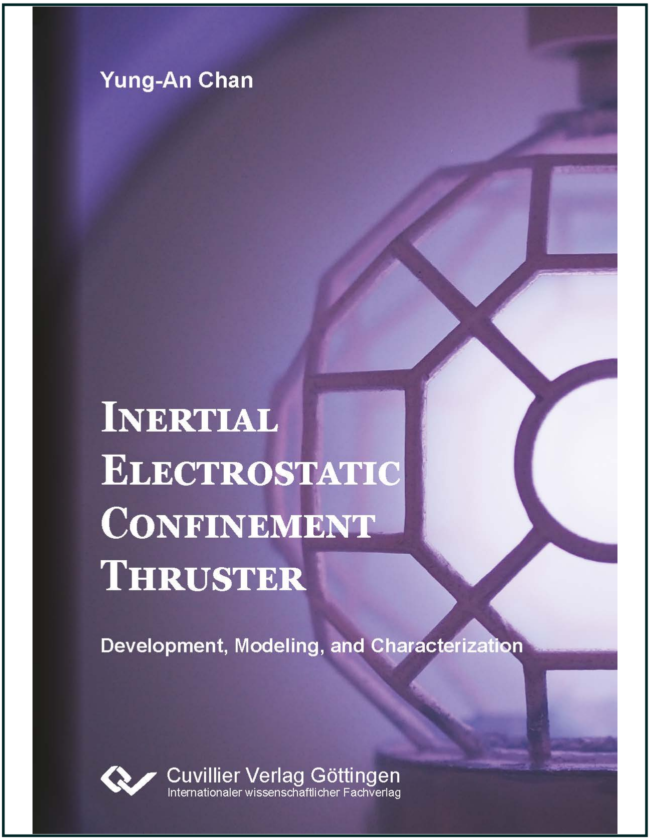
Yung-An Chan (Autor)

Inertial Electrostatic Confinement Thruster (IECT)

Development, Modeling, and Characterization



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Chapter 1

Introduction

1.1 Background of Inertial Electrostatic Confinement

1.1.1 *A short history of IEC theory development*

Inertial electrostatic confinement (IEC) was proposed for fusion application in the 1960s in both the USA [1] and USSR [2]–[4]. The working principle of IEC is described as a potential well trap in the literature, meaning a multilayer potential well structure resulting from the locally non-equilibrium distribution of ions and electrons. [4]–[6] According to Hirsch [6], this structure provides plasma confinement for the fusion reaction. However, no direct experimental evidence has confirmed the formation of a multilayer structure in IEC. On the other hand, Hirsch also mentioned in his article that IEC discharge would work like hollow cathode (HC) discharge when the collisional processes dominate the IEC discharge [6], which is also the most common condition documented in most of the IEC experiments. However, the first evidence supporting the concept similar to an HC discharge is proven by Shrier et al. [7]. They showed the divergent ion motion from the core of the IEC device, which is opposite to the ion-converging mechanism commonly used to explain the IEC working principle. It is also the first experimental evidence bridging the IEC working principle to the HC discharge theory. In 2017, Chan and Herdrich proposed a theory that the IEC discharge is dominated by the floating plasma sphere, also known as the spherical double layer (SDL). [8] This theory provides a new perspective for explaining the IEC working principle. It also opens the door to miscellaneous applications other than fusion, such as space propulsion [8] and plasma surface treatment [9].

1.1.2 *Fundamental of IEC working principle*

The illustration of an IEC discharge is shown in Figure 1-1. The IEC system comprises a pair of concentric spherical gridded electrodes. The outer one serves as the anode, and the inner one is the cathode. The anode is grounded to the protective earth, and a high differential voltage bias (V_b) is applied between the gridded electrodes. Similar to a DC discharge between planar electrodes, the discharge mechanism can be briefly described in three steps:

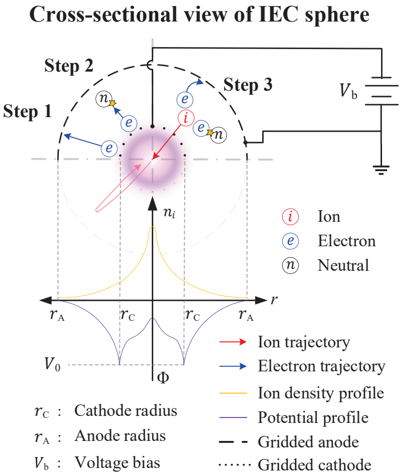

Figure 1-1 Concept illustration of IEC discharge and formation of the virtual anode at the center of the gridded cathode.

