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On the Measurement of Electron Temperature of a Pulsed Washer Gun Argon Plasma by Triple Langmuir Probe Diagnostic Technique

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Pulsed argon plasma of the order of 140 μs duration is produced by a washer gun under low pressure conditions. The low pressure plasmas have many industrial applications such as etching, coating for corrosion, diamond and diamond like carbon coating, super hard nano composite coating, synthesis of novel nanostructure etc. Measurement of fundamental parameters like electron temperature of such pulsed plasmas is always challenging and should be determined properly. Triple probe diagnostic is the most advanced, convenient and inexpensive method for measurement of plasma temperature which does not require any voltage, frequency sweeps, or switching like single or double probe diagnostic methods. In this work we have introduced a triple Langmuir probe to measure the electron temperature of pulsed washer gun argon plasma. A triple probe of pure tungsten material with appropriate circuit is designed and fabricated in our laboratory. The triple probe signal is recorded by a digital storage oscilloscope at the distance of 0.05 m from the gun mouth. It is observed that the electron temperature remains constant at ~ 1.2 eV within the small variation of base pressure ranging from 0.2 to 1.0 mbar. This method is applicable to both stationary and transient plasma which can be used for various industrial as well as research purpose.

Keywords: Electron temperature, Low pressure plasma, Pulsed plasma, Triple probe, Washer gun

Introduction

The low pressure and low temperature plasmas have various industrial application like etching[1], coating for corrosion, diamond and diamond like carbon coating[2], super hard nano composite coating, synthesis of novel nanostructure etc.[3–5] Plasma is used as a ion beam source for plasma target production, Neutral Beam Injection (NBI) for start-up of neutral beam trapping in the field of plasma physics and controlled fusion research etc.[6–8] In order to understand the properties of plasma, plasma diagnosis is necessary. Measuring plasma parameters is a demanding challenge as different applications require different types of plasma. A well-defined knowledge of plasma parameters (electron and ion densities, electron and ion temperature etc) describes the state of the plasma. There are various ways to diagnose plasma parameters. The diagnostics to measure the plasma parameters are:

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i. Langmuir Probes (Single, Double and Triple probe),
ii. Plasma Spectroscopy,
iii. Faraday Cup.

For the measurement of charged particle temperature and density cylindrical electrostatic probes have been widely used on satellites and rockets.[9] The plasma parameters like electron temperature, electron density, plasma potential and floating potential of low temperature plasmas at the edge of magnetic fusion devices, in plasma processing reactors, in dc-glow discharge and other such devices are commonly measured by electric probes.[10]

Here we have used the triple probe diagnostic technique for the measurement of electron temperature of pulsed argon plasma. The probe diagnostic is the most fundamental and suitable technique proposed by H M Mott-Smith and Irving Langmuir.[11] It is widely used in case of low temperature plasma by assuming that the energy distribution of ions and electrons is Maxwellian with

$T_e \gg T_i$.[12,13] The cylindrical shaped probe is the widely used to diagnose the plasma. In case of a single probe, one of the discharge electrodes is chosen as the reference electrode. In principle, all the parametric information about plasma can be deduced from the current obtained by biasing the Langmuir probe at different voltages. Upgradation in the probe diagnostics has been gradually accounted according to the condition or type of production of plasmas. The double probe technique was invented first by Johnson and Malter in 1950.[(14)] Availability of an electrode as a reference point as required in single probe is not always possible in electrodeless discharges like toroidal rf discharge in a gas tube or the plasma in the ionosphere.[13] For such cases a double probe can be used in which two probes are biased with respect to each other and insulated from the ground. In case of single/double probe, it is very tedious job to obtain the probe V~I characteristics curve for a pulsed/transient plasma for which a number of probe current data are required at different applied biasing potential from which one can obtain the electron temperature and electron/ion density of the plasma.[11,14] To overcome these shortcomings the advanced probe technique such as triple probe diagnostics has been used successfully. K Yamamoto and T Okuda have first proposed the triple probe method to keep the third probe always at a floating potential so that the floating probe should measure the electron energy distribution.[15] Chen & Sekiguchi developed the theory of triple probe for instantaneous measurement of plasma parameters in which the no voltage or frequency sweep is required.[16]

