Inertial Electrostatic Confinement: Innovation for Electric Propulsion and Plasma Systems

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Abstract: Inertial electrostatic confinement (IEC) is a fusion concept proposed in the 1950s. However, the detailed ionization and confinement mechanism are still under discussion, which limited the development of IEC. The observation and validation of a spherical double layer (SDL) in the IEC reveals the ionization and plasma confinement mechanism. The extraction of electron beam or plasma, both of which depend on the experimental conditions, are self-sustained. The current work assesses and verifies the IEC-SDL to a maximum possible by a comparison of model results with both respective experimental results, observations and analytical approaches. The implied extraordinary characteristics of this system indicate a wide-spectrum of applications for IECs:

- **Space propulsion from very-low orbit to deep space, e.g. Atmosphere-breathing electric propulsion and fusion propulsion, respectively.**
- **Electron beam/ plasma / neutron / radiation source for multi-disciplinary applications and industries.**
- **Calibration standard for plasma diagnostic methods such as e.g. radiation.**
- **Scientific and basic research on plasma dynamics and non-neutral plasma.**

Nomenclature

ABEP	=	Atmosphere-breathing electric propulsion
DSMC	=	direct simulation Monte Carlo
e	=	electron charge
EB	=	electron beam
EP	=	electric propulsion
EUV	=	extreme ultraviolent
HET	=	Hall effect thruster
IEC	=	inertial electrostatic confinement
IRS	=	Institut für Raumfahrtsysteme
k_B	=	Boltzmann constant
$m_{i,e}$	=	mass of ion/electron
N_n	=	number density of neutral particle
PPT	=	pulsed plasma thruster
r_{SDL}	=	radius of spherical double layer
R	=	resistance across spherical double layer
SDL	=	spherical double layer
SEE	=	secondary emission electron
$T_{n,i,e}$	=	neutral /ion/electron temperature
V_{DL}	=	double layer voltage
V_s	=	free-space electric potential
VDF	=	velocity distribution function
$v_{i,e}$	=	ion/electron velocity
VLEO	=	very low earth orbit
σ	=	collision cross-section area
Δt	=	time difference

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I. Introduction

Electric propulsion (EP) leads the way for deep space exploration due to its very high I_{sp} characteristics. The basic concept is to generate and to accelerate ionized gases by using electrical power. Besides gas-dynamics acceleration like it is typical for chemical propulsion and thermal EP, two other mechanisms are applied in propellant acceleration processes: electrostatic acceleration and electromagnetic acceleration.[1] Both mechanisms provide efficient energy transfer to charged particles. These particles gain kinetic energy in specific direction which allows the spacecraft acquiring momentum efficiently. The advantages for EP is not only more efficient acceleration, but also the comparably reduced propellant mass and applicability for the mission. Since PPT were chosen as one of the first EP system applied in space in 1960s, a bunch of different types of further EP are proposed and validated. Despite of the high efficiency EP has been proposed and applied in space mission, the improvement of thrust to power density is limited, which to some extend results from low particle density in the exhausted plume. Hence, for the development of next-generation EP devices, a plasma confinement mechanism is necessary in order to achieve higher mass specific energy in the plasma plume and an extended life time of the system.

Inertial electrostatic confinement (IEC) is a fusion concept proposed in 1950s, which offers both the plasma generation and confinement at the same time. However, the interests and studies for IEC were focused intensively on the development of neutron sources.[2,3] Other applications were rarely mentioned on scientific publications before the 2000s.

Figure 1 shows the schematic of the spherical IEC concept. Here, the IEC system is composed by a pair of concentric spherical grids, which serve as electrodes: the outer one serves as the anode and the inner as cathode. By applying high voltage between the two grids, the cathode can emit high-energy electrons, which collide with neutral particles within the inter-electrodes region initiating electron impact ionization processes producing both further electrons and, of course ions. The latter are driven by the electric field and accelerated toward the center of IEC. Due to the high transparency on cathode grid, these accelerated ions can pass through the grid gate and reach the other side of inter-electrodes region if no further collision occurs on its trajectory. It flies back and forth within anode grid envelop until collision happened. The oscillating ions encounter the three-dimensional compression effect and form a virtual anode at the center of the IEC, whereas electrons start to move into the virtual anode.[2]

