Development and Initial Testing of a Plasma Confinement Cage

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The development of a plasma confinement cage capable of characterizing electrical facility effects has been investigated through initial testing and multi-physics simulation. To facilitate neutral diffusion testing, a cube was constructed out of various stainless-steel meshes, and argon was injected into the cube. Pressure was measured both inside and outside the mesh cube. Testing showed minor pressure difference between mesh selection at flow rates below 3 sccm. Substantial differences arise between meshes at flow rates greater than 4 sccm. In addition to neutral pressure testing, multi-physics simulations were conducted to quantify the capability of each mesh to collect current for measuring current pathways. The finer mesh was shown to be more effective at current collection. For current measurement the components of a wide-band current sensor capable of measuring high frequency signals were tested in a transimpedance amplifier configuration. Bandwidth testing was conducted at select gains showing sensor frequency response. From this testing a preliminary confinement cage design was conceived.

I. Introduction

A central problem still facing electric propulsion (EP) development is the discrepancy in thruster ground testing performance compared to orbital flight. EP systems are tested in ground-based vacuum facilities where an in-space environment can be simulated by evacuating the atmosphere from a sealed vessel. The inability to create a perfect representation of an in-space environment leads to phenomena known as facility effects that are directly linked to a ground facilities' pumping capabilities and the confinement of facility walls. As ground testing is conducted in a sealed vessel, the boundaries of the chamber can introduce sputtering from the chamber walls, increases in background neutral pressure, additional current termination paths, and alterations in the flow field.

Extensive study has gone into better understanding facility effects due to background neutral pressure, specifically in Hall Effect Thrusters (HETs), showing increases in background neutral pressure led to artificially increased performance [1-3]. Previous studies have shown the role that the conductive chamber walls play is significantly affected by cathode position and magnetic field topology in HET testing [4-5]. Facility effects can have several consequences on EP systems. In HETs it has been shown to affect the acceleration region, thrust, and cathode coupling voltage and in gridded ion thrusters (GITs) facility effects result in decreased measured erosion rates [2,4-7]. These effects can result in artificially improved performances producing misleading data.

An experimental study into electrical facility effects conducted by the Air Force Research Laboratory (AFRL) termed, Electric Propulsion Test & Evaluation Methodologies for Plasma in the Environments of Space and Testing (EP TEMPEST) investigated thruster plasma and electron dynamics in the exhaust plume of HETs. A key objective of the research was to study electron transport mechanisms from the cathode to the HET channel and to understand enhanced transport caused by the conducting boundaries of a testing facility [8]. To facilitate this work, a plasma confinement cage was constructed. The confinement cage consisted of several hexagonal rings with each ring instrumented to monitor current paths [8]. This work concluded that additional plasma confinement cage experiments are needed to better

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understand electrical facility effects.

Acquiring the capability to account for and possibly prevent facility effects would allow for more meaningful ground testing. This work aims to study facility effects due to conducting facility walls otherwise known as electrical configuration effects, with the development and initial testing of a plasma confinement cage at a level significantly smaller and more attainable that that of EP TEMPEST [8]. This paper is organized as follows: Section II highlights the experimental setup, section III provides the results obtained, section IV provides a discussion of those results, section V introduces a preliminary confinement cage design and future testing to be conducted, and section VI provides concluding remarks.

II. Experimental Setup

A. Facility

All testing was completed at the Western Michigan University Aerospace Laboratory for Plasma Experiments (ALPE). Neutral diffusion testing was completed in the large cylindrical vacuum chamber measuring 1.5 meters in length and 1 meter in diameter. The chamber was evacuated with a CTI-Cyrogenics on-board 250F cryopump with a pumping capacity of 2,200 l/s of N_2 and can achieve a base pressure of 1 x 10^{-7} Torr. For internal and external pressure measurements, two 563-type Bayard-Alpert ion gauges were utilized each with a 934 Terranova vacuum gauge controller. The first gauge was mounted to the wall of the vacuum chamber and the second was mounted directly to the mesh cube through which gas was being injected. Neutral gas flow was enabled by an AliCat flow controller.

