

Characterization of an IEC Plasma Thruster Plume by a Nude-type Faraday Probe

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Abstract: Characterization of IEC tight jet mode is achieved through Faraday probe measurement. Preliminary results indicate that tight jet is a high energy electron beam with scattering of secondary ions and electrons. A novel analytical model is proposed to evaluate this non-Maxwellian plasma beam with compensation of secondary electron emission effect on probe surface. The results show promising features on the extracted jet energy and current. In addition, it implies an extra ionization mechanism dominated the generation of plasma, which supports the existence of spherical double layer within IEC.

Nomenclature

A	= area	r	= ratio
a	= constant	SDL	= spherical double layer
e	= electron charge	SEE/SIE	= secondary electron/ion emission
EB	= electron beam	T	= temperature
EP	= electric propulsion	u	= velocity in x direction
F	= distribution function	v	= velocity in y direction
HCI	= highly charged ion	V	= voltage
IEC	= inertial electrostatic confinement	VDF	= velocity distribution function
I	= current	w	= velocity in z direction
IRS	= Institut für Raumfahrtssysteme	Z	= charge
k_B	= Boltzmann constant	α	= constant for Bohm criteria
m	= molecular mass	σ	= secondary electron yield
n	= number density		

I. Introduction

Demand of spacecraft and satellite increase exponentially with the space exploration activities since 1960s. Propulsion system is a mandatory to provide spacecraft maneuvering capability. The traditional concept for space propulsion is the chemical-based rocket system. Although the concept has high reliability as well as thruster force, its low impulse density requires more propellant for maneuvering, which limits the lifetime of spacecraft. To extend spacecraft lifetime for future space mission, improvement of specific impulse is the first priority, which lead to electric propulsion concept.

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Electric propulsion (EP) is a concept to efficiently transfer electrical energy into kinetic energy of fluid by coupling thermodynamic, electrostatic, and electromagnetic effect. Due to its superiority in specific impulse and comparatively low system mass, electric propulsion is considered as an alternative solution for long-term space mission. Since 1960s, several electric propulsion concepts are proposed and deployed in space missions. However, the argument about electric propulsion is the low thrust-to-power density, which is mainly resulted from the low particle density in the exhaust plume. To overcome this drawback, plasma confinement mechanism should be involved in the development of next generation electric propulsion device to achieve higher mass specific energy in plasma plume.

Inertial electrostatic confinement (IEC), which originates from fusion reactor concept, could offer both plasma generation and confinement at the same time by strong electric field.^{1,2} Figure 1 shows the principle of a spherical IEC device.³ A strong negative bias is applied between a pair of concentric spherical electrodes, the inner one serves as cathode while the outer one as anode. Ions are generated by electron impact at inter-electrode region and accelerated toward the center of IEC. Due to the high transparency of cathode grid, most of ions travel through the gates on cathode grid with its inertia and keep flying toward the center point. If no collision occurred on the trajectory, ions are able to reach the opposite side of IEC and decelerated to zero velocity at the position with same potential as it was born. These ions are accelerated backward through the same path to its born position and oscillate in between until ion-ion or ion-neutral collision occurred. The probability of appearance of ions increases when more and more ions oscillate through the spherical cathode grid, which increases space charge and forms a virtual anode. Electrons are then driven to virtual anode to maintain charge equilibrium within cathode grid. A virtual cathode is established when the voltage bias is high enough, which can further trap ions at center and achieve fusion reaction.⁴ Though the virtual anode is proven by experiment, virtual cathode is never observed from direct measurement. Despite from that, fusion reaction is still observable. Intensive research activity for application of IEC as neutron source existed in USA⁴⁻⁷ and Japan⁸⁻¹⁰ in 1990. However, the interests in plasma extraction and application are seldom mentioned in literature. No theory exists to explain the plasma extraction phenomenon.