1. The electrostatic field accelerates the electrons emitted from the cathode surface toward the anode.
2. The electron-neutral collisions occur within the inter-electrodes region and produce ions. As a result, the primary electrons loose most of their kinetic energy upon impact.
3. Ions are accelerated to the spherical cathode grid; meanwhile, both the primary and pair-electrons keep accelerating toward the anode grid. As a result, they are either absorbed by the anode or further provide impact ionization with other neutrals.

Unlike the direct-current (DC) discharge between planar electrodes, the ions have a much lower chance of falling on the cathode surface due to their high transparency on the grid structure of the cathode. These ions can fly through the inner-cathode region and leave the gridded cathode again if they do not collide with the cathode. Their kinetic energy allows them to reach the radial position with the same initiated electric potential where the collision happened. These ions travel back and forth through the center of the IEC. Thus, a particle cloud with a positive charge is formed, which is called the virtual anode.

Many different research groups observed the formation of the virtual anode, both in simulations and experiments. [10] The virtual anode creates a unique discharge phenomenon apart from the discharge with physical electrodes. First, the plasma-wall effect from the physical electrode is eliminated, such as decreasing particle density or removing electrons. Second, some electrons released from the cathode experience the electric potential gradient toward the virtual anode. The electric circuit is no longer a single resistance loop circuit but becomes a parallel circuit. Third, the inflowing electrons compensate for the built potential in the virtual anode and, eventually, reach a quasi-neutral condition but with a higher particle density within the gridded cathode than the other regions in the IEC device. The whole process leads to the plasma confinement effect through the electrostatic field structure.

1.1.3 *Poissor's theory and measurement of potential structure*

Hirsch extended the model proposed by Lavrent'ev [2] and solved the 1D Poisson's equation in radial direction under the collisionless assumption. The result yields a multilayer potential well structure known as ***Poissor***. He also experimented with high vacuum ($\approx 10^{-3}$ Pa) to measure the neutron particle scattering and Bremsstrahlung emission across the radial position of the IEC device. The signal intensity across the radial direction also shows a multiple-peak structure. He then declared the correctness of the Poissor concept. However, these results do not directly provide evidence of the distribution of ions and electrons.

In 2000, Gu and Miley proposed a detailed schematic for forming multiple potential wells in IEC. [5] They measured the proton emission of an IEC device through a pinhole and observed the radial distribution of proton count across the plasma sphere changes from a single-peak to a multiple-peak structure when the applied current increases. It was hence concluded that was the observation of the Poissor structure. However, the proton rate could only indicate the probability of the nuclear reaction. It did not necessarily mean an ion density distribution following the nuclear reaction rate profile. In addition, their operation background pressure is about 1.3 Pa, where collisional processes dominate the discharge with the IEC device. (See Hirsch paper [6]). It was not only inappropriately concluded the evidence of the formation of the multiple-well structures from the experiment, but their experimental condition also conflicted with the foundation of Poissor theory.

Dobson [11] further extended the one-dimensional Poisson solveHirsch [6] proposed to predict IEC plasmas sphere properties. He introduced different assumptions on particle energy distribution functions to the right-hand side of the Poisson's equation, which are mono-energetic, rectangular, and thermal models. [11] The definitions and assumptions of these models are summarized in the following. (also see Ref. [8])

- Mono-energetic model: the particles assumed null angular momentum and a Dirac's delta distribution over the total mechanical energy, the same model Hirsch used. i.e., Ref [6].
- Rectangular model: the particles are assumed to have a Heaviside's step energy distribution over total energy and angular momentum.
- Thermal model: the particles are assumed to have a Maxwellian distribution function, accounting for the Coulomb interactions between particles in a collisional plasma.