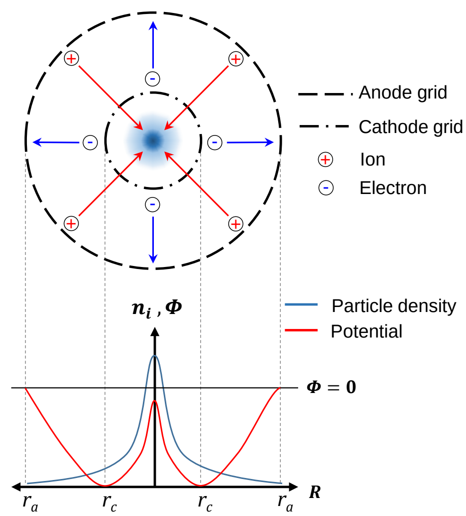


Figure 1. IEC principle

The confinement characteristics of an IEC suggests a great potential to overcome the low-particle-density and energy density issue for nowadays EP devices. Development of IEC for space propulsion purpose was initiated at IRS in 2010. The IRS-IEC is operated in non-fusion condition with a stable and constant plasma extraction. Investigations of electrical properties, discharge phenomena, and loss mechanism were performed both numerically and experimentally.[4–7] The plasma extraction is achieved through an asymmetric cathode, in which the electric potential is distorted and reshapes the distribution of charged particles. Depending on the operational conditions this leads to the two jet modes and the plasma in the core obtains an oval shape instead of a sphere.[4], see also Figure 2.

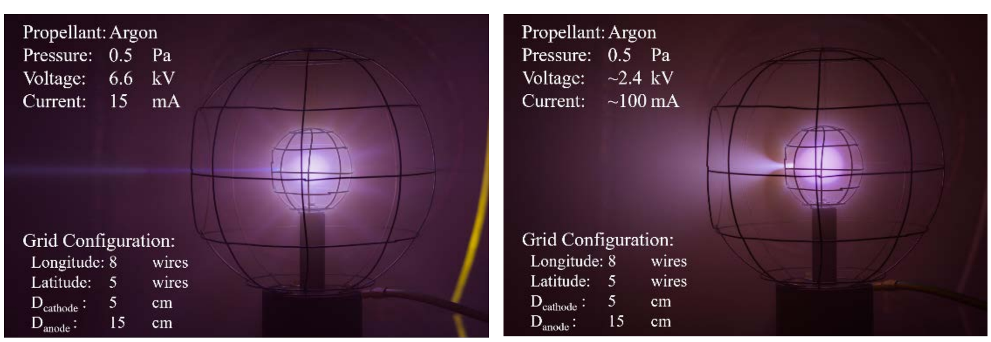


Figure 2. Tight jet (a) and spray jet (b) mode in IRS IEC.

In principle, if particles have enough kinetic energy, they are able to be extracted from the confined core region. As said above extraction of plasma can be classified into two types: tight-jet mode and spray-jet mode, both of which are shown in Figure 2. Concluding from experimental observations, the types strongly depend on the applied voltage, current, geometry of grids, and background pressure.[4] On the other hand, a clear boundary observed on the plasma ball in both conditions suggests the existence of a significant potential gradient, hence a strong particle density gradient on the boundary. From the point of view of the plasma dynamics, this boundary is the result from equilibrium of electrostatic field and gas-dynamic force, in which the electrostatic field is coupled with the potential topography within the cathode grid. However, the detail explanation of plasma confinement and jet extraction mechanism were missing to complete the IEC theory.

To promote IEC as a space propulsion concept, the confinement and plasma extraction mechanism will be revealed in the following sections. An innovative theory of IEC ionization and confinement is introduced. It is verified through theoretical analysis and a verification approach based on experimental observations for the first time (Section II B). In addition, the detailed explanation of jet extraction is also proposed in Section II C. Combining with the jet extraction mechanism as well as the confinement theory[8], several innovative propulsion concepts for next-generation EP systems are proposed, such as atmosphere-breathing EP for very-low orbits as well as fusion propulsion for future manned missions. (Section III and IV) In addition to space propulsion, the application of IEC can be further extended to plasma/neutron/radiation source for industries development and scientific research. (Section IV C)

II.Breakthrough Concepts of IEC

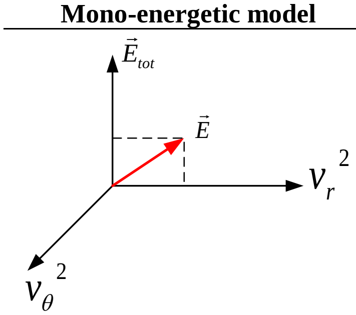
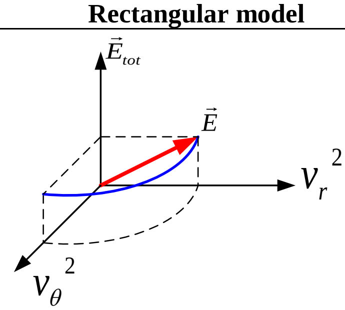
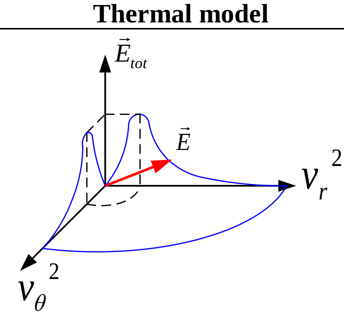
A. Inconsistence between Experiments and Potential Well Theory

