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A REPORT ON THE SOURCES USED FOR LEO PLASMA EXPERIMENTAL SIMULATION

A. M. Abd El-Hameed [1*], A. S. Farahat[2], L. H. Basmsm[2]

[1]Solar and Space Research Department,
National Research Institute of Astronomy and Geophysics (NRIAG),
1 EL Marsad Str., Helwan, Cairo, 4037101, EGYPT
[2]Faculty of Navigation Science and Space Technology,
Beni Suef University,
Bayad Al Arab, Beni Suef, EGYPT
*e-mail: mostafaafaf2000@yahoo.com

The simulation of the Low Earth Orbit (LEO) plasma environment is essential for understanding the effects of space plasma interactions on space systems and subsystems. Spacecraft charging and arcs are among the most significant problems related to plasma impact. These can cause variations in the physical characteristics of materials and spacecraft systems. Ground-based experimental studies are proposed to investigate the effects of a simulated LEO plasma environment. The experiments have shown that plasma effect variations depend on the applied conditions and plasma properties. One of the key factors determining the estimated plasma properties is the source used to produce plasma. Various plasma sources have been developed to simulate the conditions and properties of LEO plasma. This study presents various sources applied to generate a simulated LEO plasma environment. Different techniques used for measuring plasma characteristics are presented in the paper. Examples of the operating conditions and plasma properties are also addressed.

Keywords: *Conditions and plasma properties, LEO plasma simulation, measuring techniques, plasma sources and gas used.*

1. INTRODUCTION

Spacecraft navigates dynamic environments featuring neutral particles, plasma, radiation, and debris, necessitating designs robust against potential interactions and degradation. In (LEO) orbit, the dominant environment is the ionosphere, a relatively dense (ne ≈ 10^ (10) − 10^ (12) m^{-3}) but cool (Te ≈ 0.1−0.3 eV) plasma. Spacecraft interactions in LEO are strongly influenced by their high orbital velocity (vsc ≈ 7−8 km/s) relative to the plasma. This mesothermal flow imparts significant RAM energy (typically 5–10 eV for O^+ ions) onto impacting ions [1]. This directed energy, combined with plasma density, governs sheath structures, wake formation, and other critical interaction physics. Electrostatic effects, including surface charging, discharges, and arcing, are common results of spacecraft-plasma interactions in LEO [1]–[4]. Both charged and neutral species contribute to arc plasma evolution, potentially causing surface damage, power disruptions, contamination, and electromagnetic interference [5]–[7]. Moreover, high-voltage systems, like solar arrays, are particularly susceptible to plasma-induced degradation via discharging and arcs. This depends on the conditions and plasma properties close to the array surfaces [8]–[10]. Due to the challenges of in situ studies, laboratory simulations are vital for assessing the performance of spacecraft components and failure modes under LEO plasma conditions. Ground-based LEO simulations replicate the characteristic plasma densities and directed ion energies. These simulations employ vacuum facilities equipped with plasma sources applied to generate environments representative of LEO.

The fidelity of the ground tests critically depends on the appropriate selection and operation of the plasma source [6]. This work presents a variety of sources used for LEO plasma environmental simulation. The classification and operating principles of these sources are discussed further in the paper. Different techniques applied for measuring the plasma parameters are also outlined. The characteristics of the resulting plasma, focusing on the ability to achieve the specific density and ion energy ranges relevant to replicating LEO spacecraft interactions, are addressed in further sections.

2. PLASMA SOURCES FOR EXPERIMENTAL SIMULATIONS

Plasma sources are essential tools for simulating various space environments in ground-based facilities, allowing researchers to examine the behaviour of space instruments and materials under controlled conditions. To investigate how space instruments behave under different conditions and plasma properties, simulations using ground-based vacuum facilities have been conducted through numerous laboratory experiments. These studies consider the variation of components and plasma parameters, particularly, the density of plasma particles, electron temperature, and ion energy [1]. These parameters vary based on the operating condition of the facility, such as the discharge/ beam voltage, discharge current, gas flow rate, and facility background/ base pressure [3]. Two crucial factors for simulating LEO plasma are electrons and their thermal energy, as well as the ionized gases (e.g., Argon (Ar) or Xenon (Xe)). The ion flux to the spacecraft surface is determined by its orbital speed, while the ion flux in the vacuum chamber depends on the operating conditions of the plasma source [5]. Therefore, various types of plasma sources are used to generate plasma. These sources are installed inside the vacuum chamber to create a plasma environment like the intended orbits. Examples of the sources considered are discussed below.

2.1. Hollow Cathode Discharge (HC)

A hollow cathode plasma source is a metal plasma source, comparable in some respects to a parallel plate capacitively coupled plasma (CCP) source. The hollow cathode (HC) discharge is a low-pressure glow discharge occurring within a cylindrical cathode cavity. The physics behind its operation involves electron emission from the cathode surface, often initiated by ion bombardment [11]. These electrons are accelerated across the cathode dark space, gaining energy to excite and ionize a sustaining gas (e.g., He, Ar). The unique cylindrical geometry enhances electron oscillation and collision probability, increasing excitation and ionization efficiency – a phenomenon known as the hollow cathode effect. Sputtering of the cathode material, caused by ion bombardment, introduces sample atoms into the plasma, leading to characteristic light emission used in spectroscopy [3]. In LEO ground-based simulations, hollow cathode discharges are employed to generate low-energy plasma for studying spacecraft material interactions with the ionosphere. For instance, studies have used hollow cathodes to simulate the plasma environment encountered by satellites, focusing on parameters like plasma density and electron temperature. The plasma properties from this source can be varied by adjusting the discharge current and gas flow rate, which affect the stability and generation of energetic ions. Increasing the discharge current or decreasing the gas flow rate can lead to higher plasma densities and electron temperatures. Gas pressure and the geometry of the hollow cathode also play crucial roles in determining plasma characteristics [3]. Resources include inert gases (He, Ar), DC power supplies (up to 1000 V), and vacuum systems (1–20 Torr) [3]. Cathode materials like Tantalum, Thoriated Tungsten, or Barium-impregnated materials are common [4]. For this particular source, efficient hollow cathode behaviour is typically satisfied at a current of approximately 30 mA and higher. This source can produce low-temperature plasma (~1 eV) [12]. Figure 1 shows the components of the HC structure [4].

