The Development of Test Facilities for Induced, High-frequency Plasma Instabilities

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***Abstract*— We present results from modifications to test facilities equipped with a plasma source capable of producing a LEO–type environment. The modifications impose an oscillation to the output, thus simulating ionospheric disturbance. The frequency of the oscillations is adjustable as well as the base-line output of the source.**

***Index Terms*—plasma, low Earth orbit, simulation**

I. Introduction

CONSTRUCTING a laboratory apparatus to accurately simulate a low Earth orbit (LEO) plasma is a challenging, yet critical component of an ionospheric research satellite mission. The parameters of sub-auroral LEO plasma are relatively straightforward. It is considered to be "mesosonic", by which we mean that the spacecraft velocity is greater than the ion thermal speeds, but it is lower than the electron thermal speeds. Typically, the LEO plasma can be modeled as a two-species quasi-neutral isothermal plasma, where the ions are represented by a drifted Maxwellian whose primary drift velocity vector is opposite to that of the spacecraft. The electrons typically have thermal energies around 0.1 eV, and in the approximation that the ionospheric ions are dominated by atomic oxygen, the drift energies (relative to the spacecraft) are approximately 4.5 eV. In the quiet ionosphere, plasma densities may range from 1×10^3 to 1×10^7 particles per cm^3 depending on local time of day and position in the solar cycle. However, during ionospheric storms associated with equatorial plasma bubbles (EPBs), highly-organized spatially-structured depletions up to three orders of magnitude have been observed. *In-situ* plasma instruments are typically designed to cover various dynamic ranges to capture different effects of storms on ionospheric plasma densities and temperatures, and these instruments need to be calibrated in a controlled environment in order for their measurements to be used to determine the physical properties of the ambient plasma during a space mission. Unfortunately, LEO plasma simulations in the lab pose a number of difficult challenges. With the advent of the magnetic filter type plasma source (referred to as "the source"), LEO plasma simulations have been able to replicate high-density, low temperature plasmas with an ion drift energy similar to that seen in LEO [Williams]. A down-side to this design, however, is that the plasma temperature and density are not independent of each other. This precludes the ability to calibrate the instrument response function associated with each of these parameters in isolation from each other.

We present here a modification to the source that enables real-time control to the plasma density with minimal impact on the other plasma properties—especially the electron temperature. Thus, it is possible to realistically simulate changes in the ionosphere ranging from day–night transitions to localized, high frequency turbulence. This research is an extension of previous research conducted at Penn State [McTernan]. The primary differences between the two research campaigns are the frequencies of operating modes and that the modified source will be used as part of a test plan to increase the technology readiness level (TRL) of two space instruments.

The previously modified source was actuated by a lever arm in mechanical communication with a stepper motor. The time required to go from fully open to fully closed was on the order of 10 seconds (0.1 Hz). The maximum rotation angle was 30 degrees. The output grids of the modified source discussed in this paper rotates via a cable and pulley system and is capable of producing plasma oscillations in the kilohertz range (Fig. 1).

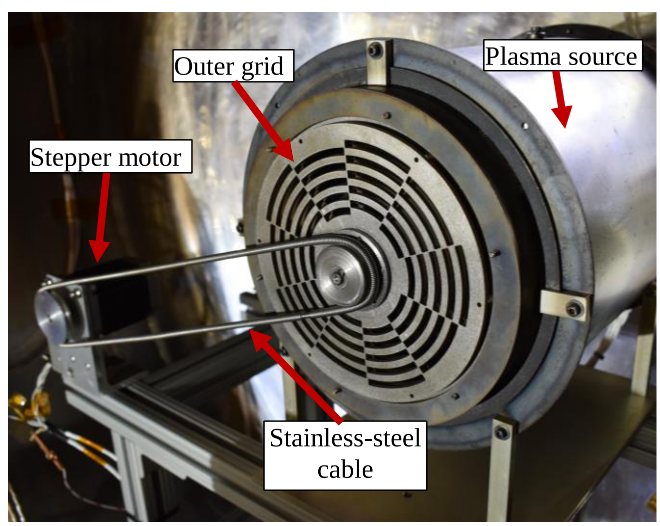

Fig. 1. Modified plasma source at Marshall Space Flight Center with stainless steel pulley and cable system used to rotate the outer grid (i.e., the aperture).

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It can undergo any number of rotations. Each complete rotation corresponds to five open/close cycles since there are ten radial sections (See Fig. 1). We will refer to the present system as the “MSFC grids” and the previous system as “Penn State grids”.

II. Experimental Setup

We conducted experiments to verify the efficacy of using a cable and pulley system to rotate an outer grid (i.e., the aperture) of the plasma source. The test facilities used were located at NASA Marshall Space Flight Center. Experiments were conducted in a cylindrical vacuum chamber approximately 2.41 m (95 in) in length and 1.21 m (48 in) in diameter. The base pressure was 7×10^{-7} Torr with an operating pressure of 8.2×10^{-5} Torr. The chamber was equipped with a plasma source capable of simultaneously producing steaming ions (1–5 eV) and relatively low energy electrons (0.17–0.35 eV)—thus producing a low Earth orbit–like plasma [Williams]. Argon gas was delivered to the source at a rate of 10.00 sccm.

Plasma properties were derived using a thin, cylindrical Langmuir probe 0.1 mm in diameter and 5 cm long and a retarding potential analyzer (RPA), both mounted on a dual-axis linear stage with a range of 60 cm axially and 50 cm radially. Standard LP techniques were used to determine the plasma properties. The distance from the source to the diagnostic equipment was 127 cm axially. The linear stages were used to alternate between centering the LP and RPA radially. Mapping of the plasma revealed a large region of uniformity compared to the scale of the plasma diagnostics equipment; therefore, error in placement was negligible.

