PLASMA POTENTIAL MEASUREMENTS IN THE EDGE REGION OF ADITYA-U TOKAMAK USING RECIPROCATING LASER HEATED EMISSIVE PROBES

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Abstract

Laser Heated Emissive Probes (LHEP) have several advantages over conventional filament emissive probes and serve as a tool for direct measurement of plasma potential. Measurement of plasma potential or Electric fields component perpendicular to magnetic field are necessary for fundamental understanding of plasma parameters, transport mechanisms, space charge distribution in plasmas. Owing to complexities of tokamak geometries and high temperature magnetically confined environment, very few attempts have been made for using emissive probes on such complex devices. A novel design of the LHEP for ADITYA-U tokamak involving radially movable probe shaft with dual probe tip provision made up of LaB$_6$ is reported and discussed here. CW CO$_2$ laser at 10.6 µm having a maximum power of 55 watt is continuously focused on probe tip, using a specialized force air-cooled fiber, despite the radial movement. The set-up is designed for direct measurement of radial profiles of plasma potential in edge plasma region of ADITYA-U tokamak. Experiments have been carried out for estimating electron emission current density and repeatability of using same LHEP probe inside tokamak. Experiments for direct measurement of plasma potential using LHEP will be carried out in future and will be reported.

1. INTRODUCTION

Precise spatial and temporal knowledge of plasma potential, electric field and its fluctuations is vital for interpreting many phenomena like particle drift, transports etc. in high temperature magnetically confined plasmas of tokamak. Energy confinement and particle flows in magnetised plasmas are strongly influenced by electric fields and their fluctuations which are function of gradients in plasma potential [1].

There are several methods for determination of plasma parameters locally each having their own advantages and disadvantages but robustness of Langmuir probes makes them most popular candidates for measuring plasma parameters in wide range of plasmas from less complex glow discharge plasma to more complex plasmas in tokamaks. Owing to ease in using Langmuir probes, the probe floating potential is used for deducing the plasma potential in tokamak edge region, but evaluating the I-V curve of Langmuir probe in magnetically confined plasma atmosphere with sufficient accuracy is equally difficult [2]. In magnetic plasma, interpretation of characteristic above floating potential of probe I-V remains problematical and usually the I-V curve below floating potential is used [2, 3, 4]. In case of a two-temperature plasma when the distribution is not single maxwellian, under certain circumstances cold component remains unregistered as in this method only high energy tail of electron distribution is sampled and the presence of cold component can be undetected by the probe. In case of tokamaks, the edge plasma under certain circumstances can be characterized as two-temperature plasma having minority population of high energetic electrons due to auxiliary heating methods used for increasing plasma core temperature, rendering a minor population of high energetic electrons in tokamak edge.

Emissive probes serves as a tool for directly measuring plasma potential. Because they are not affected by drifts and electron beams in plasma, emissive probes deliver more reliable results of plasma potential when compared to indirect measurements with Langmuir probes. Conventional Emissive Probes (CEP’s) are usually a tungsten wire bend in form of loop and is heated conventionally by external DC current, up to electron emission temperature. Very few attempts has been made for evaluation of plasma potential in tokamak edge region with
emissive probes, one such attempt is made by R. Schrittwieser and his team in CASTOR tokamak [1]. The tungsten filament used was of 0.2 mm diameter having approximate length of 6 mm, heated by external auxiliary power supply. Typical operational parameters of castor tokamak is major radius ~ 0.40 m, minor radius ~ 0.085 m, background pressure smaller than 10⁻⁴ Pa, hydrogen filled pressure around 10⁻² Pa, plasma shot duration ~ 30 ms, toroidal magnetic field ~ 1 T, toroidal plasma current ~ 10 kA, line average density ~ 10¹⁹ m⁻³, SOL T. on the order of 10 eV. The estimated plasma edge temperature from emissive probe was from 10 eV to 15 eV which was in well agreement with previous Langmuir probe experiments in CASTOR tokamak [1]. Similar type of experiments have also been done on COMPASS and ASDEX Upgrade using self-emitting emissive probes [5].