The mono-energetic model is the only one that shows the multiple-well potential despite the assumption being the most deviated from the actual IEC operational condition. The other models do not show the indication of the multiple-well structures. Nevertheless, the increase of plasma density at the core region is predicted in all the models. To observe the formation of a virtual cathode, he further compared the simulation result with the electron density measured by a microwave interferometer. However, the result hardly matches, and the measurement's low resolution cannot indicate the detailed distribution of the particles. Despite this fact, the author did observe the plasma confinement. In addition, he also stated that the potential well observed from the experiment is relatively shallow, which is consistent with the argument proposed by Meeker et al. [12] that the virtual anode might be compromised because the electron might neutralize the potential of the plasma sphere.

More direct results for the measurement of the potential well are performed with a double probe [13] and non-invasive methods, such as laser-induced fluorescence (LIF) [14], [15] and doppler shift spectroscopy [16]. Thorsen [13] performed a double probe measurement through the spherical IEC to measure the potential distribution in the radial direction operating on hydrogen and discussed the electric potential profile with the discharge behavior of IEC at relatively low-voltage conditions (max. 17 kV). [13] He found that the symmetry and depth of the potential well improved with increasing cathode voltage or background pressure. In addition, he measured the plasma sphere radius by emission intensity of the plasma sphere. He observed the decreasing plasma radius with the decreasing grid wire spacing and the applied current. He concluded that this indicates the improvement of ion flow convergence. However, he only observed a single well structure instead of multiple ones. He suggested that this might be because of the asymmetry of the potential well, which could cause the radial kinetic energy to shift to the angular momentum. Hence, the formation of the Poissor structure is diminished. Probe measurement in the IEC plasma sphere (in both Deuterium and Helium, respectively) with high voltage conditions is performed by Masuda [17] with a floating planar probe, of which the reference voltage is the same as the cathode voltage. The probe measured the floating potential from the center of the plasma sphere to the radial position equal to the cathode radius. A potential plateau is observed in every operating condition from 15 kV up to 55 kV, where plasma potential changes from 5% to 8% of the cathode bias. No indication of a double-potential well is observed.

Yoshikawa et al. [15] performed polarized LIF measurements for the IEC plasma sphere. They compare two indicative cases of the potential distribution function when ions have small and large angular momentum. The authors claim that a multiple-well structure is observed when the ions have sizeable angular momentum. Although the background pressure of their IEC experiment is much larger than the expected appearance of the Poissor structure, this is the first evidence ever presented to show a multiple-well structure. However, the analytical description is quite limited, and the resolution of the measurement is not presented in this article. A more detailed experimental result is published in a later article from Yoshikawa et al. [18]. The experiment is performed by the same polarized LIF setup and IEC facility in a similar operational condition. However, the authors claim that no clear electric field can be identified within the given error bar. They argue that the plasma dimension is too small for the given resolution of the LIF system. Nevertheless, the inconsistency of the result and conclusion raises concern about the correctness of their earlier publication.

Kachan et al. measured the ion energy distribution function in an IEC device by using doppler shift spectroscopy to observe the hydrogen Balmer H_α line. [16] They observed a continuous increase of ion energy when the measured position is moved away from the anode and closer to the cathode. It continuously increases when measured within the cathode grid. Rapid decay of ion energy is observed when the measuring position is close to the center of the IEC. This observation confirmed the formation of a virtual anode. However, the increasing ion energy extending through the cathode grid suggests that the virtual cathode might exist between the center and the cathode grid. However, Kachan et al. notice that the multiple-well structure is not supposed to be observed in the given pressure region (i.e., around 2.13 Pa). They suspect the formation of the virtual anode is much more complex than the ion-convergent theory.

