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Breakthrough of Inertial Electrostatic Confinement Concept for Advanced Space Propulsion

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Abstract

The activities of Inertial electrostatic confinement (IEC) research for propulsion application in IRS started from 2009. A breakthrough on the theoretical explanation of working principle in 2017 IEPC enabled the proof-of-concept of IEC thruster for next generation space exploration. [1] Several advanced IEC propulsion concepts have been proposed accompanying with the working principle which demonstrated a wide-spectrum application from atmosphere-breathing electric propulsion for very-low-earth orbit to fusion propulsion for deep-space manned mission. The SDL can offer both intensive ionization and confinement of ions at the same time which provide the advantage to suppress erosion from ion bombardment. Furthermore, distortion of the SDL by manipulating the applied electric field gradient are the key to achieve plasma extraction from core of IEC. This permits the applications of IEC device goes from neutron generation to electron/ion source, which opens the door to space propulsion.
Keywords: (maximum 6 keywords)

Nomenclature

m	–	Mass
n		particle density
T	–	Temperature
v	–	Velocity

Acronyms/Abbreviations

ABEP	Atmosphere-breathing electric propulsion
EB	Electron beam
EP	Electric propulsion
ERG	Electron retarding grid
ESG	Electron suppress grid
FG	Floating grid
FP	Faraday probe
FT	Feedthrough
GEO	Geostationary earth orbit
HET	Hall effect thruster
HV	High voltage
IEC	Inertial electric confinement
IEPC	International electric propulsion conference
IRG	Ion retarding grid
IRS	Institute of Space Systems
JPL	Joint propulsion lab
LEO	low earth orbit
LIF	Laser induced fluorescence
LP	Langmuir probe
NIR-	Near-infarad
OES	Optical emission spectroscopy
PPT	Pulsed plasma thruster
TDLAS	Tunable diode laser absorption spectroscopy
TRL	Technical readiness level
SDL	Spherical double layer
SIE	Secondary ion emission
SSE	Secondary electron emission
UV	Ultra-violet
VELARC	Very-low-power arcjet
VLEO	Very low earth orbit

1. Introduction

Inertial electrostatic confinement (IEC) is a device which was originally designed for fusion application. The basic concept is to heat up and to confine plasma by strong electric fields in order to achieve fusion reaction in the core of IEC. Research on IEC is being performed since the 1950's, but only limited in the studies for neutron source application, mainly exists in USA [2], [3] and Japan [4], [5]. Other applications of IEC are seldom mentioned.

From 2009, Institute of Space System (IRS) started a project with the purpose to understand the jet extraction from IEC devices as well as to evaluate the applicability for space propulsion systems. The idea behind it is to establish a stable and constant plasma extraction from the plasma core in order to provide thrust force. Several researches discussed about the operation modes and plasma extraction have been published. [6], [7] In addition, a model for estimation of plasma composition and loss mechanism basic on Maxwellian assumption were developed, which served as the preliminary understanding of IEC plasma composition. [] In addition, a numerical model based on Direct Simulate Monte-Carlo method and Particle-In-Cell method was applied in the research of IEC under support from ESA Ariadna study. [8] Summary of activities before 2016 can be found in Ref. [6]

In this paper, the author intends to provide a summary of breakthrough of IEC development and scientific investigation in IRS from 2016. In addition, several propulsion concept and their application based on IEC technologies was categorized in this paper as well. More detail can be found in the following subsection.

1.1. IEC principle

The simplified scheme and working principle of IEC are shown in Fig. 1. The setup consists of two spherical grid-like electrodes, both of which were concentrically aligned. The outer electrode served as the anode while the inner one being the cathode. The setup is placed in vacuum with a controlled particle density environment (background pressure). Having a strong electric potential gradience between the both grids, a spherical, center-pointing *E*-field topography is generated. Electrons driven by field emission on cathode fly toward anode and cause the electron impact ionization with neutral particles, which provides the production of ions between two spherical grids. Ions get accelerated toward the cathode while electrons are kept directing to the outer grid with the respective electric potential energy they experienced at position they collide. The chance of ion-grid collision is respectively low due to grid-like configuration of cathode which offer high transparency for ions. Most of the inward driven ions can travel through the grid gate and fly toward to opposite side of IEC with their inertia if no further collision happened on their path. When these ions reach to the equal-potential position, they are push inward again by the *E*-field. This keep ions flying back and forth until their kinetic energy are dissipated by another collision processes. If the kinetic energy of ion is sufficient, fusion relevant processes might occur in either ion-ion or ion-neutral collision within IEC device. These oscillating ions increase the probability of ions appearance at the center of IEC which accumulates the electrical potential and