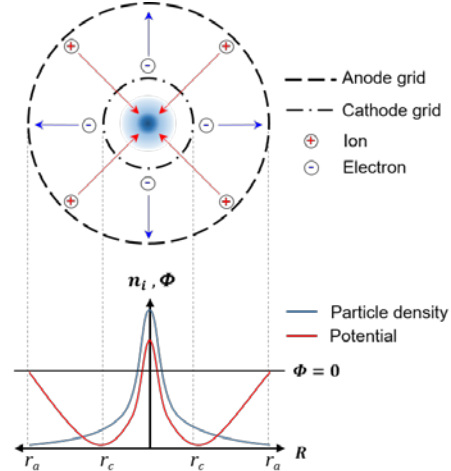


Figure 1 Schematic of IEC working principle

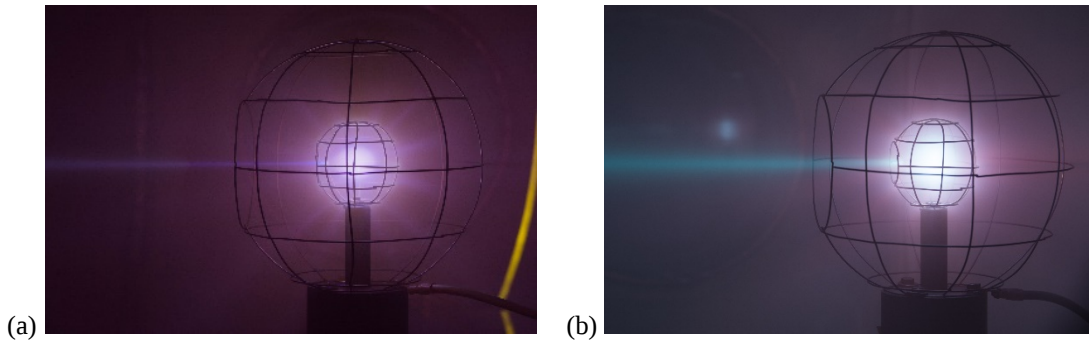


Figure 2 IEC tight jet in Argon (a) and Helium (b)

For application in space propulsion, plasma extraction from IEC device is mandatory. Institute of Space System (IRS) started the research in IEC device since 2009, both analytically and experimentally, to understand the jet extraction mechanism and to evaluate the applicability for space propulsion systems.^{3,11-13} Experimental observation concluded the jet extraction could be controlled by reshaping the electric field topography, e.g. create a field weak-point by non-spherical symmetric grid configuration. Two IEC tight jet operations in Argon and Helium are shown in Figure 2. Although plasma extraction is observed, the explanation of the plasma generation, confinement, and jet extraction mechanism was still missing in the past.

In 2017, the spherical double-layer (SDL) theory for IEC is, for the first time, proposed which explain the concept of plasma generation, confinement, and extraction for IEC device as a whole.² This theory demonstrates the great

potential for IEC device to offer a better ionization efficiency as well as to provide plasma confinement for improving the particle density in the plume. These characteristics indicate that IEC device is promising for next generation electric propulsion development.

Preliminary result from electrostatic probe measurement indicates that tight jet is a high-energy electron beam (EB) while spray jet is composed by diffused ion plume with EB. In this paper, the investigation of the plume is initiated to understand more about the properties of tight jet by using a nude-type Faraday probe. Accompany with non-Maxwellian plasma model for Faraday probe measurement, electron temperature and density can be estimated through curve-fit along with experimental data. The experimental method and setup are introduced in Section II while the non-Maxwellian probe model is explained in Section III. The experimental results and discussions for both Argon and Helium are shown in Section IV respectively.

II. Experimental Method and Setup

Electrostatic probe has been applied on plasma diagnostics for decades, among which Langmuir probe is the most well-known one. The basic concept is to measure current-voltage characteristics in plasma by applying different voltage bias on probe surface. Depends on the probe configuration, several plasma parameters can be identified, e.g. electron temperature, electron density, etc.^{14–16} Probe selection mostly depends on the measured plasma source with some known plasma properties, e.g. Maxwellian plasma. However, for source like IEC, the selection of probe is critical due to the fact that no theory for explaining IEC jet extraction.

From observation, tight-jet mode shows extremely collimated beam contour, see also Figure 2, which has diameter in the range of couple of millimeters. In addition, radiation emission indicated the possibility of highly charged or highly energetic beam, which might contain high enthalpy in the jet plume. Furthermore, secondary electron emission (SEE) by either electron or ion bombardment might occur intensively on probe collector. Accordingly, the collector should at least have high temperature sustainability and a planar configuration to mitigate alignment problems. Moreover, probe material is required to suppress SEE, or at least capable to be calculated with incoming beam energy. These criteria lead to a decision on Faraday probe with high purity tungsten collector.

