Influence of Cathode Dimension on Discharge Characteristics of Inertial Electrostatic Confinement Thruster

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Abstract: The concept of electric propulsion based on inertial electrostatic confinement (IEC) was proposed in 2017 IEPC accompanying with new theory explains the formation of its unique non-neutral plasma, which is called spherical double layer (SDL). To verify the theory and to realize this innovative thruster concept, design of cathode grid is the most crucial step, which determines the electric potential topography for triggering and maintaining the non-neutral plasma phenomenon. In addition, 3D-printing technologies are brought in for cathode manufacturing due to its complexity. Six different cathode geometries are tested and discussed with different flowrate of argon to figure out their respective influence with respect to the IEC discharge. Experimental results reveal decisive evidences supporting the SDL theory. The impact of extraction port design on plasma extraction are also disclosed in this paper. These certainly establish its role among next-generation electric propulsion concept and layout the roadmap for optimization of IEC plasma source.

Nomenclature

AM	=	Additive manufacture
AS	=	Archimedean solid
D_a	=	inner diameter of hollow anode
D_c	=	diameter of cathode envelop
D_{SDL}	=	spherical double layer diameter
EM	=	electromagnetic
EPT	=	electric potential topography
FWHM	=	full width half maximum
IEC	=	inertial electrostatic confinement
IRS	=	Institut für Raumfahrtsysteme (Institute for Space Systems)
SDL	=	spherical double layer
SLM	=	selective laser melting

I. Introduction

Inertial electrostatic confinement (IEC) development for space propulsion application starts in IRS since 2009 [1]. Several advanced concepts and designs based on the application of IEC plasma source are proposed respectively in 2017 IEPC and 2018 IAC [2,3].

The theory on plasma ball formation and extraction from IEC is only vaguely verified. Traditional theory proposed the formation of the IEC plasma core is due to the accumulation of ions oscillating in between the spherical cathode and anode. It forms a special multi-layer potential well structure called Poissor, in which electron emitted from cathode

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are trying to neutralize the potential built up by ions. [4]. In other words, this theory does not consider the ionization processes triggered by the electron and suggests the discharge is dominated only by the physical electrodes.

The other theory identified the formation of plasma ball is caused by a non-neutral plasma effect called spherical double layer (SDL), which is an equilibrium condition of a special non-neutral plasma phenomenon observed in both astrophysics and laboratory plasma.[5–8] An intensive, steady electron-impact ionization processes is generated by the electric potential gradient between cathode and SDL, which serves as an virtual anode drives electron flying toward the plasma ball. The discharge is dominated by the cathode and the plasma ball. [2]

Charge non-neutrality of the plasma ball are able to maintain due certain electron leakage from the core through the gate on the cathode to IEC outside. If no electron leakage from the core of IEC, electrons coming from cathode to SDL will compensate the charge built by the ions cloud within SDL and diminish the discharge. Consequently, the existence of the electron leakage(s) is extremely important for maintaining this non-neutral plasma (SDL discharge). In other words, the electric potential topography (EPT) forming by the cathode geometry and grid pattern become the most critical concern in IEC plasma source development.

Preliminary investigation of discharge in an open-grid IEC has already been assessed in IRS [9]. Two types of plasma extraction from the core have been identified: tight jet and spray jet. Tight jet was revealed as high-energy electron beam by measuring with Faraday probe. The result was rebuilt by mulit-fluid Maxwellian model with secondary electron emission from probe surface. [10] The result for spray jet was limited. However, according to the measurement result, it shows the characteristic similar to quasi-neutral plasma.

Despite investigation on discharge behavior has been done with open-grid IEC, it is still difficult to explain correlation of discharge behavior with cathode geometry as well as the plasma extraction mechanism. According to SDL theory, the EPT is the key for the formation of plasma ball, which is determined by the cathode grid pattern and geometry (in case of IEC with grounded anode). However, the grid used in previous investigation was designed with a geographical coordination which leads to non-uniform grid arrangement. In addition, this grid was manufactured by spot welding processes, which creates uncertainty and distortion of grid. These issues cause a lot of uncertainty on the EPT, which bring up the demand for a better cathode grid design. Meanwhile, investigation of discharge behavior is the upmost priority for understanding the characteristic of IEC plasma source, which could provide detail of the operation characteristics as well as point out the direction for IEC thruster design and optimization.

In this paper, the design concept of the IRS IEC thruster and current status will be briefly introduced for lighting up the roadmap of the IEC plasma source development. Investigation and experimental campaign are focused only on the IEC plasma source to promote the understanding of its unique discharge behavior. Cathode design principle and manufacture will be mentioned in the following section. The experimental results and further discussion on the discharge characteristics in different IEC cathode geometry will be presented.

II. Design concept of IEC thruster

A. IEC thruster overview

Figure 1 shows the cross-section view of IEC thruster concept. The thruster composed by a spherical hollow anode, a cathode grid, high-voltage feedthrough, and electromagnetic (EM) nozzle for plasma acceleration. The IEC serves as the plasma generator which operates in spray jet extraction from the core of IEC. Due to high applied voltage on IEC cathode, the extracted plasma is composed mainly by a divergent electrons plume with kinetic energy up to few 1 keV. The diffused plume continuously triggered electron-impact ionization on the way to EM nozzle which generates great number of secondary electrons and ions.