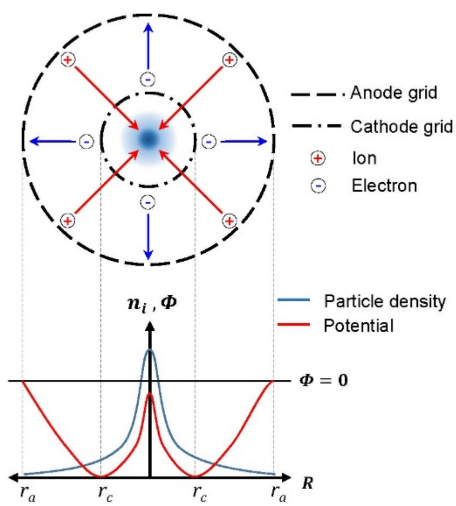

Fig. 1 Concept schematic of IEC [9]

forms a non-neutral plasma floating within cathode grid, as known as virtual anode.

Four different modes have been identified from several research, naming the spot mode, star mode, tight-jet mode, and spray-jet mode, respectively, see Fig. 2.[6] The spot mode can be considered as the formation of potential well by recirculating ions within IEC, while star mode is likely to be the combination of potential well and ions/electrons leakage from core. The other two mode are tight-jet mode Fig. 2 (c)) and the spray-jet mode (see Fig. 2(d)), respective. These two modes are resulted from distortion of *E*-field topography by enlarging one of the grid gates on a spherical-symmetric cathode grid configuration. Plasma experience the change of E-field and attempt to escape from the weakest point of the field. Considering the application for space propulsion, these are the most preferable two modes. The pictures for these two operation conditions in IRS-IEC are showing in Fig. 4.

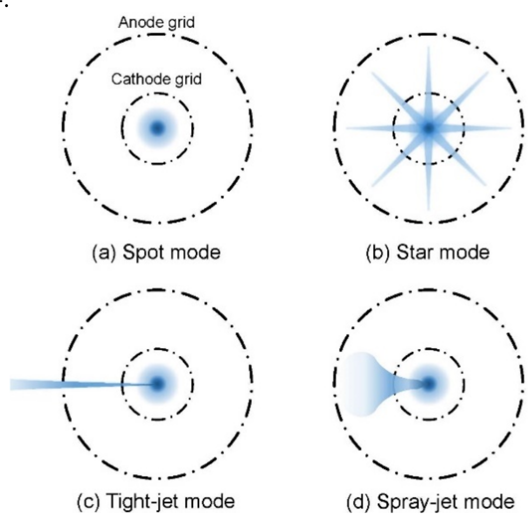

Fig. 2 Operation modes in IEC [6]

1.1.1. Conventional concept and confliction

Conventional IEC confinement hypothesis indicates the virtual anode could further form an inner virtual cathode by trapping electrons at center of IEC via a similar formation processes as virtual anode did. [2] Accordingly a nested potential well shells, known as "Poissors", can be formed as the applied current further increased. The electron's Poissor shell and ion's Poissor shell serves as the confinement mechanism for each other due to its potential well gradience. This hypothesis has been tried to verify since 1990s but never been experimental confirmed. On the other hand, several 1D potential models were developed to solve the potential distribution along the radius of a spherical IEC in order the verified the concept. However, none of it can perform the expected Poissor's structure without impractical assumptions. [10] In addition, the estimated plasma ball dimension is the same size as the cathode gird, which is

