Effect of Magnetic Filter in a Volume Production Multicusp Ion Source

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Abstract. D-Pace's volume production multicusp ion source utilizes dipole magnetic fields inside the plasma chamber to filter out energetic electrons that lead to the destruction of negative ions inside the source. The ion source uses the same magnetic field for the extraction of negative hydrogen and deuterium ions. The amount of deuterium ions extracted from the source is about 1/3 of the amount of negative hydrogen ions extracted. In this paper, we investigate if different magnetic field strengths are required for hydrogen and deuterium plasmas for maximum negative ion extraction. The effect of varying the strength of the magnetic filter fields in the extraction of negative ions of hydrogen and deuterium is studied. The response of plasma parameters like electron temperature and electron density to different magnetic fields are determined using a Langmuir probe.

INTRODUCTION

The ion source used for this study is a D-Pace filament based multicusp ion source licensed from TRIUMF[1], which produces negative ions based on volume production methods and uses low-pressure discharge plasmas of H_2 and D_2. This ion source is capable of producing 18 mA of H^- beam current at a beam energy of 30 keV[2]. However, the ion source achieves only 6 mA of D^- beam current under the same conditions[2]. We are attempting to increase the D^- beam current to 10 mA, so that the D-Pace ion source can achieve the requirements for Boron Neutron Capture Therapy (BNCT) applications[3].

The reactions producing D^- ions are believed to be the same as those producing H^- ions[4]. It is clear that volume production of negative ions of H^- and D^- occurs through dissociated electron attachment of low energy electrons (~0.5 eV) to molecules at a higher vibrational level[5]. Vibrationally excited molecules are created inside the volume production ion source mainly through collisions of gas molecules with high energy electrons in the plasma [6]. The filtering of high energy electrons in the region close to the extraction is accomplished through the presence of transverse magnetic fields (magnetic filter)[7].The ion source uses the same magnetic filter strength for the extraction of both hydrogen and deuterium ions. Since the D-Pace ion source is optimized for the production of H^- ions, it will be interesting to study if the same magnetic filter field strength is optimized for the formation of maximum amount of D^- ions.

Magnetic filters of different strengths are placed near the extraction region of the ion source in the current study. The maximum amount of H^- and D^- beam currents that can be extracted from the ion source under these different magnetic fields are measured. The variations in the plasma characteristics of H_2 and D_2 under different magnetic fields are analyzed using a Langmuir probe.

ION SOURCE AND MAGNETIC FILTER FIELDS

The schematic of the ion source used is presented in Fig.1a). Plasma is sustained inside the plasma chamber of the ion source via thermionic emission from the electrically heated filaments. Filaments are made of four half circles of tantalum. The plasma is confined by 10 rows of Sm_2Co_{17} magnets and another 4 rows of magnets on the back plate, which holds the filaments. These magnets form cusp fields which confine the electrons in the plasma.

The ion source uses three electrodes in the extraction system, consisting of the plasma electrode, the extraction electrode and the ground electrode, as shown in Fig. 1 b). Different power supplies control each of the electrodes. The plasma electrode and the extraction electrode are biased positively. The co-extracted electrons are dumped on the extraction electrode. Thus, the current measured on the extraction electrode power supply approximates the co-extracted electron current. The ion source is biased at a negative potential with respect to the ground electrode for the extraction of negative ions. The magnitude of the negative potential determines the energy of the beam (0-30 keV).