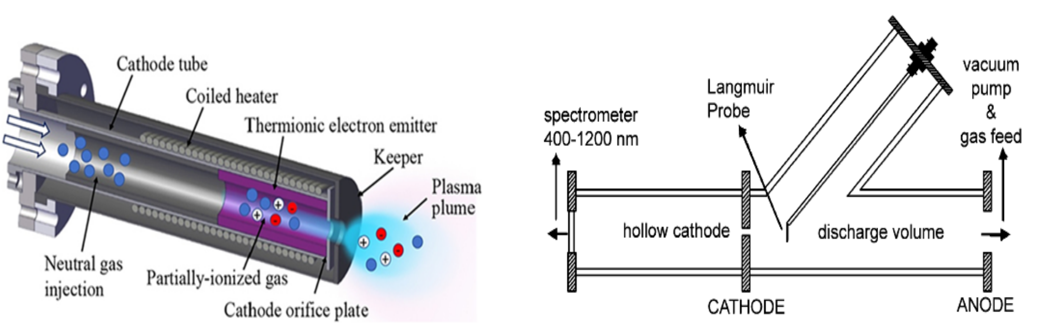

Fig. 1. Cathode schematic showing the electrode components.

2.2. Kaufman/Ion Source

The Kaufman ion source is a broad-beam, multi-aperture electron bombardment source featuring an independent discharge chamber and a double-grid ion extraction system. Its principle of operation involves introducing a working gas – commonly Argon, Xenon, or Oxygen – into the discharge chamber, where it is ionized by electrons emitted from a thermionic cathode, such as a filament or hollow cathode. A magnetic field, often generated using multipole arrangements of permanent magnets, enhances ionization by confining electrons and increasing their path length and probability of collisions with neutral atoms. Once ionization occurs, positive ions are extracted from the plasma sheath using a set of grids. The potential difference across the grids forms a controlled electric field that accelerates and collimates the ions into a well-defined beam [2]. This ion beam makes the Kaufman source suitable for simulating LEO-like plasma conditions in laboratory environments. Ground-based investigations have utilised Kaufman ion sources to replicate the low-energy, high-density ion flux typically experienced in Low Earth Orbit (LEO) [2]. For example, the scientists at NASA Marshall Space Flight Centre employed a compact Kaufman source to generate Xenon plasma for spacecraft material interaction studies under LEO-relevant ion energies and densities. These experiments generally simulate plasma environments characterised by ion densities in the range of 10^5–10^6 cm^{-3} and energies from a few to tens of electron volts (eV), allowing detailed investigation of erosion, surface charging, and material degradation [1].

This source is formed as a broad-beam, multi-aperture electron bombardment source featuring an independent discharge chamber and a double-grid ion extraction system. Its principle of operation involves introducing a working gas (e.g., Ar, Xe) into the discharge chamber, where it is ionized by electrons emitted from a cathode (filament or hollow cathode). A magnetic field, often in a multipole configuration using permanent magnets, enhances ionization efficiency by trapping electrons and increasing their collision probability with neutral gas atoms. Positive ions are then extracted from the plasma sheath into the double-grid acceleration zone. Applied potentials on these grids create an electric field that accelerates and focuses the ions into a directed beam [2]. Figure 2 (a) shows a schematic top view of the ion beam system featuring a Kaufman-type ion source. The setup includes a sample holder centrally positioned relative to the ion beam and Faraday cups for beam characterisation. The entire arrangement operates within a vacuum chamber, and an ESMS spectrometer is attached for ion analysis. The internal structure of the Kaufman-type ion source is shown in Fig. 2 (b). The gas inlet, discharge chamber, and magnetic confinement are displayed in the figure. The ions generated between the cathode and anode are extracted and accelerated through a set of grids (screen and accelerator grids) under controlled voltages [6]. Relevant ground-based LEO investigations have utilised Kaufman ion sources to simulate the ionospheric plasma environment [1]. Resources include gases such as Ar, Xe, with DC or RF power supplies, and high vacuum system [2]. Due to their stability and tunability, Kaufman sources are not only utilised in space environment simulations but also extensively applied in ion beam processing technologies such as ion beam etching, surface modification, thin-film deposition, and electric propulsion systems. Operational requirements typically include high-vacuum systems (<10^{-3} Pa), DC or RF power supplies, and a feed gas system capable of delivering inert or reactive gases like Ar, Xe, O2, and N2 [2].