A Compact Plasma System (CPS)[17] is successfully accomplished in our laboratory in which a washer gun is used as a source of pulsed plasma for investigating the mechanism of ejection of plasma blobs[18] from the gun plasma structure. Coherent plasma structures/ Blobs are observed at the open magnetic field lines in the Scrape-Off-Layer (SOL) region of various fusion devices like Tokamaks. These blobs along with the plasma particles are propagated radially outwards across the SOL.[19] In order to investigate the mechanism of blob formation the electron temperature of gun plasma must be measured with a suitable diagnostics technique. In our case the plasma is generated under low pressure (0.2 mbar to 1 mbar) condition and it sustains for a 500 μs.

In order to measure the electron temperature of the washer gun argon plasma, we have designed and fabricated a triple probe which is an advanced probe diagnostic technique[15,16,20] for the measurement of transient/pulsed plasmas. Using this probe, we have measured the plasma parameter (electron temperature T_e) by taking the data for a particular probe biasing voltage. It does not require a numbers of probe current data with varying the probe biasing voltages like single and double Langmuir probe.

Materials and Methods

The schematic diagram of experimental set up (CPS) consisting of a curved vacuum chamber made up of SS-304 material (circular cross section) and other equipment as shown in Fig. 1. In this system Langmuir probes (single & double), spectroscopic diagnostics techniques have been used to measure the plasma parameters. High speed imaging diagnostic has also been used to study the plasma blobs ejected out from the gun plasma. The triple probe which is an advanced diagnostic technique is newly introduced in this system for measuring the electron temperature of pulsed/transient argon plasma. Triple probe and its circuit is designed and fabricated in our laboratory. The arrangement and findings of other diagnostic techniques of our system have given in references.[17,21,22] Here, a brief description about the system and triple probe with its circuitry are discussed as follows,

The curved vacuum chamber has diameter of 0.2 m and has two horizontal and two vertical ports. A rotary vane vacuum pump (Model No.: IVP300) is used to make the base pressure of chamber lower up to 0.2 mbar. The base pressure inside the chamber is

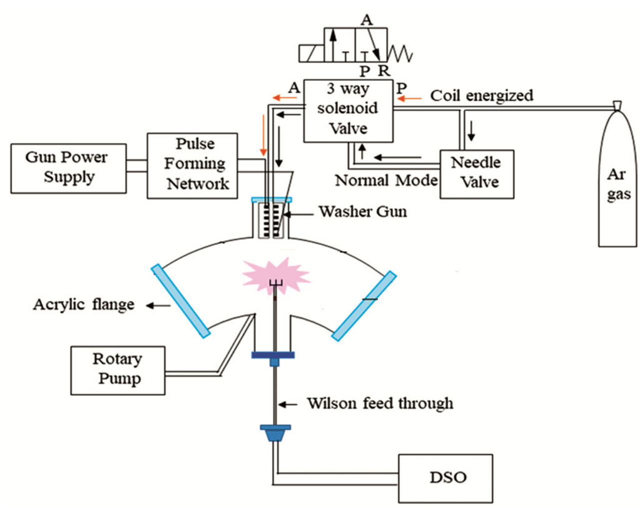

Fig. 1 — Schematic diagram of Compact Plasma System (CPS) with the pulse forming network, washer plasma gun, gas feed system, power supply and positioned triple probe

