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AIAA Gossamer Systems Forum
April 23–26, 2012 / Honolulu, HI

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This paper explores using Electrostatically Inflated Membrane Structures (EIMS) in a plasma flow. In particular, experiments are presented illustrating EIMS inflation in an electron flux while studying the structural stability. EIMS consists of conducting membranes coupled with active charge emission to provide an inflationary electrostatic pressure. Of interest is how the light-weight membrane charge distribution will interact with an electron flux, and will the deflection of this charge cause a structural response. Vacuum chamber experiments are performed with electron flux energies up to 5keV, while the membranes are charged using an external power supply up to 10kV. The experiments show that EIMS will remain inflated in the presence of this low-energy electron flux, which provides critical insight into developing Low-Earth Orbit EIMS experiments. At particular EIMS voltages and electron flux energy levels, unknown membrane vibrations are observed. Studying the experimental setup, these vibrations are not due to variations in the power supply or the electron flux, nor are they due to the momentum exchange of charge deflection. Rather, it is postulated these vibrations are due to the charge flux causing local membrane charge distribution changes. As the membrane structure inflation pressure is changed, the shape responds, and causes the observed sustained vibration. Having identified this phenomena is important when considering implying EIMS in a space environment.

I. Introduction

Since the early days of launching spacecraft, reducing mass has been a crucial aspect of spacecraft design. Lightweight gossamer structures are an alternative to more massive and complex traditional mechanical systems. Gossamer structures have been proposed for applications such as communications antenna, solar arrays, and drag devices. Examples of gossamer technology which has flown in space is the ECHO I sphere, which launched in 1960 to serve as a communications reflector,[1] or the L'Garde inflatable antenna, which was launched from the Space Shuttle in 1996.[2] Examples of current research on gossamer structures is solar sail technology,[3] inflatable solar arrays,[4] and space habitats.[5]

A subset of gossamer structures is inflatable gossamer structures. These commonly use pressurized gas, sublimating chemicals, or evaporating liquids[6] for inflation. In References 7 and 8, an alternative idea of inflation with electrostatic forces is discussed. The general idea is shown in Figure 1. Electrostatically inflated membrane structures, or EIMS, can use two conducting membranes interconnected by membrane ribs. Active charging causes tensioning of the structure by the repulsive electrostatic force on the charged membranes while the internal ribs limit the separation distance. The electrostatic pressure inflates the membranes to a stable structure, much like inflation of an airbag with gas. EIMS shares the benefits of low-mass and compact stowage with the classical inflatable structure, but does not suffer from sensitivities to puncture or the requirement for a closed shape. The electrostatic inflation concept is particularly applicable to structures such as arrays, solar power reflectors, or drag augmentation devices for de-orbiting

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and space debris avoidance purposes. Further, electrostatics has been proposed to perform active radiation shielding of lunar colonies,[9] or deep space vehicles. Such EIMS concepts would enable extremely lightweight capacitors to be created for active radiation shielding.[10]