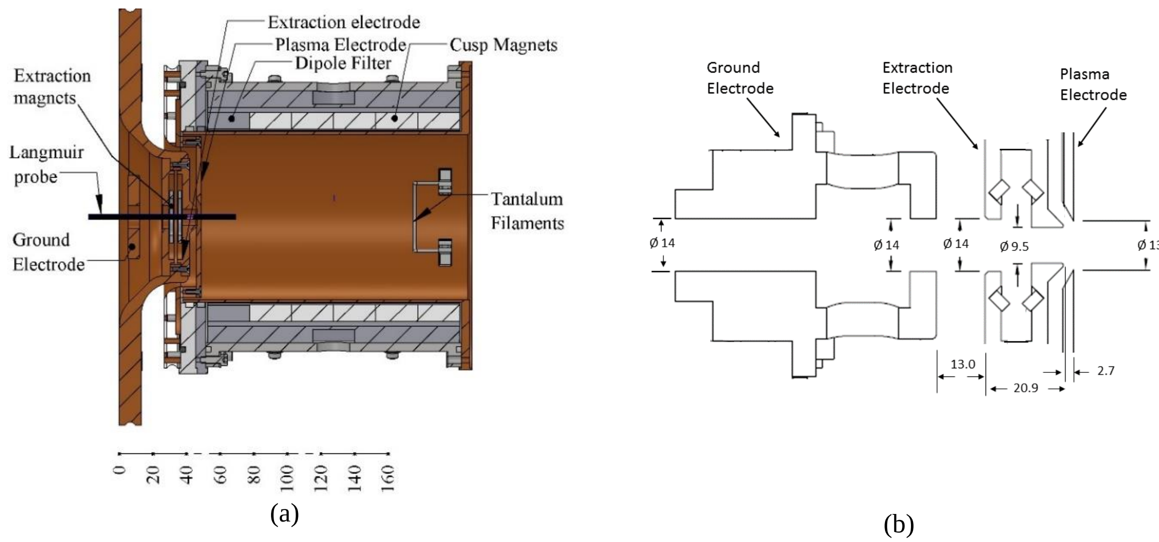


FIGURE 1. a) Section view of the ion source. b) Schematic of the extraction system used for ion extraction.

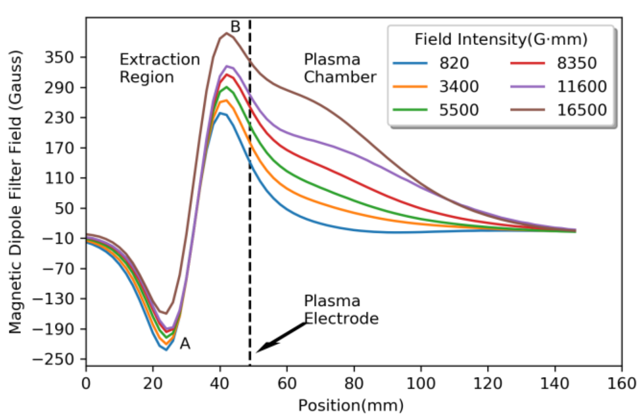


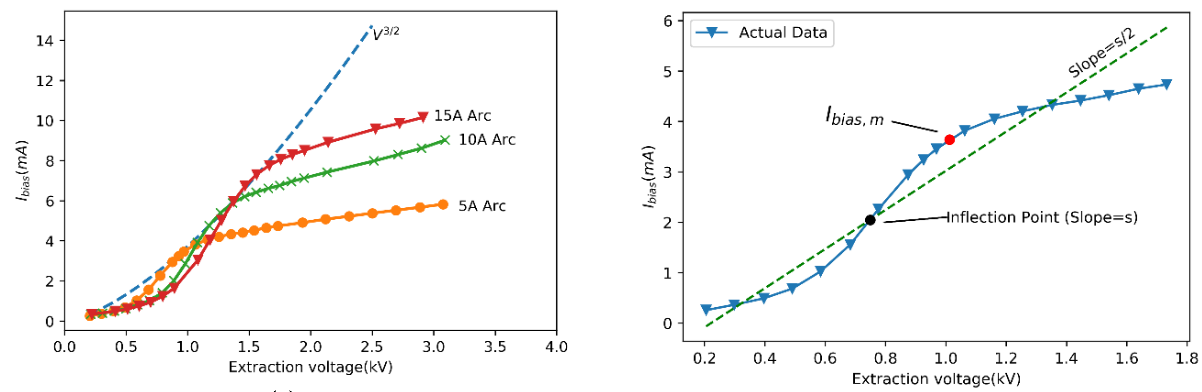
FIGURE 2. Variation in the magnetic field strength along the central axis of the ion source for different magnetic dipole filter fields. The position values correspond to the locations indicated in Fig. 1a). Each field is indicated with the integrated field value (Gauss·mm) over the 160 mm length.