In short, the Poissor theory is based on the assumption of collisionless plasma, which requires a high vacuum (e.g., background pressure $\leq 10^{-1}$ Pa). Only then the multiple-well potential structures are formed by the continuously oscillating electrons and ions in the IEC device. However, most traceable IEC devices operate at relatively high pressure, where the collisional effect dominates in the plasma. The scattering effect soon quenches the kinetic energy of particles. Hence, the Poissor structure is unlikely to be formed in these devices. Many research groups confirm the observation of the virtual anode at the core region. However, the virtual cathode cannot yet be identified except only in Ref. [15][15], which still has controversy on their later results published next year, i.e., Ref. [17], [18]

1.1.4 *Summary of IEC discharge theory and new perspective*

With the above information, the formation of Poissor structures in the IEC is contradicted by its fundamental assumption of collisionless plasma. In addition, most IEC devices operate in a relatively high-pressure environment, in which the collisionless assumption is invalid. Furthermore, the experimental evidence declared that the observation of the virtual cathode is plausible. On the contrary, some empirical evidence has pointed out the similarity between HC and IEC discharges. For instance, the HC discharge experiment with a "cage cathode" performed by Kolobov et al. [19] has demonstrated a similar concept to the IEC discharge. This concept aimed to increase the utilization efficiency of fast electrons and ions. In addition, discharge simulation based on the Monte-Carlo method/particle-in-cell method is performed to understand the fast and slow electron dynamics within the cage electrode. [20] A virtual anode is also presented in the result. Moreover, the cage discharge experiment from Arslanbekov [21] indicates ions accumulated near the cathode. His result suggests a strong ionization effect, and high electron temperature is located more at the periphery of the plasma.

The more apparent similarity of IEC and HC discharges can be observed when considering the IEC discharge with a directional plasma jet extraction, which is achieved through a non-uniformly distribution of the grid pattern on a spherical IEC cathode. [8], [22]–[26] The idea is to create a non-uniformly distributed electric potential field over the enclosed space of the spherical cage cathode and enable plasma flow according to the potential field gradient. A controllable plasma jet extraction was realized and presented in 2015 for an IEC device [22]. The theory to explain the extraction mechanism was proposed by Chan in 2017, together with the spherical double layer theory (SDL). [8] In short, the SDL theory is based on the theory of sheath developed by two plasma clouds in different electric potentials, as known as the double layer (DL) theory. Unlike the collisionless sheath assumption, the DL theory considers the electron impact ionization when the electron penetrates the sheath. This consideration provides a balancing criterium on electron and ion flux when both charged particles get accelerated through the sheath's potential fall (i.e., the DL). This phenomenon can be considered a confinement effect for each side of the plasma.

On the contrary, the concept of jet extraction is to break the criterium of particle flux balance by manipulating the electron potential topography and creating a locally non-uniform potential gradient. The potential gradient enables the imbalance of particle flux on a local position of the DL. Thus, the charged particles can leak through a specific point. This process is the same as the HC discharge. Accordingly, the realization of plasma self-extraction through the IEC core indicates the importance of leakage for discharge sustainability. In other words, the formation of a plasma sphere in an IEC cathode with a uniformly distributed lattice pattern is related to the plasma leakage from the core through the grid gate. However, more experimental investigation has to be performed to examine this possibility. Nevertheless, the application of the IEC device as a plasma source is achieved through controllable plasma extraction.

The plasma extraction from the IEC device can generally be categorized into tight-jet mode and spray-jet mode (see Figure 1-2). The name of the jet mode is given according to the visual characteristics of the plasma plume. From the visual observation, the radiative intensity of the plasma sphere in spray-jet mode is more intense than in the case of tight-jet mode. In addition, a clear boundary of the plasma sphere that detaches from the cathode surface is observable in both cases, especially in the spray-jet mode. This boundary suggests an intense plasma sheath gradient and the presence of the DL.

In addition, the discharge characteristic of both jet extraction modes is reported in Ref. [23], [24], [26]. In short, tight-jet mode exists in high-voltage bias (few kilo-volts in argon) and low discharge current ($I_{\mathrm{IEC}} \lesssim 20$ mA on argon) between cathode and anode. The spray jet mode appears in lower voltage bias