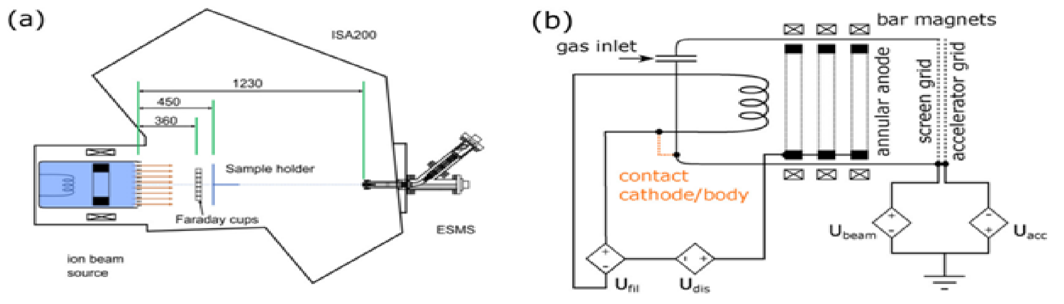

Fig. 2. (a) Schematic top view of a Kaufman-type ion source, and (b) Internal structure of the source.

At NASA's Marshall Space Flight Centre, a simple Kaufman source is used. The filament current is up to 6 A, and the bias filament negative with respect to the container is varied approximately from 20 V to 25 V. Xenon gas (Xe) is used. The image displays the source, and the schematic diagram of the applied circuit is shown in Fig. 3. The scientists apply two separate power supplies (HP 6030A), and a short pipe piece at a height of 5 cm is used for gas flow, exactly perpendicular to the filament line. Pieces of permanent magnets (PM) are used and mounted on top of the canister in a circle. This source provides an electron density of 10^6 cm^{-3} and temperatures ranging from 0.2 eV to 0.3 eV with a xenon gas flow. All of these are suitable for large chambers (Vertical 2 m diameter and 3 m height, horizontal 2 m x 2 m, respectively) [13].

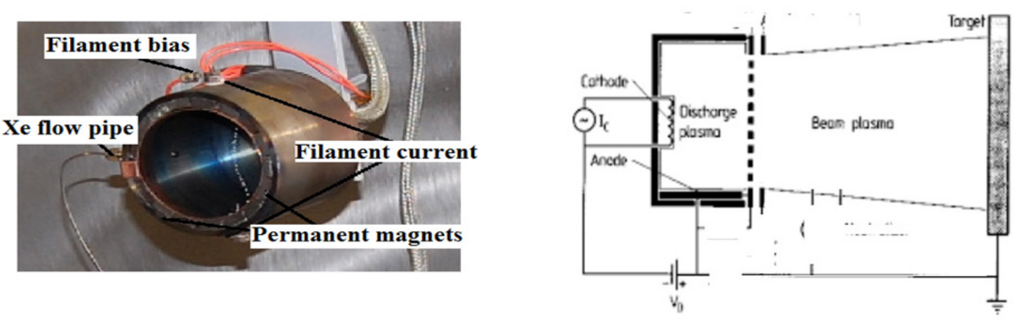

Fig. 3. Kaufman ion source used at the NASA Centre.

2.3. Penning Discharge/Plasma Ion Source

This source is one of the common sources used to simulate the LEO plasma environment. It is suitable for producing low temperature plasma with a density of

10^6 cm^{-3}. The Penning discharge plasma source operates based on the principle of applying a DC voltage between a cathode and an anode ring, with an axial magnetic field present. Electrons emitted from the cathode are trapped by the axial magnetic field, causing them to oscillate and increase their path length, thus enhancing the probability of collisions and ionization of the low-pressure gas (e.g., Xe, Ar) [6]. A feature of this source is its ability to sustain a discharge at relatively low pressures and voltages due to the efficient electron trapping and ionization processes. The outer cylinder is metallic and encircled with coils to generate the axial magnetic field required for electron trapping and enhanced ionization [7]. The electrons from the heated filament are accelerated toward the biased anode, striking the Argon atoms and leading to ionization.

This source is one of the common sources used to simulate the LEO plasma environment. It is suitable for producing low-temperature plasma with a density of ~10^6 cm^{-3}. Relevant ground-based LEO investigations have utilised penning discharges to study spacecraft interactions with the ionosphere [14]. The properties of such generated plasma involve low-temperature plasma with a density of 10^6 cm^{-3}. Operating conditions typically involve gas pressures in the range of 0.1 to 10 mTorr and magnetic field strengths from 10 to 500 Gauss [6], [15]. Resources include gases (Xe, Ar, He, H), DC voltage power supplies (20–200V, potentially up to kV), magnetic field sources (permanent magnets or electromagnets), and vacuum systems (0.1–10 mTorr) [6], [15]. Figure 4 shows a cross-sectional schematic and structure of a penning discharge plasma source [7]. Schematic diagrams and structure, for example, of the experimental configurations are shown in Fig. 5 [16], [17].