Depending on the design of overall EPT combination on IEC cathode and EM nozzle's anode, secondary electron can keep accelerating according to the electric potential gradience and magnetic flux lines. These electrons are guided and collimated by the magnetic flux line to the positive biased electrode and transfer most of its axial kinetic energy to gyrational direction. The electrons are trapped nearby the electrode of EM nozzle which continuously provides ionization for the neutral particles by electron-impact.

On the other hand, secondary ions generated from the electron plume might drift backward to the core or be further accelerated by EM nozzle. The backward-drifting ions can increase the ion density at the core of IEC, hence enhance the potential; while the others are pushed toward EM nozzle.

The extracted ions are driven by the specific design of electric and magnetic field in different way. The positively biased electrode in EM nozzle causes radical separation of the extracted plasma along the axis of EM nozzle, of which ions are pushed toward the axis and electron are gyrated along the axis. . Lower mass and higher temperature allow electron bounded with the magnetic flux line; while ions are only influenced by the electrostatic field. In this paper, the author intends to simplify the problem before involving external electric and magnetic field. Therefore, the

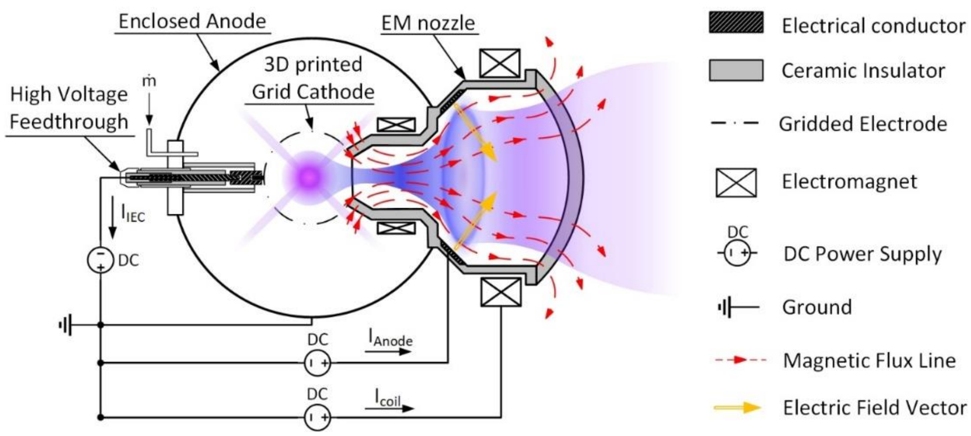

Figure 1. Schematic of IEC thruster concept.

discussion will only focus on the influence of discharge behavior of IEC plasma source regarding difference cathode dimension as first step. The discussion on the EM nozzle is beyond this work and, therefore, excluded from this paper.

The experimental model and hence the IEC plasma source design is shown in Figure 2. The hollow anode has inner diameter D_a = 147 mm. Different from the planned IEC thruster concept, the EM nozzle is here replaced by a ceramic nozzle. In addition, four CF40 ports are implemented on the equator plane of the hollow anode, of which the axes are 90-degree to each other. In addition, an extra CF40 flange and a CF75 port are center-aligned and placed in the (artic and nardi) of the sphere, which serves and the power feeding port and plasm extraction port respectively. The ceramic nozzle provides enclosure of the discharge chamber with respective electrical insulation, while the adapting port is designed only for the experimental model for the observation the discharge behavior within the IEC plasma source e.g. using optical emission spectroscopy. A special design on the insulation of cathode feedthrough prevents the electrical breakdown from the high differential voltage between power feeding line to the ground (up to 10kV). The cathode grid is manufactured via 3D-printing technologies, which enables electrodes with delicate geometry and complex grid pattern. More detail regarding to the cathode design criteria and philosophy will be explained in the following subsection.

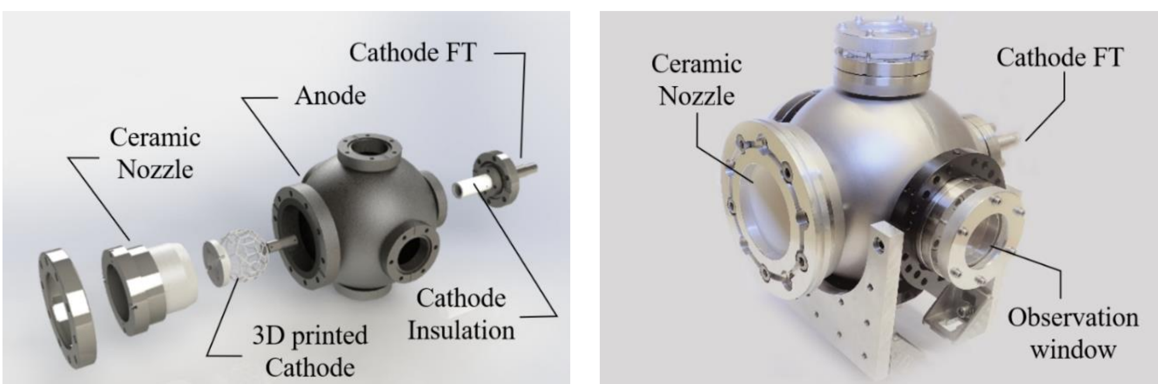

Figure 2. IEC plasma source 3D CAD drawing (left) and assembly (right).