In ideal spherical symmetric IEC, the distribution of ions and electrons, theoretically, can be assumed as static, in which the energy provided by the power supply can be transferred into potential energy and thermal energy of the particle. According to the classical IEC confinement hypothesis, the virtual anode could further form a virtual cathode by accelerating electrons inward to the center of IEC and go through a similar formation processes as virtual anode did. [2] Theoretically, a nested potential well shells, known as “Poissors”, can be formed as the applied current further increased, which serves as the confinement mechanism for ions. To verify this concept, several 1D potential models were developed to solve the potential distribution along the radius of a spherical IEC, these models are monoenergetic model, rectangular model, and thermal model.[9]

The models are based on the Poisson equation; the differences here are the description of particle distribution which is the right-hand-side of the Eq.(6) in Ref. 8. The definition is summarized in Table 1. Calculation results of electric potential and particles distribution based on IEC configuration and operation condition in IRS are shown in Figure 3.[10] In these figures, the virtual cathode within IEC core cannot be observed as expected. In addition, the number density for the ions has a relative maximum at the cathode except for the case of the monoenergetic model, in which the ion density has a singularity around IEC center. Despite the thermal model has the most reasonable assumption, the distribution of the particles, in particular the aforementioned ion density maximum, does not match the experimental observations and, hence, with experimental measurements.[9]

The exclusion of particles momentum conservation as well as ionization processes is the reason for the inconsistency because this assumption eliminates that the confinement is resulted from the dynamic effect of the plasma. To further understand the plasma confinement, equilibrium of momentum is needed to be considered as well.

Table 1 Assumptions for kinetic energy of particle for Poisson solver

Mono-energetic model	Rectangular model	Thermal model
		

B. Reveal of Ionization and Confinement Mechanism: Spherical Double Layer

The formation of virtual anode at center of IEC is verified and observed in a lot of researches.[2,11–13] The appearance of virtual anode indicates the existence of non-neutral plasma inside IEC cathode grid. This virtual anode drives electrons by its potential gradient. When the local potential gradient is high enough, the spherical double layer (SDL) can form.

SDL, also known as fireball, is widely observed when a positively biased small electrode is inserted in plasma where an ambipolar field is created and electrons are driven by the electric potential to the biased electrode. When the biased voltage of the inserted electrode is higher than the ionization energy of the background gas, a further electron impact ionization process is initiated within the sheath. Ions are created in sheath with approximately same thermal velocity as background gas ($v_i \approx \sqrt{2k_BT_n/m_i}$) and confined by the center-pointing electron wind which has high drifting velocity ($v_e \approx \sqrt{2eV_{DL}/m_e}$). The momentum of incoming electron flux and outgoing ion flux can reach equilibrium forming a distinct boundary of plasma. This boundary is called double layer.[14–19]

Based on Raadu[18], ions or electrons require high enough kinetic energy to penetrate the double layer, which is unlikely in the case of non-drifting neutrals or ions. In other words, a double layer can serve as confinement mechanism for plasma. This confinement effect of SDL has been proved by Barkan and Merlino by inserting charged dust particles into the SDL.[20] Theoretically, the ionization and confinement mechanism of the SDL can provide a high degree of ionization within the fireball.

To verify both IEC confinement and ionization, a SDL model is introduced. The schematic of an IEC-SDL is shown in Figure 4. Ions are generated and confined within DL sheath due to their respectively low thermal velocity, while electrons are driven toward the SDL by its potential difference. Hence, based on the SDL concept, ion production can be simply related to electron impact ionization on double layer. Introducing Langmuir condition, a simple equation expresses the correlation of SDL radius, r_{SDL}, can be written in Eq.(1):[15]

