Inertial Electrostatic Confinement Plasma Devices – Potential thruster technology for very accurate attitude control systems

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Abstract: Inertial Electrostatic Confinement (IEC) plasma systems were investigated experimentally at the University of Kentucky with air and argon as working gas at pressure levels between 10 and 100 mTorr and at electrical powers up to 60 W clearly aiming at non-fusion IEC operation. Starting from conventional spherical grid configurations, a cylindrical system with helix shaped electrodes was developed and tested in a rectified AC mode of operation rather than in the more conventional DC mode. The presented data focuses mainly on this cylindrical design in tight jet mode which is considered to have significant potential as a direct electric propulsion system. The electrical characteristics of different geometries are described in form of current-voltage and power-voltage characteristics. Initial emission spectroscopy measurements were carried out confirming the presence of heavy particles in the IEC beam. From the interaction of the IEC beam with an aluminum foil target in combination with the emission spectroscopy results, first estimates of heavy particle velocities and potential thrust of this system were obtained to be in the range of 5-6.4 km/s and about 1 mN, respectively. A design concept for an encapsulated system with dedicated mass flow provided to the IEC for future operation is presented.

Nomenclature

\[ a = \text{cylinder diameter} \]
\[ A_{\text{hole}} = \text{hole area, m}^2 \]
\[ AC = \text{Alternating current} \]
\[ c_e = \text{effective exhaust velocity, m/s} \]
\[ DC = \text{Direct current} \]
\[ F = \text{thrust, N} \]
\[ IEC = \text{Inertial Electrostatic Confinement} \]
\[ k = \text{Boltzmann constant, } 1.38064852 \times 10^{-23} \text{ J/K} \]
\[ \dot{m} = \text{mass flow, kg/s} \]
\[ M_{\text{part}} = \text{particle mass, kg} \]
\[ n_{\text{part}} = \text{number density of particles, } 1/\text{m}^3 \]
\[ N_{\text{part}} = \text{number of particles} \]
\[ p_{\text{stat}} = \text{static pressure, Pa} \]
\[ q_{\text{evap,Al}} = \text{mass specific heat of evaporation of aluminum, 10,530 kJ/kg} \]
\[ Q_{\text{evap,Al}} = \text{heat of evaporation of aluminum, J} \]
\[ \rho_{\text{Al}} = \text{density of aluminum, 2,700 kg/m}^3 \]

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I. Introduction

Recent years have shown an increasing interest in small satellites in particular since the introduction of a
standardized modular architecture in form of CubeSats in 1999 through California Polytechnic State University
and Stanford University with major applications in low earth orbit (LEO). Long term missions, missions which
require a particular orientation, or swarm concepts which require defined positions of individual satellites to each
other demand for on-board propulsion systems. Weight and fuel restrictions call for most efficient propulsion
systems, preferably with low mass flows and high specific impulses. Amongst current propulsion systems, electric
propulsion is known to generate the highest specific impulses but, however, increases system complexity and comes
with the penalty of additional hardware and the need of electrical power. In particular small satellites will be subject
to severe power constraints given by a limited amount of batteries or also limited size of solar panels. For different
missions, these requirements will vary, so an ideal propulsion system should be easily scalable. For such
applications, an Inertial Electrostatic Confinement (IEC) plasma creating an ion beam is proposed as a propulsion
system operating at low power levels.

IEC plasma devices are a highly interesting way of generating plasmas at high temperatures and have been
investigated in the past with special respect to fusion plasmas.1-5 Fusion related applications were also investigated
with respect to the development of electric propulsion systems6,7, non-fusion systems involved the use of IEC
deVICES for technical applications for surface modification and as neutron or x-ray sources.8,9 Typical devices were
operated in DC mode with moderate to high voltages at low pressures although RF IECs have been reported, too.10

II. Experimental investigation of IEC plasmas at UK

A. Basics of IEC plasmas
An IEC plasma is created when a Paschen breakthrough forms between two concentric electrodes at low
pressure and high voltage, and a steady discharge is formed. The electrodes consist of wire structures creating
relatively homogeneous spatial electric field distributions. Ions are accelerated towards the inner cathode,
penetrating the wire structure, collide with each other in the center, and create the high temperature plasma by
converting their kinetic energy into thermal energy. A space charge is built up by accumulating positive ions, and a
potential well confines the plasma in the center region of the inner electrode. To compensate the local space charge
created in this region, one or more ion beams form to exit the plasma cloud at a location with the lowest electric
field strength.

