrils. The bubble size distribution was constructed by considering a total of 42 such structures from three different HRTEM micrographs (Fig. 8c). The maximum bubble size was 22 nanometer. Bubble sizes were measured from edge to edge across the widest part of the bubble, using the Image J (https://imagej.nih.gov/ij/) software. Selected Area Electron Diffraction (SAED) was carried out for the sample, which shows a faint spotted pattern that corresponds to α-tungsten (Fig. 8d). However, no sign of oxides was revealed from the electron diffraction pattern. The compositional analysis carried out by EDX shows the presence of oxygen and carbon in addition to tungsten (not shown in the paper). It is assumed that oxygen is in the tungsten-oxide form, which remained amorphous. Nano-tendrils have a very high specific-surface area, and probably got surface oxidized after being exposed to the environment during the material characterization process. Similar observations were recently done while synthesizing tungsten nanoparticles by a plasma-assisted method, where also a thin amorphous tungsten-oxide coating was observed to have formed [13].

GISAXS was used to probe the W-fuzz and helium nano-bubbles that remain embedded in the exposed tungsten samples just under the top surface. Measurements were done as a function of the x-rays incidence angle, so as to probe material as a function of depth from the top surface. Fig. 9a shows a typical 2D GISAXS image for angle of incidence ($\theta_i = 0.3^\circ$) with respect to sample surface. A horizontal strip was extracted around the specular spot in order to get the scattered intensity as a function of in-plane scattering vector $q_x$ for GISAXS analysis. Fig. 9b shows the extracted GISAXS data for different x-ray incidence angles with respect to sample surface. In order to investigate the effective size of nanobubbles, asymptotic approximation is considered in this paper [14]. Here, one expects a linear variation of $\ln|q^4 I(q)|$ as a function of $q^2$ for larger $q$, where $q$ is the scattering vector. The extrapolation of this linear dependence to $q = 0$ allows us to find the Porod constant, designated as $K_p$. If the Porod
constant $K_p$ is known, the Porod integral invariant ($Q$) can be given as $Q = \int_0^{q_0} q^2 I(q) dq + \frac{K_p q_0}{q_0}$. Where, $I$ designates intensity [14]. Then effective diameter of nano-bubbles will be given as: $D = \frac{8Q}{\pi K_p}$.

\[ \begin{align*}
\text{FIG. 9, a) 2D GISAXS Image for } \theta_i = 0.1^\circ, & \text{ b) GISAXS data as a function of angle of incidence, c) Variation of bubble diameter (nm) as a function of } \theta_i.
\end{align*} \]

From Fig. 9c, it is seen that sizes (diameter) of the nanostructures at grazing incidence of 0.1 degree is about 18 nanometers, which corresponds to penetration depth of 4.7 nm is about 18 nanometers, which then drops abruptly to about 5 nanometers at penetration depth of 19 nm, after which it remains more or less constant. At smaller angle of incidence, the scattering is occurring mainly from the fibre-foam fuzz structures, so the bigger diameter value (18 nm) must represent primarily the size of the tungsten nanotendrils. This conforms to the diameter of the W-fuzz as measured from the FESEM photographs before, which was in the range of 15-35 nanometers. On the other hand, about 8 nanometer sizes from the graph must correspond to the average diameter of the helium bubbles that remain embedded in the sub-surface areas. It may be compared with the HRTEM derived average size of the helium bubbles remaining inside the nanotendrils that was 7 nanometers, which also is in good agreement. We carried out GISAXS measurements of few more helium-plasma exposed samples just to ascertain the consistency of this measurement technique and to reconfirm that our assertions above in terms of the interpretation of GISAXS results were correct. The first two samples had growth of fuzz (with differences in biasing voltage), for both of which GISAXS demonstrates once again relatively bigger sizes from the top layer, which then falls suddenly without much variation after that. There were two more samples that were exposed to helium at lower target temperature and as such with no surface growth of fuzz but likely to have subsurface bubbles. GISAXS of these samples as expected demonstrated only smaller sizes and less variation than before that reconfirmed the reliability of the technique.

To see the effect of change in sample temperature in CIMPLE-PSI, helium-fuzz experiments were repeated for target temperature of 1430 K. However, plasma power had to be varied over a narrow regime in order to keep the target temperature constant (220±30A). A high-resolution micrograph of this sample is presented in Fig. 10a, which was taken with a 300 kV HRTEM. Size distribution of the helium nano-bubbles was constructed once again (Fig. 10b), which shows for the 1430K sample the tail of the distribution marginally extends little more compared to the sample before exposed at lower temperature.

\[ \begin{align*}
\text{FIG. 10, a) HRTEM micrograph of the tungsten nano-tendrils grown at 1430K target temperature, b) size distribution of the embedded helium bubbles constructed from HRTEM photograph.}
\end{align*} \]
Another important observation was, W-fuzz in CIMPLE-PSI at 1430 K shows a higher degree of crystallinity. Crystal planes of $\alpha$-tungsten were clearly seen in most of the HRTEM photographs (Fig. 11a). This was further verified by the SAED measurements (embedded in Fig. 11a). This may be a consequence of the high heat flux, under which the fuzz remains exposed. EDX reconfirms presence of tungsten and oxygen, although there was no indication of crystalline oxides. Only in one photograph (Fig. 11b) few very small crystallites are observed whose atomic plane separation corresponds to WO$_3$.