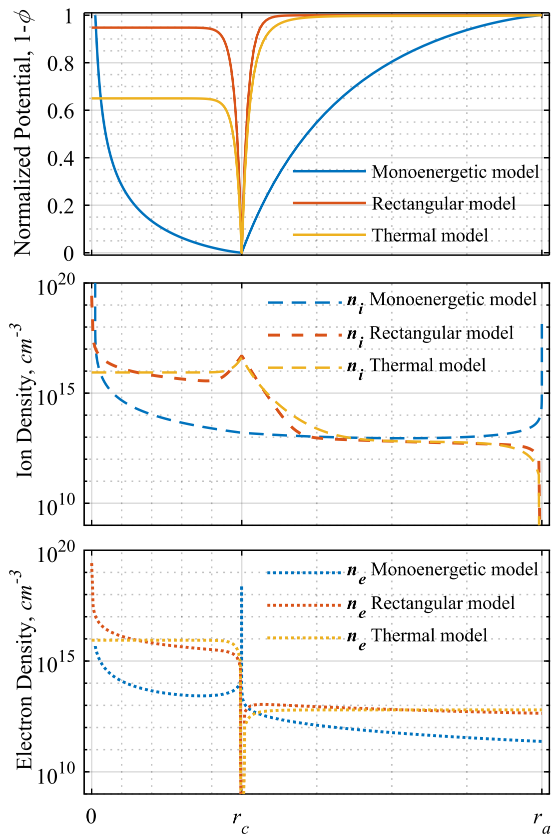


Figure 3. Calculation result from Poisson's solver

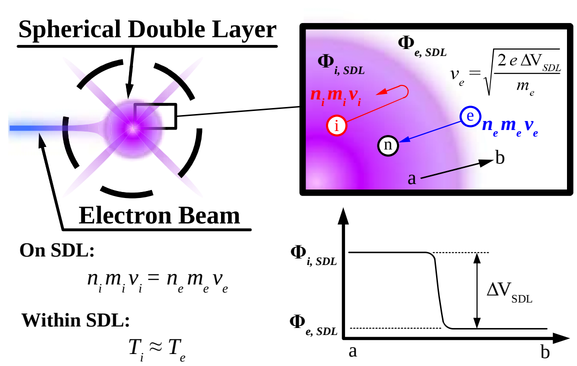


Figure 4. Schematic of SDL model

$$\sigma(V_{DL})N_n r_{SDL}\sqrt{\frac{m_i}{m_e}} = 1$$

Here, $\sigma(V_{DL})$ and N_n are ionization cross-section of gas and neutral particle density, respectively. The parameters m_e and m_i are the mass of electrons and ions respectively. The radius of SDL can be estimated given that the ionization cross-section is known. In addition, the voltage across SDL can be further derived through Ohm's law and the conservation of current flux which is proposed in Ref. 15 The radius of SDL can be written in the following form

$$r_{SDL} = \sqrt{\frac{(V_s - V_{DL})}{\beta\ R\ N_n}}$$

where V_s represents free-space potential around the SDL and β is a semi-experimental parameter proposed by Song[15].

The resistance of SDL R and the double layer voltage V_{DL} can be calculated from Ohm's law based on the extracted jet current, which is measured by a Faraday probe.[8] By solving these two equations numerically, the double layer radius (r_{DL}) and voltage (V_{DL}) can be determined. Figure 5 indicates the SDL dimension against the jet current at free-space potential 2 kV and background pressure 0.5 Pa for first charge state of Argon.[21] The dimension of the SDL is slightly smaller than the experimentally observed radius. The possible reasons might be the exclusion of high charge ions as well as of the gas-dynamics effect. In addition, the variation from jet current measurement and evaluation of plasma ball dimension might also cause some deviations from the calculation result. Moreover, the derivation of the geometry from the photographs may suffer from certain plasma related information discrepancies. The detailed calculation method can be found in Ref. 21.

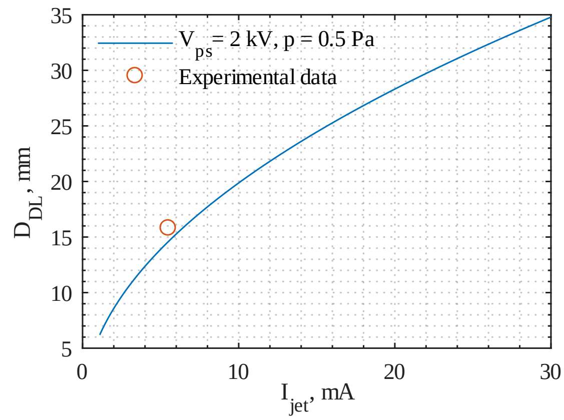


Figure 5. Calculation results of SDL model for IRS IEC concept

Observation from experiment also supports and explains the dominance of ionization on SDL. Experimental history shows a spontaneously current jump from power supply as soon as plasma jet formed. This instant conductivity change in the IEC circuit suggests the main current flow through IEC core instead of inter-electrode region. [21] In other words, the generation of plasma is then dominated at intra-cathode region instead of inter-electrode region, which leads to a further affirmation that IEC can produce high plasma density inside the SDL

Due to the unique IEC-SDL characteristics, as Figure 4 shows, ions are generated by electron impact within the SDL, which allows an efficient energy transfer from electrons to the potential energy through ionization of neutral particles. After non-elastic collision processes, the impacting electrons lose kinetic energy and stay at the similar low thermal temperature as secondary electron. While ions keep at the same thermal temperature as the neutral particle at the beginning of ionization and reach to thermal equilibrium with electrons within SDL confinement.

In general, the SDL model offers a more reasonable assessment of an IEC configuration by solving momentum conservation equation and ionization of plasma. The results show a much better and reasonable correspondence with the experimental data and observations than the potential and density histories from the Poisson's solver. In addition, the change of the main current path suggests that the SDL dominates the ionization processes of a spherical IEC operated in a jet mode. These indications provide very strong evidence for the existence of an SDL in the IEC numerically, affirmed by the currently available and relevant experiments. The SDL offers both efficient ionization and confinement of plasma. Correspondingly, an efficient plasma source for a broad application is provided by IECs. Furthermore, IEC can be designed and estimated in a scaling law based on this model, which facilitates the development of IEC as a next-generation plasma source.