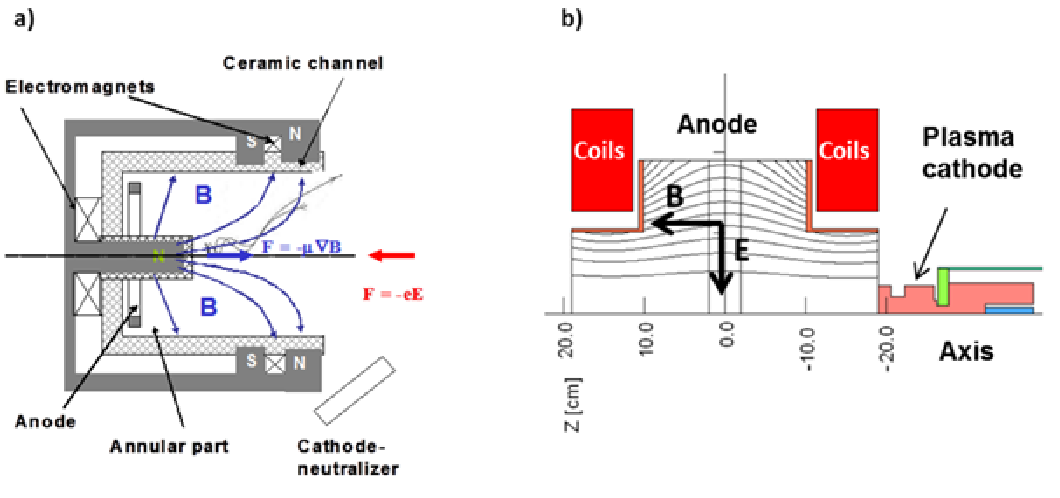

Fig. 4. (a) Cross-sectional schematic of a Penning discharge plasma source, featuring an annular ceramic channel surrounded by electromagnets that generate a radial magnetic field (B). Electrons are confined by the crossed electric (E) and magnetic (B) fields, enhancing ionization efficiency. The cathode-neutralizer maintains overall plasma neutrality. (b) Field line distribution along the axis, showing how magnetic and electric fields are structured around the anode and plasma cathode, optimising plasma confinement and extraction.

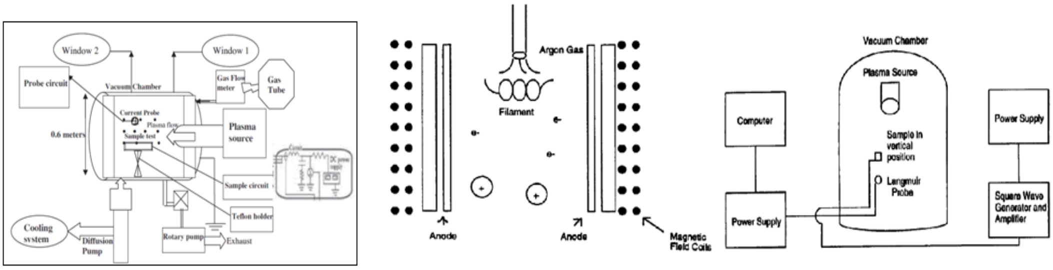

Fig. 5. Schematic diagrams of the discharge and penning ion source used in the experiment.

2.4. Electron Cyclotron Resonance (ECR)

The (ECR) is a source used to produce low-energy plasma from argon gas flow. In the work of Tahara and Masuyama (2006) [18], microwaves of maximum power of 1 kW and frequency of 2.45 GHz are introduced into a chamber of the ECR discharge. By applying an input power of 300 W, the argon gas flow rate is increased to over 8 sccm until the plasma is generated with a low temperature value of 1eV and an electron number density of 4.5 x 10^ (13) m^{-3}. Through the ECR source, stability and precise control over plasma density and electron temperature can be maintained [18].

Specific features of this plasma source include its ability to produce high-density plasmas at low pressures and the potential for independent control of ion energy and flux [19]. Relevant ground-based LEO-related works have utilised ECR plasma sources to generate plasmas with properties mimicking the ionosphere. These sources can produce low-density plasmas with adjustable ion and electron energies relevant to LEO conditions. The generated plasma properties often include electron temperatures around 0.1 eV to a few eV and ion densities in the range of 10^ (6) cm^{-3} [19]. ECR plasma sources are also uniquely applied in semiconductor processing and fusion research. Resources include a microwave source, magnets (permanent or electromagnets), a vacuum system (10^{-4} to 10^{-2} mbar), and various gases (e.g., (He, N_2, O_2, Ar) [19]. Figure 6 presents examples of multi-polar based systems driven by a single ECR plasma source [20], [21].

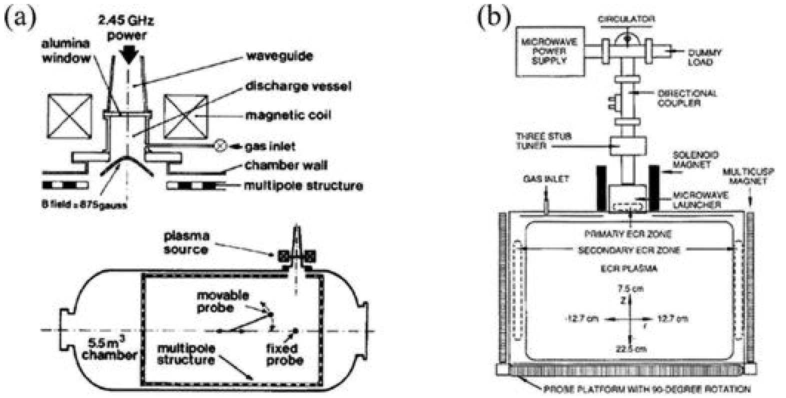

Fig. 6. Examples of multipolar based systems driven by a single ECR plasma source.

2.5. Radio Frequency (RF)

One of the more interesting configurations of plasma sources is the Radio Frequency (RF) discharge between two plane electrodes. Plasma is generated by applying the RF beam source under suitable pressure. In this arrangement, the plasma is capacitively coupled, and the power supply almost exclusively interacts with the plasma through displacement current. The "RF" discharge is typically used with electronegative gases, which can create negative plasma through the electrostatic acceleration of ions. The beam source includes a discharge tube, a water-cooled RF coil, an inert gas (argon or xenon), a viewport for observation, and a shutter. The radical beam allows for obtaining radicals from a small aperture, which is used for differential exhaust. The operating procedure involves using an RF generator (typically at 13.56 MHz) to create an oscillating electric field in CCP or an oscillating magnetic field in ICP. This field energizes electrons in the gas (e.g., Ar, O_2), leading to ionization and plasma formation [22]. A specific feature of RF sources, particularly ICP, is their ability to generate high-density plasmas with independent ion density and energy control.