The magnetic dipole filter indicated in Fig. 1 a) creates a transverse magnetic field. The electrons traversing the fields experience the Lorentz force and they follow the Larmor radius trajectory. This filters out the high energy electrons from the extraction region. The strength of the transverse magnetic filter field is varied by changing the Sm_2Co_{17} magnet arrangement in the magnetic filter around the central axis of the ion source. The variation of the magnetic field along the axis of the ion source for different magnet arrangements in the magnetic filter is shown in

Fig. 2. The peaks (A, B) correspond to the field created by the two sets of magnets in the extraction electrode, as shown in Fig. 1a). The magnetic field created by these magnets deflects the co-extracted electrons towards the extraction electrode, which is biased at a positive potential and thus removes the electrons from the beam line. A Faraday cup located 510 mm downstream from the plasma electrode is used for measuring the magnitude of the ion beam current.

MAXIMUM ION CURRENT EXTRACTED FROM THE ION SOURCE

An upper limit exists for the maximum amount of ion beam current that can be extracted from the D-Pace ion source, for a particular plasma density, due to space charge effects. This is predicted by the Child Langmuir law[8]. The total amount of charged particles reaching the ground electrode from the plasma chamber is denoted as the bias current (I_{bias}). It is measured on the power supply, which controls the magnitude of the negative bias between the ion source and ground electrode. The variation of I_{bias} for different voltages on the extraction electrode at constant arc currents is shown in Fig. 3a). It can be seen that the ion source extraction system follows the space charge limited emission model, where the total amount of current extracted from the source follows a $V^{3/2}$ characteristic [9]. The extracted current flattens out beyond a particular extraction voltage, as it approaches the plasma density limit.



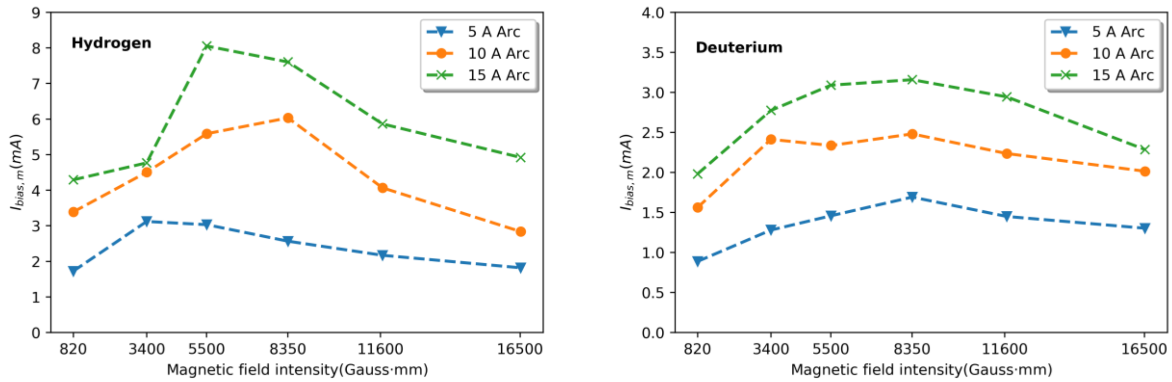
(a) (b)

FIGURE 3. a) Variation of total extracted current (I_{bias}) in hydrogen plasma for different extraction voltages, at constant arc currents, an arc voltage of 120 V, a bias voltage of 5 kV, a plasma voltage of 3.5 V and gas flow of 7.5 sccm. The $V^{3/2}$ line is shown for reference only. b) Method of finding $I_{bias,\ m}$ value from the data.

A method of finding the maximum I_{bias}, ($I_{bias,\ m}$) for a particular plasma density (constant arc current) is illustrated in Fig. 3 b).The typical shape of the data curve indicates the presence of an inflection point. At first, the inflection point of the actual data curve is found using the second derivative method. Inflection point is the point where the second derivative value equals zero and crosses from positive values to negative values. Then, a new line is created with a slope value equal to half of the value of slope at the inflection point. The actual data curve will have a maximum and a minimum with respect to the new line. The maxima value is determined by the derivative method (differentiating the actual data curve with respect to the new line) and this value is assigned to $I_{bias,\ m}$.