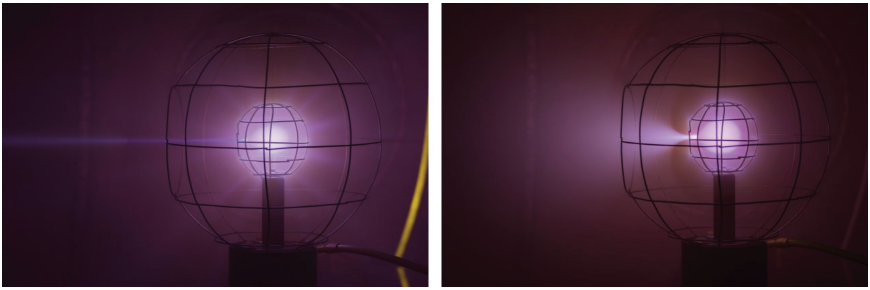

Figure 1-2 Example of two jet extraction modes for argon plasma in an open-gridded IEC configuration with an aperture on the cathode grid for plasma extraction: Tight-jet mode (left) and Spray-jet mode (right) [8]

(hundreds of volts), but the applied current is quite flexible. The presence of tight-jet mode strongly depends on the discharge pressure and gas species, which can only be observed when $p \lesssim 2$ Pa in the case of argon. [27] An instantaneous voltage jump accompanies the transient from tight-jet mode to spray-jet mode. The voltage-to-current transient behavior is similar to the transient curve of the HC discharge at low-pressure conditions, where the pd is smaller than the minimum of Paschen's curve. (See discussion in subsection 2.2.1 Figure 2-6 for more detailed information)

Plasma characterization of the tight-jet mode with the Faraday probe is performed by Chan [26]. The experiment reveals that the tight jet is a high-energy electron beam, as observed in the current-to-voltage curve of the Faraday probe measurement. In addition, the normalized ratio of beam energy in both argon and helium plasma demonstrates the same curve function with the applied voltage bias. The result shows that the extraction of the electron beam is independent of the background pressure and species but determined by applied voltage bias. The characterization of the plume in spray jet mode is not yet performed.

Despite the many theories and experimental evidence presented in the HC discharge investigation, the HC discharge theory has not yet been implemented to explain the IEC discharge. Therefore, some empirical evidence and the physics of the IEC discharge are concluded here to set the foundation for the IEC discharge model construction:

1. The formation of a virtual anode suggests the existence of a strong sheath. Hence, the double layer must be involved in the IEC discharge theory.
2. Townsend's discharge theory must be fulfilled to sustain the DC discharge. However, to the author's knowledge, the concept of Townsend discharge has not yet been implemented for the IEC discharge model. Although some experimental data have been used to fit the Paschen curve, the results deviate from the theory.
3. The electron emission is assumed to naturally occur in the IEC cathode device for the existing model. However, the ion bombardment effect on the cathode is expected in such high voltage DC plasma. Accordingly, secondary electron emission (SEE) from the IEC cathode surface must be considered in IEC discharge.
4. Although experimental evidence has pointed out the leakage of electrons and ions from the plasma sphere, the balance of particle flux has never been considered in IEC discharges. Accordingly, a detailed definition of the particle flux balance in the IEC grid cathode is included in the model.

1.2 Magnetic Nozzle for IEC Plasma Acceleration

1.2.1 *Short Overview of Magnetic Nozzle*

The magnetic nozzle (MN) concept describes an externally applied (static) magnetic bottle with the vector axially aligned to the plasma flow direction to eject the plasma at a high velocity for thrust generation. The magnetic field inhibits the transportation of charged particles across the streamline of magnetic flux, providing plasma confinement and preserving the kinetic energy of the charged particles, which significantly reduces the contact of plasma on the physical surfaces, i.e., plasma bombardment. Hence, thermal capability and material compatibility in engineering design are more flexible. With proper design of the field topography, the magnetic bottle could resemble a de Laval nozzle, which transforms the thermal energy of the plasma into directional momentum flux without direct contact. Despite its promising features for multi-discipline applications, the interpretation of plasma dynamics in MN is complex, and many physics problems remain unclear, such as plasma detachment from MN.