![Figure 1. IEC plasma with conventional gridded electrodes in star mode and with spherical helix electrodes
in focused beam mode at different pressure levels.](image)

The most common design is a configuration with two spherical electrodes. For fusion applications, the main goal
is to maximize the energy density in the contained plasma, resulting in the so-called “star mode” where multiple ion
beams leaving the plasma at usually random locations as shown in the first picture from the left in Fig. 1. Through
modification of the electrode geometry, operational behavior can be restricted to one single ion beam which leaves
the plasma at a defined location.
Depending on power and pressure levels, this beam can be well focused or expanding (spray mode). The transition from focused beam mode to spray mode is demonstrated in Fig. 1 for increasing pressure levels with otherwise constant operating conditions. Only very recently, increased interest has been shown in using this beam for propulsion processes\textsuperscript{1,12} and detailed knowledge about the nature of these beams is still limited.

In the recent years, first steps have been undertaken at the University of Kentucky to develop low power IEC designs with optimized geometries with respect to robust and easy manufacturing and operational behavior.

B. Vacuum facility and optical setup

The experiments were conducted in a vacuum chamber with approximately 12 inch diameter and a height of 14 inches. Vacuum was provided through a BOC Edwards XDS5 dry pump as a pre-stage and a BOC Edwards EXT255H turbo-molecular pump for vacuum levels down to about 0.1 mTorr. The pressure was controlled through a defined gas flow provided with a digital mass flow controller and measured with a Kurt Lesker 275i Pirani pressure gauge. Operation with residual air and argon at pressure levels between 10 mTorr and 2 Torr have been accomplished so far. High voltage was fed to the electrode through Lesker vacuum feed throughs with 6.35 mm diameter copper rods. Inside the chamber, the feeding cables were clamped to these rods and electrically insulated to prevent undesired discharges. The vacuum chamber has several observation ports from the side, one of which was equipped with a quartz glass window for emission spectroscopy measurements, and one flint glass window on top of the chamber. Several cameras were used to observe the IEC operation with images and video.

For the emission spectroscopy measurements two different optical setups have been utilized. For overview spectroscopy with marginal spatial resolution (measurement spot diameter \( \sim 5 \) mm at a distance to the electrode center of 205 mm) a Thorlabs Mirror collimator was coupled through an optical fiber to a Stellarnet Black Comet miniaturized spectrometer, sensitive between 200 and 1,100 nm. This setup was used for taking spectra of the plasma generated in the electrode center. For measurements of the ion beam exiting the inner electrode, the collimator was mounted onto a Newport linear stage to adjust the measurements position inside the vacuum chamber. The stage was mounted to the optical flange of the vacuum chamber equipped with a KJL quartz window. For the ion beam measurements, a line of sight at a vertical distance of about 10 mm to inner electrode was chosen.

For measurements with higher spatial resolution a parabolic mirror with 445 mm focal length was placed in a distance of 1080 mm to the electrode center to focus the light on the optical fiber in a distance of 780 mm to the mirror. This configuration provided roughly 1.2/1 imaging with a spatial resolution of less than 1 mm. With the latter imaging setup, radial profiles of the ion beam were measured. The optical components were mounted onto an Oriel linear stage to be able to measure the horizontal profiles. In addition, this setup allowed to measure profiles at different vertical positions of 2.5, 5, 7.5, 10, and 12.5 mm distance to the inner electrode edge by tilting the focusing mirror.