While specific ground-based LEO investigations using RF plasma sources are not explicitly detailed in the provided references, RF plasma sources, especially ICPs, can generate plasmas with densities and energies relevant to the LEO environment. Researchers might utilise these sources to study the effects of simulated LEO plasma on spacecraft materials by adjusting parameters like RF power and gas pressure [23]. Resources include an RF generator, a matching network, a vacuum system, and various gases [4], [5], [22]. A diagram illustrates the "RF" principle, and the reaction mechanism is shown in Fig. 7, while the "RF" discharge and a schematic diagram illustrating the source applied and the experimental setup are shown in Fig. 8 [23], [24]. Moreover, RF plasma sources are also broadly used in industrial and research applications, including surface modification and thin film deposition [23].

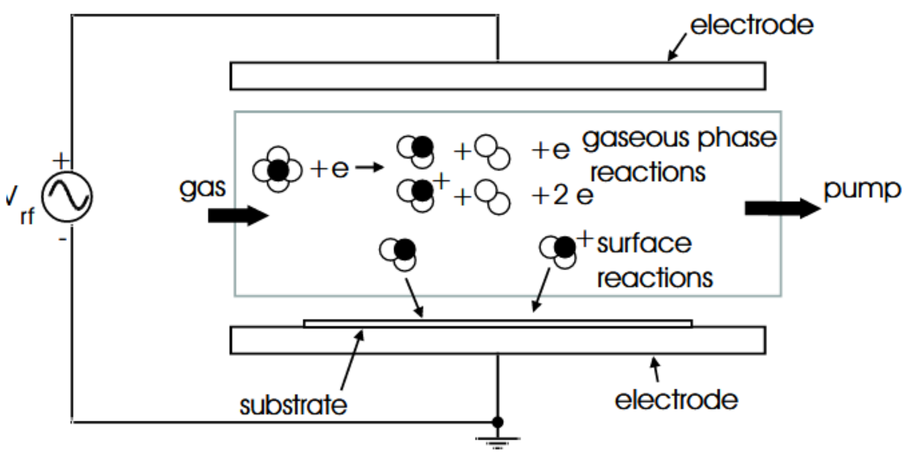

Fig. 7. "RF" principle and plasma-surface reactions.

Fig. 8. RF discharge tube and a schematic diagram of the experimental setup of the source with an RF generator (13.56 MHz).

2.6. Magnetic Filter-Equipped Plasma Source

The characteristics of the magnetically filtered plasma sources have been illustrated and discussed in previous studies by many authors [1], [25], [26]. Figure 9 shows a schematic diagram of the cross-section of the magnetic filter set and the plasma source [26]. These sources are particularly relevant for LEO ground-based simulations. For example, a 16-cm diameter plasma source using a transverse-field magnetic filter has been described for simulating LEO conditions, producing low electron temperature plasmas (0.14 to 0.4 eV) with streaming ion populations (4 eV to 6 eV) using argon "Ar" gas. These properties closely imitate the LEO environment [27]. In the work of Enloe et al. (2004) [25], the authors stated that the typical flow rate of argon gas used was about 16 sccm, resulting in a background pressure inside the vacuum chamber of 8.5 × 10^ (–5) Torr. The plasma is maintained and kept approximately steady through a bias voltage applied between the hot filament cathode and anode. The authors clarified that, for these data, although the anode was electrically separated from the discharge chamber, it was kept at the potential of the vacuum chamber. This discharge electrical potential varies between 10 V and 80 V. Typically, for the currents in the range of 10 A to 12 A required to heat the filament, there is a decrease in voltage of approximately 20 V across the filament. The system operates when the voltage required for the discharging process is held constant, while the filament current should be adjusted to regulate the current in the discharge occurring in the region between the filament cathode and the anode.

In the research work of Williams et al. (2004) [1], the authors used a power supply attached between an anode and the filament cathode to investigate the plasma created using argon gas flow. They stated that the magnetic filter was a better applicant to simulate LEO plasma. The source produces plasma of low electron temperature within the range of 0.14 eV to 0.45 eV. Rubin et al. (2009) [26] stated that the collection of experimental data in the expanding plasma downstream of the source was a good candidate for use as a LEO plasma simulator, as the expanding plasma has a very low electron temperature and contains streaming ions – the plasma environment encountered by satellites in the LEO orbit. The authors confirmed that this applied source could produce plasma of streamed ion energies within the range of 2 eV to 5 eV and electron temperatures of 0.17 eV to 0.35 eV. These resulting data are obtained by the variation in the adaptable conditions of the operating system concerning the flow rate of the used gas and the discharge current. The authors showed that beyond the above demonstrated system, an optimisation for both the plasma source and the magnetic filter should be performed to enhance the properties of the plasma. This could help achieve the production of a higher reliability LEO plasma environment.