A. Faraday Probe and Circuit

Faraday probe is similar to planar Langmuir probe except for the fact that it has a shield around side of collector, see Figure 3. The current coming from the side can hence be identically isolated and the incoming current from the front could be calibrated by simply applying a correction factor^{17,18}. This approach is widely applied for the research of plasmas and electric propulsion. It is a good option as a point of departure of the IEC jet characterization.

The probe is composed by a $\phi 20\text{ mm}$ tungsten collection and a stainless-steel case with $\phi 22\text{ mm}$ outer diameter. The gap in-between is 0.5 mm . The insulation of collector and case is made by Boron Nitride. The probe is installed on a 2-dimensional moving platform and is aligned with tight jet set at 300 mm downstream of IEC extraction port as Figure 4 shown. Tight jet hit straightforward on tungsten collect. The probe bias is controlled by Keithley 2410 the current through collector is monitored by an ammeter. The biased voltage sweeps in between -200 V to $+30\text{ V}$ in order to access the I-V characteristics of tight jet.

From preliminary results, the measured current is consisted by EB current, SEE on probe surface, and the electron impact ionization on background gases. The measured I-V characteristics need to be corrected by subtracting SEE effect on collector, which will be explained detailly in section III.

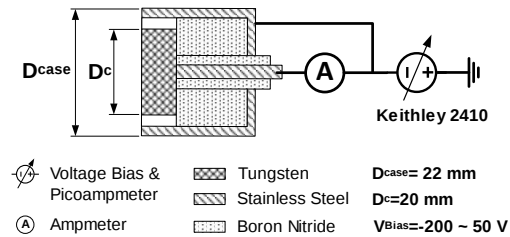


Figure 3 Schematic of Faraday probe configuration and measurement circuit

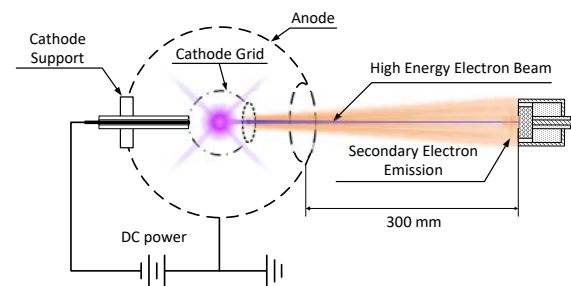


Figure 4 Arrangement of IEC and Faraday probe for measurement of tight jet

B. IEC Configuration

The IEC prototype was designed based on a sphere-symmetric grid pairs with extraction ports on both cathode and anode. These ports are axially aligned to establish a weak point on center-pointing electric field topography. Both spherical grids are made by ϕ 1 mm stainless steel wire and have diameters of ϕ 50 mm and ϕ 150 mm on their enclosed sphere, respectively. The wires on both cathode and anode are structured with five latitudinal wires and six longitudinal wires. The extraction ports on both cathode and anode are made by ϕ 1 mm stainless steel ring-wire with ring tours of ϕ 10 mm and ϕ 50 mm, respectively. Boron Nitride was selected as electrical isolation as well as the cathode support between electrodes; while PEEK serves as the base support for IEC. Cathode is connected to power supply through high voltage feedthrough.

C. Experimental Facility

IEC is tested in IRS tank 12 facility. The vacuum chamber is a ϕ 1.0 m $\times$ 2.75 m stainless steel cylinder which connected with a 3-stages pumping system. The pumping speed and ultimate pressure are up to 675 l/s and 10^{-3} Pa for Argon, respectively. A mass flow controller is installed on gas-supply pipeline to control the chamber pressure by flooding test gas into tank. The power supply for IEC could provide voltage up to 20 kV with maximum output power 10 kW. A 2D moving table is setup in tank for plume characterization such as electrostatic probe measurement and optical diagnostics. Detail description about test facility can be found in Ref. 3.

D. Test Conditions

The appearance of IEC jet mode is strongly related to the operating background pressure and gas properties.¹¹ In this paper, two gases are investigated, Argon and Helium, respectively. To establish stable tight jet extraction for characterization, the operating pressure is controlled at 0.4 Pa to 0.5 Pa for Argon while 3.0 Pa to 4.0 Pa for Helium. The other controlled parameter is IEC voltage, which goes up to -7 kV maximum or until spray jet occurs. IEC current is set as floating and strongly depends on the applied voltage as well as the background pressure. To mitigate the influence from pressure variation in vacuum chamber as well as IEC grids temperature, Faraday probe starts measuring when IEC current and background pressure reach to stable condition.