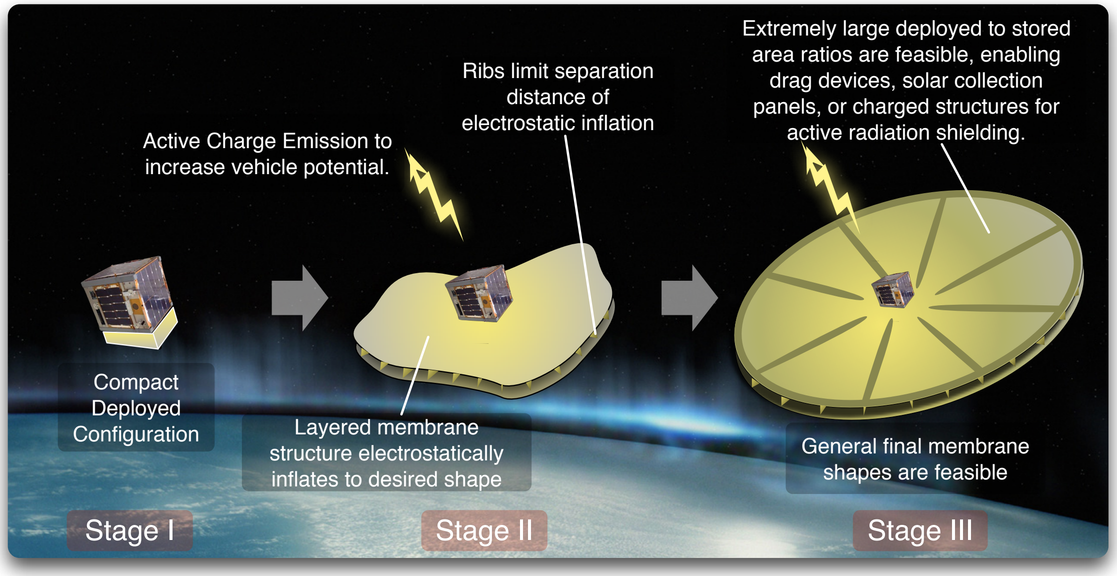


Figure 1: Electrostatic inflation concept illustration.

This paper investigates a particular challenge of EIMS, how the presence of a charge flux from the local space environment interacts with the charged structure. It is important to understand both how charged particles contact and deflect around the structure, and if the structure shape remains stable during this process. The charge deflection capability of the Coulomb membranes leads to the interesting application of EIMS for active radiation shielding. A laboratory experiment is designed to study the EIMS/charge interactions using an electron source and charge detector in a vacuum chamber environment. Experiments are performed to study the charge deflection patterns, the radiation shielding capabilities, and the stability of and interaction with the membrane structure.

II. Background

The concept of electrostatic inflation of membrane space structures is explored in References 7 and 8. The analysis in these papers focuses on the voltage required on a two-membrane sandwich structure to offset normal compressive orbital perturbations to the structure. An illustration of such a structure is shown in Figure 2. In GEO, solar radiation pressure is the dominant compression pressure of the orbital perturbations. In LEO, solar radiation pressure dominates until an orbit altitude of approximately 500km, under which atmospheric drag becomes the dominant pressure. The potentials on the membranes must be high enough to produce sufficiently larger electrostatic forces to offset these compressive differential forces which would be experienced in orbit in order to keep the structure inflated.

The required charge densities to create the minimum electrostatic pressure to remain inflated were determined. Numerical solutions were required to determine the corresponding voltages, as an analytical solution to the capacitance of a sandwiched finite plate system does not exist. To offset the normal compressive orbital pressures, it was found that only hundreds of Volts are required in GEO and a few kilo-Volts in LEO.

Many challenges to the electrostatic inflation concept remain, such as plasma Debye shielding, space weather, orbital perturbations which may tend to collapse the structure, and complex structural dynamics including how to initially inflate and charge such a structure. In References 7, plasma effects on EIMS were briefly discussed in relation to the Debye shielding phenomenon. In the space plasma environment, electrons and ions rearrange to maintain macroscopic neutrality when perturbed by an external electric field.[11] This phenomena causes a steeper drop-off in the potential surrounding a charged object than would occur in a vacuum. The Debye length is a measure of the shielding due to the plasma, signifying the distance at which a charged object is essentially shielded. This makes the LEO EIMS capacitance evaluation very complex and challenging. In the Geostationary orbit (GEO) regime, the Debye length is nominally on the order of hundreds of meters, dependent on the changing electron and ion temperature and