$I_{bias,\ m}$ values are determined using the method mentioned above for different arc currents and magnetic filter field intensities for H_2 and D_2 plasmas. Plasma electrode voltages and gas flows are optimized before each measurement by tuning them to achieve maximum current at the Faraday cup, for a fixed arc current.

The results are shown in Fig. 4a) and 4b). As evident from the graphs, the magnetic filter field intensity should be optimized for maximum ion extraction. Low intensity fields (< 3500 G·mm) and very high intensity fields (>10000 G·mm) will decrease the amount of beam current extracted from the ion source. As already known[2], more ion current can be extracted from hydrogen plasma compared to deuterium plasma. The graph indicates different responses for deuterium and hydrogen for the varying filter fields. The magnetic field intensities required for maximum ion extraction is higher for deuterium plasma (~ 7000-8000 G·mm) compared to hydrogen plasma (~ 4000-6000 G·mm).



(a) (b)

FIGURE 4. a) ,b) Variation of $I_{bias,\,m}$ for Hydrogen and Deuterium plasmas at different magnetic filter field intensities and arc currents, at an arc voltage of 120 V and a bias voltage of 5 kV. Gas flows and plasma electrode voltages are tuned such that the Faraday cup current is maximum.

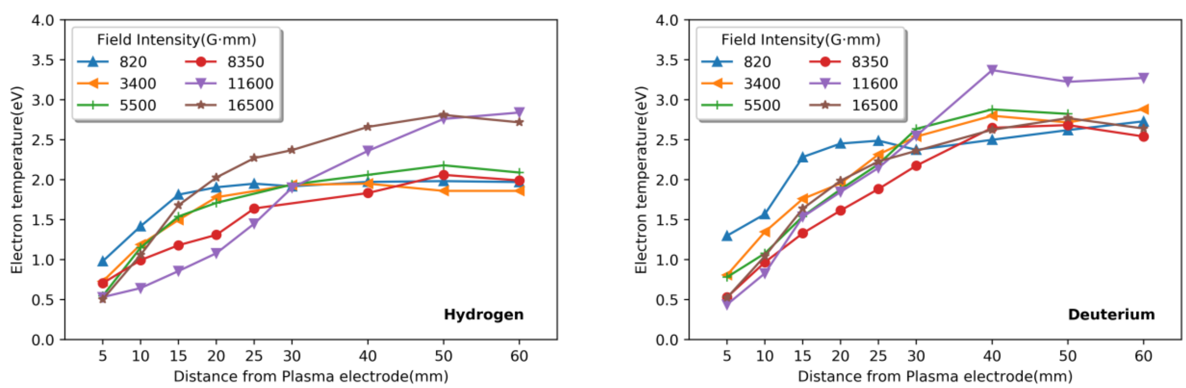
PLASMA PARAMETERS FOR H_2 AND D_2

A movable Langmuir probe made of tantalum and enclosed in a ceramic sleeve is used for measuring the plasma properties of H_2 and D_2. The probe has a tip length of 5 mm and a diameter of 1.6 mm. It is inserted into the plasma through the extraction side of the ion source as shown in Fig. 1a). The current-voltage characteristics of the probe is determined at different locations inside the plasma chamber for H_2 and D_2 plasmas. Plasma electrode potential and bias potential are maintained at ground for the Langmuir probe measurements. A gas flow of 7.5 sccm and an arc current of 5 A at an arc voltage of 120 V is used for the study.

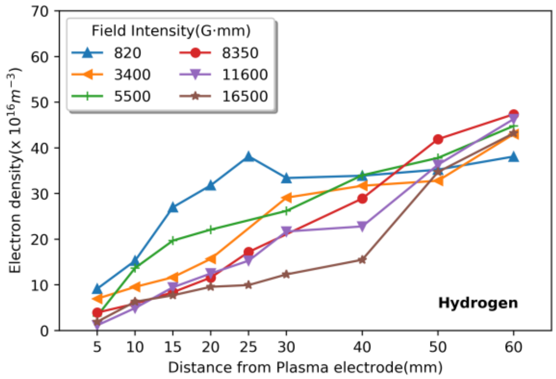
The plasma potential V_p is determined by finding the inflection point of the V-I characteristics through the second derivative method. An exponential fit using the equation (1) is used to find the electron temperature (T_e) and electron density (n_e) [10].