B. Pressure Cube

A system termed the pressure cube was utilized to measure neutral transmission capability of a confining mesh material. The pressure cube used in neutral diffusion testing consists of a 6-inch cube constructed from 8020 T-slotted bar creating the outer structure. The outer structure is then covered with a fine stainless steel (SS) wire mesh with varying open areas of 37%, 52%, and 73%. For internal pressure measurement, one of the 563-type Bayard-Alpert ion gauges is mounted to a section of 8020 T-slotted bar and inserted through a hole in the mesh. A second hole is cut into the mesh allowing a gas line to be positioned inside of the cube. Neutral gas flow into the cube ranged between 0.5 – 10 sccm. A diagram of the experimental set up for neutral pressure testing is shown below in Fig. 1.

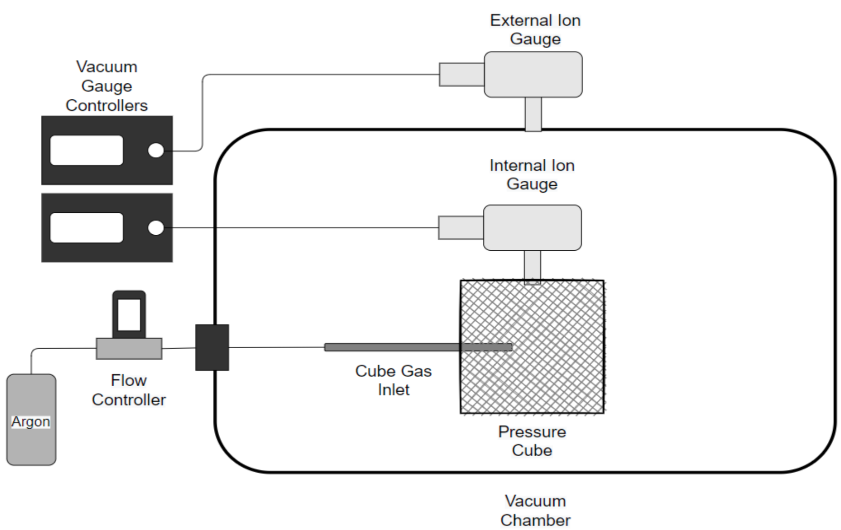

Fig. 1 Neutral pressure testing set up.

C. Current Sensors

To facilitate current measurement from the confinement cage mesh walls, several low-impedance wide-bandwidth current sensors were constructed based on the design utilized for the EP TEMPEST project [8]. Similar to EP TEMPEEST, each sensor will be mounted to an individual ring segment of the confinement cage, allowing the measurement of termination pathways. These sensors utilize an OP467, a quad precision high speed operational amplifier in conjunction with a CD4051 multiplexer, allowing the selectable gain of a particular op amp within the sensor configuration. This enables a singular sensor the capability to provide the required gain where less significant amounts of current are terminated enabling the signal to be accurately measured. The operational amplifiers within the OP467 will be individually characterized.

III. Experimental Results

A. Neutral Pressure Testing

Argon gas was injected into the pressure cube covered in the various SS meshes. Additionally, neutral diffusion testing was conducted without a mesh. The flow rate was initially stepped up at 0.5 sccm increments beginning at 0.5 sccm up to 5.0 sccm. Then flow rate was incremented by 1.0 sccm up to 10.0 sccm. After a two-minute interval at a set flow rate, the pressure was measured from each vacuum gauge controller. The resulting pressure measurements are shown in Fig. 2. At zero flow, the measured pressure was the same both inside and outside the cube. The pressure difference begins to rise with increasing flow rate. As expected, mesh with a larger transparency maintained a pressure inside the pressure cube closer to that outside the pressure cube when compared with finer mesh, indicating better diffusion with a greater open area mesh. Regardless of mesh size, the pressure difference increased with increasing flow rate. There appears to be a slight inflection point at 3 sccm where the difference in pressure inside and outside the cube begins to increase more with increasing flow rate. At flow rates above 3 sccm significant differences begin to arise. Fig. 3 displays the difference in pressure measurement between the vacuum chamber gauge and the pressure cube gauge. The greatest difference occurs with the 37% open area mesh reaching a maximum difference at 10 sccm of 1.1 x 10^{-4} Torr.