Nevertheless, the MN might be the most promising mechanism for further confinement and acceleration for the plasma extracted from the IEC source. Nevertheless, several issues should be considered to bridge the concept of IEC and MN. First, preliminary investigations of the IEC plume properties suggest high energy/temperature electrons. Accordingly, the discussion of MN here will focus on the condition when free electrons are present in the magnetic bottle. Thus, the scope of the MN design criteria can be briefly categorized into three parts and is shown in the following Figure 1-3:

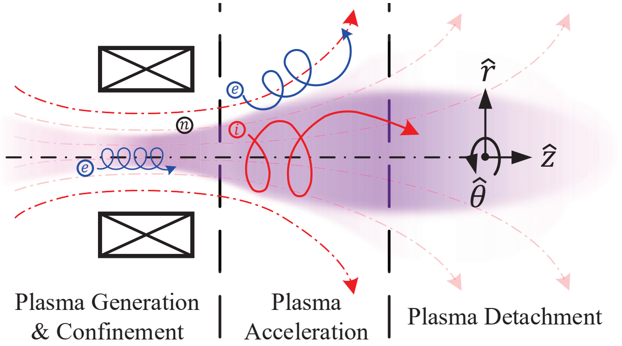

Figure 1-3 Concept schematic of plasma confinement, acceleration, and detachment mechanism in a magnetic nozzle.

- ***Plasma generation and confinement***

  Electrons start gyrating along the streamlines of the B-field when they are injected into the magnetic bottle. This configuration is known as the electron beam ion source (EBIS), widely used in synchrotrons to deliver highly charged particles. [28] EBIS provides two advantages for plasma: controlling the ionization state and population through the injected electron properties and forming a virtual cathode column that provides a radial electric field pointing inward for ion confinement. This concept can offer an ideal confinement mechanism and significantly enhance the ionization rate for the high-energy electron extracted from the IEC plasma source.

- ***Plasma acceleration***

  The concept of plasma acceleration in a divergent magnetic field is based on the research of magnetohydrodynamics (MHD) flow from solar activity [29]. The concept combines the discussion of plasma in fluid dynamics and electromagnetism, which discusses Lorentz force on the plasma dynamics. The concept of MHD being introduced for propulsive purposes starts from the magnetoplasmadynamic thruster (MPDT), which utilizes high current to provide plasma generation, magnetic confinement, and acceleration. [30] In 2001, Manheimer and Fernsler [31] extended the theory by focusing on plasma acceleration through an expanding magnetic bottle. They considered the presence of plasma sheath and modification of the Bohm condition in the plasma. The evaluation set the basis in the field of MN research in the past two decades, including electron thermodynamics and ambipolar acceleration.

- ***Plasma detachment***

  MN enables energy transfer from plasma thermal energy or electric potential to kinetic energy, providing plasma acceleration. However, the streamline of magnetic flux is in a closed loop, in which the charge particles will eventually turn back to the thruster if they keep attached to the streamline of the B-field. Accordingly, the plasma detachment must occur to gain momentum for propulsion purposes. Therefore, understanding the decoupling mechanism is needed to optimize the plasma thruster's momentum gain. Several theories on plasma detachment have been discussed since the 1990s (which will be introduced in Chapter 3), and the verification is still undergoing.

1.2.2 *Plasma Confinement and Generation in Electron Beam Ion Source*

The concept of EBIS was firstly proposed by Donets in 1967 [33], [34]. It is a type of cross-field discharge device which steers a cylindrical plasma around the axis of a magnetic bottle by the $E \times B$ effect. [32]. The idea is similar to a Penning ion generator (PIG) developed in 1937 as a manometer [35] and is still widely used today. The Penning geometry was first reported as a positive ion source by Louis Maxwell, working at the Franklin Institute in Philadelphia in 1930 [36]. A schematic of the Penning ion source can be found in Figure 1-4 (a). The system is usually composed of a static magnetic bottle aligned with the axis of a cylindrical tube, which provides a radial electric field perpendicular to the streamline of magnetic flux. The high differential voltage is applied to provide electron emission from the cathode. A magnet is implemented to spiral up the electron paths perpendicular to the anode. Primary and secondary electrons oscillate between two cathodes inside an anode tube until they diffuse across the streamline of magnetic flux to the anode. By measuring the discharge current, PIG could accurately measure very low pressures. [37]

The PIG has the advantage of compact and high current density. However, the instability of the discharge, impurity of plasma from electrode material, and low efficiency are noted. These disadvantages could be avoided by implementing a mechanism of free electron injection to provide more significant electron flux with lower discharge voltage. This concept established the ground of EBIS.