B. Potential influences and concerns on IEC discharge

Several aspects might possibly influence the discharge performance of IEC, such as cathode dimension, grid pattern, transparency, material, extraction port design, gas flowrate, discharge pressure, etc. Start from the most basic operation principle of IEC, the discharge is enabled by the SDL within spherical cathode grid. Successful discharge required specified designed of electric potential gradience to guide electron flows from cathode surface through the extraction direction to the outside of IEC. This is determined by the design of the EPT shaped by cathode geometry and extraction port. Different grid transparency could also influence the EPT around the gate and the potential at the center. It does play a role on confinement of plasma but has less influence on of extraction port. Material could determine the work function for the electron emission which is not related to the EPT design. Accordingly, the grid geometry and extraction port design become the most important concerns regarding to the IEC performance. The investigation of the influence on material as well as grid transparency are excluded from this paper to simplify the discussion.

Some engineering issues for designing grid's geometry should be considered beforehand. First of all, the grid pattern is required to be as spherical-symmetrical as possible in order to provide a uniform EPT, which is important proper plasma confinement. On the other hand, it still needs to provide a certain flexibility for implementing a weak confinement on the extraction port. Additionally, scalability in grid dimension should be considered for investigating the scaling effect on the cathode dimension to discharge behavior. Furthermore, the grid pattern should be manufactured in an accurate and reproducible processes to ensure its reliability and reproducibility. Conclusively, the ultimate solution for grid pattern is designed based on the concept of Archimedean solid (AS), which provides three-dimensional symmetrical grid arrangement. The manufacturing process can be realized by the additive manufacture technologies.

C. Cathode design and manufacture

AS is a group of global symmetrical structures composed by regular polygons with identical vertices. Only one type of AS fulfills the criteria of parallelogram and symmetry arrangement on both face and edge of the polygon: truncated cuboctahedron, which is shown in Figure 3 (left). However, the gate enclosed in-between vertices is also important for plasma confinement. Refined vertices are required on hexagon and octagon face opening and to provide similar open area of the square gate. Figure 3 (middle) shows the cathode design with refinement vertices. The refined gate (gate *a b c*) provides a similar solid angle as the square gate (gate *d*). This potentially mitigates the uneven EPT, which prevents current leakage from the plasma core through confinement gate (gate *a b c d*), and allows a scalability concerning the grids' dimensions, diameters, and gate sizes at the same time. The vertices diameter is set at $\phi 1.2$mm to provide an adequate mechanical strength for the cathode. The manufactured grid cathode is shown in Figure 3 (right).

The design of the extraction port (gate *e*) is critical because it determines the electric field gradient for the electron mobility. This means the extraction port size and volume are closely related to the performance of ignition and discharge. In addition, a surface area of extraction port might also contribute emissive electrons for ionization processes. The judgmental criteria for designing the extraction port are still not exactly clear for the moment. As a start, the extraction port is designed as a circular gate with an adapting interface for ceramic nozzle to remain the symmetry of the EPT. The gate open area is 4-times larger than the circular one in confinement gate (gate *a*).

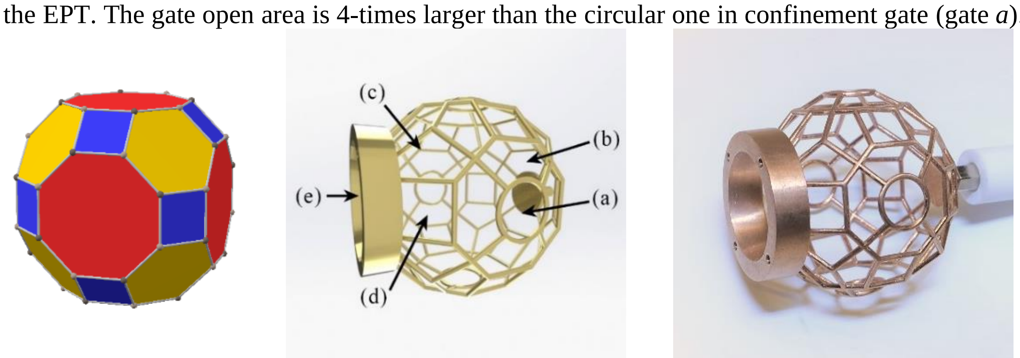

Figure 3. CAD and picture of IEC cathode grid (middle and right) with extraction port based on design of truncated cuboctahedron in Archimedean solid group (left).

Welding, as performed in previously research, is unsuitable for producing the cathode due to its complex configuration. On the other hand, manufacture via milling/cutting required a 5-axis CNC/laser cutting machine is to provide respective precision in 3D geometry, which is extremely expansive. Therefore, additive manufacture (AM) technologies is brought into the electrode manufacture.