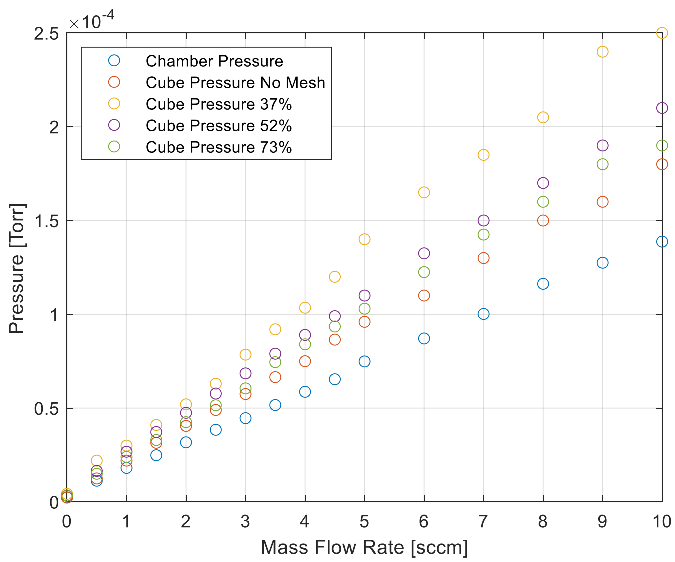

Fig. 2 Pressure measurements of selected open area meshes.

B. Current Collection Simulation

COMSOL multi-physics simulations were performed to determine the transparency of the mesh when a potential was applied. Simulations were conducted on a 2.54-cm by 2.54-cm piece of stainless-steel mesh with the same varying open areas. The particle tracing module was used to impinge electrons onto the mesh from a direction perpendicular to the square. The potential of the mesh is swept from 0 – 50 V. Current is measured to be terminated at the mesh, the walls before the mesh, and the walls after the mesh. This simulation provides information on the ability of a particular mesh transparency to collect current. Fig. 4 shows the measured simulated current terminated on each mesh with varying potential. The greatest amount of current collected was by the 37% open area mesh, reaching a maximum of 74% of total current collected.

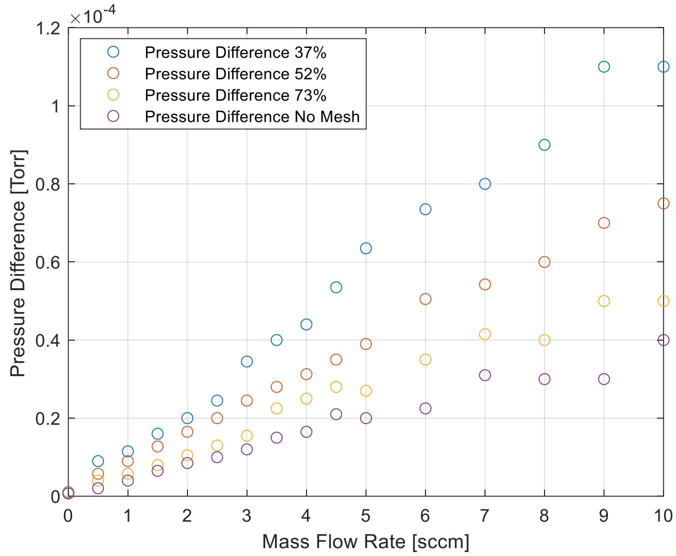

Fig. 3 Pressure difference measurements between internal and external ion gauges.

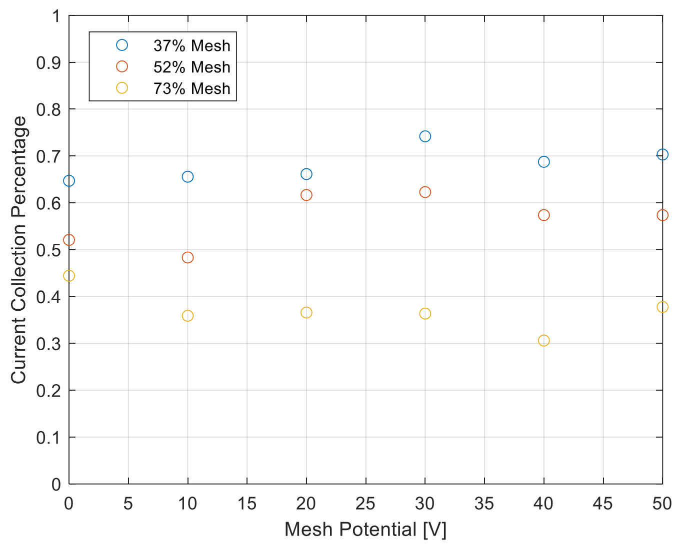

Fig. 4 Multiphysics current measurement simulations with varying mesh potential.