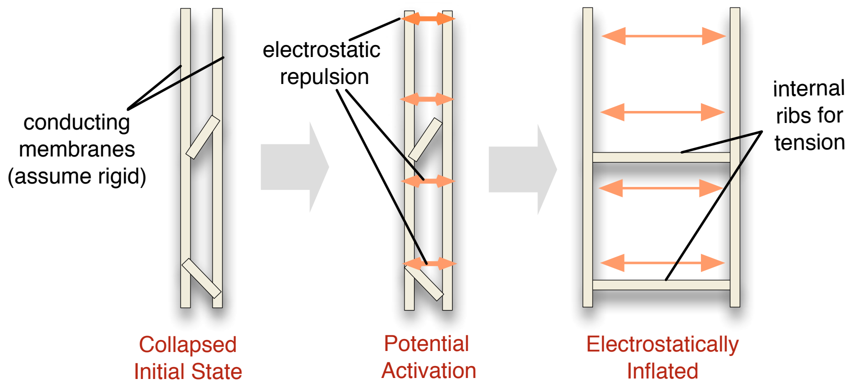


Figure 2: Sample open-ended membrane rib structure undergoing electrostatic inflation

number density.[12] Deep space at 1AU can have 10-40 meter Debye length, making electrostatic actuation actually more challenging than in GEO. In low Earth orbit (LEO), however, the plasma is much more dense and the Debye length is generally on the order of millimeters or centimeters.[13] The LEO environment, therefore, may be a challenging environment for EIMS due to the limited distances for electrostatic actuation. As illustrated in Figure 3, the charged gossamer structure is subjected to a low-energy ion flux from the orbital velocity direction due to LEO spacecraft moving master than the mean ion speed. This ion ram flux will react to a charged object, and cause an ion wake. In contrast, the faster moving electrons can hit the EIMS from any direction. Because the highly flexible membrane shape is only maintained through electrostatic inflation, which can be influenced by nearby charges, it is of interest if such coupling can lead to observable shape fluctuations.

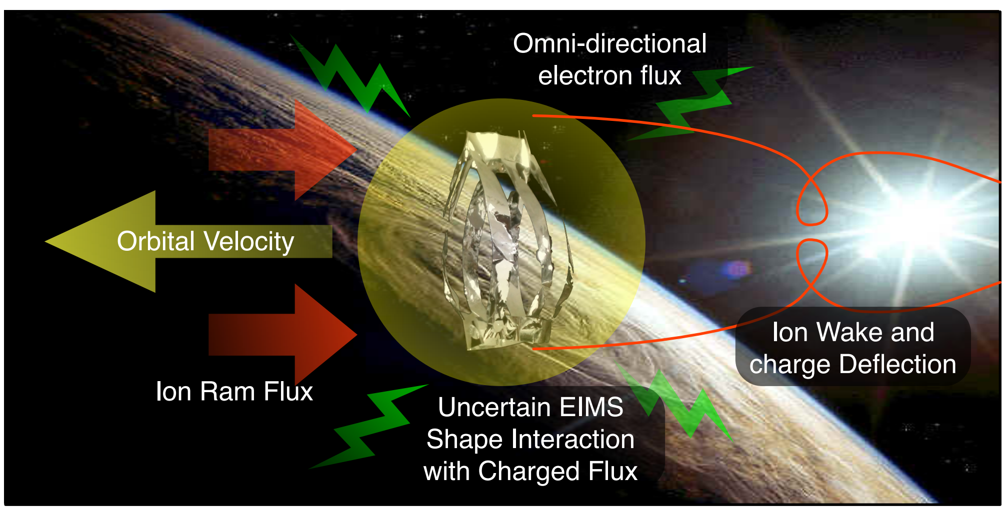


Figure 3: Illustration of Expected Positive and Negative Charge Flux About EIMS in LEO.

In addition to Debye shielding, the plasma complicates charging of a spacecraft due to ram effects as a spacecraft moves through the plasma and also wake effects behind the moving craft as illustrated in Figure 3. For the EIMS concept, it will be important to understand how the charge will flow around the structure and affect inflation. This paper aims to understand how a plasma could affect shape stability by engaging novel laboratory charge deflection experiments. LEO charging experiments over short durations have been performed on the SPEARS-I mission.[14–16] Here two 10-cm radius solid spheres attached to a rocket body are charged up to 40kV while in LEO. A similar future EIMS experiment is envisioned in LEO where the charging is used to electrostatically deploy and test an EIMS concept. Such a deployed device can act as a deorbiting device or a solar collector.