Conventional heating of emissive probes requires potential drop across the probe wire to pass the heating current, making probe surface at different potentials spatially. Moreover, this potential drop is added to spatial potential in case of continuously glowing probe [6]. Emissive probe measurements can be influenced by a space charge resulting from emission current from hot probe surface [5, 7]. Furthermore, mechanical contacts at the probe end terminals in CEP’s reduce the temperature at ends, resulting in non-uniform heating across the length of probe wire, facilitating development of relative negative potentials across probe end terminals [6]. In high magnetic environment like of tokamak plasmas the J×B forces on CEP’s restrict orientation inside plasma, affecting probe’s lifetime [6]. Apart from such issues, the CEP’s gets gradually consumed and are prone to breaking or twisting in high magnetic environment. Along with the associated problems stated above, unavailability of breaking UHV of tokamak vessel for frequently replacing tungsten filament ceases their use in tokamaks.

A suitable substitution can be using a novel method for heating the emissive probes as well as using a different probe material which is less prone of breaking, twisting in high magnetic atmospheres, along with high output of electron emission current with less input power. One such alternative is Laser Heated Emissive Probes (LHEP) in which powerful laser is used to heat the probe material. Heating probe with this technique ensures even emission of electrons from probe surface as it eliminates need of potential drop across probe wire for heating. Furthermore, LHEP avoids the problems with CEP’s by its nature, providing near to accurate plasma potential values with simple circuitry. Again, as no heating current passes through the LHEP probe tips, they are not subjected to any JxB forces when used in presence of magnetic fields, practically there is no deformation of LHEP probe tip in strong electric and magnetic fields [6]. On addition, LHEP have high density, high thermal conductivity, low work function (tungsten: 4.5 eV and LaB₆: 3.6 eV) and low reflectivity, thereby heating up to electron emission temperatures with comparatively less powers can be achieved, with advantage of durability or repeatability for using inside tokamaks. We have tested LaB₆ in lab and verified its repeatability for LHEP experiments inside ADITYA-U, results are reported in section IV, overview of the ADITYA-U parameters and diagnostics installed in tokamak is given in section II. Section III describes the designing and installation of the LHEP assembly onto the ADITYA-U tokamak and finally the paper is concluded in section V.

2. ADITYA - U TOKAMAK

ADITYA a medium size tokamak having major radius~ 75 cm and minor radius~ 25 cm with limiter configuration [8, 9] has been recently upgraded to ADITYA – U with Diverter configuration. Typical discharge parameters of ADITYA-U tokamak are plasma current~ 80-120 kA, magnetic field~ 0.75-1.25 T, hydrogen filled pressure~ 10⁻² torr, central electron temperature~ 300-400 eV, plasma edge temperature~ 2-15 eV and plasma discharge~ 80-180 ms.

Many diagnostics are installed in the tokamak for measuring edge plasma temperature. Spectroscopic diagnostics measure edge temperature by line ratio method of Hα/Hβ radiation. Several Langmuir probes at different radial, poloidal and toroidal locations have been installed in order to measure edge temperature, density and potential.

3. RECIPROCATING LASER HEATED EMISSIVE: DESIGN AND INSTALLATION

3.1 choice of LHEP probe tip

Choosing correct probe material and laser is very crucial for LHEP experiments. High mechanical strength along with higher thermal conductivity and low specific heat capacity is essential for ensuring repeatability of experiments. Probe material should have high melting point, good conductivity of both electricity and heat, low specific heat capacity and low work function. Low volatility rate is desirable at high operational temperatures (~
1400°C). Lower work function of material is also important to ensure rapid temperature rise of probe with respect to laser power. At the same time, high reflectivity of the probe material is undesirable as it can result in damaging tokamak wall and other diagnostics mounted in the vicinity of probe. Theoretical results shows temperature >1000°C is required for electron emissions in microamperes/m² from probe. Lafferty has concluded that rare-earth borides of MB₆ type are better emitters than alkaline earth metals or thorium borides [10]. Majorly used emissive probe materials are Lanthanum Hexaboride (LaB₆) and Graphite [11 - 16]. Studies are ongoing for using Cerium Hexaboride as emissive probe material.

