Production and characteristics of low temperature and low density plasma using a magnetic filter

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Abstract: Plasma with low temperature (~ 0.3 eV) and low density (~ 10^5 cm^-3) electrons is produced in a DP device using magnetic filter. The magnetic filter allows the passage of low energy electrons and ions from the source where plasma is produced. Plasma parameters for different discharge current and discharge voltage at different partial pressure of Argon are measured with the help of plane Langmuir probes of 20 mm and 6 mm diameter in target and source section respectively. The magnetic filter is found suitable for production of low temperature plasma with T_eS/T_eT ~ 10 and low density with Z_{glyph8:7}eS/Z_{glyph8:7}eT ~ 10^5 (where T_eS and T_eT are electron temperature and N_eS and N_eT are electron density in source and target section respectively). Such type of low temperature and low density plasma can be useful in fields like producing negative ion rich plasma; study of lower ionospheric plasma and study of sheath mechanism, beam plasma interaction, waves and instabilities.

1. Introduction
Negative ion rich plasma with almost negligible electrons is an important subject of recent studies. Naturally negative ion containing plasma appear in DC discharges of halogen and oxygen [1,2] and in lower ionosphere (D layer) [3]. Negative ion plasma of Cs-Cl [4], SF_6 [5], iodine [6] and oxygen [7] are artistically produced. The ratio of electron to positive ion density (N_e/N_+) in such plasma ranges from 10^{-1} to 10^{-3}. Almost electron free plasmas with iodine [8] and oxygen [9] are also attained by diffusion from DC plasmas through grids and magnetic filters where N_e/N_+ was 10^{-4} to 10^{-5}. This is considered to be near the limit of probe measurement. It is a fundamental problem to determine to what extent the electron density can be suppressed in such plasma. We can produce negative ion rich plasma with positive ions and negative ions in a DP device using a magnetic filter by introducing SF_6 gas in Ar plasma. The diagnostics for negative ion rich plasma can be developed. In the lower ionosphere (D layer), plasma containing negative ions occurs with the following plasma parameters: Ion saturation current I_+ (A)= 10^{-10} to 2x10^{-8} ; Electron saturation current I_e (A)= 2x10^{-9} to 10^{-6} ; \beta (=I_e/I_+) = 20 to 6 (65-80 km), 6 to 70 (80-90 km); negative ion density N_-(cm^-3) = 10^2 (65-74 km), 10^3 to 10^5(74-85 km) and then decreases from 85 km to E layer; positive ion density N_+(cm^-3) = 10^2 to 10^5; \alpha ( = N_+/N_-) = 0.77 to 0.88 (65-80 km), 0.88 to 0.3 (80-90 km); electron density N_e(cm^-3) = 10 to 7x10^3; electron temperature T_e(eV) = .02 [10]. Characterization of thermal charged particle in
ionosphere is complicated by plasma sheath structures around satellite or sounding rocket payloads [10,11,12]. It is therefore necessary to explore both ion and electron sheaths with ionospheric plasma densities and temperature [13]. However to attain such plasma with suitable plasma parameters, the production of low temperature and low density plasma is important. Magnetic filters are most often used to control the plasma behaviour [14]. The magnetically filtered plasma with low temperature and low density electrons is useful in production of negative ion rich plasma, simulation of D layer [9], plasma processing [15] and study of sheath mechanism[13,16,17], beam plasma interaction, waves and instabilities.

In the present paper, plasma with low temperature and low density electrons is produced using a magnetic filter. Section 2 describes the experimental set up for the production of such plasma and the detailed measurement procedure. Experimental results are discussed in section 3. Section 4 contains the conclusion.

2. Experimental Set up and procedure

The experiment is performed in a cylindrical stainless steel chamber of 55 cm diameter and 110 cm in length. The schematic diagram of the device is shown in figure 1. Two magnetic cages with multidipole magnet arrangement for surface plasma confinement are inserted into the chamber. The outer diameter of each magnetic cage is 40 cm and each one is made up of 24 rectangular stainless steel bars of 50.5 cm length, filled with permanent bar magnets of field strength ~ 2 K Gauss. A magnetic filter is made using permanent magnets (~1 K Gauss) sealed in vacuum tight stainless steel rectangular tubes and placed 2.5 cm apart. The magnetic filter is placed in the central region of the chamber dividing the chamber into two sections Source (S) and Target (T). The base pressure of the chamber is brought down to 10^{-6} Torr by using an oil diffusion pump backed by a rotary pump. Argon plasma is produced at a partial pressure of 10^{-4} ~ 10^{-3} Torr of Argon. Discharge is made only in the source section with 10 hot tungsten filaments of 6 cm in length and 0.01 cm in diameter as cathode and magnetic cage as anode. Typical discharge parameters are: discharge voltage ($V_d$) ~ 60 V, discharge current ($I_d$) 100 ~ 500 mA. The magnetic filter allows the passage of low energy electrons and ions from the source where plasma is produced [18,19]. Plasma parameters such as electron density ($N_e$) and electron temperature ($T_e$) are measured with the help of plane Langmuir probes of 20 mm and 6 mm diameter in target and source section respectively. The presence of ion beam is detected with the help of a retarding potential analyzer (RPA). Typical ion temperature is $T_i$~ 0.1 eV.