Figure 2. Vacuum chamber used for IEC plasma operation with (a) DSLR and GoPro camera for observation, (b) Thorlabs mirror collimator mounted in front of the optical window, and (c) parabolic mirror focusing setup.
C. Electrical Configuration

Instead of the traditionally used pure DC mode, a rectified AC approach was chosen at UK. Preliminary data indicates that a more stable operational behavior is achieved with the potential to extend the operational range, and arcing was significantly reduced in this operational mode. A 60 Hz AC voltage, provided by a Variac source with continuously adjustable output voltage up to 120V and maximum output power of 1.4 kVA was fed into a center-tapped 9,000 V transformer with an amplification of 75 and a maximum current of 30 mA. The resulting output voltage was rectified through a custom built high voltage diode circuit to maintain the electrode bias with the inner electrode being the negative pole (cathode) and the outer electrode working as the anode at ground potential. The resulting output signal oscillating with 120 Hz as illustrated in Fig. 3 was supplied to the IEC. A quasi-stationary IEC plasma fluctuating with a frequency of 120 Hz was obtained for a wide variety of pressures and voltages. High speed camera imaging showed a continuously oscillating plasma beam, IEC operation was possible at voltages up to 4 kV with currents up to 30 mA.

![Electrical circuit and illustration of the 120 Hz rectified AC voltage supplied to the IEC.](image)

D. IEC designs investigated at the University of Kentucky

The starting point were traditional wire grid designs with first models made of copper wire with soldered joints as shown in Fig. 4 (a) which, however, proved not suitable due to frequent arcing preferably at the soldered parts. An initial cylindrical design was made of steel wire with point welded joints shown in Fig. 4 (b) which showed rather stable operation. Finally, a geometry that does not require welding or soldering was designed by replacing the grid through a coil geometry as shown in Fig. 4 (c). This design was very successfully tested for a range of operating conditions and was defined as the UK baseline configuration for spherical IECs. In first designs, the ion beam chose a random location until a sufficiently large gap was introduced at the pole to force the ion beam leaving the inner electrode at this location. All designs were run with residual air in the vacuum chamber at pressures between 10 mTorr and 2 Torr.
A preliminary test campaign was conducted to optimize the electrode geometry of the spherical helix design with respect to the diameter ratio of the inner and outer electrode. The diameter of the outer electrode was kept constant at the maximum diameter allowed by the chamber dimensions of 6 inches. Inner electrode diameters of 1, 1.5, 2, and 2.5 inches were tested under similar conditions and the brightness of the plasma inside the inner electrode was chosen as optimization criterion. The brightest plasma was obtained with a 1.5 inch diameter inner spherical helix.

After successful operation of the spherical design, the development of a cylindrical helix configuration was started. The outer electrode was made from 2.1 mm diameter copper wire, as inner electrode, conventional steel springs were used and cut to length. For the recent versions 1 mm stainless steel wire was used to manufacture the inner electrodes due to the possibility of creating customized electrodes. These cylindrical designs qualitatively showed very similar operational behavior as the spherical ones.

E. Operational Behavior of the spherical and cylindrical helix IEC plasmas

The characterization of the IEC is of course a major task, especially since the knowledge about these devices is rather small and not much data is available, in particular for the rectified AC mode in which the UK-IECs are operated in. Since the cylindrical devices with helical wire electrodes are considered the most promising design for future applications, the following characterization focuses on these designs. As a starting point, the electrical characteristics were of main interest, in particular how they differ with different electrode configurations. The outer electrode, made of 2.1 mm copper wire with an outer diameter of 58 mm and a height of 75 mm, was kept the same for all tests. Our versions of the inner electrode have been manufactured out of stainless steel wire (11 mm, 13 mm,
and 17 mm diameter with 10 revolutions each; and a 11 mm electrode with 20 revolutions, see Fig 6.) and tested. The testing gas was mainly air, but also a few tests have been performed in Argon. During each test, the pressure was kept constant while the output setting of the Variac transformer was raised in 5% steps.