An interesting application of EIMS is in the field of active radiation shielding,[9,10,17,18] where it can provide large and light-weight capacitors to shield humans from harmful radiation. This is explored in small-scale manner within this paper by considering how an electron flux is deflected by an electrostatically inflated structure. Radiation shielding is an important, unresolved problem for deep-space human exploration. The dangers of radiation must be understood and protection incorporated into any human space travel, especially that of long duration and travel beyond Low Earth Orbit. Radiation shielding can be accomplished with passive or active methods, or a combination of the two. One drawback of passive shielding is the mass of thick materials required for adequate radiation safety. Use of electrostatic fields is one active method which provides an alternative to bulk material passive shielding.[18] Other forms of active shielding include plasma shields, confined magnetic fields, and unconfined magnetic fields.[17] Some of the challenges of active electrostatic shielding, such as high potentials and size limitations due to electrical breakdown, have deterred further research on the subject.[10] In Reference 10, Tripathi challenges the claim that electrostatic shielding may be unsuitable and explores a feasible design for radiation shielding, as shown in Figure 4. In all active radiation shielding research using electrostatic large capacitors are required to store enough charge to provide sufficient high-energy particle deflection. The charged gossamer structures can provide a weight-efficient solution for creating large, self-supporting membrane structures. In this application precise shape control is not necessary, and the robustness of EIMS to micro-meteorite punctures makes it even more attractive.

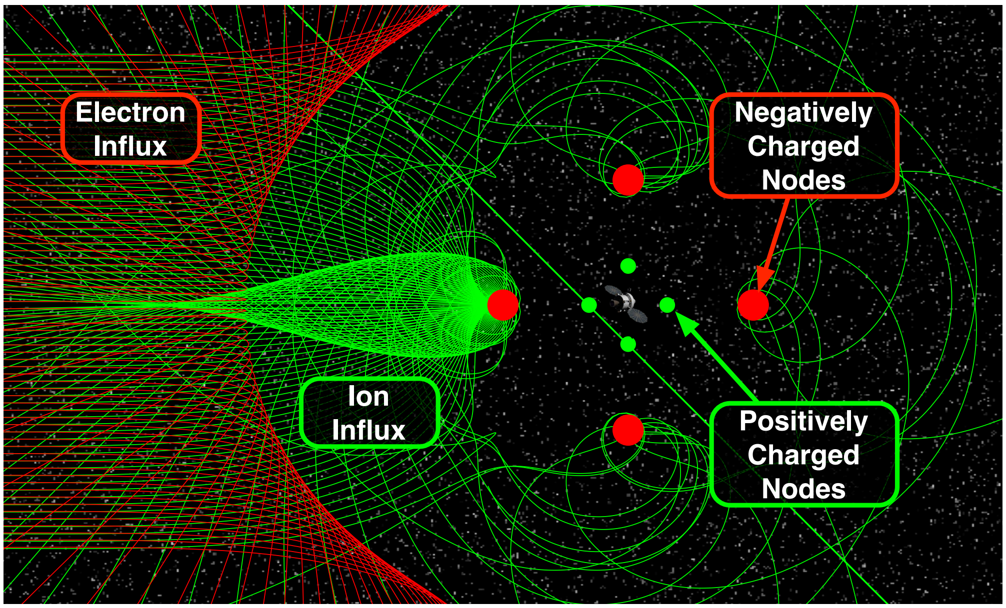


Figure 4: Electrostatic space radiation shielding concept for a deep space application