Tungsten is better choice when compared in terms of specific heat capacity (134 J/ (kg °C)) and melting point (3422 °C) with other probe materials like LaB₆ (specific heat~ 1974 J/ (kg °C), melting point~ 2210 °C), Graphite (specific heat~ 707 J/ (kg °C)) and CeB₆ (melting point~ 2552 °C). However, tungsten has highest work function (4.5 eV) on comparison with LaB₆ (2.7 eV) and CeB₆ (2.65 eV) but with better thermal conductivity (173 watt/(m. k) than 47.7 watt/(m. k) for LaB₆). Typical service lifetime of tungsten is 30 – 100 hours, whereas both CeB₆ and LaB₆ have lifetimes of 1000+ hours. Furthermore, tungsten is denser 19.25 g/cm³ than any other probe materials 4.2 g/cm³, 4.80 g/cm³ and 2.26 g/cm³ for LaB₆, CeB₆ and Graphite respectively. Balancing all parameters, LaB₆ and CeB₆ are more suitable for LHEP material. Although no attempts have been made till now for using LHEP inside tokamak as per my knowledge. Studies on borides have shown they are excellent electron emitters as compared to conventional tungsten.

Diffusion length, the distance the heat will travel out from centre of beam with reference to the duration of laser pulse is given by \( L^2 = 4 \times D \times \tau \) [17] where \( D \) is the diffusivity (= \( K / (\rho \times C) \), \( K \) is thermal conductivity and \( C \) is heat capacity). Suppose laser power is incident on LaB₆ for 120 seconds, then by using above formula, diffusion length will be \( 2.436 \times 10^{-3} \) m or 2.43 mm. Considering parameters of ADITYA-U, the Debye length comes out to be in orders of micrometre. Thus for LHEP experiments, the chosen probe tip is having 3 mm diameter.

3.2 Choice of laser

Choice of Laser plays an important role in emissive probe experiments, as it is used as a heating source. ADITYA-U is designed for maximum discharge duration of ~ 300 ms. Considering this, it is necessary that probe is heated up to steady thermionic emission temperature at the time of plasma flat top regime. Current controlled air cooled Continuous Watt (CW) CO₂ laser having 10.6 micron wavelength and 0 – 25 kHz operating frequency with a maximum power capacity of 55 watts is chosen for our experiments. Typical laser beam of 2 mm diameter will be focussed up to ~1 mm diameter by ZnSe lens on the probe tip.

3.3 Designing LHEP

Owing to complexities of tokamak geometries and high temperature magnetically confined environment, very few attempts have been made for using emissive probes on such complex devices. A LHEP system is designed for ADITYA-U tokamak, which consists of radially movable probe shaft with dual probe provision. Figure 1 shows the schematic of the assembly.

The assembly is designed in a way that every time the probe tip is placed ±25 mm (or less then) inside/outside limiter inner radius, laser power will be continuously focused on probe tip, irrespective of the radial movement, using an optical fiber. The set-up has been designed for direct measurement of radial profiles of plasma potential in edge plasma region of tokamak. The radial motion of the probe is synchronized with the radial movement of the optical fiber.
Fig. 1. Schematic of LHEP system. Red light symbolizes the laser radiation.

150 – 63 CF transition flange (a) will be installed on 150 CF port of the tokamak vessel followed by customized 63 CF flange (b) and whole LHEP system (including laser delivery system and probe system) will be accessible via this port. The 63 CF port comprises of two ports, port c is for IR viewport installation and port d is for probe shaft. The probe shaft is fixed onto an Actuator (e) via tee (d). The intermediate tee facilitates taking out of electrical connections from tokamak vessel via electrical feedthroughs. Finally, a ceramic piece (f) is placed at the other open end of the probe shaft to hold probes tightly in position.

Ceramic piece is designed such that along with dual probe provision it provides insulation between electrical connections of both probe tips. Provision of holding the ceramic piece firmly with SS probe shaft is also given, to secure the probe holder. The probe shaft is designed to match the height of the viewport. Tee has been used to take out electrical connections of probes, and is finally terminated by an Actuator. The actuator facilitates radial motion of probe in one direction and seals UHV at the same time.

The schematic of the probe holder and the actual photograph of the holder is shown in figure 2a and 2b respectively. Figure 2c shows all three parts of the probe holder individually. As shown in the figure, centre piece consists of two groves grooved along the length of piece, to give proper insulation between electrical connections of both probes that will be held with single piece.