Figure 7. Different cylindrical configurations at 40 mTorr in air, from left to right: 11 mm (20 revs), 11 mm (10 revs), 13 mm (10 revs), 17 mm (10 revs)

The operational behavior of the IEC plasma is presented by voltage-current and voltage-power characteristics at different pressures. In general, the trend of the data is very similar for all electrode configurations. The current of the increases with applied voltage at a given pressure and with ambient pressure for a given voltage. With increasing pressure, the slope of the current-voltage characteristic increases and the maximal current of 30 mA provided by the high voltage transformer is reached at decreasing voltage. The actual values depend on the geometrical configuration of the electrodes. With the higher diameters, higher pressures can be reached with stable IEC operation.

Figure 8. Current vs. voltage for the cylindrical helix electrode configuration with a diameter of the outer electrode of 58 mm and diameters of the inner electrode of 11, 13, and 17 mm with 10 winding and one 11 mm electrode with 20 windings.

If the different electrode configuration are compared at the same pressure, it can be seen that the inner electrode with larger diameter tend to higher currents at lower voltages. This can be explained through the smaller distance between the inner and outer electrode which requires a weaker potential to establish the plasma discharge. Additionally, it is interesting to see that the number of windings has apparently almost no influence on the electrical
characteristics at low pressure and power levels, even though the plasma discharge looked very different, as can be seen in Fig. 9. At 40 mTorr and 50% power setting no or only a very weak beam could be observed leaving the inner electrode. And at higher pressures and power setting, however, the 11 mm electrode with only 10 windings tended to form an ion beam leaving the electron in between random winding to the side. An increased number of windings definitely helps to form a more stable plasma discharge with a defined exit direction for the beam.

If power is plotted vs. voltage, it can be seen that the power increases with pressure for the exact same Variac setting. Unfortunately, settings up to 100% Variac output were only possible for pressures of 50 mTorr and below since at higher pressures the current limitation of the high voltage transformer of 30 mA was met before the power limit of the variac could be reached. The measured maximum power was around 62 W for all electrode configurations at 40 mTorr.

Within this test series it was possible to observe the change of the beam characteristics over pressure as shown in Fig. 12, which displays the 11 mm electrode with 20 windings. Above 80 mTorr the beam tends more and more to transform into a spray mode. The larger diameter electrodes tend to have this transformation already at lower pressures, e.g. the 17 mm electrode is changing around 60 mTorr. Surprising was the observation that, independent of the electrode configuration, the most distinct beam seems to appear at pressures around 40 mTorr.
Some first tests have been performed using Argon as the working gas which turned out to be less stable than with air. Only at pressures below 30 mTorr a stable discharge could be established which showed a clear ion beam leaving the top of the electrode. At higher pressures and higher Variac settings, a different discharge forming a bright plasma cloud at the lower half of the electrode was formed which, however, was not reproducible. Sometimes. The 13 mm electrode with 10 windings formed sometimes a spray mode beam leaving the side of the electrode. Figure 13 shows a few of these undesired operating modes.

![Image](image1.jpg)

**Figure 12.** Change of beam characteristics over pressure at constant Variac setting using the 11 mm electrode with 20 windings: 20 mTorr, 40 mTorr, 60 mTorr, 80 mTorr, and 100 mTorr

Nevertheless, some data were taken at 10 mTorr and 20 mTorr which already show an obvious difference between air and argon operation, see Fig. 14. At comparable voltages, in argon operation significant higher currents were measured indicating higher power levels at comparable conditions. Additionally, it seems that the larger diameter of the 13 mm electrode has a higher impact on the current levels in argon than in air, most pronounced at 10 mTorr.

![Image](image2.jpg)

**Figure 13.** Operation in Argon, left two pictures 11mm (20 revs), right two pictures 13 mm (10 revs)

![Image](image3.jpg)

**Figure 14.** Current vs. voltage at 10 and 20 mTorr in air and argon using the 11 mm electrode with 20 windings and the 13 mm electrode with 10 windings.
mTorr. The increased current values in argon can be explained with the easier ionization of argon which provides a higher concentration of charged particles and eventually leads to higher currents in the plasma.

The testing with argon just started at UK and it is necessary to gain more information about the operational characteristics. First of all, it will be important to find out if a reliable operation with argon can be established, potentially with other electrode configurations (e.g. a shorter cylinder) which stabilize the plasma discharge. This is of high interest with respect to the utilization of the IEC as a propulsion system with noble gases in general and argon in particular as potential propellants.