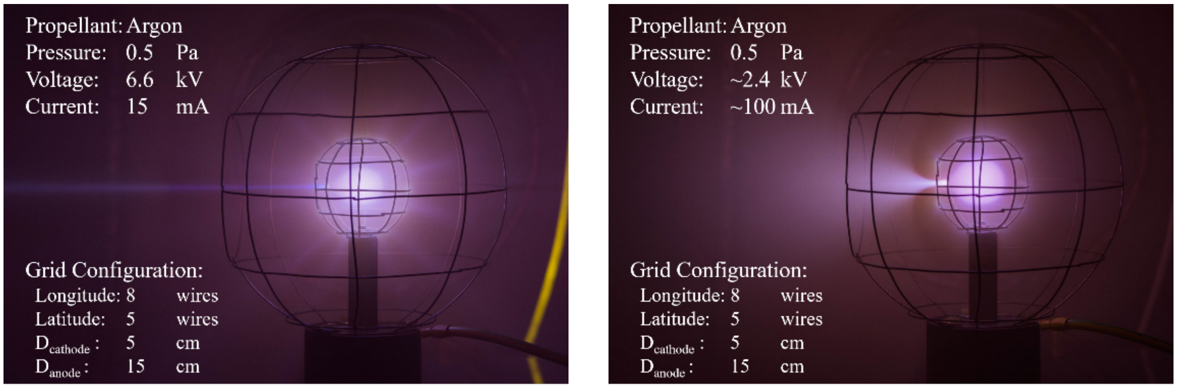

Fig. 4 Tight jet (left) and spray jet (right) mode in IRS IEC [1]

far from experimental observation. On the other hand, the conventional hypothesis can not explain the plasma extraction mechanism of from the core of IEC. This leads the concerns on the accuracy of the hypothesis.

1.1.2. Spherical double-layer theory

The problem of the conventional hypothesis is the ignorance of the momentum balance of particles, which is a dominated factor for the distribution and extraction of charge particles within IEC. To establish the momentum balance on ions and electron cloud in a non-neutral plasma, double layer theory is needed.

Double layer is widely observed in most of plasma condition, which is a boundary representing a dynamic equilibrium of non-neutral plasma. The electric potential gradience between both side of double layer is usually slightly above the ionization energy of gas. The potential gradience creates an ambipolar field where electrons and ions are driven toward the thin layer and reach a momentum balance. This strong potential gradience provide the electron with respectively high kinetic energy which initiates electron impact ionization on the layer.[11] The produced ion is mostly trapped in the high potential side because they have low kinetic energy compared to electrons before they were ionized. [11][12]

The SDL model was developed in IRS in 2017 which is implemented with double layer theory for estimating

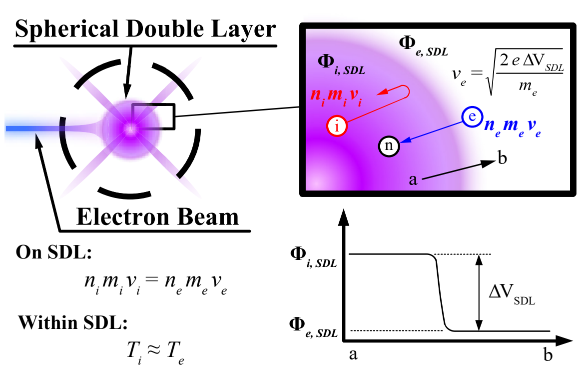

Fig. 3. Schematic of SDL model

plasma ball dimension and properties. The schematic of SDL occurred in IEC device can be seen in Fig. 3 Ions are created on the layer with approximately same thermal velocity as background gas ($v_{ion} \approx \sqrt{2k_B T_n/m_i}$) and constricted by the center-pointing electron wind which has high drifting velocity ($v_e \approx \sqrt{2eV_{DL}/m_e}$). The electron energy is usually high enough to trigger electron impact ionization, accordingly, high ionization efficiency is expected. The kinetic energy of incoming electrons is dissipated by the ionization processes and trapped within the layer. Some electrons can escape the envelop through the weak point of potential topography due to accumulating of the electron pressure. [1]

In addition, the extraction mechanism, as above mentioned, initiated by the non-uniformity of electric field. This will result the non-uniformity of incoming electron's kinetic energy, and hence, the imbalance of momentum between incoming electron cloud and trapped plasma around the weak point of SDL. Therefore, the plasma obtains an oval shape instead of a sphere and the extraction of plasma can be initiated. [1]

The model performed great correlation on the dimension of plasma ball in IRS-IEC device. [1] More scientific results will be performed with the plasma diagnostic tools, which will be introduced in the following section. In other words, SDL can serve not only as an ionization mechanism but also a confinement mechanism for ions. This provide the great advantage and competitiveness of IEC for plasma generation and confinement with merely DC source, which is not able to be achieved by other plasma generator concept without magnetic field presented.