The concept of EBIS proposed by Donets in 1967 [33] uses a dense mono-energetic electron beam injected at the axis of a magnetic bottle for ionization. Simultaneously, the magnetic bottle provides confinement on the electrons. A schematic of EBIS is shown in Figure 1-4. Electrons are magnetically constrained on the solenoid axis. A drift tube is axially aligned and serves as a physical constraint for the neutral particles. A plasma column with negative potential is established in which electrons are accumulated and gyrated around the axis. This concept provides a high ionization rate along the plasma column and a radially electric field pointing toward the axis of a magnetic bottle for ion confinement simultaneously. The ionization rate of EBIS was reported approximately 10^3 higher in electron energy and 10^8 higher in ionization rate than PIG. [33]

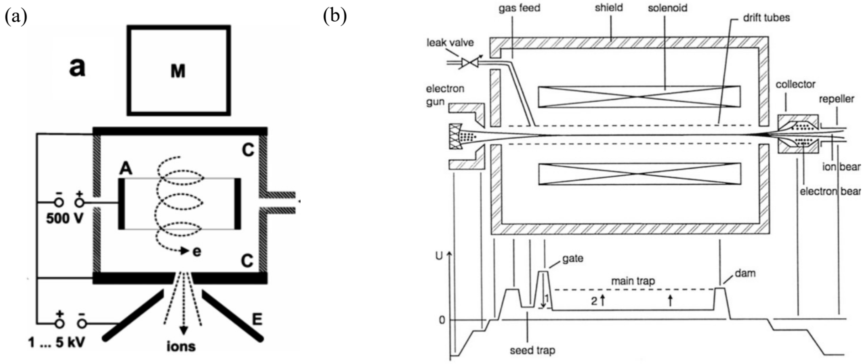

Figure 1-4 The concept of Penning ion gauge (a) [32] and the electron beam ion source (b) [28]

The ions are mainly lost through the charge-exchange collision with neutral particles and the ion-wall collision. The dielectric recombination is unlikely due to high electron energy. Accordingly, the ions can be trapped in the electron beam where only depletion of neutral particles occurs. The concept of EBIS benefits from the inward-pointing, radial electric potential gradient. The potential gradient drives ions away from the wall and traps them in the plasma column, which minimizes the ion-wall loss. Furthermore, the EBIS offers the possibility of controlling the ion charge state and the ion production rate by simply regulating the injection of neutral particles flux and energy of electron beam. These advantages are why EBIS is popular in elementary physics and synchrotron research.

1.2.3 *Plasma Acceleration in Divergent Magnetic Field*

Plasma acceleration in MN discusses the conservation momentum and thermal energy of an MHD flow. From the MHD theory (see subsection 3.1), the momentum gain of plasma is mainly provided by the Lorentz force and pressure gradient in MN, while the thermal energy gain of plasma is primarily from the resistive processes in the plasma. Both effects are closely related to the current density/flux flowing in the plasma, which indicates its importance in the MHD flow.

The current density in a quasi-neutral plasma flow is generated from the diamagnetic effect, which determines the magnitude of the Lorentz force acting on the plasma. Without this effect, plasma acceleration is determined by the gas-dynamics processes. The pressure accumulated in the plasma is caused by the Joule heating of the particle flow and the ionization effect that multiplies the particle density. These two effects are also considered the damping mechanism for the diamagnetic current flowing in the plasma. Therefore, the balance of the resistive effect and preservation of diamagnetic current density is crucial to optimize the performance of MN. [38]

Most of the MN experiment's practical work was based on the helicon plasma source (please refer to subsection 3.2 for detailed information), which provides pre-heated plasma flow before entering MN. This kind of design is an advantage from the engineering point of view because it minimizes the requirement of plasma heating in MN by simply adapting a heated plasma source. However, it further complicates the discussion of momentum and thermal transfer by mixing the RF wave heating in an MHD flow from the research and optimization perspective. For instance, one of the major difficulties is the undetermined effects in the RF source, such as the wave-particle interaction, which triggers instability and plasma turbulence either on a large scale or microscopic scale. These difficulties further restrict the progress of MN research.