III. Analytical Modeling for Faraday Probe

The schematic of measured current on Faraday probe is shown in Figure 5. According to preliminary results, incoming plasma to the probe is composed by high energy EB (aka. primary electrons) as well as secondary ions/electrons emission (SIE/SEE) from electron-impact-ionization of background gases, which depend on biased voltage on probe surface. The incoming plasma is, for sure, with non-Maxwellian distribution. However, classical electrostatic probe theories are valid only in Maxwellian plasma. Some modification is required for non-Maxwellian plasma characterization.

To simplify the problem, current measured by Faraday probe can be assumed as the combination of incoming high energy EB as well as the incoming secondary ions and electrons, which depends on the probe bias. According to theory of electron-impact ionization, secondary ions are usually with high-charge-state, while secondary electrons still have respective high energy in the beginning of electron-neutral collision.¹⁹ However, high-collision-rate between secondary particles with neutral particles in the medium vacuum to upper region of high vacuum (10^{-4} Pa $\sim$ 10^0 Pa) forces secondary electrons shifted to low-energy condition²⁰ and HCIs are quenched fast to low-charge-state^{21,22}, respectively. In this condition, both secondary electrons and ions can be considered as Maxwellian distributed²⁰.

On the other hand, the energy distribution function of high energy EB is still an unknown question. Base on the jet extraction mechanism proposed in Ref. 2 the extracted EB can be considered as a drifted Maxwellian distributed plasma with respectively low thermal energy. Therefore, the measured current on Faraday probe can be considered as the combination of several Maxwellian distributed particles clusters with different drifting velocities. Figure 6 shows an example of velocity distribution function in several Maxwellian distributed particle clusters. The secondary particles, which has only thermal velocity, therefore have Gaussian distribution in velocity domain. However, high energy EB, which has extremely high drifting velocity in specific direction as well as respectively small thermal

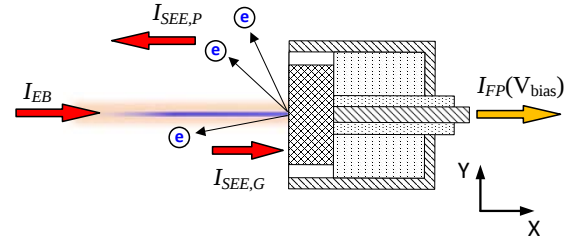


Figure 5 Current balance on Faraday probe

velocity, results in a shifted Gaussian distribution on velocity coordinates. The VDF of both primary EB and secondary particles still follow Maxwellian distribution.

In addition to the incoming current from high energy EB and secondary particles, the SIEs/SEEs on probe surface should be taken into account for V-I characterization via Faraday probe. SEE resulted from EB-metal bombardment is intensively investigated since early 20th century. The SEE current is a function of incoming electron beam current density and material.²³ On the other hand, the SIE current induced by electron bombardment is rare due to most of beam energy transferred to X-ray and SEEs generation.^{19,22} The SIE current is neglect in this research. In general, to allow a better estimation on SEE current, tungsten is chosen as the probe collector due to its high thermal resistance, lower SEE, and more reliable information on SEE database.

The balance of currents is shown in Eq.(1). I_{FP} is current reading on collector, which is a function of probe biased voltage (V_b). It is equal to the current of high energy EB (I_{EB}), current of SEE on probe surface ($I_{SE,P}$), and net current of secondary electrons/ions from the ionization of background gases ($I_{SE,G}$). The detail derivation for each term will be explained in the following subsections.

$$I_{FP}(V_b) = I_{EB} - I_{SE,P} - I_{SE,G} \quad (1)$$

A. Interpretation of Electron Beam and Non-Drifting Plasma

Maxwellian distributed particle can be described in the following formula:²⁴

$$F_s(u, v, w)_{Maxwellian} = \left(\frac{m_s}{2\pi k_B T_s}\right)^{1/2} \exp\left(-\frac{m_s(u^2 + v^2 + w^2)}{k_B T_s}\right) \quad (2)$$

Here, the subscription s denotes to the species (ion or electron). u, v, w represent in the velocity in x, y, z directions, respectively. m_s and T_s are molecular mass of the specie and mean kinetic temperature for all particle the specie. When a Maxwellian distributed particle beam has drifting velocity u_0 , the distribution of particle beam can be expressed in a non-drifting Maxwellian distributed plasma with velocity shift, which is shown Eq.(3)(2).