$$I = \frac{1}{2} e A n_e U_B \left\{-1 + \left[\frac{2M_i}{\pi m}\right]^{1/2} \exp\left(\frac{-e\left(V_p - V\right)}{kT_e}\right)\right\} \qquad (1)$$

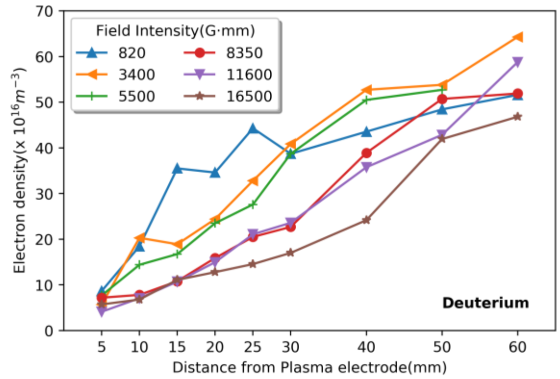
M_i and m represent the H^+ ion mass and electron mass respectively. U_B is the Bohm velocity, A is probe surface area, k is the Boltzmann constant and V is the varying voltage on the probe. The results of measurement of the electron temperature and the electron density at different locations inside the ion source for different magnetic filter field intensities are shown in Fig. 5.



(a) (b)



(c)



(d)

FIGURE 5. a), b) Variation of electron temperature inside the ion source for different magnetic filter fields for H_2 and D_2. c), d) Variation of electron density inside the source for different magnetic filter fields for H_2 and D_2. An arc current of 5 A, arc voltage of 120 V and gas flow of 7.5 sccm is used.

The results indicate a higher electron temperature and electron density distribution inside the ion source for deuterium plasma compared to hydrogen. As evident from the graphs in Fig. 5 a) and 5 b), increasing the magnetic filter field intensity reduces the electron temperature close to the plasma electrode region. The lowest magnetic field intensity (820 G·mm) results in an electron temperature on the order of 1eV at 5 mm from the plasma electrode for H_2 and D_2. The electron temperature needed for dissociative electron attachment reactions[5], which produces H^- and D^- ions, is on the order of 0.5 eV. The graphs reveal that a magnetic field intensity around 5000 G·mm is required for hydrogen plasma to reduce the electron temperature to 0.5 eV, whereas deuterium plasma require fields around 8000 G·mm to achieve this temperature. This can explain the behavior observed in Fig. 4, where a higher magnetic field intensity is required for achieving maximum extracted current for deuterium, compared to hydrogen.

Figures 5 c) and 5 d) shows that the filter field reduces the electron density in the regions close to the plasma electrode (0-30 mm), with the lowest field resulting in the highest density and vice versa. The decrease in the electron density for high magnetic fields can be one of the reasons for the decrease of extracted ion currents at high magnetic filter fields.

CONCLUSION

The study was conducted to understand the influence of different dipole magnetic filter fields on beam currents extracted from the TRIUMF licensed D-Pace ion source. The maximum beam current that could be extracted from the ion source for a given plasma density was determined for H_2 and D_2 plasmas. This revealed that deuterium plasma requires a higher magnetic filter field intensity (7000-8000 G·mm) compared to hydrogen (4000-6000 G·mm) for extraction of maximum current. Plasma parameters of H_2 and D_2 under different magnetic filter fields were studied with a Langmuir probe. Results indicated that a higher magnetic field was required for the D_2 plasma compared to H_2, for reducing the electron temperature near the plasma electrode (at 5 mm) to ~0.5 eV. The distribution of electron temperature and density along the central axis of the ion source for H_2 and D_2 plasmas were also determined in the current study.

Future works aim at measuring the maximum ion current that can be extracted from the TRIUMF licensed D-Pace ion source for D_2, for very high arc currents (~50 A) at a bias voltage of 30 kV. We need to determine if the differences in the intensity of the optimum magnetic field for H_2 and D_2, observed in the current study, are present at very high arc currents also.

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