Fig. 2a. Schematic of ceramic piece holder  
Fig. 2b. Manufactured probe holder.  
Fig. 2c. Dissembled Ceramic Holder
Laser delivery system comprises of an optical fiber, cooling gas inlet, laser focusing coupler, cooling system, laser and its controller. Laser power will be focused onto probe tip from the specially fabricated high power air cooled Polycrystalline Infrared optical fiber. This fiber is non-toxic, very flexible having spectral transmittance region of 4 - 18μm with a capability of operating over wide range of temperature range of 4K up to 420 K. They are manufactured in a core: clad structure of AgCl: AgBr with a diameter of 900:1000μm. The PEEK polymer jacket fiber is terminated with SMA – type connector having a special non-magnetic, high temperature resistant titanium ferrule. The attenuation at 10.6μm is 0.1-0.5 dB/m. The specially made optical fiber will be air cooled at a pressure of 1 – 0.5 bar.

4. CALIBRATION OF LHEP PROBE IN LAB SET UP

The experimental goal is to bias Laser Heated Emissive Probe with respect to plasma potential and acquire I-V characteristics of edge plasma with high sampling frequency. Obtained I-V will be explored for the estimation of ion density, electron temperature and plasma potential. One of the important parameter is determination of optimum laser power required to heat the probe up to thermionic emission temperature, at which probe emits required emission current density. Experiments in air have been done for calibrating temperature rise with respect to different laser power.

LaB$_6$ probe tip was placed at a distance of 19 cm from laser head and laser power was focused onto probe tip via ZnSe lens of 18 cm focal length. Probe tip of 3 mm diameter and ~3.3 mm length and laser power is dumped for 100 seconds for studying its heating dynamics and for another 60 seconds the probe is allowed to cool for studying its cooling dynamics. IR camera with frame rate of 50 Hertz, was used for monitoring the probe temperature, was placed at 50 cm distance from probe tip. The camera was looking at the opposite face of the probe from the face that was receiving laser power. As camera had a limitation of three temperature ranges, temperature measurement at lower powers are done by setting 150°C to 600°C temperature range and temperature measurement at higher laser powers are done by setting 400°C to 1200°C temperature range. The graph is shown in figure 3.

![Fig. 3. Graph showing rise in temperature with respect to different laser powers for LaB$_6$ probe tip.](image)

For estimating repeatability of using same probe inside ADITYA-U tokamak for LHEP experiments, experiment is done in air under approximately same environmental conditions in the same set up described above. Constant laser power of 10 Watts is dumped onto LaB$_6$ probe tip for 100 seconds and for another 60 seconds the probe is allowed to cool. This set was repeated 30 times in air. It was observed that the probe sustained the laser dumping without being ablated or damaged. The graph shown in figure 4 describes the rise in probe temperature on dumping constant laser power.
It can be easily seen from the graph that approximately after 5 repeated sets, the probe tip sustains almost stable equal temperature zone. The same observation is observed in CeB$_6$ probe tip. Material chunks can be seen coming out from graphite after repeating sets approximately 15 times thereby confirming ablation or eradication of surface by laser power. Theoretical estimation of electron emission density with respect to temperature has been done using Richardson-Dushman equation [11, 12] for LaB$_6$ probe tip having 3 mm diameter and length with 3.6 eV work function. The graph is shown in figure 5. From calculation, it is predicted that 1000 degrees of temperature suffice electron emission of orders in milliAmperes/m$^2$.

5. SUMMARY

Set of experiments have been done in lab under controlled experimental conditions to verify repeatability of using the LHEP probe tips inside tokamak for measuring plasma potential directly and for calibrating the temperature response of respective probes with respect to different laser powers. These sets are repeated with all three probes and it is concluded that LaB$_6$ and CeB$_6$ are better candidates for experiments in tokamak as compared to normal graphite or special quality graphite.

5.1 future work

Same set of experiments for temperature calibration are needed to be repeated in vacuum of orders of $10^{-7}$ torr. Once calibrated, these probes can be successfully used for experiments in tokamak. Components for LHEP diagnostics on ADITYA-U tokamak have been procured and work has been initiated for assembling as
well as mounting the diagnostics into tokamak vessel. After mounting of the diagnostics, experiments will be carried out for recording $I-V$ by biasing the LHEP with respect to floating potential.

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