In contrast, the discussion of momentum gain in the MN is simplified by combining IEC and MN because the effect is controlled by the injected DC electron beam (EB) and neutral particles. This combination narrows the discussion into a DC plasma interacting with a static electric and magnetic field, which simplifies the physics and leads to the possibility of design optimization. However, the discussion from this perspective is scarce. Inevitably, the design and evaluation for MN require a comprehensive review of the research on RF plasma sources.

1.2.4 *Assessment of Plasma Detachment*

Although the magnetic field could effectively enhance the electron pressure, the overly strong one could also set back the performance of MN by making the charged particles adhere to the streamline of magnetic flux. Eventually, the accelerated particles are pulled backward and compromise their momentum gain from the magnetic nozzle. Despite ions being unmagnetized and detached from the streamline of magnetic flux, the charge separation can develop the electric field simultaneously and pull back the ions if the electrons remain magnetized. [39] Consequently, instead of infinitely increasing the magnetic field strength to gain more performance, the design of plasma detachment is more crucial because it is the final process that determines the efficiency of momentum transfer in MN.

Several mechanisms have been proposed since the 1990s to explain plasma detachment, also known as plasma demagnetization. The discussion could be briefly summarized in the following directions: [40]

1. Collisions and resistive detachment [41]
2. Finite Larmor radius (FLR) [42], [43]
3. Magnetic field perturbation [44], [45]
4. Instabilities [46]

The first two approaches use Newton's Law perspective to describe the plasma detachment resulting from the collisional processes or electron inertia. The last two approaches consider that detachment is triggered by the electromagnetic effect, such as the oscillation of the electromagnetic field or the self-induced magnetic field. The discussion of plasma detachment for propulsive application mainly focuses on the FRL and the magnetic stretch theory. Details of these two theories will be summarized in Chapter 3.

1.3 Potential Applications

The IEC plasma source inherits the characteristics of the IEC fusion reactor, which can provide plasma confinement with DC discharge in a compact and straightforward design. In addition, further plasma confinement and acceleration for the plasma extracted from the IEC cathode can also be realized by the MN. Combining both concepts provide a promising solution to enable a high thrust-to-weight ratio for the next-generation EP concept. In addition, both concepts can be operated in a wide range of operational power and discharge pressure, which offers significant flexibility in design implementations and applications. These are attractive characteristics for space propulsion applications. A proper design and implementation of the IEC plasma source and MN can enable the possibility for other engineering and scientific applications.

- ***Conceptual Approach for Fusion EP for deep-space exploration***

The major advantage of fusion EP is the high power-to-weight ratio mandatory for future interplanetary traveling and human-crewed space missions. Extra energy produced from the fusion reaction can further promote the plasma's internal energy and increase the plume's exhaust velocity. Most fusion propulsion concepts are nuclear thermal propulsion, among which magnetic confinement, e.g., Tokamak, is the most well-known device.[47], [48] However, the complex plasma dynamics and massive magnetic systems increase the difficulty of thruster design, validation, and implementation. These restrictions make magnetic fusion a less attractive propulsion concept for space.

The propulsion concept based on IEC fusion has the advantages of simplicity and required system mass. [49] In addition, the long development history of the IEC fusion makes it a more suitable solution for in-space fusion propulsion. However, the engineering design and the validation of discharge theory are comparably immature. This deficiency can be resolved by firstly establishing the IECT concept.

- ***Advanced intake for Atmosphere-breathing Electric Propulsion***

Atmosphere-breathing EP (ABEP) is a concept for collecting the residual atmosphere at low altitude orbits as the propellant for EP and generating thrust, eliminating the requirement for carrying propellant and the respective subsystems. The concept aims at offering a self-sustainable solution for a satellite to stay in low-altitude orbit. However, the extremely low particle density increases the difficulty of maintaining the required discharge pressure for EP devices by simply using a passive inflow collector, i.e., an intake.[50] For instance, the pressure created at the end of the intake can reach between 0.03 – 0.45 Pa for a satellite at 120 km on Earth's orbit. [51] Realizing a high-efficiency intake becomes a bottleneck for the success of the development of ABEP.