monitored by a digital Pirani gauge (Model: DHPG 020). A pulsed washer gun is installed in one of the horizontal ports of the vacuum chamber. Washer like shaped copper anode and brass cathode are used in the gun whereas four brass washers are inserted in between the cathode and anode. All the electrodes and washers are properly insulated by using teflon. The inner diameter of all the electrode and washers are ~1 cm. A seven stage Guillemin E type Pulse Forming Network (PFN) producing a voltage pulse of width 140 μs is used and the pulse is fed to the gun. PFN has been fabricated with seven capacitors and inductors having equal capacitance and inductance of 10 μF and of 10 μH each respectively, whereas the inductance of the inductor near the load is increased by ~30% to avoid overshoot.[23–26] The PFN frequency is estimated as ~ 7 kHz. To charge the PFN a direct voltage of 1.2 kV is applied for which a DC power supply (5 kV, 50 mA) is used. The coil of the solenoid valve is energized along with the charging of PFN and argon gas flushes into the gun from the cathode side through a 3/2 way solenoid valve i.e. through output port A via port P with vent R closed when PFN discharges across the gun. A 3/2 solenoid valve as shown in Fig. 2 given below is used to inject the argon gas into the gun. The 3/2-way designation indicates a valve with three ports and two modes of operation. When coil is energized, the input port P is connected to the output port A, with the vent R closed. In normal mode the input port P is closed and the base pressure of chamber is regulated using a needle valve through vent R connected with output port A. When desired pressure is attained inside the chamber, the coil of the solenoid valve is energized along with the PFN discharge to the gun. When the A-R channel is disconnected and gas flushes into the chamber through P-A channel of solenoid valve. The impedance matching of source circuit (PFN) with the load (Plasma gun) has been made to achieve maximum power transfer.[27]

The triple probe used in this work made by a tungsten cylindrical wire is brazed with a copper wire. A piece of ceramic tube is used at the brazing area for proper insulation as only the active part of three probes can face the plasma. Probes made of tungsten wires (of length 0.005 m and diameter of 0.00025 m) having high melting point faces the plasma and the brazed area is insulated from plasma. Hence, it does not affect the experimental data.

Other end of the copper wire is connected to the biasing power supply with proper insulation. The circuit diagram of triple probe for collection of floating potential V_f and plasma potential V_p is shown in Fig. 3. The floating probe signal is taken across a high resistance register of 1 MΩ and the plasma potential signal is taken across a resistance of 1 kΩ by biasing other two probes as a double probe at a fixed potential of 18V. All the signals are recorded by the battery operated digital storage oscilloscope (Model No.: S_{mart}DS7102-MetroQ). In battery operated oscilloscope the ground potential does not affect the applied potential so that the system becomes completely isolated from electrical noise. The signals are analyzed by Origin Lab software.

Theory

Triple probe consists of three identical Langmuir probes as shown in Fig. 3, in which the middle one

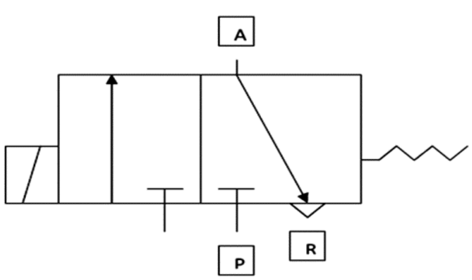

Fig. 2 — Circuit for 3/2 way solenoid valve

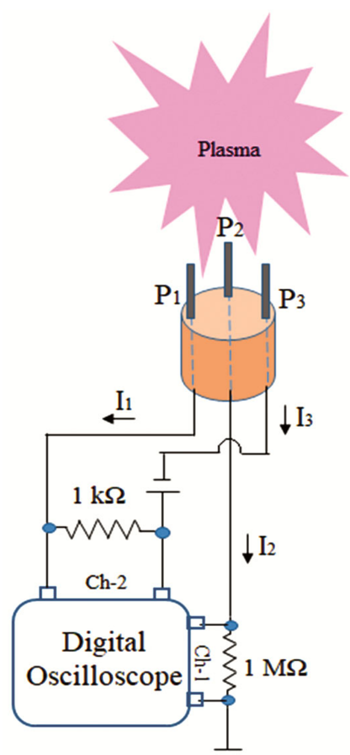

Fig. 3 — Circuit diagram of the triple Langmuir probe biasing

i.e. probe P_2 acts as floating and other two (P_1 and P_3) as floating double probe. A fixed biasing potential of few volts is applied to the two probes to record the plasma potential V_p. Weakly ionized plasma is collision dominated. Excitation and ionization processes of species occur due to collision of electrons with neutrals/ions. As electron transmits their energy to the plasma particles, electron temperature is assumed to be equivalent to plasma temperature.