2. Experimental activity

The IEC thruster was parallelly developed with the diagnostic tools for its characterization activities. The goal is to promote IEC thruster up to TRL3 by the end of 2019. The thruster design concept is finalized and presented in 2017 IEPC. The parts are manufactured and delivered in the 2nd season of 2018. On the other hand, the plasma diagnostic capability for IEC is established in

IRS Tank 12 facility, both intrusive and non-intrusive methods. The detail of thruster design and diagnostic method is summarized in the following subsections.

2.1. Tank 12 facility for IEC characterization:
IRS Tank 12 facility is a φ1 m * 2.75 m vacuum chamber with 3 stages pumping system, which includes am rotary pump, a roots pump, and molecularturbopump. The ultimate pressure is 0.03 Pa. The power supply used for IEC operation is a Heiden HE-HPSn10020, which provide up to 20kV with 10 kW maximum power output. A two-dimensional translational platform is implemented in the tank for plasma diagnostics, such as plume characterization by electrostatic probe. Upgrade of platform to and controlled four-axis system is current processing.
UV to NIR fiber optic feedthrough (FT) and diagnostic window are both implemented on the chamber to offer optical diagnostic capability for laser interferometry and vacuum optical emission spectroscopy (OES). Further diagnostic capability such as tunable-diode laser absorption spectroscopy and laser induced fluorescence (LIF) are implementing currently to fully extend the capability of tank 12 for small plasma source characterization.

2.2. IEC thruster development status
The thruster concept and hardware views are shown in Fig. 5. The thruster is composed by a spherical hollow anode, a 3D-printed spherical grid cathode, a HV cathode FT, and a ceramic cone. The connection of nozzle and HV-FT connect through CF DN75 and CF DN40 flanges, respectively. The inner diameter and wall thickness of anode are ϕ150 mm and 3mm, respectively. In order to provide plasma observation for discharge chamber, spherical anode has extra four CF flanges around. These extra flanges are designed only for observation purpose and can be removed in engineering model.

The design of HV-FT is important for the IEC concerning of its electrical insulation. A special insulation design has been applied around the connection port to avoid unexpected arc discharge or current leakage. The design insulation capability of HV-FT can be survived up to 30 kV. Further test for the insulation is needed.

Cathode grid is manufacture by 3D printing technology. The configuration is composed by a pattern of squares, hexagons, octagons, and circle in order to achieve scalability. The gate area is maintained in the similar size to prevent current leakage resulted from non-uniformity of E-field. A large gate is right attached with ceramic cone to enable the extraction of plasma.

Ceramic cone is made by Al_2O_3. The design creates an enclosed volume for IEC to prevent the leakage of neutral particle as well as provide respective electric insulation. An EM acceleration mechanism will be

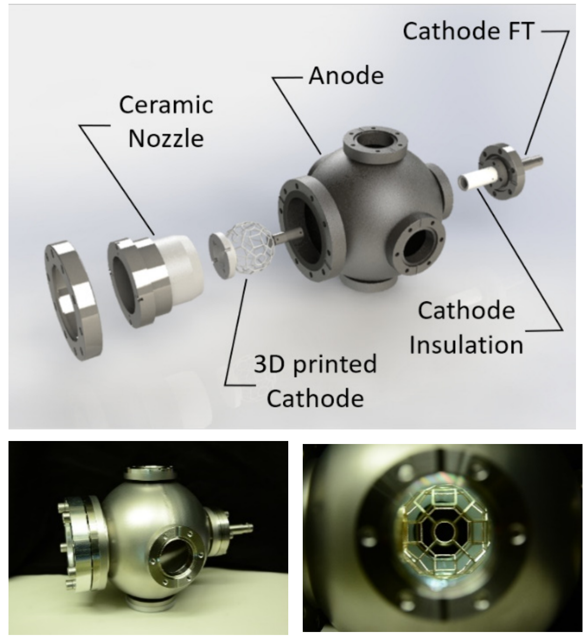

Fig. 5. Schematic of IEC thruster prototype and manufactured assembly

designed and implemented in the ceramic cone after characterization of IEC plasma is performed.