Although the AM technologies have become more and more mature in recent years, the applicable materials are majorly based on plastics. Metal printing can possibly be achieved by sintering metal powder with laser or electron beam. However, it is also limited concerning the resulting surface quality, object's porosity, and deformation issue during the manufacturing processes themselves, any of which would cause poor efficiency or a defect of the electrode. For example, selective laser melting (SLM) is one of the most commonly used powder-based AM for sintering high-temperature resistant metal, such as stainless steel. However, extra design of supportive structure is required in case of IEC spherical grid to avoid deformation, which would greatly increase the cost in manufacturing as well as degrade grid's surface quality when removing the supportive structure. On the other hand, powder-based AM usually encounters the issue of porosity and anisotropy stress in the object, which might potentially influence the mechanical strength and electrical properties of the grid. (SLM parameter) Further investigation are required for using SLM technologies as EP electrodes.

Combing wax-printing with casting can potentially solve the problem of precision and remain good surface quality at the same time. The idea is using a stereolithographic process to produce the master mold of the object out of resin as a reference. The mold is placed in a container and then filled with plaster over it. Once the plaster mold becomes solidify, liquid metal is injected into the mold to replace the resin which is melted and drained away. This offers a relatively good surface quality for complex structure without extra supportive structure on object's surface. In addition, this process eliminates the concerns on the electrical conductivity and internal stress which is suitable for the electrode application. However, material selection is limited to metal with low melting point, such as silver or copper alloy. Based on previous investigation, the cathode temperature of gridded IEC remains in low temperature. (< 400 °C for total power less than 100 W). Over-heating of cathode can be eliminated. Therefore, this process is selected in this paper and as for the later cathode manufacture. Concerning about the selectable material, Brass is chosen as the cathode material in this case.

III. Test facility and experimental results

D. Test facility

Test for IEC plasma source is performed in IRS Tank 12 facility, which is a ϕ1 m * 2.75 m vacuum chamber with a three-stages pumping system. The maximum pumping capability is 2400 m^3/hr with N_2 and the ultimate base pressure is 0.05 Pa. The power supply used for the IEC operation is a electron source, which provides up to -20kV with 10 kW maximum power output. Two thermal mass-flow-controllers are installed to provide precise amount of gas supply down to 50 $\mu g/s$ with argon. Two pressure gauges are monitoring the pressure inside IEC and tank. The correlation of pressure and argon flowrate can be found in Figure 4. A three-dimensional closed-loop-controlled platform is implemented in the tank for plasma plume characterization in the future. It could provide two translational and one rotation motion with control precision down to 0.1 mm and 0.5°, respectively.

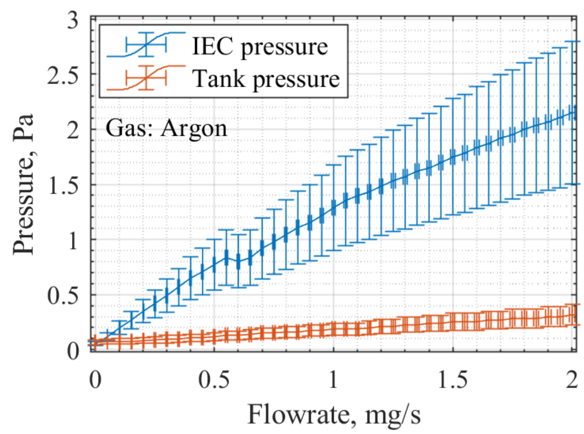

Figure 4. Correlation of argon flowrate to pressure in IEC chamber and in test environment.

E. Investigating conditions

This paper intends to understand the effect of the cathode dimension on the discharge characteristic of an IEC. Three different cathode's dimensions have been investigated, which are listed in the following table. The gate size on each cathode are similar in each dimension provide scaling effect on the EPT. In addition, the role of the extraction port on the discharge behavior is also investigated in the performed test campaign. Two conditions are discussed in this paper: insulated and non-insulated port. This allows the EPT remaining the same but limits the contribution of electron emitted from the surface of extraction port. The extraction port is insulated with Kapton® tape. (see Figure 5) Testes of these cathode conditions are performed in different argon flowrate in order to provide an overview of the correlation between cathode dimension and discharge behavior.

Table 1. Cathode dimension and gate geometry.

Gate	Amount	D_c = 41.70 [mm]	D_c = 53.55 [mm]	D_c = 63.65 [mm]	Unit
(a)	4	0.14	0.15	0.17	
(b)	20	0.15	0.17	0.17	
(c)	8	0.13	0.15	0.15	sr
(d)	12	0.14	0.16	0.16	
(e)	1	0.77	0.79	0.74	

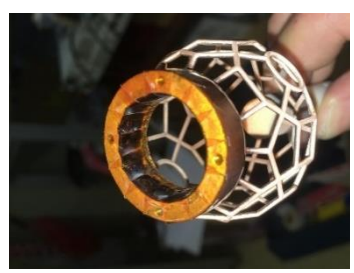

Figure 5. Kapton insulation on the extraction port of cathode.