III. Results

We first compared the performance of the MSFC grids (Figs. A and B) with Penn State’s grids (Fig. C) by measuring plasma properties as a function of aperture opening. In both cases, electron density increased as a function of aperture opening, where 100% corresponds to fully open, while electron temperature remained nearly constant (within a range).

The electron and ion density range from the MSFC grids was not as large as Penn State’s grids (approximately two orders of magnitude). This could be because the MSFC grids have washers between the inner and outer grid, while there was no gap between the Penn State grids. In addition, the MSFC outer grid is not parallel to the inner grid. Both the gap and misalignment allow plasma to escape the source even when the aperture is “fully closed”.

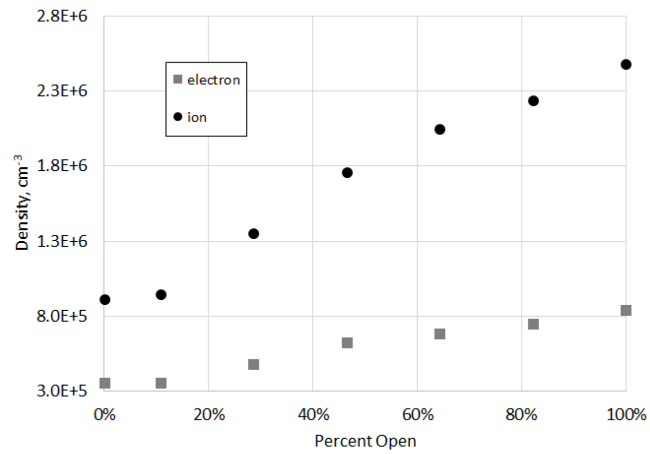

Fig. A. Electron density and ion density increases as a function of aperture opening. 100% corresponds to fully open. Data from MSFC grids.

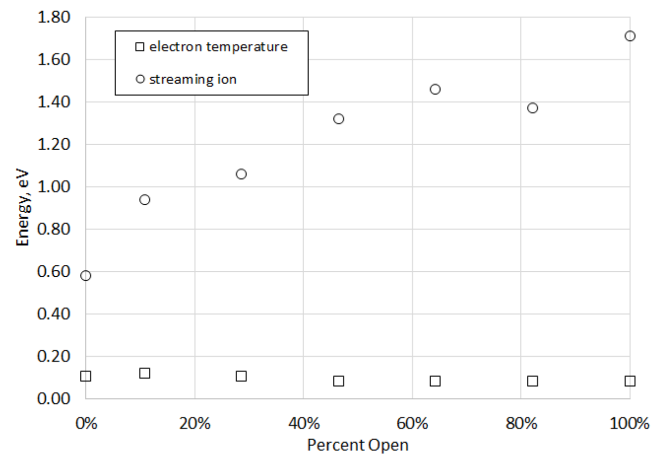

Fig. B. The electron temperature remains nearly constant through the range of aperture openings while the energy of the streaming ions increases with aperture opening. Data from MSFC grids.

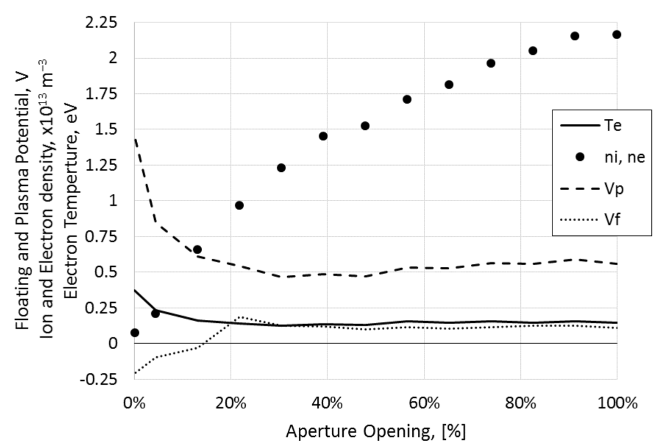

Fig. C. Data from Penn State’s grids. Used with permission.

IV. Conclusion and Future Work

We modified a LEO-like plasma source to be able to vary the density of the plasma with minimal impact on other plasma properties. In the future, we first plan to improve the MSFC grids to allow for greater range in electron and ion densities by addressing the mechanical concerns. The next task will be to confirm rotation speeds and mechanical stability at high rpms. Preliminary test indicate that rotations speeds of 30 Hz (150-Hz open/close cycles) is obtainable. We intend to increase this speed by a factor of 10. The misalignment of the outer grid with the inner grid causes unwanted wobble. The deleterious effects are amplified at high rotation speeds. Another concern is the temperature of the source, which affects the bearings. As the bearings heat up, the tolerances change. In addition, high temperatures and the vacuum environment preclude the use of plastic spacers or certain lubricants. Maximum temperatures measured on the outer surface of the source have been as high as 250 °C. Suitable bearings are needed for that temperature range.

Once mechanical control and stability have been achieved, we will use the modified source to simulate ionospheric disturbances. This controlled, oscillating plasma source can then be used for instrument development.

REFERENCES

Rubin, B., Farnell, C., Williams, J., Vaughn, J., Schneider, T. and Ferguson, D. (2009). Magnetic Filter Type Plasma Source for Ground-Based Simulation of Low Earth Orbit Environment. Plasma Sources Sci. Technol. 18, 025015.

J. K. McTernan, S. G. Bil´en, and J. D. Williams, “Real-time Plasma Density Control via a Modified Hollow-Cathode Plasma Source with a Variable Aperture,” in 14th Spacecraft Charging Technology Conference, ESA/ESTEC, Noordwijk, 2016.