2.3. IEC Characterization
Plasma characterization is mandatory for establishing the insightful understanding of discharge and extraction mechanism, especially for developing an EP device. Without proper evaluation method, the design of EM field might lead to extremely low acceleration efficiency or server erosion problem. The required plasma properties for IEC thruster design include the particle's

Table 1 Diagnostic method for IEC plasma properties

	Invasive			**Non-invasive**		
	LP	**FP**	**RPA**	**OES**	**TDLAS**	**LIF**
$n_{i,core}$				Δ	X	X
$n_{e,core}$				Δ		
$IEDF_{core}$						X
$EEDF_{core}$				Δ		
$n_{i,jet}$	Δ	Δ	X	Δ	X	X
$n_{e,jet}$	Δ	Δ	X			
$IEDF_{jet}$	Δ	Δ	X	Δ		X
$EEDF_{jet}$	X	X	X			

1. X: accessing through measurement data directly
2. Δ: accessing through measurement data plus assumptions

energy and density distribution function, both in the core and plume. However, the diagnostics of IEC is extremely challenging because its non-Maxwellian plasma characteristic, of which most conventional plasma diagnostics method doesn't fully applicable. Therefore, selection of diagnostic tool should be very careful.

A summary of diagnostic tools and their functions has been proposed in the Table 1. These methods can be categorized into two groups: intrusive diagnostics and non-intrusive diagnostics. The respective function for understanding IEC plasma characteristic is indicated as well.

2.3.1. Langmuir probe and Faraday probe

Electrostatic probe (e.g. **LP** and **FP**) is the most common approach to access the plasma properties. Such as *EEDF* of plasma plume. However, for non-Maxwellian plasma such as IEC tight jet, some modification of the theory should be applied.

A cylindrical LP has been developed in IRS and performed a standardization of LP diagnostic approach toward verification of EP device. The characterization of an IRS arcjet system, VELARC, is served as the basis for the verification procedure. The characterization activities was performed in both IRS and ESTEC in order to verified the reproducibility of the current-voltage characteristics. [13]

In addition, a nude-type FP is developed in IRS which based on the design of JPL. Beside from that, a pure tungsten collector is selected in order to resist in high temperature as well as compensate the current leakage through secondary electron emission (SEE) when encountering high energy electron bombardment. [9], [14] The arrangement of FP and IEC can be found in Fig. 6.

To enable FP for non-Maxwellian plasma diagnostics, a novel analytical model is proposed together with the FP to evaluate this non-Maxwellian plasma beam. The model assumes that the exhausted electron beam (EB) is composed of several Maxwellian plasma components with different drift velocities and temperatures. In addition, SEE from probe surface and SIE/SEE resulted from the ionized background gas are considered in this model as well to compensate the current loss through EB bombardment. The current-voltage characteristic through the FP collector is recorded and analyzed with least-square-minimum method. The revealed results indicated a strong linear correlation of electron kinetic energy with the applied voltage of IEC. [14] On the other hand, preliminary measurement result of IEC spray jet suggested a quasi-neutral plume extraction. Further investigation of spray jet is planned in the end of this year.

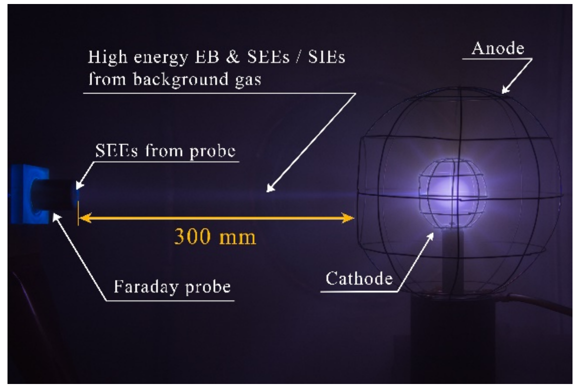

Fig. 6. IEC tight jet characterization with Faraday probe

2.3.2. Retarding potential analyzer

Though LP and FP are able to interpret plume characteristic in some assumptions. It is still not able to access the ion energy distribution function, n_e, and n_i directly. In this concern, RPA is the best option for precise and relatively low-cost plasma characterization.