![HRTEM micrograph of W-fuzz grown at 1430K that shows crystal planes of $\alpha$-W, b) HRTEM of the same sample shows very few crystal planes that correspond to tungsten-oxide.](image)

**FIG. 11.** a) HRTEM micrograph of W-fuzz grown at 1430K that shows crystal planes of $\alpha$-W, b) HRTEM of the same sample shows very few crystal planes that correspond to tungsten-oxide.

5. CONCLUSION

The paper reports on the design, development and commissioning of a linear magnetized plasma device at CPP-IPR, India, for controlled plasma surface interaction studies and material testing under fusion-relevant conditions. A segmented plasma torch assisted high heat flux device was first developed which could reproduce the extreme heat flux that is foreseen in the ITER tokamak with argon plasma. Formation of tokamak analogue tungsten dust particles with highly nonequilibrium morphologies were observed in this device, which were measured to demonstrate much higher absorption of hydrogen gases compared to bulk tungsten. CIMPLE-PSI is a complete tokamak divertor simulator, which in addition to intense heat could also reproduce ITER relevant extreme ion-flux while operating with fusion relevant gases. This communication reports design, development and commissioning of the individual sub-components of CIMPLE-PSI that includes: a segmented plasma torch, water cooled copper electromagnet, vacuum pumping, water cooling systems, double-walled vacuum chamber, temperature-controlled substrate holder and plasma/material diagnostics systems. A magnetized, collimated helium plasma jet was produced, which is an ideal configuration for arranging a PSI experiment under controlled laboratory conditions. The plasma jet at the first viewport of the system was characterized for wide variation of plasma current and the strength of the magnetic field. We also identified an experimental regime under which most stable operation of the device was possible for prolonged period (250A plasma current, 0.4 Tesla). The peak helium ion and heat flux density under that condition was measured as $1.01 \times 10^{24}$ m$^{-2}$s$^{-1}$ and 5.1 MWm$^{-2}$ respectively. It should be possible to produce fluence beyond $10^{28}$ m$^{-2}$ in the future under few hours of operation.

Few PSI experiments were also arranged in the CIMPLE-PSI device, temperature-controlled and negatively biased tungsten targets were exposed to helium plasma, that led to the formation of tungsten fibre foam structures, popularly also known as W-fuzz. They had been observed before even inside tokamak machines, and might lead to enhanced production of dusts or may also influence the surface mechanical properties of the tungsten wall. However, their formation mechanism is still not very well understood. We here demonstrate that GISAXS could be an ideal technique for measuring the sizes of the helium nano-bubbles that remain embedded just below the top surface of the exposed tungsten samples.

ACKNOWLEDGEMENTS

We acknowledge Director, IPR for supporting this experiment. We also acknowledge Professor Y.C. Saxena, and Mr. A. Vartharajulu, IPR, Gandhinagar for their crucial support at various stages of this development. Technical help is greatly acknowledged from the following persons: Mr. Sailesh B. Bhatt, Prashant Singh, Mr. Sudhir Kumar Sharma, Mr. N.C. Gupta, Dr. P.M. Raole, Dr. Paritosh Chaudhuri, Dr. Samir Khrirwarkar, Professor Mainak Bandyopadhyay, Mr. Ashok Mankani, Dr. Arun Kumar Chakraborty, all from IPR, Gandhinagar, Mr. S.K. Thakur, VECC, Kolkata, Professor Rabindranath Pal, SINP, Kolkata and Dr. Sanjeev Kumar, NCCCM, BARC,
Hyderabad. We specially acknowledge Mr. Subhas Pai, Excel Instruments, Vasai, Maharashtra for his excellent cooperation during the design and fabrication of the new torch configuration. Help of Dr. S. Roth and Dr. P. Pandit in GISAXS measurements is acknowledged. Travel support for performing experiments at PETRA-III was provided by the Department of Science and Technology, India through Jawaharlal Nehru Centre for Advanced Scientific Research. Thanks to Kandeswar Deka, Tradesman B, CIMPLE-PSI Laboratory, CPP-IPR for his assistance all throughout the experiments. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

REFERENCES