$$F_s(u, v, w)_{drifting\ Maxwellian} = F_s[(u - u_0), v, w]_{Maxwellian} \quad (3)$$

Considering an EB hit on the Faraday probe, which is assumed in 1-D as Figure 5 illustrated, the EB current can be derived by integrating the distribution function in Eq. (4) and (5):

$$F_e^j(u)_{1D} = \iint_{-\infty}^{\infty} F_e^j[(u - u_0), v, w]_{Maxwellian} dv dw \quad (4)$$

$$I_{EB} = \sum_j e A_{EB} n_{EB}^j \int_{v_{min}}^{\infty} F_e^j(u)_{1D} u du \quad (5)$$

Where the superscription j denotes as different Maxwellian distributed drifting plasma while e denotes as electron charge. The size A_{EB} is the beam cross-section area and n_{EB} is electron density in respective Maxwellian distributed plasma. The parameter v_{min} is the minimum velocity which the electron required to overcome the retarding field and reach to probe. Accordingly, v_{min} is equal to probe bias velocity v_b , which is a function of retarding field:

$$v_{min} = v_b = \sqrt{-\frac{2ZeV_b}{m_s}} \quad (6)$$

Here, Z is the charge-state of the particles of concern, e.g. for electrons, $v_b = \sqrt{-2eV_b/m_e}$. The integration of Eq.(5) leads to:

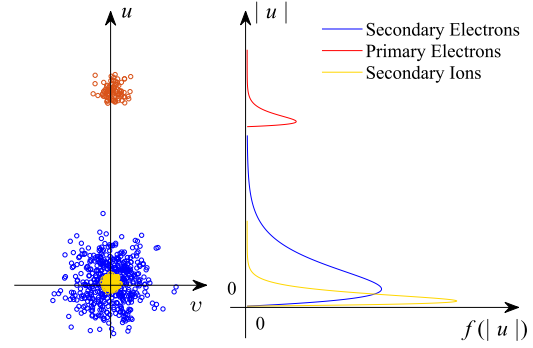


Figure 6 Schematic of measured particles in non-Maxwellian plasma on velocity coordinated (a) and VDF (b)

$$I_{EB} = \sum_j e A_{EB} n_e^j \frac{v_t^j}{2} \left[r_{u_0}^j \sqrt{\pi} \operatorname{erf}(r_{min}^j) - \exp(-r_{min}^j{}^2) \right] \quad (7)$$

$$v_t^j = \sqrt{\frac{2k_B T_{e,EB}^j}{m_e}} \text{ and } r_{min}^j = \left(\frac{v_b}{v_t^j} - \frac{u_0^j}{v_t^j} \right) = (r_{v_b}^j - r_{u_0}^j) \quad (8)$$

The parameter r represents the normalized drifting kinetic velocity of Maxwellian plasma, which is the ratio of EB drifting velocity (u_0) to thermal kinetic velocity of EB (v_t). The term v_t can be derived from electron temperature of EB ($T_{e,EB}$), which the drifting velocity of EB is excluded. The sizes r_{v_b} and r_{u_0} are the normalized term for the probe bias velocity and drifting velocity of the plasma, respectively. Here, r_{min} indicates the minimum normalized kinetic velocity needed to overcome the potential barrier of probe bias.

B. Interpretation of Secondary Electron Emission on Probe Surface

$I_{SE,P}$ is correlated to I_{EB} with a factor called secondary emission yield σ , which is shown in following equation.

$$I_{SE,P} = \sigma I_{EB} \quad (9)$$

According to Gibbons²³, an universal secondary emission yield curve, which is independent from the material of concern, can be derived from a normalized factor as (10) - (12) shown.^{23,25}

$$\frac{\sigma}{\sigma_{max}} = a_1 \ln(a_2 r_{SEE} + 1) \times \frac{1 + a_3 \exp(-a_4 r_{SEE})}{r_{SEE} + 1} \quad (10)$$

$$r_{SEE} = E_{imp}/E_{SEE,max} \quad (11)$$

$$E_{imp} = eV_{imp} = \frac{1}{2} m_e u_0^2 - eV_b = \frac{1}{2} m_e v_t^2 (r_{u_0}^2 + r_{v_b}^2) \quad (12)$$