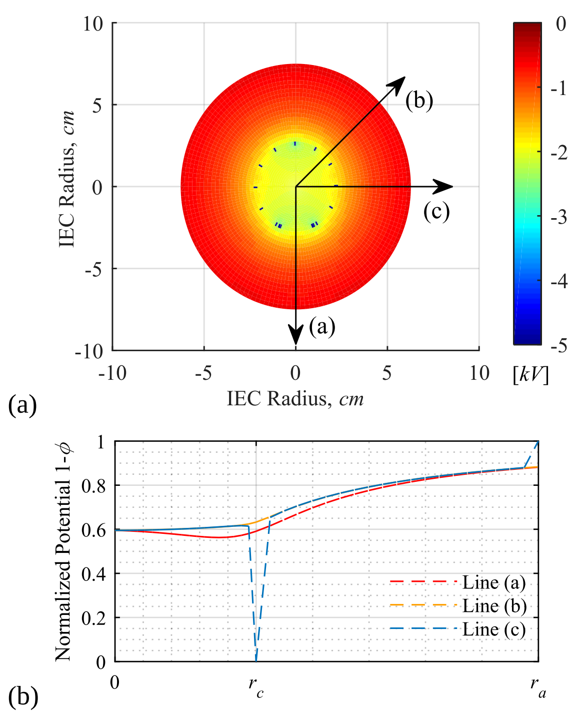


Figure 6. Free-space potential of a 3D grid IEC with -5 kV bias at inner cathode grid

C. Plasma Extraction Mechanism from IEC-SDL

With the distortion of electrostatic field topography inside the SDL, the plasma can be extracted. To understand electric potential gradience within a grid IEC system, a 3D free-space potential solver was developed at IRS based on the work from Ref. 22. According to Figure 6, the free-space potential topography at the design opening has smaller potential than other gates, which enable the distortion of the plasma ball.[23] This distortion can, before some point, still confine plasma by incoming electron wind. The electrons can be extracted from the tip of distorted DL confinement, where the contribution of momentum from incoming electron wind is the weakest, as Figure 6 illustrates. Plasma extraction is initiated when the pressure of electrons and ions within SDL reach to a critical value, where momentum imbalance occurs. Particles are then able to escape from the SDL confinement. The behavior of ions and electrons after extraction is respectively different.

Electrons are able to escape from the confinement through this extraction point when the thermal kinetic energy is larger than the incoming electron wind momentum, which serves as an energy filter for electron extraction. The extracted electrons can be further accelerated by the electric field forming by the biased voltage between inner cathode and outer anode. Hence, the extracted electron beam (EB) has low thermal energy but high kinetic energy, which offers a collimated non-thermalized EB.

The supply of the collimated EB from the IEC, known as tight-jet mode, is experimentally confirmed from recent measurements.[8] The extracted EB has an extremely confined contour with distinct shape edge from background environment. A diagnostic method combining Faraday probe measurement and secondary emission electron (SEE) model has been applied for the characterization of tight-jet properties, which is published in Ref. 8. The results indicate that the beam consists of high energy electrons which have energies of about several keV, depending on the applied voltage on cathode grid. The power transmission efficiencies are above 55% according to the measurements.[8]

As it is the case for the electron extraction, the ions' extraction also results from the momentum imbalance between incoming electron wind and gas-dynamic pressure forming within the SDL. As the images from the high speed camera show in Figure 8, the double layer at this point collapses and soon reforms a radical confinement around the extraction channel, which provides the same mechanism as a DL and limits the expansion of ions in radial direction. This confinement at the throat of the plasma channel can be seen as a virtual nozzle. Based on nozzle theory, the extracted plasma plume can reach to plasma sonic speed at the throat.

As the ion plume moves downstream, the particles getting diffused due to less confinement in radical direction. The ions with enough kinetic energy in axial direction can escape from IEC opening; while the others are driven back by the electric field of the IEC electrodes. Though diffused, the plasma plume has a high degree of ionization due to the confinement effect in the SDL. With an adequately designed magnetic field at the extraction port, the plasma plume can be further collimated and be accelerated. Preliminary measurements suggest that the spray jet consists of both electrons and ions. The characterization of the spray jet is still ongoing at IRS.