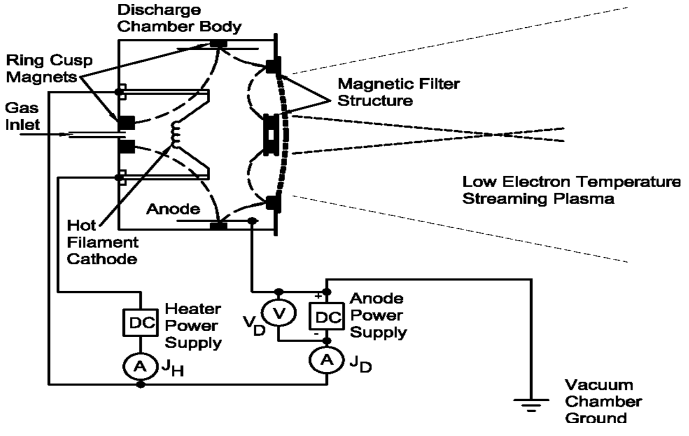

Fig. 9. Diagram of the magnetic filter set and operational plasma source.

3. PLASMA CHARACTERISATION AND MEASURING TECHNIQUES

Accurate characterisation of plasma environments is critical for validating ground-based simulations of space conditions, such as those in LEO orbit, and for understanding plasma-material interactions. While Langmuir probes are a cornerstone of plasma diagnostics, a comprehensive analysis requires a suite of advanced techniques to measure key parameters such as ion energy, electron temperature, density, and species composition. This section provides a detailed, professionally crated overview of several established diagnostic methods such as Retarding Potential Analyzers (RPAs), advanced Langmuir probe configurations, Faraday Probes, ExB Probes (Wien Filters) and non-intrusive optical techniques – each supported by in-text citations to publicly accessible sources.

3.1. Retarding Potential Analyzers (RPAs)

Retarding Potential Analyzers (RPAs) are electrostatic instruments designed to measure the ion energy distribution function (IEDF) along their axis. They are vital for studying ion acceleration, plasma potential variations, and energetic ion populations relevant to spacecraft charging and material sputtering in space environments. RPA consists of multiple grids and a collector plate. Grounded entrance grids define the acceptance angle and shield internal components from external plasma potentials. A negatively biased grid (e.g., -50 V) repels electrons, while an ion-retarding grid with a swept positive potential filters ions based on their kinetic energy. A suppressor grid, if present, prevents secondary electron escape [28]. Design considerations of the RPAs include grid transparency and alignment to reduce collision effects, with spherical grids improving resolution for divergent flows [28]. RPAs are widely used in space plasma studies and laboratory experiments, such as ion beam and thruster plume analysis. A grid with an applied voltage repels the incoming ions. Only those ions with high enough energy to overcome the repulsion can come through the grid [29]. A diagram representing the RPA principle is shown in Fig. 10 [29]. In ground-based LEO plasma simulation, RPAs are applied for measuring ion energy distribution, which is crucial to understand spacecraft charging and erosion effects due to the ion impacts [1].

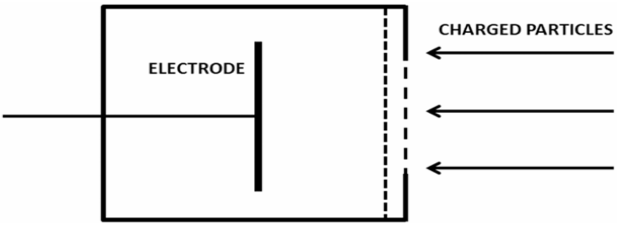

Fig. 10. RPA principal.

3.2. Langmuir Probes

Langmuir probes are considered a system used to determine the physical characteristics of plasma parameters. This instrumentation system works by inserting one or more electrodes immersed in the plasma and applying a fixed or time-varying electric potential between the electrodes. Langmuir probes provide localized measurements of plasma parameters such as electron temperature, electron density, ion density, and plasma potential through current-voltage (I-V) characteristics of an immersed electrode. There are various types of Langmuir probes including:

- Single Probe: Measures the full I-V curve but may perturb the plasma;
- Double Probe: Utilises two probes for a floating characteristic, reducing plasma perturbation [30];
- Triple Probe: Offers instantaneous measurements of electron temperature and ion density without the need for sweeping, making it ideal for fluctuating plasmas.

The simplest configuration for collecting different Langmuir probes is shown in Fig. 11 [31]. The choice of probe geometry (planar, cylindrical, and spherical) depends on the plasma environment (e.g., density, magnetic field, flow) and affects the applicable theoretical analysis for current collection [32]. In the study by Williams et al. (2004) [1], RPA was utilised to measure the ion energy distribution in ground-based LEO plasma simulation, replicating the charging effects observed on spacecraft surfaces. Polzin et al. (2023) used a Langmuir probe downstream of a magnetic filter plasma source to assess the electron temperature and plasma potential, validating the similarity to ionospheric-like LEO plasma [27].

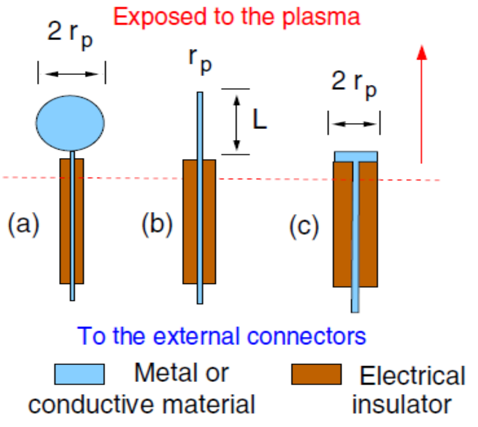

Fig. 11. Langmuir probes with radius r_p; a) spherical, b) cylindrical, and c) planar geometries.