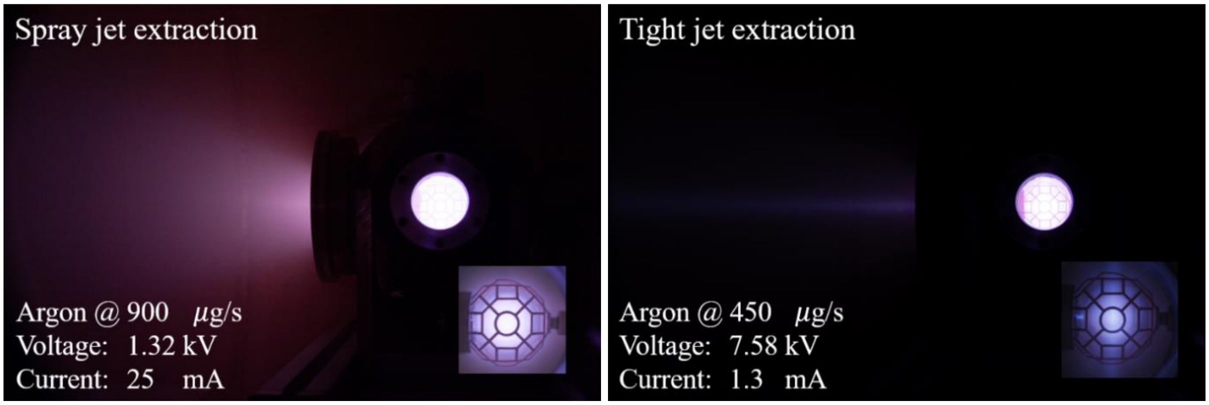

Figure 6. Operation condition of IEC plasma source with spray jet (left) and tight jet (right) extraction from D_c = 41.7 mm.

F. Experimental results

Figure 6 shows the operation condition of IEC plasma source with spray jet and tight jet extraction with Argon supplied using the cathode with D_c = 41.7mm. It can successfully reproduce both extraction conditions observed with the IEC using grid anode design in previous investigations. [2,3,9,10] Moreover, the discharge within the IEC cathode is monitored through the fused silica window on observation port. The improvement of symmetry of the grid pattern indeed reduces the electron leakage through gate from cathode (see no plasma leakage from the gate except from extraction port in srary jet operation as well as the weak spikes only coming out from the upward and downward circular gate in case of tight jet extraction) and provide an even more spherical shape of the plasma ball than the globally coordinated grid pattern in the open-grid IEC. [9] It is a solid proof that the symmetrically gridded pattern improves the confinement of the plasma ball.

Figure 7 summarizes the discharge V-I characteristics and relevant resistances of the IEC plasma source using different cathode dimensions and flowrates of argon. The circular marks represent the condition with insulated extraction port while the cross marks indicate the cases without insulation. The color of the mark defines different argon flowrate supplying to the hollow anode of IEC. Both jet extraction modes, tight jet and spray jet, can be observed from discharge behavior, which shows similar characteristic observed in opened gridded IEC from previous study. [9,10]. Marks of tight jet extraction is located around the high voltage with low current; while marks of spray jet appears with low voltage but high current.

1. Influence on cathode dimension

The difference on the cathode dimension is explicitly shown on the discharge voltage. Smaller cathode grids required higher biased voltage to achieve the same amount of current. In addition, the tight jet is observed with both cathodes with D_c = 41.7 mm and 53.6 mm but not in the largest cathode grid (D_c = 63.7 mm). In addition, the smallest cathode provides a larger operational envelope for the tight jet extraction. Unstable discharges are observed during the transience from tight jet to spray jet for the two smaller cathodes. Accompanied by this discharge behaviour, the plasma ball is continuously switching in between spray jet and tight jet operation (as shown in Figure 6). The discharge becomes stable again when the voltage and current fulfill each mode's criteria. The plasma ball in spray jet extraction is accompanied by a comparably intensively luminating core within the cathode and a discontinuous descrease in resistance curve, which indicates a boosts of electron mobility after the transience. It suggests the enhancement of the plasma discharge on the plasma ball from tight jet to spray jet operation.

2. Influence on flowrate

The difference of flowrate represents different pressures within IEC hollow anode. (see Figure 4) The maximum flowrate in this test campaign is 2.0 mg/s argon. As the flowrate is lower, the discharge voltage increases (and the resistance as well) for all the cathode dimensions no matter the operation is with or without insulated extraction port. A decrease of the flowrate seems to have less effect on the discharge voltage if the largest cathode is used. Once the flowrate (and hence the pressure in the hollow anode) is low enough, the tight jet extraction can be observed in case of D_c = 41.7 mm and D_c = 53.6 mm). This suggests that the reduction of gas flowrate (and hence discharge chamber pressure) would reduce the electron's conductivity. Once the conductivity is lower than a certain limit, a collimated electron beam extraction (tight jet) is observed from the core of IEC.