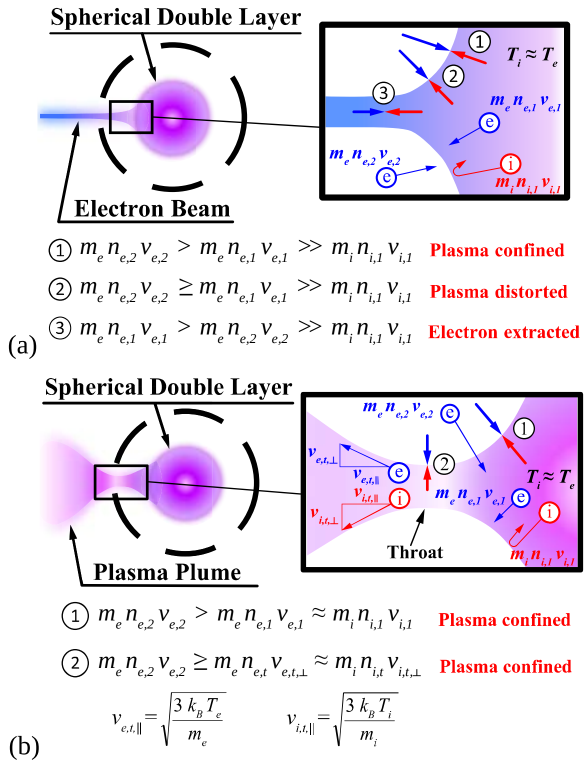


Figure 7. Schematic of electron extraction (a) and ion extraction (b)

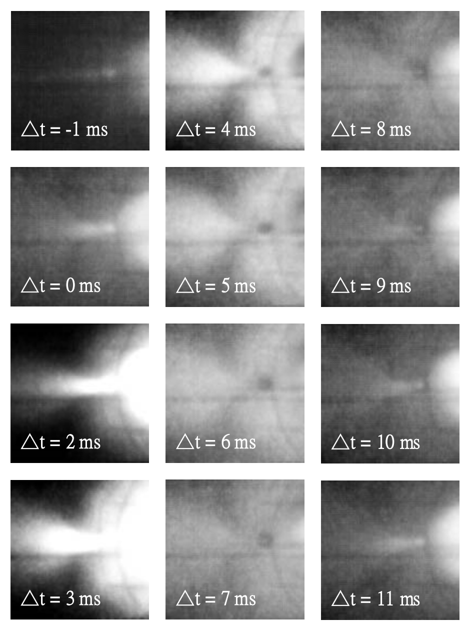


Figure 8. Transition from tight jet to spray jet

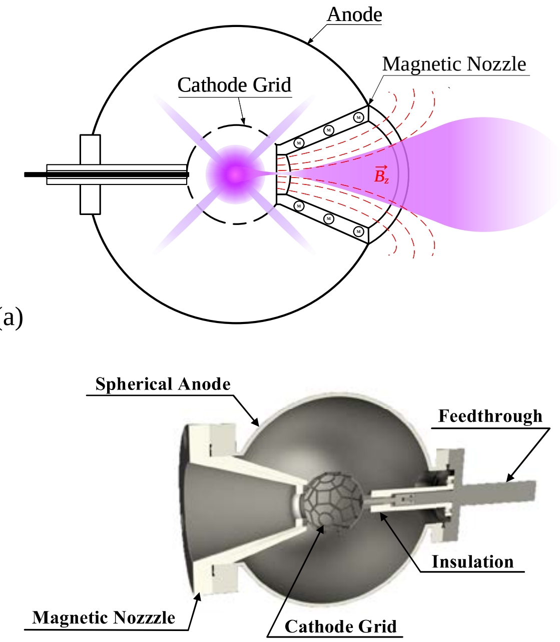
III. IEC Thruster Concept

As mentioned in the last section, IEC has the advantages to provide dual functions as an electron source and an ion source leading to a variety of potential applications. The unique ionization and confinement mechanism from SDL allows IEC to reach a high degree of ionization as well as high plasma density. The SDL also plays a role in the plasma extraction mechanism. Electrons and ions can be extracted and accelerated by passing through a thermal energy filter or virtual nozzle, respectively. These promising characteristics suggest the great potential for IEC as a future space propulsion device. The calculation and experiment results indicate that IEC spray jet has great potential to be a high-density ion source for space propulsion. Nevertheless, the tight-jet mode also has promising prospective for next generation EP. With the SDL model, the scaling law of SDL can be estimated simply and straightforward which promotes the feasibility for IEC commercialized.

A. IEC Ion Thruster Concept

For the spray jet, the extraction of ion plume results from the imbalance of momentum between incoming electron and confined plasma within SDL as mentioned in subsection II B. As a benefit from the DL confinement, the plasma plume can be accelerated by the virtual nozzle and reach to speed of sound at the throat without inducing thermal problems and erosion issues. After the throat, the plasma plume can be accelerated to high speed by further applying a magnetic nozzle.