3.3. Faraday Probes

Faraday probes measure ion current density in plasma beams, offering insights into beam profiles and thruster performance. Variants include planar probes with guard rings (PPGR) and Faraday cups (FC). The collector, which is negatively biased to repel electrons, measures ion current [33]. Materials like molybdenum could be utilised to minimise sputtering. A Faraday Cup probe is employed to measure the ion beam current from a hollow cathode discharge in order to simulate LEO plasma induced erosion on spacecraft materials [5]. The structure and components of the Faraday probe are shown in Fig. 12 [34].

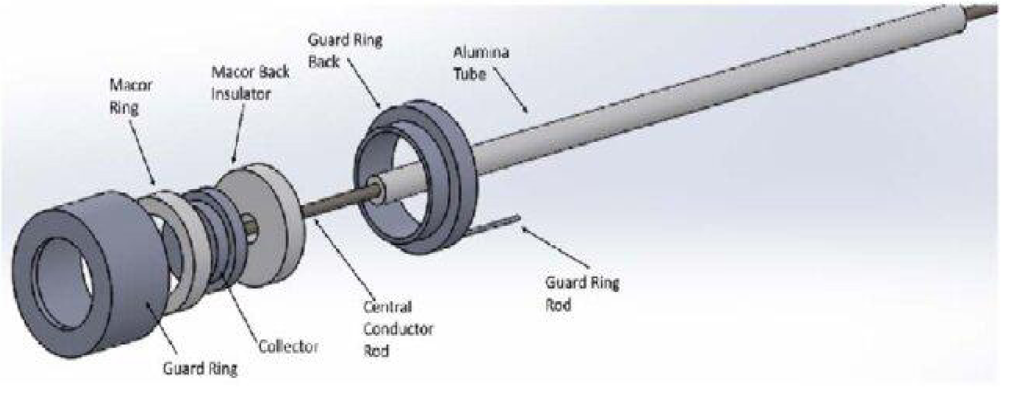

Fig. 12. View of Faraday probe.

3.4. ExB Probes (Wien Filters)

ExB probes use crossed electric (E) and magnetic (B) fields to resolve ion species by their charge-to-mass ratio. Some ions pass undeflected, while others are filtered, enabling "q / m" spectral analysis by varying (E) or (B) [35]. In the research by Yevgeny et al. (2019) [36], a modified ExB Penning discharge was analysed using both Langmuir probes and ExB energy filter to evaluate ion transport across the magnetic field, aiding in simulating magnetized LEO plasma conditions [4]. The images shown in Fig. 13 illustrate the structure of a Wien Filter probe [37].

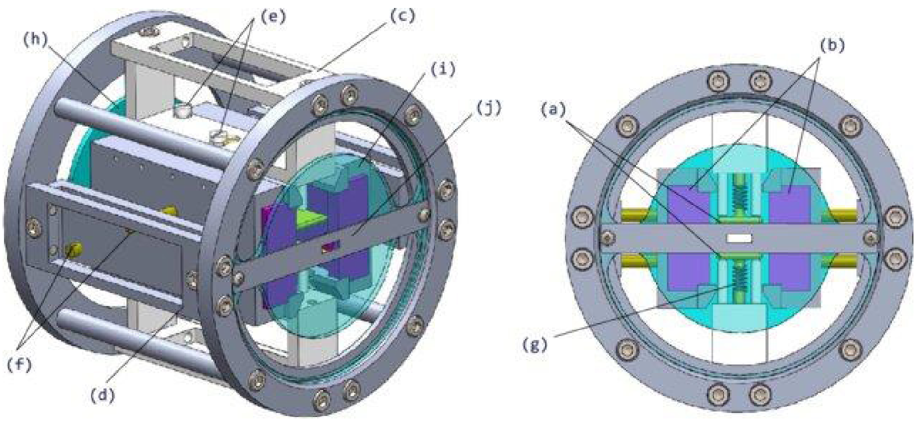

Fig. 13. Wien Filter probe: (a) electrostatic deflector plates, (b) permanent magnets, (c) deflector plate supporting bridge, (d) magnet supporting bridge, (e) deflector plate alignment screws, (f) magnet alignment screws, (g) plate positioning spring, (h) entrance plate, (i) exit plate, and (j) collimating slit.

3.5. Non-Intrusive Diagnostic Technique (NIST)

The key methods of the NIST technique can be summarised as follows [38], [39]:

- Optical emission spectroscopy (OES): This method identifies species and estimates electron temperature through the emitted light;
- LIF: It measures density and velocity distributions using laser-excited fluorescence;
- Mass Spectrometry: It is used for detailed species analysis (neutrals and ions);
- Microwave Interferometry for line-integrated electron density;
- Thomson Scattering for direct, localized measurement of temperature and electron density.

The review of NIST presented the application of optical emission spectroscopy (OES) in identifying species and excitation temperatures in low-pressure glow discharges. This application of OES parallels diagnostics in LEO plasma facilities [23]. Whilst the described diagnostics provide localized data, understanding spatial variations within the plasma volume requires mapping. Mounting probes on computer-controlled linear or rotational translation stages enables systematic measurements at multiple points. Spatial mapping of parameters like electron density and current density of ions is achieved using translation stages, providing one, two, or three-dimensional profiles critical for validating simulations [39].

4. APPLIED CONDITIONS AND PLASMA PROPERTIES

We focus on understanding how these different sources generate plasma under specific operating conditions and how these properties compare to those found in the D, E, and F layers of the ionosphere. Examples of the conditions and plasma properties resulting from various sources applied in simulating the LEO plasma environment are given in Table 1. The data presented in the table help identify the optimal source configurations for achieving realistic ground-based simulation of LEO plasma environments.