Here, r_{SEE} is the normalized value for incident electron energy, in which E_{imp} represents the impact energy of incoming particle, $E_{SEE,max}$ is the impact energy where the maximum secondary electron yield occurred. The impact energy can be written in eV_{imp} while the maximum SEE yield occurred at $V_{SEE,max} = 650$ V for pure tungsten. Parameters a_{1-4} and σ_{max} are constants from experimental database. Their values can be seen in Table 1.²⁵

Table 1 Parameters for Secondary emission yield²⁵

Parameter	Value
σ_{max}	1.35
a_1	1.533
a_2	2.676
a_3	0.2218
a_4	14.032

Consequently, secondary electron yield becomes a function of the incoming electron energy, which can be further simplified into the normalized velocity based on EB current. The curve of SEE yield along with normalized electron energy is shown in Figure 7. This curve is proven to be independent from material properties.²³ As long as σ_{max} and $V_{SEE,max}$ are known, the calculation of SEE current can be much simpler.

C. Ion current from background gases ionization

As mentioned in section III, SIEs/SEEs can be considered as Maxwellian plasma due to high collision rate between neutral particles and induced charge particles

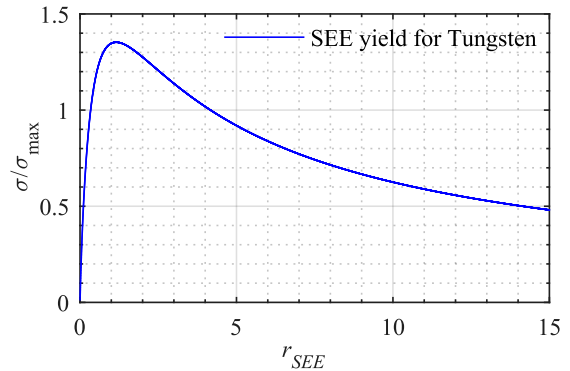


Figure 7 Normalized SEE yield along with the normalized incident electron energy.

in medium vacuum environment. The VDF and current contribution from SIEs/SEEs measured by Faraday probe can then be written in the following equations:

$$F_i(u)_{1D} = \left(\frac{m_i}{2\pi k_B T_i}\right)^{1/2} \exp\left(-\frac{m_i u^2}{k_B T_i}\right) \quad (13)$$

$$i_{SE,G} = \alpha \sum_l Z^l e A_p n_i^l \int_0^{v_{min}} F_i(u)_{1D} u du = \frac{1}{2} \alpha e A_p \sum_l Z^l n_i^l \exp\left(-\frac{Z^l e V_b}{k_B T_i}\right) \quad (14)$$

Here, the indicator l represents different charge states of ions and A_p is area of probe collector. The parameter α is coming from the Bohm criteria, which is usually 0.5 for planar probe configuration.¹⁴ From the optical emission spectroscopy, the results indicated that the population of ion species is composed mainly by Ar^+ on tight jet trajectory.²⁶ Assuming charge-exchange effect is the only loss for SIEs, ion density should be equal to electron density to maintain charge neutrality. Electron density can be easily accessed from the measurement of electron saturation current by Faraday probe.^{14,15} The ion temperature is equal to the temperature of the neutral particle. Hence, ion current becomes a simple function of probe bias.

By substituting Eq.(7) (9) (14) into Eq.(1), the current balance equation becomes $f(u_0, v_t, n_e, A_{EB})$, which can be solved by curve fitting with the I-V curve from Faraday probe measurement. An example of the experimental results with the respective fitting curve is shown in Figure 8. The fitting in negative voltage is close while in positive bias has separation. This is resulted from the expansion of the sheath and absorption of SEE with large positive bias. The fitting in negative bias are much more important for EB characterization, therefore, mismatching of electron saturation current is not an issue for analyzing EB properties. In general, the model demonstrates a good fitting along with the experiment data.