Figure 9 (a) shows the concept of IEC ion thruster. Borrowing from the advantage of SDL, IEC not only can provide high plasma density as well as ionization degree, it also has the characteristics to mitigate the erosion problem due to the SDL confinement. Figure 9(b) shows the 3D mechanical drawing for IEC thruster based on two concepts mentioned above. Both concepts are composed by a ceramic cone with applied magnetic field, a spherical anode, the inner cathode grid, and the cathode feedthrough for the propellant and DC power. The ceramic cone and the spherical anode create an enclosed space which makes the pressure regulation within IEC easier and increases the propellant utilization efficiency. On the other hand, the magnetic field for the plasma plume confinement and acceleration can be implemented at the ceramic cone for both tight-jet and spray-jet operation. The cathode grid is designed with a complex grid pattern in order to achieve the high transparency, symmetry distribution of electric potential, and clear port for non-invasive diagnostics. The grid is not able to be manufactured by traditional mechanical machining, accordingly, generative manufacturing technology is needed. The cathode feedthrough requires specific interface design and insulation for high voltage operation.



(a)

(b)

Figure 9. Basic concept of IEC ion thruster (a) and 3D drawing (b)

B. IEC Cathode Concept: IEC-HET as an example

Electron impact ionization is widely used in EP, e.g. Hall effect thruster (HET), which equipped hollow cathode as electron source and, hence, neutralizer.[1,24] Although well developed, hollow cathodes provide thermalized electrons which have wide velocity distribution functions (VDF).[25–27] On the one hand, the energy of the thermalized electron bulk increases the difficulty for the design of electron guidance and traps. The magnetic field topography for guiding these electrons interweaves with the accelerating processes of the secondary electrons and ions making the design of magnetic field more complex and challenging. On the other hand, the kinetic energy of bulk electrons is not efficiently transferred in ionization processes considering no further effect involved, which is about 1/3 of total kinetic energy. In this concern, a collimated non-thermalized EB provided by an IEC electron source shows its superiority for ionization processes.

The collimated non-thermalized EB has lower thermal velocity but collimated drift direction, which enable a simpler design of magnetic field topography for electron guidance and control. The requirement of magnetic field intensity is lower when the EB has higher drifting velocity and specific drifting direction. The acceleration of secondary electrons and ions can be decoupled from the ionization processes.

The basic concept of IEC cathodes is originated from the tight jet as shown in Figure 10 (a). The expansion of EB can be achieved through the EB condensed optics.[28,29] With proper design of electron guidance and trap, ions can be generated at specific position and at controllable charge state. Figure 10 (b), shows an example for IEC- HET concept. The High energy EB (HEEB) after expansion can be driven through divergence magnetic field. Due to the characteristics of HEEB, the required magnetic field strength is small to control the trajectory of HEEB. The HEEB trajectory is redirected from axial direction to toroidal direction with small axial velocity by traveling through magnetic field contour. With proper design of the field strength and topography, the HEEB can be trapped at desired position of HET and lose kinetic energy by continuous electron impact ionization. In addition, HEEB has a more flexible operation range on background pressure and power. The ionization rate and ion charge state are linearly dependent with collision frequency and electron drift kinetic energy, which make HET more flexible on mission application. The plasma generated in the ionization zone is quasi-neutral and is driven toward downstream by potential bias. Whether it is necessary to have a neutralizer is still needed is to be checked in future investigations.

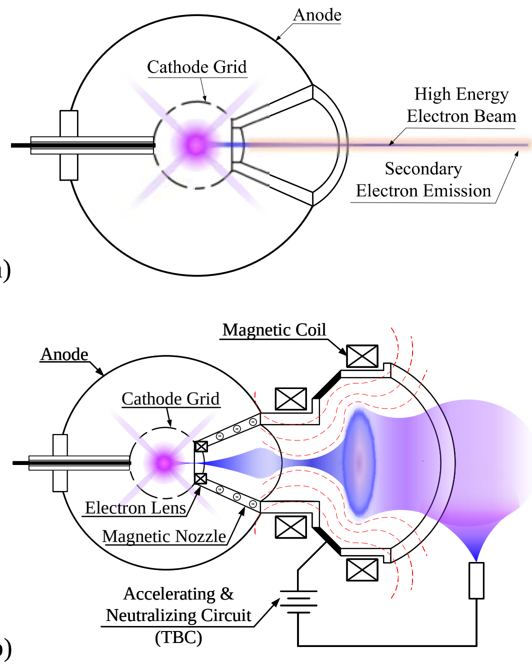


Figure 10. Basic concept of IEC cathode (a) and IEC-HET concept (b)

IV. Potential Application

IEC-SDL plasma source has a wide operation range in power and background pressure which not only provide the promising application as space propulsion in space, but also enables the possibility for lower orbit and deep space explorations.

A. Atmosphere-breathing Electric Propulsion

Atmosphere-breathing EP (ABEP) is a concept for providing thrust by collecting the residual atmosphere at low altitude orbits for EP as propellant in order to eliminate the requirement for carrying propellant and utility. The concept is aimed at offering a self-sustainable solution for satellite to stay in orbit. A proper design of air-intake and high efficiency of both intake and EP are the main issues for the successfulness of the development.[30] Unlike conventional aircraft, the particle density is extremely low at VLEO which increases the difficulty for intake design. Most of the intake concepts are based on passive drive of the inflow.[31] To further increase the particle collection efficiency, an active concept is necessary.