![Figure 1. Schematic diagram of the experimental set up.](image)

3. Results and discussions

Figure 2 shows probe current-voltage (I-V) characteristics $i_p$ as a function of probe bias voltage ($V_{pb}$) measured by the plane Langmuir probe of 6 mm disc diameter in source section at $P_{Ar}$ = 4 x 10^{-4} Torr when $I_d$ = 300 mA and $V_d$ = 60 V. The electron temperature $T_e$ is measured from the slope of the semi-log plot of the exponential region of $i_p$ - $V_b$ curve and electron density $N_e$ is measured from the electron
saturation current $I_{es}$ and $T_e$ as $N_e \propto I_{es}/T_e$. The plasma parameters in source plasma are: $T_e = 2.75$ eV and $N_e = 6.72 \times 10^9$ cm$^{-3}$.

![Figure 2. I-V characteristics and double derivative in Source Plasma. Measured electron temperature is 2.75 eV and electron density is 6.72 x 10$^9$ cm$^{-3}$.](image)

The Druyvesteyn’s method [20] connects the second derivative of probe characteristics $i_p'' = d^2i_p/dV_b^2$ with the energy distribution function $f(E)$ as [8]

$$i_p'' = e^2S(2em^{-1})^{1/2}f(E)0.25(V_p - V_b)^{1/2}$$

where $E \equiv e(V_p - V_b)$ is the electron kinetic energy, $V_p$ is plasma potential, $e$ and $m$ are electron charge and mass respectively, $S$ is the probe surface area. The second derivative $i_p''$ is plotted together in figure 2(a). Plasma potential $V_p$ is recognized as the point where $i_p''$ cuts the zero level of $i_p$. $i_p''$ curve consist of two peaks. Peak 1 denotes the thermal electrons. Peak 2 near the peak 1 may be due to the primary electrons emitted from the tungsten filament. The electron temperature can be measured from the semi log plot of the $i_p''$ curve [21,8].

![Figure 3. I-V characteristics and double derivative in Target Plasma. (a) $P_{Ar} = 4\times10^{-4}$ Torr. Measured $T_e = 1.14$ eV and $N_e = 1.57\times10^5$ cm$^{-3}$ (b) $2.5\times10^{-3}$ Torr. Measured $T_e = 0.32$ eV and $N_e = 9.03\times10^5$ cm$^{-3}$.](image)

Figure 3(a) and figure 3(b) show examples of measured $i_p(V_b)$ and $i_p''$ in target section when $I_d = 300$ mA and $V_d = 60$ V at $P_{Ar} = 4\times10^{-4}$ Torr and $P_{Ar} = 2.5\times10^{-3}$ Torr respectively. It is seen that with increase in $P_{Ar}$, the slope of the exponential region of the $i_p - V_b$ curve increases which indicates that $T_e$ decreases. On the other hand the electron saturation current $I_{es}$ increases with increase in $P_{Ar}$. Decrease in $T_e$ and increase in $I_{es}$ lead to increase in density with $P_{Ar}$.
The $i_p$ curve in figure 3(a) and figure 3(b) consists of only thermal electrons (peak 1) showing absence of energetic primary electrons in target section. The second derivative method [20] was applied for obtaining the electron energy distribution function. The electron distribution curve decreases its width and a sharp peak is seen with increase in $P_{Ar}$ at constant $i_d$ and $V_d$ showing decrease in electron temperature. The width of the thermal electron peak in target section is much smaller than that in the source section (figure 2) under same discharge condition. At $P_{Ar} = 4 \times 10^{-4}$ Torr, $I_d = 300$ mA and $V_d = 60$ V, the electron temperature is found to be 2.75 eV and 1.14 eV and electron density to be $6.72 \times 10^6$ cm$^{-3}$ and $1.57 \times 10^5$ cm$^{-3}$ in source and target respectively.