C. Sensors

The sensors fabricated for the confinement cage were tested for bandwidth by sending a 1 V sinusoidal signal from a Siglent SDG 1032X arbitrary waveform generator and measuring the response through a Siglent SDS1204X-E digital oscilloscope. Individual gains of 2x, 10x, and 100x were swept at a frequency range of 1 kHz – 10 MHz. Only a singular operational ampilifier was utilized for this initial testing period, verifying its base function and informing future testing of the fully developed sensors. The frequency response of each selected gain is displayed below in Fig. 5.

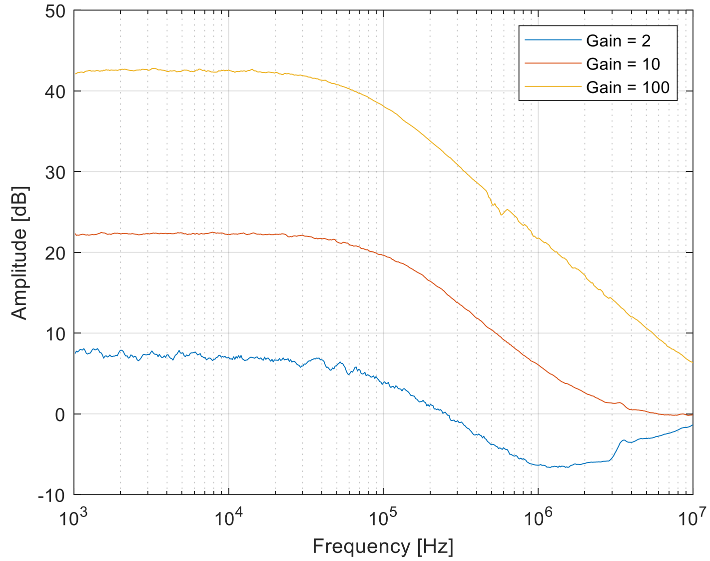

Fig. 5 Bandwidth testing of current sensor operational amplifier.

IV. Discussion

The primary motivation for this work is to establish a preliminary design for an electrical coupling confinement cage (EC3) for EP testing to determine alternative conducting paths to ground during vacuum facility experiments. This initial design has been informed by results obtained from the previous section. Discussed first is the selection of the mesh used in the EC3 design since it plays a vital role in the functionality of the diagnostic. The selected mesh must be able to collect sufficient current to discern current termination pathways between the individual cage sections with minimal error while adequately enabling diffusion of ions and neutrals through the mesh. Neutral diffusion testing showed, as expected, a mesh with a greater open area would lead to increased diffusion. A strong linear behavior is observed in recorded pressure with increasing flow rate for all mesh selections. As stated, the 37% open area mesh resulted in a maximum pressure difference of 1.1 x 10^{-4} Torr. While 73% open area mesh reached a pressure difference of 5.0 x 10^{-5} Torr. Little difference in pressure is observed between the 73% open area mesh and the no mesh case showing that this particular mesh does not confine the neutral gas to any major extent. It is important to note that the ion gauge inlet is within a direct line of site of the neutral gas inlet which in turn is located approximately 7.5 cm directly beneath the internal ion gauge. The location of the gas inlet may be, in part, attributed to the pressure measured in all cases.

The termination of electrons at the mesh has shown that a mesh with a smaller open area results in a greater amount of collected current. Current collection is the primary function of EC3 mesh and must be capable of doing so with minimal leakage. Adding charged particle transmission as a consideration along with the neutral flow confinement supports the basis for which mesh should be chosen for EC3. As shown in Fig. 4, a finer mesh will result in an improved current measurement; however, the mesh must still be able to effectively diffuse gas. A tradeoff between pressure diffusion and current collection must be made. Both the smallest and largest open area meshes can be eliminated from cage mesh selection for they lead to poor pressure diffusion or a lack of current collection, respectively. The 52% open area mesh shows adequate performance in both metrics. Therefore, the percentage of open area for the mesh selected should be within several percent of the 52% open area mesh.

As stated, the ability to accurately measure current pathways is of vital importance to the function of the confinement cage. The sensors must be capable of measuring a variety of different current magnitudes and frequencies. Initial testing of the individual op amps within the OP467 operational amplifier showed the expected behavior for a given gain. Inspecting the frequency response of each gain in Fig. 5, the cut-off points was measured to be between 58 kHz to 1 MHz with the cut-off frequency increasing with gain. Bandwidth testing was conducted on a solderless breadboard facilitating potential frequency limitations which may appear in the results presented in the previous section. However, a greater bandwidth can be obtained with the fully constructed sensors eliminating frequency limitations with proper PCB layout practices and alternative frequency compensation techniques.