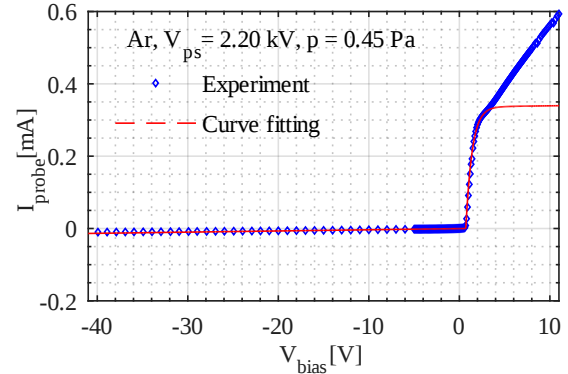


Figure 8 Example of curve fitting

IV. Discussion

Figure 9 - Figure 12 show analysis results in Argon and Helium environment with the probe model. In Figure 9, EB kinetic energy increases with the IEC voltage in both gases environment. The normalized voltage shown in Figure 10 indicated that EB energy is independent from the gas species, but only a function of background pressure and IEC voltage. This implies that extraction of tight jet is driven by electric potential within the core region, which support the extraction theory proposed in Ref. 2. On the other hand, beam energy can go above than IEC voltage in higher background pressure. The reason is still not confirmed. However, it suggests a potential well forms by plasma around core region which provide further acceleration for electrons.

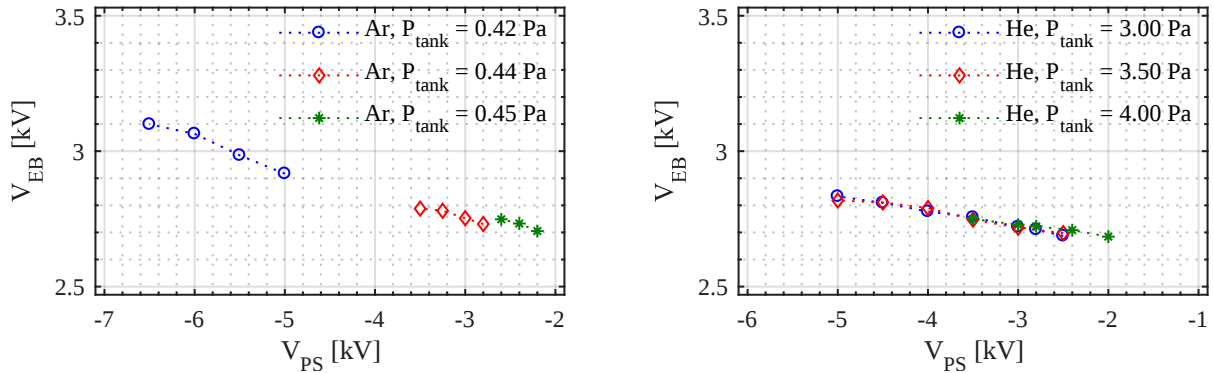


Figure 9 Electron beam energy in Argon and Helium

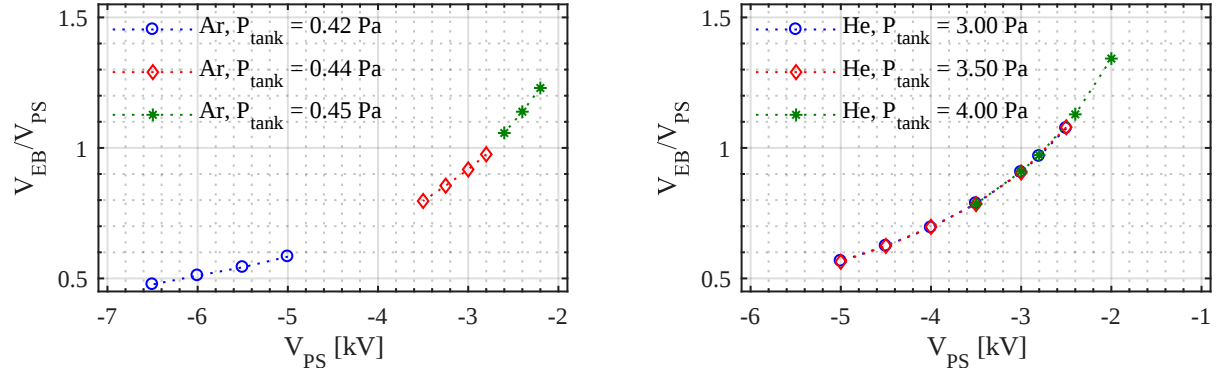


Figure 10 Normalized electron beam energy in Argon and Helium

The background pressure shows a strong influence on EB current. The EB current increases much faster with IEC voltage in higher pressure in both gases environment. This might be resulted from the increase of plasma density in IEC core as well as EB impact ionization with background gases. In addition, the current value is much higher in helium environment. This might due to the fact that much more SEEs involve in the acceleration according to much higher pressure. Furthermore, ratio of EB current in most of the condition are more than the current applied on IEC, which is an indication that another ionization mechanism involved in the IEC discharge. This further suggests SDL existed within cathode grid as mentioned in Ref. 2.