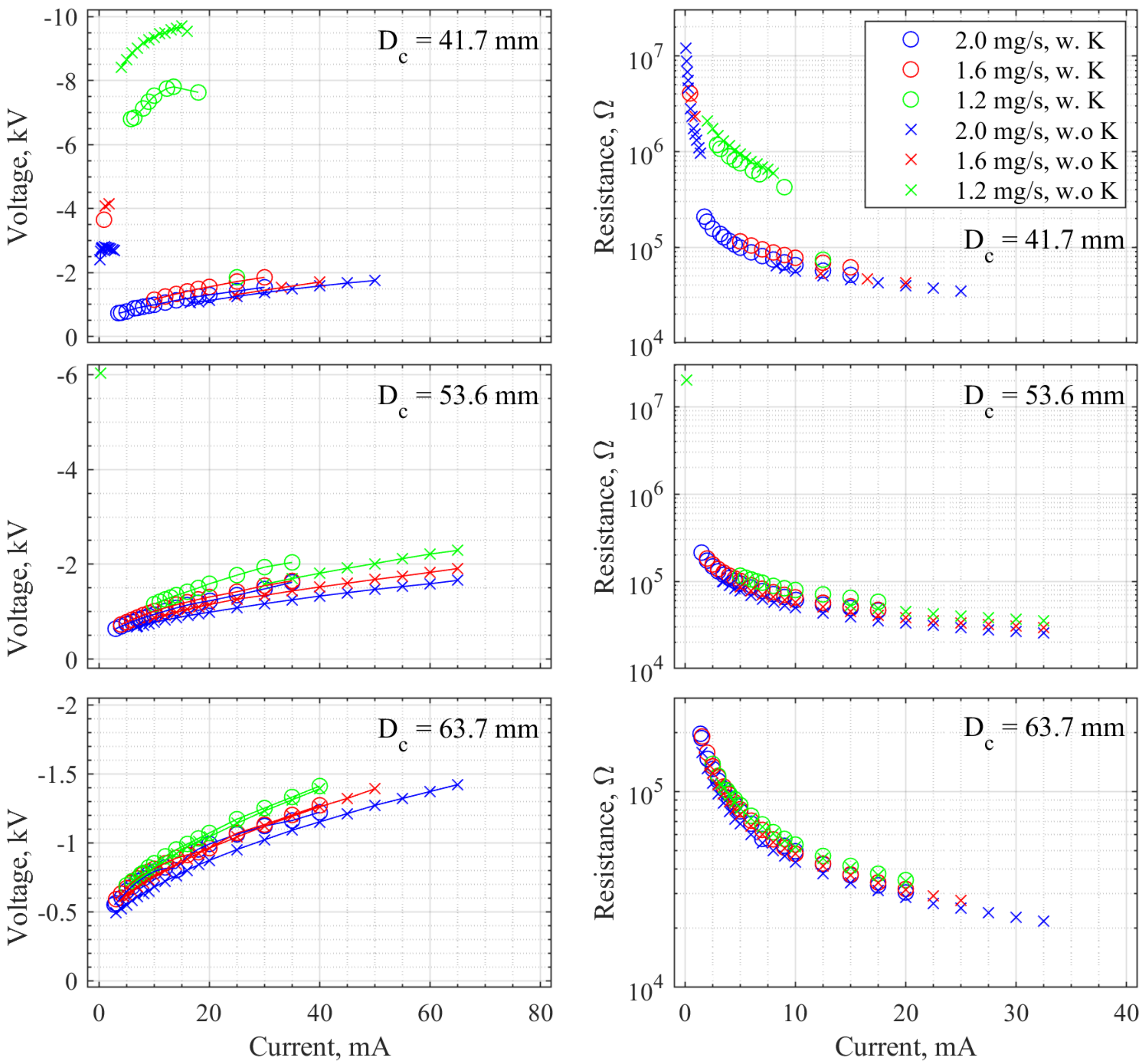

Figure 7. Voltage-to-current correlation (left) and resistance (right) in different cathode geometry and flowrate of argon. Different colors represent the operation with different argon flowrate; while different marks (o and x) indicated the cathode with/without Kapton insulation on the extraction port.

3. Influence on extraction port

The extraction port plays an important role on the observed plasma extraction behaviour. The effect is in the opposite direction referring to tight jet or spray jet extraction. In tight jet extraction (D_c = 41.7 mm), the non-insulated extraction port required a higher voltage to achieve the same current flowing. On the other hand, it requires lower voltage in spray jet extraction in all cathode dimension. In other word, the emitting electron from extraction port surface would hinder discharge with tight jet extraction but it could at the same time enhance the discharge with spray jet extraction. More detail regarding the interaction of plasma ball and discharge characteristic will be discussed in the follow section.

IV. Discussion

G. Evidence of the dominance in IEC discharge

To further clarify the mechanism of plasma ball formation within the IEC cathode, a Paschen breakdown curve is mapped by the ignition condition of the spray jet extraction. The Paschen curve depicts a linear correlation of breakdown voltage to the distance and pressure in between a pair of electrodes. In other words, known breakdown voltage and discharge pressure are able to indicate a linear tendency with a known electrode's distance. Figure 8 shows the comparison of Paschen curve based on the ignition condition of spray mode with respect to the distance between cathode to hollow anode $(D_a - D_c)/2$ and distance between cathode to SDL $(D_c - D_{SDL})/2$. A linear correlation can only be observed in case of $(D_c - D_{SDL})/2$ for both insulated and non-insulated extraction port. This proves that IEC discharge is dominated by SDL instead of physical electrodes, and further supports the fundamental argument of SDL theory in IEC discharge.