The formula for the measurement of electron temperature of the plasma by triple Langmuir probe is derived as follows.[10,16,28] According to principle of triple probe, the triple probe satisfies the following equation,

$$\frac{I_1+I_2}{I_1+I_3}=\frac{1-e^{\frac{-eV_{12}}{kT_e}}}{1-e^{\frac{-eV_{13}}{kT_e}}} \quad \dots (1)$$

since, $I_2=0; I_1=I_3=I$, Eq. (1) becomes

$$\frac{1}{2}=\frac{1-e^{\frac{-eV_{12}}{kT_e}}}{1-e^{\frac{-eV_{13}}{kT_e}}} \quad \dots (2)$$

Re arranging Eq. (2) yields,

$$2e^{\frac{-eV_{12}}{kT_e}}=1+e^{\frac{-eV_{13}}{kT_e}} \quad \dots (3)$$

For sufficiently large applied voltage $eV_{13} \gg kT_e$, that ensure the collection of ion saturation current, the Eq. (3) becomes,

$$1=2e^{\frac{-eV_{12}}{kT_e}} \quad \dots (4)$$

Taking logarithm of both sides of Eq. (4) and rearranging it becomes,

$$kT_e=\frac{-V_{12}}{\ln 2}$$

where, $-V_{12}=V_p-V_f$

The plasma potential V_p, floating potential V_f and the electron temperature T_e of plasma are related by the following equation.[29, 30]

$$V_p-V_f=T_e \ln\left(\frac{M_{ion}}{2\pi m_e}\right)^{\frac{1}{2}} \quad \dots (5)$$

where, M_{ion} is the mass of ion of the gas used to produce plasma and m_e is the mass of the electron. Rearranging the Eq. (5) and substituting the values of argon ion and electron mass we get,

$$T_e=\frac{V_p-V_f}{\ln(106.32)} \quad \dots (6)$$

Hence from the triple probe, obtaining both plasma potential V_p and floating potential V_f at a time we can calculate the electron temperature of the pulsed/transient plasma very easily by taking a single shot data.

Results and Discussion

The floating potential V_f and the plasma potential V_p obtained by the triple probe from the pulsed argon washer gun plasma at base pressure 0.2 mbar is shown in Fig. 4.

We have taken the plasma potential signals by biasing the two probes at a potential of 18 V. All signals are recorded by a battery operated Digital Storage Oscilloscope. From the triple probe signal we found that the difference between plasma potential and floating potential for the base pressure 0.2 mbar is

$$V_p - V_f = 5.56\ V$$

Substituting this value in Eq. (6) the electron temperature of the pulsed washer gun argon plasma is

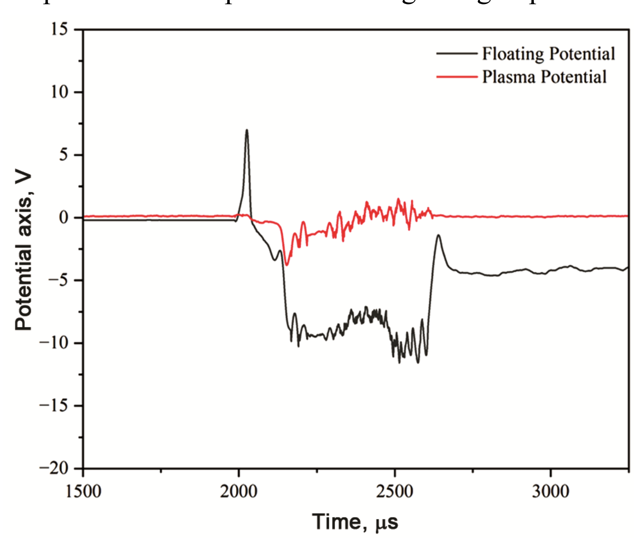

Fig. 4 — Triple probe signal of washer gun argon plasma at base pressure 0.2 mbar