At NASA's Marshall Space Flight Research Centre, the scientific team encountered several problems with the use of "Ar" gas in their experimental studies [13]. The use of argon resulted in higher filament temperatures and reduced lifespan. The electron temperature was consistently measured at 2–3 eV, which seems too high for "LEO" space plasma simulations. Many years ago, such a source was used in a bell jar measuring 60 cm in diameter and 90 cm in height. However, the source overheated within minutes of operation, prompting the scientists to implement water cooling resulting in a very complicated setup. Attempts to use a hollow cathode as a plasma source were unsuccessful due to the high gas flow requirement, leading to elevated neutral gas pressure in the chamber (above 100 μTorr) and increased electron temperature (above 2 eV).

Consequently, the scientists concluded that the hollow cathode was not a suitable source, particularly, for use in a small bell jar for space plasma simulation. The scientific team compared the mass number and ionization potential of argon and xenon. Argon has a mass number (A=40) and an ionization potential (I=15.2 eV), while Xenon has values of A=131 and I=12.1 eV. This indicates that an "Ar" atom spends approximately half the time in the ionization zone compared to "Xe". Additionally, xenon gas has a higher cross-section than argon. The 3.1 eV difference in ionization potentials influences the ionization probability exponent. As a result, the scientists concluded that the Kaufman source was not the optimal choice for "Ar" plasma. The use of the Kaufman source with xenon gas flowing in large chambers is more preferred and suitable to conduct real tests in a simulated plasma environment, and the magnetic field in the centre of the gap/hole is stronger than that at the cathode surface. They have recommended that plasma generation and the operating process depend on the choice of the type and operating pressure of the gas used [13]. Moreover, Goebel and Katz (2008) [33] confirmed that both "Ar" and "Xe" gases were frequently used due to their relatively high atomic mass, which allowed for better momentum transfer during sputtering processes, and their inert nature, which minimised unwanted chemical reactions with the simulated environment and spacecraft materials.

Table 1. Applied Sources and Plasma Characteristics

Source	Plasma Properties	Operating Conditions (Pressure, Voltage, Current)	Gas Species	Orbital Equivalent	Ref
Hollow Cathode Discharge	Electron temp: 0.5–1 eV, Density: 10^5–10^6 cm^{-3}	Pressure: 1–20 Torr, Voltage: up to 1000 V, Discharge Current: ≥ 30 mA	He, Ar	D Layer (low altitude, cold plasma) E Layer (denser, cooler plasma)	[3]-[5], [40]
Kaufman Ion Source	Ion energy: few eV to tens of eV, Density: 10^5–10^6 cm^{-3}	Pressure: <10^{-3} Pa (high vacuum) Beam Voltage: tunable (a few V to tens of V) DC/RF Power Supply	Ar, Xe, Kr, O_2, N_2	E Layer (mild ion density, flowing ions) Transition to F Layer (if high energies)	[1], [2]
Penning Discharge Source	Electron temp: ~0.1–2 eV, Density: ~10^6 cm^{-3}	Pressure: 0.1–10 mTorr, Magnetic Field: 10–500 Gauss, Voltage: 20–200 V (up to kV)	Ar, Xe, H_2, He	D Layer (low temp plasma) E Layer (with higher discharge energies)	[6], [7], [14]
Electron Cyclotron Resonance (ECR)	Electron temp: 0.1–few eV, Density: 10^5–10^6 cm^{-3}	Pressure: 10^{-4}–10^{-2} mbar, Microwave Power: 2.45 GHz, Magnetic Field: 875 Gauss	H_2, He, N_2, O_2, Ar	E Layer (low density plasma) F Layer (higher density at low energy)	[19], [41], [42]
Radio Frequency (RF) Plasma Source	Electron temp: adjustable, Density: 10^5–10^6 cm^{-3} (ICP mode higher)	Pressure: variable, Frequency: 13.56 MHz, Discharge Power: RF-dependent (adjustable)	Ar, O_2, Fluorocarbo	E Layer (for moderate density plasmas) Possibly lower F Layer (at higher density conditions)	[15], [22]
Magnetic Filtered Plasma Source	Electron temp: 0.14–0.4 eV, Ion energy: 4–6 eV, Low-density plasma	Moderate pressure (exact depends on setup) Transverse Magnetic Field, DC/RF Powered Plasma Generation	Ar, O_2	D Layer (cold, low energy plasma) E Layer (depending on ion energies)	[40], [27]

5. CONCLUSIONS

LEO plasma environments present unique challenges and opportunities for space missions, necessitating the development of specialised plasma sources that replicate the conditions encountered by satellites and spacecraft. To simulate these conditions on the ground for testing, various plasma sources have been developed, each with distinct operational characteristics and suitability for different applications. Plasma sources operated with different gases, such as argon or xenon, are effective for simulating LEO plasma conditions. They offer distinct advantages depending on the specific requirements of the simulation or application, such as the need for high-density plasmas, low electron temperatures, or specific ion energies.

Understanding the properties and operational conditions of these sources is crucial for effectively replicating LEO plasma environments and advancing space research and technology. The presented work provides insight into various types of sources utilised in simulating LEO plasma environments. The explanation of factors such as the gas used to affect the properties of examples of the applied sources has been provided. Different techniques used for measuring the resulting plasma characteristics have also been given.

The recommendations to scientists and researchers include the estimation and identification of the optimum source as a LEO plasma simulator that satisfies the physical conditions and plasma parameters required to verify the best performance of the simulated ground tests for a specific application. This may help in understanding the necessity of developing experimental simulation ground tests related to the plasma sources used for testing the charging and arcs, and degradation of spacecraft structural materials due to plasma impact.

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