III. Plasmadiagnostic Results

Emission spectroscopic data of the plasma cores was taken for almost every configuration investigated. All data was taken with the Stellarnet Black Comet fiber coupled miniaturized spectrometer in the wavelength range from 200 to 1100 nm and calibrated to spectral radiance. For measurements of the plasma core of the spherical and cylindrical configurations, the collimator was aligned with the center of the inner electrode, for measurements of the ion beam spatial variations were performed.

A. Emission spectroscopic investigation of the plasma core

First measurements were performed with the spherical electrode configuration with a 1.5 inch diameter inner electrode with residual air in the chamber with the valve to the pump closed. Through adjusting a needle valve to the outside atmosphere, the pressure was increased but no constant gas stream was supplied. Emission signatures of atomic oxygen (O), ionized and neutral molecular nitrogen (N2⁺ and N2), nitric oxide (NO) were seen. In addition, hydrogen species such as atomic hydrogen (H), OH, and NH were present and actually dominate the spectra at low pressures. With higher pressures, the emission of hydrogen species drops down and the emission of air species as expected in an air plasma starts to dominate the spectra. Although the IEC process postulates an accumulation of ions in the center of the inner sphere, most of the observed emission comes from neutrals. One possibility is that the neutrals are simply artifacts of the residual air in the center of the inner electrode and are only electronically exited through collisions with the ions. However, the spectral composition does not change with time if the operating condition is held constant. Furthermore, the spectral composition changes with operating pressure.

![Emission spectra between 200 and 1000 nm along a line of sight through the IEC center perpendicular to the ion beam (no contributions through the ion beam)](image-url)

Figure 15 Emission spectra between 200 and 1000 nm along a line of sight through the IEC center perpendicular to the ion beam (no contributions though the ion beam)
The dominance of hydrogen containing species at low pressures indicates that the lighter species are more efficiently accelerated towards the center since the accelerating force depends solely on the electrical charge while the obtained velocity depends on the mass of the accelerated particles. The charge/mass ratio is the more beneficial the lighter the atoms and molecules are. At higher pressures, collisions on the way to the center might diminish this effect. This, on the other hand, indicates that the radiating species indeed get to the center through the IEC process. It might be hypothesized that the space charge which builds up in the center actually acts as a secondary electrode which triggers a secondary discharge between the plasma in the center and the cathode. This would yield an electron flux towards the center which might partially neutralize ions. To check this hypothesis, electron density measurements would be needed.

B. Emission spectroscopic investigation of the ion beam

Dedicated emission spectroscopic measurements to characterize the ion beam were performed with the cylindrical helix configuration with 20 windings over the electrode height. Initial measurements with the collimator and low spatial resolution showed a very similar spectrum to the measurements of the plasma core showing spectral bands of NO, N$_2^+$, N$_2$, and atomic oxygen. However, if the focal point (which was significantly larger than the ion beam diameter) was moved horizontally, the emission of NO and N$_2$ showed almost no variation. Fig. 16 shows spectra taken at the centerline of the electrode and at a radial position where measurement spot did no longer contain the IEC beam. Apparently, the main emission from these systems does not come from the ion beam but is generated from a surrounding plasma cloud. (It also might be possible that this emission might be caused by reflections from the chamber wall.) To obtain the emission from the beam only, the spectrum taken at a radial offset was subtracted from the center line spectrum. In this differential spectrum, the main emission comes from N$_2^+$ with contributions from oxygen lines.

![Figure 16. Measurement geometries with the Thorlabs mirror collimator and the focusing setup with the parabolic mirror.](image)
Figure 17. Emission spectra measured with the Thorlabs collimator align on and off the center axis and difference spectrum.