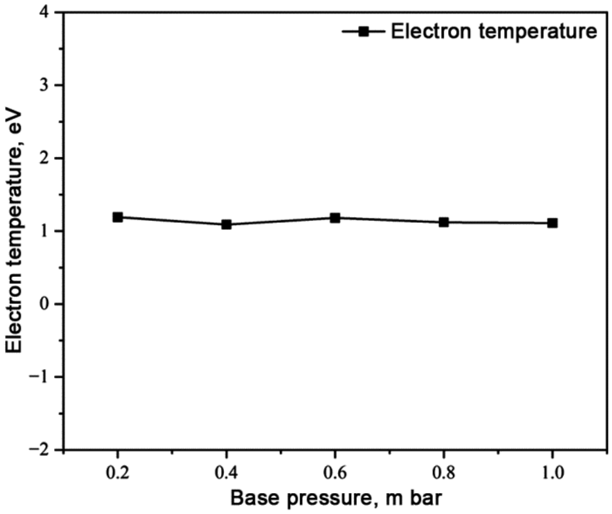

Fig. 5 — Variation of electron temperature of the pulsed argon plasma with different base pressure ranging from 0.2 mbar to 1.0 mbar.

found to be ~1.19 eV. The electron temperatures are also measured for different base pressures ranging from 0.2 mbar to 1.0 mbar within the interval 0.2 mbar by keeping the gun parameters same. Similar nature of the triple probe signals of both floating potential and plasma potential are obtained for all other base pressures up to 1 mbar as shown in Fig. 4. The plot between the electron temperatures vs different base pressures is shown in Fig. 5.

It has been observed that the electron temperature of the plasma does not vary significantly within the variation of base pressure inside the chamber. Variation of electron temperatures obtained by triple probe with base pressure as shown in Fig. 5 exhibits the similar trend as seen in spectroscopy diagnostic technique used previously in our laboratory[22] in which the electron temperatures within the base pressure range 0.2 mbar to 1.0 mbar remained almost constant. The variations in the relatively low pressures in the chamber do not affect the electron temperature because the plasma comes out along with the neutral argon present inside the gun at high pressure of ~ 2 bar. From the spectroscopic diagnostic technique, the electron temperatures have values nearly equal to 2 eV.[22] With triple probe diagnostics we found that the electron temperature of the same washer gun argon plasma has little bit lower value i.e., ~ 1.2 eV than the electron temperatures obtained by spectroscopic technique. This is because in spectroscopic technique we measure the average electron temperature over the line of sight without disturbing the plasma[13,31] where as in case of probe technique the temperature is measured in a localized area within the plasma. In case of triple probe reduced value of electron temperature may be due to the cooling of the plasma at the region around the probe assembly (active part of probe and its holder) as it touches directly the plasma.

Conclusions

This work presents the result of our effort to characterize time dependent plasma produced by a washer stacked plasma gun using Langmuir triple probe technique. A triple Langmuir probe is designed, fabricated and installed successfully inside the chamber by which the electron temperature of the pulsed washer gun argon plasma is measured. We found that Triple probe technique is more suitable and applicable for pulsed/transient plasma. The variation of electron temperatures for different base pressure ranging from 0.2 mbar to 1.0 mbar is remained almost constant and have the value nearly equal to1.2 eV. The electron temperature of the plasma is independent of the base pressure. The difficulties faced while measuring the electron temperature of pulsed plasma by single/double probe may be overcome by using this method. The advantage of this method is that probes are simple to construct, relatively inexpensive and easier to operate. In triple probe technique at a particular biasing voltage, the plasma potential and the floating potential signals are obtained simultaneously from which electron temperature is calculated. Hence, voltage sweep is not required in triple probe.

This method may be a powerful tool for stationary plasmas as well as transient plasmas. It is concluded that the triple probe technique for measurement of electron temperature of low pressure pulsed plasmas used in various industrial and research applications can be done in easier and inexpensive way than the other diagnostic techniques.

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