![Figure 4](image-url)

**Figure 4.** $T_e$ vs $P_{Ar}$ curves for different $I_d$ at $V_d = 60$ V. (a) Source (b) Target.

Figure 4(a) and figure 4(b) show measured $T_e$ versus partial pressure of Argon ($P_{Ar}$) in source and target respectively at fixed discharge voltage ($V_d = 60$ V) for different discharge current ($I_d$). In the source section, $T_e$ decreases with increase in $P_{Ar}$ when $I_d$ is fixed. The measured $T_e$ decreases in the range from 2.85 eV to 2.2 eV when $P_{Ar}$ is varied from $4.0 \times 10^{-4}$ Torr to $2.5 \times 10^{-3}$ Torr for $I_d = 100$ mA - 500 mA. $T_e$ remains almost constant with $I_d$ (100 mA to 500 mA) at a fixed $P_{Ar}$. In the target section, $T_e$ decreases with increase in $P_{Ar}$ at a fixed $I_d$. The measured $T_e$ decreases from 1.14 eV to 0.3 eV when $P_{Ar}$ is varied from $4.0 \times 10^{-4}$ Torr to $2.5 \times 10^{-3}$ Torr for approx all $I_d = 100$ mA - 500 mA. The electron temperature remains almost constant with $I_d$ (100 mA to 500 mA) at a fixed $P_{Ar}$. The lowest electron temperature measured in target section is 0.3 eV, when $I_d = 500$ mA, $V_d = 60$ V, $P_{Ar} = 2.5 \times 10^{-3}$ Torr. Under the same plasma condition, $T_e$ in source section is 2.23 eV. This shows that the electrons in the target section posses much lower temperature compared to the source section giving the electron temperature ratio $T_{es}/T_{et} \sim 10$ (where $T_{es}$ and $T_{et}$ are electron temperatures in source and target section respectively).

Figure 5(a) and figure 5(b) show electron density ($N_e$) versus $I_d$ at a fixed discharge voltage ($V_d = 60$ V) for various $P_{Ar}$ in source and target sections respectively. It is seen that in the source section, the electron density increases with increase in discharge current at a fixed $P_{Ar}$. At a fixed discharge current, electron density increases with increase in $P_{Ar}$. It is observed that at higher $P_{Ar}$, electron density increases at higher rate with increase in discharge current. This is due to the increase in $I_0$ and decrease in $T_e$. The measured electron density is found to be in the range of $1.9 \times 10^9$ cm$^{-3}$ to $2.2 \times 10^{10}$ cm$^{-3}$ corresponding to $P_{Ar} = 4.0 \times 10^{-4}$ Torr to $2.5 \times 10^{-3}$ Torr. In the target section, however, the electron density is found to be much smaller and in the range of $4.0 \times 10^5$ cm$^{-3}$ to $1.6 \times 10^7$ cm$^{-3}$ corresponding to $P_{Ar} = 4.0 \times 10^{-4}$ Torr to $2.5 \times 10^{-3}$ Torr. Lowest electron density obtained in target section is $4.0 \times 10^6$ cm$^{-3}$ when $I_d = 100$ mA, $V_d = 60$ V, $P_{Ar} = 4.0 \times 10^{-4}$ Torr. Under the same plasma condition, $N_e$ in source section is $1.9 \times 10^9$ cm$^{-3}$. This shows that the electron density is reduced in the target section compared
to the source giving the electron density ratio \( N_{eS}/N_{eT} \sim 10^5 \) (where \( N_{eS} \) and \( N_{eT} \) are the electron density in source and target section respectively).

The magnetic filter allows only the low energy electrons and ions to enter into the target section, hence it is found suitable for the production of low temperature and low density plasma which can be controlled in a desired range.

![Figure 5. \( N_e \) vs \( I_d \) curves for different \( P_{Ar} \) at \( V_d = 60 \) V. (a) Source (b) Target.](image)

4. Conclusion
A magnetic filter is used to produce low temperature and low density plasma. Plasma with low temperature \( T_{eS}/T_{eT} \sim 10 \) and low density \( N_{eS}/N_{eT} \sim 10^5 \) is produced. The magnetic filter is found suitable in producing such plasma. Dependence of \( N_e \) and \( T_e \) on various discharge parameters has been investigated. Attempts have been made to measure the sheath profile in front of a negatively biased grid using an emissive probe. The work will be extended to multicomponent plasma with negative ions.

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