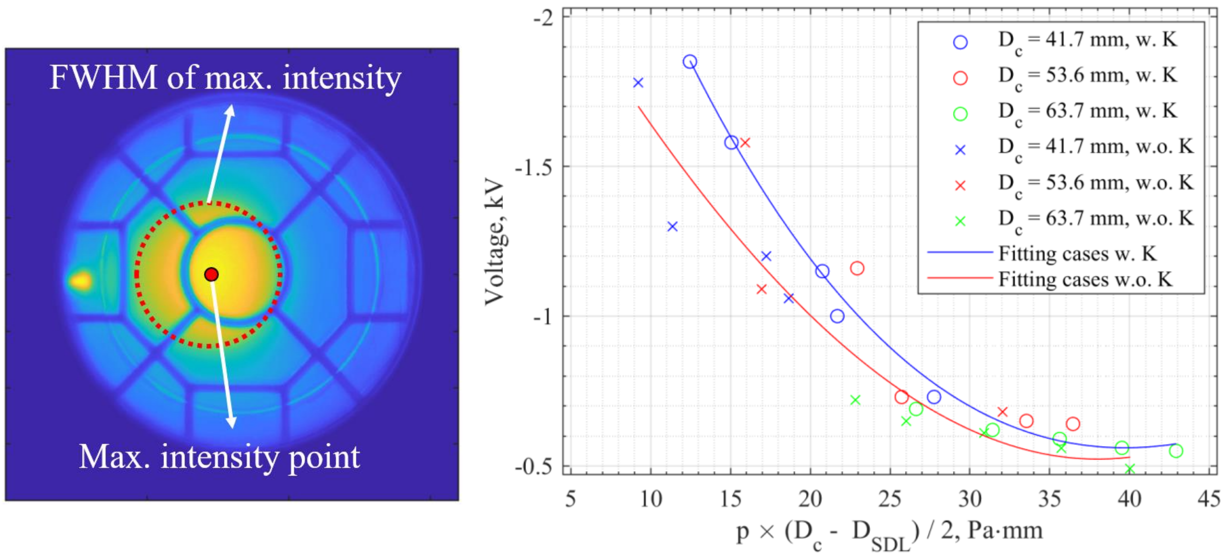

Figure 8. Mapping of Paschaen's law at ignition point IEC unevils the fact of SDL discharge.

H. Correlation between resistance and flowrate

Figure 9 shows the influence of the flowrate on the change of resistance at the same amount of current (30 mA) in spray jet extraction. In general, the smaller dimension of the cathode, the larger the resistance. This is probably due to the larger diameter of the SDL in higher flowrates (see **Error! Reference source not found.**), which then leads to a smaller distance between SDL and cathode grid.

Cases with insulated extraction port have higher resistance than without insulated port for one and the same cathode though it is not much more for the largest of the three cathodes. This supports the argument that the extraction port

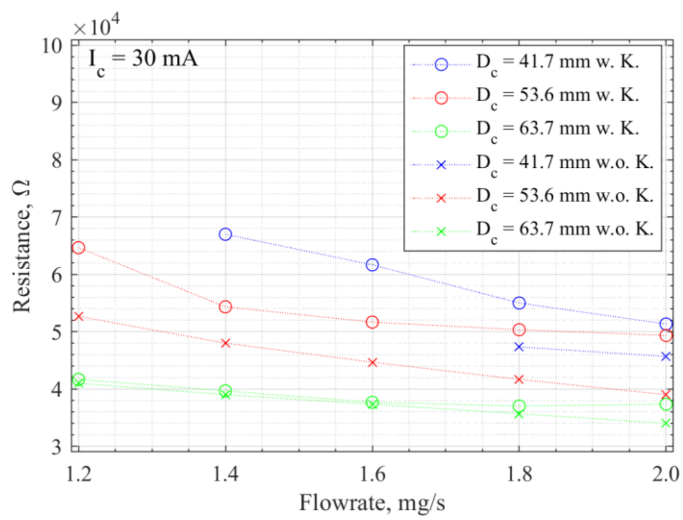

Figure 9. Linear correlation of discharge resistance for different argon flowrates.

could contribute electrons to enhance the discharge efficiency when the discharge pressure gets lower, which is beneficial for the spray jet extraction. In addition, the tendency of resistance change seems to be almost linearly increasing with reduced gas flowrate in cases without insulated extraction port. In cases of insulated extraction port, the resistance curves seem to have an exponential increase when the flowrate is reduced. This suggests that the discharge is more related to the background pressure than the supplying gas flowrate.