To confirm this observation, the focusing setup with the parabolic mirror with 445 mm focal length was used with the same spectrometer, now providing a measurement spot of less than 1 mm diameter therefore being on the same order as the ion beam. Horizontal profiles of the plasma emission from -5 to 5 mm distance to the center line were measured with increments of 0.5 mm. These profiles indeed confirm that the main emission from the ion beam consists of N$_2^+$ and atomic oxygen with some contributions from N$_2$. Horizontal profiles were recorded at different vertical distances to the end of the inner electrode of 2.5 to 12.5 mm in increments of 2.5 mm. Fig. ??? shows radial profiles of the integrated emission of the N$_2^+$ 0-0 band between 385 and 405 nm at different vertical distances to the coil exit. For these profiles, the spectrum at the highest radial position measured was subtracted as a background emission from the spectra at all other positions. The strongest emission is seen at 5 mm above the inner coil exit. From there, the peak intensity decreases and the radial profile diverges which is well in agreement with the slightly diverging beam seen in Fig. 16.

Figure 18. Radial profiles of the N$_2^+$ 0-0 band at different heights above the inner electrode exit.

The molecular components of the beam emission gathered with the Thorlabs collimator for the 11 mm diameter inner coil with 20 windings at the center line 7.5 mm above the coil end were investigated by comparing the measured spectra to simulated ones created with the NASA Ames line-by-line simulation code NEQAIR. The emission of N$_2$ and N$_2^-$ was simulated separately and then scaled to the measurement. The best fitting simulation is considered to give the rotational and vibrational temperatures of the radiating system of concern (here the N$_2^+$ 1$^\text{st}$ Neg. and the N$_2$ 2$^\text{nd}$ Pos. systems). Fig 19 shows measured and simulated spectra for a pressure of 80 mTorr and different power setting of the Variac of 40%, 60%, and 80% corresponding to power levels of 9.73, 21.85, and 38.42 W, respectively.

In the simulation, rotational and vibrational temperatures of 1,600 K and 1,800 K provided the best fit for the N$_2^+$ emission for all three power levels. These temperatures are rather close to each other and significantly lower than the
ones for N\textsubscript{2} where a rotational temperature of 3,000 K and vibrational temperatures in excess of 5,000 K had to be used.

Figure 19. Emission spectra measured with the Thorlabs collimator align on and off the center axis and difference spectrum.
The spectral resolution is certainly not sufficient to consider these temperatures more than a first estimate, and the integration over multiple oscillations of the plasma (2 s exposure time vs. 120 Hz plasma oscillation) yields a time averaging over changing plasma conditions. However, the vibrational temperatures of N₂, much different from its rotational temperature indicates a vibrational excitation through chemical processes rather than pure thermal excitation. The amount of N₂ emission increases with electrical power supplied to the IEC. A first interpretation might be that N₂ is generated through recombination of N₂⁺ with electrons in the beam. Future diagnostics will focus on further characterizing this process.

C. Estimate of beam velocities

For a propulsion application, knowledge of the beam velocity is of high importance to get an idea about specific impulses achievable with these devices. Initial measurements with Langmuir probes in a time-of-flight configuration were inconclusive. Therefore, an indirect method of getting first estimates of beam velocities was applied by inserting a target into the beam. Aluminum foil of a thickness of 0.0254 mm was placed in a distance of about 5 mm to the exit of the inner target and the generator was quickly powered up to a selected operating condition. These tests were conducted at a pressure level of 40 mTorr. At maximum power achievable with the current configuration of 63.34 W, the beam penetrated the aluminum foil as shown in Fig. 20 within about 1 s and created a hole of roughly 2.5 mm diameter.

Neglecting heat conduction in radial direction within the aluminum foil, at least the evaporation heat of aluminum \( q_{\text{evap, Al}} = 10,530 \text{ kJ/kg} \) times the volume of evaporated material times the density of aluminum \( \rho_{\text{Al}} = 2,700 \text{ kg/m}^3 \) or \( Q_{\text{evap, Al}} = 3.545 \text{ J} \) would have to be provided by the IEC beam within the one second it took to penetrate the foil. Due to the low pressures, conduction heat transfer from the beam to the aluminum foil might be negligible for this process. If therefore is assumed that the heat of evaporation is provided by the kinetic energy of heavy particles hitting the aluminum foil, a number of particles providing the needed energy can be calculated if a value for the particle velocity is assumed.