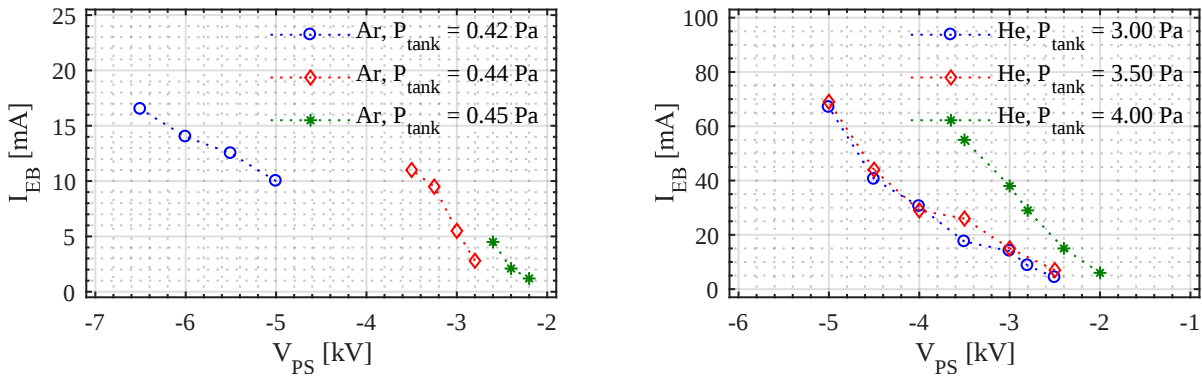


Figure 11 Electron beam current in Argon and Helium

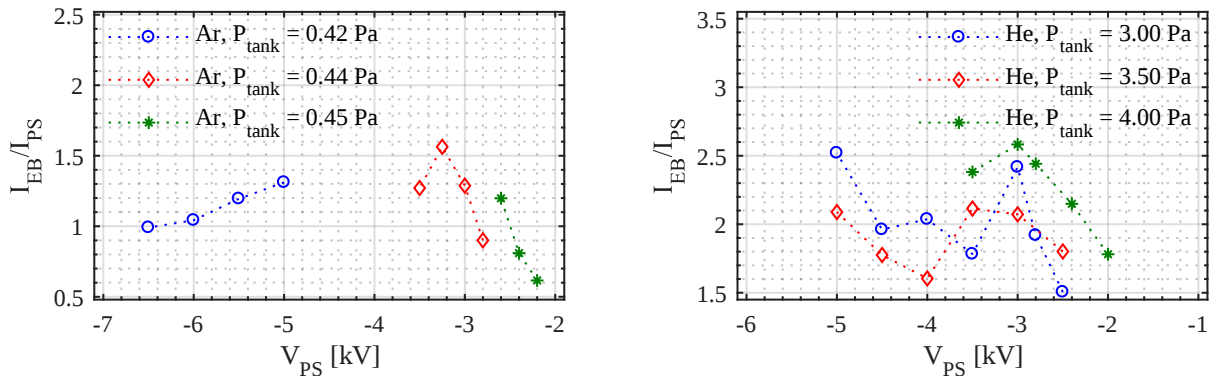


Figure 12 Normalized EB current with IEC supply current

V. Summary

In this paper, characterization of IEC tight jet mode is achieved through Faraday probe measurement. Preliminary results indicate that tight jet is a high energy EB with scattering of secondary ions and electrons. A novel analytical model is proposed to evaluate this non-Maxwellian plasma beam. The model assumed the exhausted EB is composed by several Maxwellian plasma with different drifting velocity and temperature. In addition, SEE on probe surface are considered in this model as well to compensate the current loss through electron beam bombardment.

The results shown a linear tendency between beam energy and IEC voltage. In addition, the beam energy shows independence from the gas species while the background pressure and IEC voltage are the controlled parameters for the EB extraction. The EB current linearly increases with applied voltage. However, it is affected strongly by background pressure, which suggests improvement of vacuum degree is required. Based on observation, the extracted EB current can be more than the IEC supply current. This suggests a strong ionization process occurred within IEC core to generate electron which has not yet been consider in the past research. The results imply another ionization mechanism dominated within IEC which turn out to be an SDL as mention in Ref. 2.

Acknowledgments

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