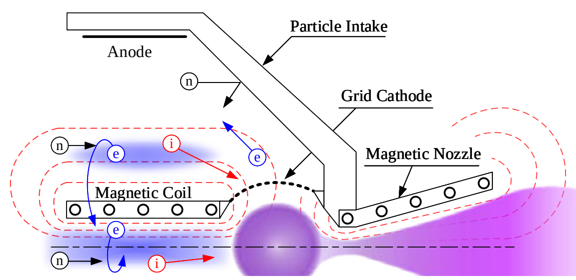


Figure 11. IEC concept for ABEP

IEC is an extremely suitable concept for collecting inflow particles due to its system simplicity, compact design, and low system weight. Based on DSMC[30], the pressure created at the end of the intake can reach between 0.03 – 0.45 Pa, depending on the intake design, for a satellite at 120 km in Earth and Mars orbits, respectively. The pressure range is located within the IEC operation region, which further supports the applicability of IEC as an ABEP system. The concept schematic is depicted in Figure 11. Electrons emitted from cathode grid can be firstly trapped into the magnetic field. Before collision happens, electrons continuously circulate within this magnetic field loop and form an electron cloud. Neutral particles can be ionized by electron impact ionization as they pass by this electron trap. While the other neutrals, that do not collide with electrons, can be reflected to the grid or to the trapped electrons by the intake wall. Ions and neutral particles are driven toward the cathode grid to create locally higher density of particles, as well, as a virtual anode. With the same concept as the IEC ion thruster, plasma in the core can be further accelerated to create thrust.

The advantage for IEC-ABEP is the combination of active particle collection, as well as the acceleration processes. Compared to other ABEP intake designs, it offers a larger collection area without losing too much kinetic energy of the incoming particles, which enables a promising collection efficiency. In addition, particles can be further accelerated by the same mechanism as in the IEC ion thruster.

B. Conceptual Approach for Fusion EP

The major advantage of fusion EP is the high power-to-weight ratio which is mandatory for interplanetary traveling and manned space mission in the future. Extra energy can be accessed by fusion reaction to increase exhausted velocity of plume. The majority of fusion propulsion concepts are nuclear thermal propulsion, among which the magnetic confinement, e.g. Tokamak, is under consideration.[32] The propellant can be either provided by the additional working gas or the fusion "ash".[33] Despite of that, the plasma dynamic effect is extremely complex which not only increases the difficulty for thruster design and validation, but also raises the barrier in spacecraft implementation. Furthermore, the system mass to achieve plasma confinement and control would increase exponentially, which makes the application for magnetic fusion propulsion concept become less attractive.

Unlike magnetic confinement device, the propulsion concept based on IEC fusion have superiority in simplicity, thrust-to-weight ratio, and system mass.[34] The application of IEC for fusion has been proposed since 1980s. The concept of IEC fusion thruster has been mentioned in some of research works. [35–38] However, the detailed design and validation is comparably low in maturity.

With the discovery of SDL and jet extraction mechanism, the feasibility of IEC fusion propulsion becomes more possible. The ions generated at inter-electrode region can be driven to high velocity while ion generated on SDL have low kinetic energy and are confined in local space within intra-electrode region. Intensive fusion activity on SDL can be expected. Fusion products and generated energy can be confined in SDL and provide thermalization effect of local plasma. With same extraction mechanism, the fusion energy can effective transfer to the kinetic energy of exhausted plasma. Theoretically, the IEC thruster can be directly upgraded to fusion mode without changing design.

C. Scientific purposes: Electron beam (EB) source, X-ray/EUV source

The application of IEC devices was extended to different fields such as X-ray generator and neutron source, which serves for the purpose in medical diagnosis and detection.[2] With understanding of SDL and extraction mechanism, the application as an electron source as well as plasma source is confirmed, which further expands the potential in the scientific and engineering applications. e.g. EB fluorescence for plasma diagnostics[39] and material surface treatment. The existence of both virtual anode and nozzle eliminates the contamination of plasma and offers the maximum flexibility for different gases application. Furthermore, the unique characteristics on plasma generation can further extended to be a radiation source for calibration and scientific research. The development of SDL theory can further promote the understanding of plasma-dynamics in RF plasma source and non-neutral plasma. [40–45] All-in-all, IEC-SDL concept brings endless possibilities and the revolution of plasma source.

V. Summary

The discovery of SDL and the extraction mechanism in IEC device indicates characteristics in ionization and plasma confinement which can lead to an advanced perspective for EP development. Besides, the validation of IEC-SDL theory further promotes additional applications in several advanced propulsion concepts, such as ABEP and fusion thruster, which enables IEC in all-spectrum space exploration. Moreover, the promising applications such as electron/plasma source, radiation source, and neutron source illustrates the potential of IEC in scientific and engineering development. This core technology will bring a significant innovation ("revolution"), not only on Earth but also in space.

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