\[
Q_{\text{evap, Al}} = N_{\text{part}} \cdot M_{\text{part}} \cdot \frac{u_{\text{part}}^2}{2} \quad \text{or} \quad N_{\text{part}} = \frac{2 \cdot Q_{\text{evap, Al}}}{M_{\text{part}} \cdot u_{\text{part}}^2}
\]  

(1)

Furthermore, a particle density can be calculated by dividing the total number of particles by the cross-sectional area (assumed to be the hole area) and the particle velocity and multiplying this values with the time need to penetrate the aluminum foil. This particle density has to obey the equation of state \( p_{\text{stat}} = n \cdot k \cdot T \). With the known chamber pressure, a plasma temperature needed to fulfill the above conditions can be calculated.

\[
p_{\text{stat}} = n \cdot k \cdot T_{\text{plasma}} = \frac{N_{\text{part}}}{A_{\text{hole}} \cdot u_{\text{part}} \cdot t_{\text{penetration}}} \cdot k \cdot T_{\text{plasma}}
\]  

(2)

Combining equations (1) and (2) yields an equation for the particle velocity:

\[
u_{\text{part}} = \sqrt[3]{\frac{2 \cdot Q_{\text{evap, Al}} \cdot k \cdot T_{\text{plasma}}}{p_{\text{stat}} \cdot M_{\text{part}} \cdot A_{\text{hole}} \cdot t_{\text{penetration}}}}
\]  

(3)

If the N₂⁺ rotational temperatures of 1,600 K determined in the previous section is assumed as the plasma temperature, lower and upper bounds can be obtained assuming that the beam consists only of nitrogen molecules (providing the highest mass per particle) or only of nitrogen atoms (lowest mass per particle), respectively. With the given numerical values a particle velocity between 5 and 6.4 km/s is obtained.
This value originates from a time averaged measurement over multiple oscillations of the IEC power. It seems reasonable to assume that peak velocities will be significantly higher. Given the amount of assumptions made in this first estimate, though, it seems unreasonable at the present time, to try and assume a velocity distribution over time to try and estimate maximum beam velocities. Future work should include direct measurements of such velocities.

For the averages values above, a mass flow of particles can be calculated and thrust values can be estimated from $F = \dot{m} c_e$ (under the assumption of $c_e = u_{part}$) between 0.75 and 1 mN.

### IV. Future Plans

Future plans for the investigation of IEC plasmas at the University of Kentucky involve more detailed diagnostics of the plasma core and the ion beam than the preliminary emission spectroscopy performed so far. In addition, the current system draws the working gas from residual gas in the whole vacuum chamber. This would be interesting for in-orbit application if the rest atmosphere could be used as propellant with the benefit of not carrying propellant on-board. Unfortunately, achievable pressures and therefore particle densities in orbit seem too low to provide operating conditions sufficiently similar to those investigated so far. Therefore, an encapsulated plasma generator design is needed to which a defined propellant flow can be provided. Finally, air is certainly not a preferred propellant for propulsion applications. Although conventional satellite propellants (e.g. hydrazine or ammonia) might be interesting from a system design point of view, and multi-propellant applications using waste gases and liquids as present on a space station or on other manned spacecraft might be interesting concepts in the future, the near term focus will be on traditional inert propellant gases such as argon, krypton, or xenon.

#### A. Improved plasma diagnostics

The currently available overview spectroscopy is interesting in providing a general picture of major processes in the plasmas of concern but is certainly limited for the extraction of thermodynamic quantities such as particle densities, plasma velocities, or species concentrations. Emission spectroscopy with lab spectrometers in higher wavelength resolution with focus on temperature determination methods has been proven successful in the investigation of plasmas in ground test facilities for the experimental simulation of re-entry conditions, in particular from molecular emission in various wavelength resolutions. Although not necessarily applicable for propulsion purposes, the use of molecular gases (air, pure nitrogen, NO, ...) provides valuable information on the governing processes in IEC plasmas through access to electronically, vibrationally, and rotationally excited states.