The principle of RPA is a kinetic energy filter for charge particle. It mainly composed by a floating grid (FG), a negatively biased electron retarding grid (ERG), a positively biased ion retarding grid (IRG), a collector, ceramic spacers, and the housing. [15] The FG is biased to the plasma potential to avoid disturbing of plasma plume. ERG can filter out electrons which comes into the RPA with ions. The IRG is swept in positive voltage and serve as a high-pass energy filter for ions. Collector continuously monitors the current flux for ions which manages to pass the IRG.

Although RPA is a cost-effective option for plume characterization, it suffers from the problem of ion accumulation in-between ERG and IRG when the probing time is too long or incoming plasma density is too high. High plasma density plume is a foreseeable condition toward high-power EP. Therefore, an extra design to overcome the limitation is needed.

The first back-vacuum RPA was designed and under-manufactured currently in IRS. (see Fig. 7) This advanced design aims at solving the issue for RPA measuring in high density plasma plume. In addition, there is an electron suppress grid ESG in front of

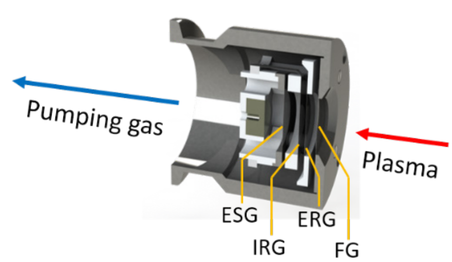

Fig. 7 Schematic of back-vacuum RPA

collector to suppress SEE when high energy ions bombarding on the collector. Test of RPA with IEC is planned in January 2019.

2.3.3. Optical emission spectroscopy

An UV to NIR OES is design and planned for characterization of IEC core and plume. A vacuum collimator has been designed and verified by performing time-resolved OES for PETRUS, which is a pulsed plasma thruster (PPT) developed in IRS. The vacuum spectroscopy can avoid the interference of existing air, which cause absorption of specific spectrum and broadening of detected peak, to provide more reliable characterization result. In addition, this spectrometer setup provides UV to NIR spectrum reading with which enable a broader overview of plasma composition.

An analysis program is developed to interpret the OES data, which was implemented with NIST database to define species precisely.

2.3.4. Tunable-diode laser absorption spectroscopy

Development of TDLAS and LIF provide the possibility to quantitively characterize plasma properties at the core of IEC which is an important step for IEC thruster design.

TDLAS is a non-dispersive concept, which means that no spectrometer is required. The laser which provides extremely high spectrum collimation (small spectrum interval) and scans over a large wavelength spectrum. A photodiode is used to monitor the laser intensity along with scanning wavelength. The wavelength of scanning laser is monitored by an etalon a Fabry-Perot Interferometer. When the scanning wavelength matched with the absorption spectrum of gas, the absorbed energy of laser beam can be measured.

An external cavity laser with Littman configuration is used in IRS. [16] The tunable wavelength is between 838nm – 853nm with 60GHz mode-hop-free tuning range while the maximum output power is 7mW. The Fabry-Perot interferometer is used to check the mode of the probing laser. By applying this method, particle density of specific species and its translational temperature can be derived based on the measured signal. The resolution of this method can be very high as it only depends on the linewidth of the laser and not on the properties of a dispersive element, e.g. a prism or grating in spectrometer.

The plan of TDLAS system for IEC investigation is in in the implementation phase. The expected test would begin at March, 2019.

2.3.5. Laser induced fluorescence

The basic concept of LIF is sending a probe beam as TDLAS. The difference is that LIF has a fixed beam wavelength right at the absorption spectrum of target species. When the target species absorbs the probing photons, they are pumped to excited state and spontaneously de-excited by releasing the photons in random direction. The velocity of probed particles along the laser beam direction can be determined by measuring the Doppler shift of absorbed photons via a collimator.