V. Electron Coupling Confinement Cage Design and Future Testing

The fully assembled EC3 was designed to fit into the large vacuum chamber at ALPE, providing the capability for electrical vacuum chamber interactions with EP thrusters to be studied. EC3 incorporates the same components as the pressure cube with the addition of an outer aluminum honeycomb for structural support of the inner stainless-steel mesh. The cage consists of three sections: the back ring, the forward ring, and the beam dump as illustrated in Fig 6. The back ring holds the thruster test mount and acts as the first current collection ring segment. This section is 0.6 meters in length with a cross-sectional side length of 0.38 meters. The second section is a larger current collection ring with the same side length as the first section with a length of 0.8 meters. The beam dump is the final section and consists of six individual graphite segments. Each approximately 0.3-m-long individual segment is angled slightly aiding in the reduction of reflected particles. To facilitate current measurements, a series of low impedance current sensors are connected to each section, allowing the individual current signals to be monitored.

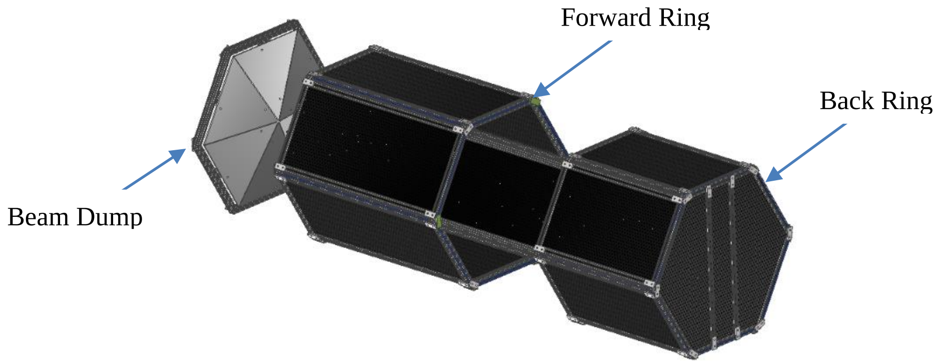

Fig. 6 Initial plasma confinement cage design.

Further testing of the stainless-steel mesh for the confining walls and the sensors for current measurement will be conducted, refining the overall confinement cage design. Neutral diffusion testing will be carried out again with the fully assembled confinement cage with a selected mesh based on results from the pressure cube testing. This will better inform on the ability of the mesh to diffuse the neutral gas at a larger volume. Future sensor testing will consist of the fully constructed sensors utilizing multiple OP467 op amps allowing a programmable gain. Testing will first be conducted with an evaluation board before the final sensors are fabricated. Finally, with EC3 constructed, the sensors will be integrated, and a full systems test will be carried out to measure functionality utilizing a Kaufman ion source.

VI. Conclusion

This work has initiated the development of an electron coupling confinement cage (EC3) by conducting initial experiments to determine primary design features of the confinement cage. EC3 will allow for the characterization of electrical facility effects. Neutral pressure diffusion testing in conjunction with multi-physics simulations were carried out to verify material selection. Diffusion testing showed the transmission capability of each mesh with varying open area. As expected, a mesh with a more open area resulted in a greater amount of diffusion. The minimum pressure difference recorded at the greatest flow rate was 5.0 x 10^{-5} Torr. As the primary function of the cage is to monitor current termination paths, COMSOL multi-physics simulations allowed the current collection ability of a specified mesh to be quantified. In contrast to neutral diffusion testing, a finer mesh resulted in a better performance with more significant current collection. It was shown a mesh within a few percent of the 52% open area mesh would satisfy both neutral diffusion and current collection performance metrics. To determine the amount of current terminated throughout the cage, a series of low-impedance wide-bandwidth current sensors will be constructed. Initial testing preceding the fully designed sensors consisted of bandwidth testing of the individual operational amplifiers. Bandwidth testing provided the frequency response of the individual operational amplifiers at a variety of selected gains, showing improvement in overall bandwidth is required.

A preliminary EC3 design fitting within the vacuum facility at Western Michigan University was conceived, consisting of three individual sections, the back ring, forward ring, and beam dump. This design serves as a starting point for the finalized design. The finalized design will include access ports for cabling and instrumentation. Additionally, the cage will be made portable to be used in other facilities. Lastly, future testing of EC3 design will be completed to further the development of a more mature design.

Acknowledgements

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