For inert gases, electronic excitation remains the only excitation form accessible to traditional emission spectroscopy. For atomic oxygen and nitrogen, and for argon and xenon, such experiments have been proven valuable both with equilibrium and non-equilibrium assumptions, in particular in comparison with numerical simulation of the plasma flows.

A second optical diagnostic method available at the UK labs and already applied to re-entry plasmas is Fabry-Perot interferometry which basically is a form of ultra-high resolution emission spectroscopy through multiple beam interference which allows for the investigation of line profiles, preferably of atomic lines. The measured profiles contain information about the translational temperature from Doppler broadening and potentially on electron density from Stark broadening. In addition, the Doppler shift of emission lines if observed under an angle to the flow, allows for the determination of directed plasma velocities.

For both emission spectroscopy and Fabry-Perot interferometry, the application to the IEC plasma in rectified AC mode is complicated by the plasma fluctuations. It is anticipated that the plasma properties, both in terms of temperatures and beam velocities will fluctuate as well. For emission spectroscopy, exposure times clearly below the fluctuation will have to be chosen and must be correlated to the plasma oscillations with a defined phase shift. For Fabry-Perot interferometry, a long ramping time covering numerous oscillations has to be chosen. The oscillation will be observable in these data and a defined phase shift to the oscillation frequency can be obtained in post processing by selecting only data points with the chosen phase shift. One scan would therefore provide time resolved velocity information throughout the entire oscillation.

Finally Langmuir probes and Faraday cups will be applied for beam diagnostics, as already demonstrated for IEC applications.

#### B. Design of an encapsulated IEC propulsion module

Initial designs have already been pre-developed at the University of Kentucky for the cylindrical IEC. In the proposed design, the outer electrode is contained in a glass or ceramic tube (the first option still would provide optical access for plasma diagnostics), and the working gas is supplied at the base, preferably close to the outer electrode. An additional gas feed at the center line is proposed to feed seed elements, either for diagnostic or...
material sciences purposes. It will be investigated of a partial coverage of the exit plane of the cylinder (e.g. enclosing the radial region between outer and inner electrode) might have operational benefits. In a final version, the outer helix might be replaced by a metallic coating on the inside of the glass or ceramic tube which is anticipated to yield weight benefits and potentially a higher homogeneity of the electric field distribution.

Figure 21. Design concept for an encapsulated IEC plasma generator design with defined gas feeding.

V. Summary and Conclusions

A cylindrical inertial electrostatic confinement plasma generator, operated in rectified AC configuration, was developed and tested with air and argon at power levels up to 60 W in tight beam mode. The tests with air showed a broader range of stable operation than those with argon. With increasing pressure from 20 mTorr to 100 mTorr, the tight jet mode gradually transformed into a spray mode.

Emission spectroscopy measurements were conducted in the plasma core and in the IEC beam. Preliminary results for the beam show the presence of N$_2$, N$_2^+$, and atomic oxygen. Comparison with spectral simulation of the molecular radiation yielded rotational and vibrational temperatures of N$_2^+$ between 1,600 and 2,000 K. The same temperatures for N$_2$ were higher and showed clearly higher vibrational temperatures in excess of 5,000 K with the N$_2$ signal increasing with IEC power for otherwise similar conditions, indicating a recombination of N$_2^+$ to N$_2$ inside the beam. The measurements are planned to be repeated in higher spectral resolution in the near future to increase the fidelity. Concepts for directly measuring these velocities are in preparation.

First estimates of particle velocity and equivalent thrust, the device would generate were derived from an energy balance of the IEC beam penetrating an aluminum foil target. Particle velocities between 5 and 6.4 km/s were obtained if the rotational temperature derived from the N2+ emission was assumed as plasma temperature. Although only a preliminary estimate with high error margins, this indicates some interesting potential for the use of the cylindrical IEC as an electric propulsion system. For such applications, an encapsulated design with defined gas feedings was presented which will be realized and tested in future work at the University of Kentucky.

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References