The LIF concept for IEC characterization is based on the TDLAS setup. Implementation of LIF concept would start around March, 2019.

3. Potential of IEC technologies

IEC can provide extremely wide-spectrum applications from VLEO to deep space exploration due to its compactness on design, simplicity on implementation, and flexibility in propellant. The respective application concept based on IEC technologies is demonstrated in the following subsections.

3.1. IEC thruster – exploration from LEO to GEO

IEC provide two kinds of plasma extraction mode: high energy EB from tight-jet mode and diffusive ion plume from spray-jet mode. The extraction mechanism are explained in Ref. [1] These can be implemented as EP device with its respective plasma characteristics. For EB extraction, an advanced IEC-HET thruster is proposed, which is shown in the Fig. 9. Due to high kinetic energy in the EB, high ionization degree can be easily achieved by EB impact ionization. In addition, it required much weaker magnetic field intensity for harvesting electron Hall current. This can suppress the plasma hydrodynamic instability induced by ions and magnetic field.

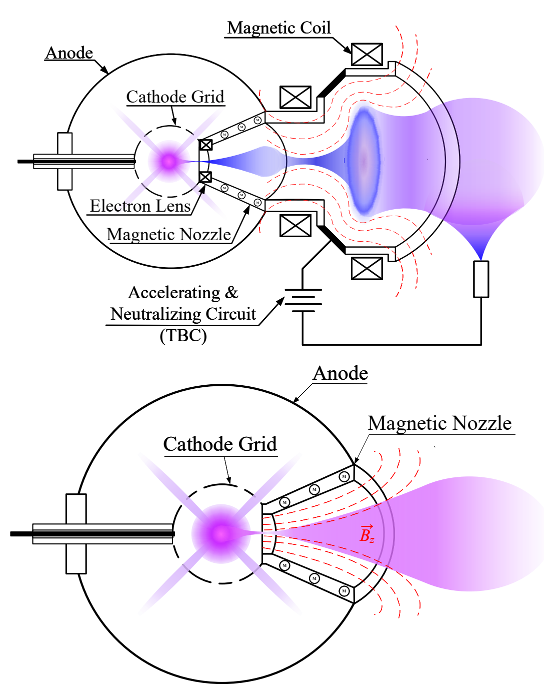

Fig. 8 Design concept of IEC-HET (upper) and IEC thruster (lower) [1]

For spray modes, high density plasma is produced and confined within the SDL of IEC and extracted though the self-induced throat region. (see Fig. 8) This enables high specific energy density as well as high degree of ionization in the diffusive plume. The exhausted plume can be further accelerated by implementing an acceleration mechanism, such as electromagnetic nozzle. In addition, the enclosed grounded anode configuration provides electrical insulation for satellites as well as improves the propellant usage efficiency concerning relatively small extraction port. The thruster components are prepared which is shown in Fig. 5. The verification processes for IEC thruster will be initiated in IRS from December, 2018.

3.2. *VLEO solution - ABEP*

VLEO provides great advantages regarding to earth observation and communication due to its much shorter distance to the ground. Unlike satellite in LEO to GEO, this can save budget for optics development and implementation I with the same resolution quality; at the same time, provides wide field of regard for camera. The shorter orbiting time increases the geostationary accuracy and reduces the price for communication. Concerning on the mission perspective, it greatly reduces the possibility of space debris collision and offers the self-disposal capability at the end-of-life service. However, it is a not yet explored place for satellites due to the issue to compensate induced drag force from the thin residual gas, where Atmosphere-breathing EP (ABEP) can overcome this issue.

ABEP is a concept which allows spacecraft flying in VLEO by providing drag compensation continuously through EP device without the need of extra propellant supply. A specific design air-intake is enable the passive collection of the residual atmosphere at low altitude orbits for EP as propellant. [17], [18] A active collection mechanism with gas turbine has been proposed by Li et. al. as well. [19] However, in passive mechanism, the collecting efficiency of residual gas fully depends on the controllable particle reflection on the intake wall due to low particle density. It is difficult to find a proper material to serve this purpose at this moment. The gas turbine might significantly increase the systematic weight and induce stability issue on formation flying. In addition, both concepts encounter the erosion issue of existence of atomic oxygen in VLEO. To further increase the particle collection efficiency as well as providing thrust throughput, IEC can serve as a promising concept for ABEP.