V.Conclusion

In the past, IEC development was usually mentioned in the application of fusion. [4] The application and discussion as plasma source was rarely discussed before. In recent years, more and more discussions and practical applications were proposed due to revealing of new discharge theory, which provides more insightful perspective for explaining this particular discharge behavior. [2] Benefitting from its simplicity in design and diversity in application, IEC are emerging to be a promising future plasma source as well as innovative electric propulsion. Several different concepts for space and earth exploration were proposed in 2017, including the IEC thruster (IECT). [2]

IECT is a concept composed by an IEC plasma source as well as an acceleration stage. It is the outcome of several different advanced technologies nowadays, such as super-symmetry cathode design, AM technologies, EM nozzle, and SDL theory. Detail working principle is mentioned in this paper. The discharge behavior for this design is discussed in this paper for the first time, which greatly improved the understanding of this unique plasma source and supports the correctness of the SDL theory.

The discussion of discharge characteristics regarding to argon flowrate variation with different cathode dimensions has been summarized in this paper. The results show a great improvement referring to the plasma ball geometry by a super-symmetry cathode grid pattern arrangement than the previous research.

In addition, electric potential gradients are created by implementing a larger gate as an extraction port, which successfully controls the extraction direction of plasma. This give the evidence that design EPT is important for triggering motion of plasma from the core of IEC and maintain the discharge.

Moreover, the discharge characteristics at ignition point of spray jet proves the IEC discharge is dominated by the SDL and cathode grid instead of the physical electrode enclosed around the cathode. SDL serves as the provider of electric potential gradients as well as a buffer to transform the kinetic energy of electron to the electric potential through ionization processes. The short distance between SDL and cathode provides high electric potential gradience, which serves as the driven mechanism for electron emitting from cathode toward the SDL. To maintain discharge, leakage of electron is necessary to remain in non-charge-neutral characteristics within the SDL.

Further correlation between flowrate and discharge behavior is observed and concluded. The discharge behavior and plasma ball geometry are more related to the background pressure than the effect of flowrate in case with insulated port. On the other hand, unchanged plasma ball dimension and the resistance-to-flowrate correlation in case of non-insulated port suggest the emissive electron from extraction port could also contribute in the ionization processes for spray jet operation.

Further investigations are required to optimize the plasma source, such as influence of gases species on the discharge, scaling of extraction port, impact from the external electric/ magnetic field, and so on. Meanwhile, plasma diagnostics for the understanding the plume characteristic are preparing in the near future. EM nozzle and thrust measurement would be implemented to prove the concept and promote the TRL as a space propulsion device.

Results in this paper not only conclude the discharge characteristics of IEC plasma source, but also solidify its working principle proposed in 2017 IEPC. [11] In addition, the design concept and criteria for this source are partly summarized and discussed. Several upmost advanced technologies are successfully realized in this plasma source. Beyond this, versatile applications based on IEC technologies are getting possible which bring the new era for the next-generation plasma source.

References

[1] Chan, Y.-A., Syring, C., and Herdrich, G., “Development of Inertial Electrostatic Confinement Devices for Space Propulsion in IRS,” *5th Space Propulsion Conference*, SP2016 3125348, Rome, Italy, 2016.

[2] Chan, Y.-A., and Herdrich, G., “Inertial Electrostatic Confinement: Innovation for Electric Propulsion and Plasma Systems,” *35th International Electric Propulsion Conference*, IEPC 2017-599, Atlanta, GA, U.S.A, 2017.

[3] Chan, Y., and Herdrich, G., “Breakthrough of Inertial Electrostatic Confinement Concept for Advanced Space Propulsion Y.-A. Chan,” *69th International Astronautical Congress*, IAC-18,C4,7-C3.5,12,x47993, Bremen, Germany, 2018, pp. 1–5.

[4] Miley, G. H., and Murali, K. S., *Inertial Electrostatic Confinement (IEC) Fusion: Fundamentals and Applications*, Springer, New York, 2014.

[5] Hairapetian, G., and Stenzel, R. L., "Observation of a Stationary, Current-free Double Layer in a Plasma," *Physical Review Letters*, vol. 65, 1990, pp. 175–178.
[6] Raadu, M. A., "The physics of double layers and their role in astrophysics," *Physics Reports*, vol. 178, 1989, pp. 25–97.
[7] Song, B., D'Angelo, N., and Merlino, R. L., "On Anode Spots, Double Layers and Plasma Contactors," *Journal of Physics D: Applied Physics*, vol. 24, 1991, pp. 1789–1795.
[8] Song, B., D'Angelo, N., and Merlino, R., "Stability of a Spherical Double Layer Produced Through Ionization," *Journal of Physics D: Applied Physics*, vol. 25, 1992, p. 5.
[9] Syring, C., and Herdrich, G., "Jet Extraction Modes of Inertial Electrostatic Confinement Devices for Electric Propulsion Applications," *Vacuum*, vol. 136, 2017, pp. 177–183.
[10] Chan, Y.-A., and Herdrich, G., "Jet extraction and characterization in an inertial electrostatic confinement device," *Vacuum*, vol. 167, Sep. 2019, pp. 482–489.
[11] Chan, Y.-A., and Herdrich, G., "Development of SDL Model for IEC Plasma Ball Evaluation," IRS-17-IB08, Institute of Space Systems, University of Stuttgart, Stuttgart, Germany, 2017.