IEC can be used as an active particle collecting concept by using the SDL for ionization and confinement. A schematic of IEC-ABEP is shown in Fig. 9. [1]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 both driven toward the hollow cathode grid and trapped by SDL. The ionized gas can be further driven to the exhaust by accelerated by an electric magnetic nozzle to provide thrust.

IEC provide the ionization and concentration mechanism for the residual gases at the same time, which offers the possibility of high particle collecting efficiency with no need of a controllable particle reflection as well as provides thrust force production of ionized particle by a fixed mechanical structure.

Based on simulation for the enhanced funnel design intake from IRS verified operatable pressure criteria of IEC-ABEP concept.[1] In addition, separation of ionization and acceleration mechanism in IEC concept enables a scalable thrust force production in a fluctuated particle density environment during earth orbiting by simply adjusting the DC applied voltage.

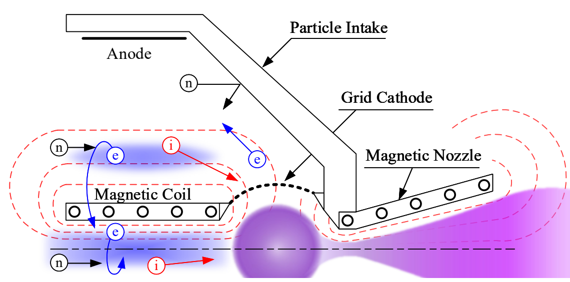

Fig. 9. IEC concept for ABEP [1]

3.3. *Potential fusion EP for deep-space mission*

Fusion EP can provide great power-to-weight ratio, which is mandatory for future interplanetary traveling and manned space mission. The majority of fusion propulsion concepts are nuclear thermal propulsion.[1] The magnetic confinement, e.g. Tokamak, is under consideration.[20] However, the plasma dynamics in magnetic confinement fusion is extremely complex which not only increases the difficulty for thruster design and implementation. Furthermore, the system mass for magnetic confinement fusion is significantly high, which makes the its application in space propulsion becomes less attractive.

IEC is straightforward fitting into fusion propulsion category due to its heritage as neutron source. In addition, it also have superiority in system simplicity, compactness, and thrust-to-weight ratio.[21] Though some IEC fusion thruster concepts has also been mentioned in the past, the working principle, detailed design, and validation of the concept is not yet understood or realized.

Feasibility of IEC fusion propulsion becomes possible thanks to the verification of working principle - SDL ionization and confinement. The ions generated at inter-electrode region can be driven to high velocity by the applied electrostatic field; while the ions 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. Theoretically, the fusion energy can effective transfer to the kinetic energy of exhausted plasma with same extraction mechanism as IEC thruster.

4. Conclusions

The short-term goal for IEC development is to promote the IEC thruster concept to TRL3 by the end of 2019. Several verification processes are required to achieve this goal, such verification of IEC operation characteristics, extracted plasma properties, and thrust performance. Currently, tank 12 vacuum system is prepared for testing of 1kW-scale EP device. The two-axis translational platform for invasive and non-invasive diagnostics is upgrading to four-axis control (extra one more translation and one more rotation). The upgrade of platform is planned to be finished in January, 2019. Development diagnostic tool is aimed at promoting the understanding of IEC thruster, which includes electrostatic probe and laser spectroscopy. The operation principle and development status for each tool was introduced in subsection 2.3. It can offer verification capability for other EP device below 1kW power level as well, such as Hall effect thruster or Ion thruster. Furthermore, a holographic interferometer is implemented on tank 12 facility which offer the potentially time-resolved plasma dynamics diagnostics for PPT.

The application of IEC thruster is not only limited in the LEO and GEO. It has a great potential in ABEP for VLEO as well as heritage in fusion propulsion for deep-space mission. The multi-discipling application of IEC technology enables promising future not only in space exploration but also for human habitation.

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