III. Inflation Experiments

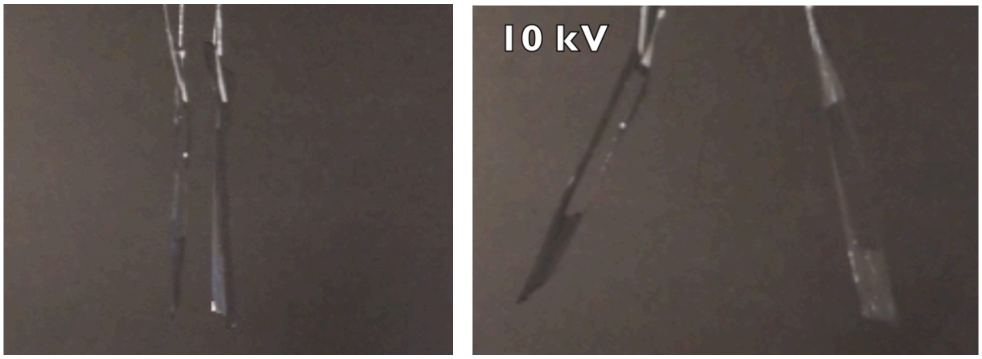
A high voltage charging setup was constructed to perform electrostatic inflation of decimeter-scale membrane structures. The goals of the experiments are to validate inflation capabilities for different membrane shapes and connections in vacuum.

Testing of inflatable structures in a 1-g environment is more challenging than in a near weightless space environment. Any inflation must overcome the force of gravity. A simple configuration to study inflation forces which do not need to overcome 1-g is by hanging the mylar structures and performing charging experiments which repel horizontal to the gravity field, as shown in Figure 5. This setup allows lower voltage EIMS structures to be tested and subjected to an electron flux, than if EIMS needed to overcome gravity just to inflate.

A. Atmospheric Inflation Experiments

EIMS inflation experiments were first performed in atmospheric conditions to explore feasible shapes for EIMS. Preliminary inflation experiments include hanging independent aluminized Mylar sheets both unconnected and connected with ties. Figure 5 shows a simple inflation test where each independent sheet is charged to 10 kV using a high voltage power supply.

Inflation of multi-micron think aluminum coated Mylar sheets in atmospheric conditions is observed at charging levels as low as 4 kV. At low voltage levels, however, atmospheric ionization effects have a significant impact. At charging levels below 4kV, attraction between the like-charged membranes was often observed. This counter intuitive



a) Before inflation, 0 kV **b)** Inflation, 10 kV

Figure 5: Laboratory inflation demonstration

phenomena is caused by an ionization of the atmosphere which creates an air flow, and thus a low-pressure zone attracting the plates. To eliminate these hindering atmospheric effects, the inflation experiments are moved to a vacuum chamber environment.

B. Vacuum Inflation Experiments

An important step in the development of the electrostatic membrane inflation concept is to test inflation capabilities in a vacuum environment. A vacuum environment is required to eliminate atmospheric effects and more realistically simulate the space environment. The chamber used for the experiments described in this paper provides a vacuum environment of approximately 10^{-7} Torr. A high voltage power supply attached to a vacuum feedthrough is used to charge membrane structures hanging in the chamber. Without the air ionizing about the EIMS system, the attractive forces seen in atmospheric inflation tests vanish as expected. It was found that significantly lower voltage magnitudes were required in the vacuum environment to induce the same inflation levels that were seen in the atmosphere at higher voltages. Inflation was observed at levels below 2 kV where the membranes begin to separate. Finding a test setup where the structures are inflated with voltages less that 5kV was important as the electron flux source available for these test has energy outputs ranging up to 5keV.

In addition to the goal of verifying the capability of electrostatic inflation in a vacuum, the vacuum chamber environment is used to explore different membrane shapes suitable for electrostatic inflation. The goal is to determine what shapes can provide reliable electrostatic inflation and to reveal any inflation issues with the shapes or connections. A variety of membrane shapes beyond the solid two-sheet membrane structure were constructed and inflated in the vacuum chamber environment. Experiments have shown that membranes with cut-out sections exhibit superior inflation to solid membrane sheets. Figure 6 shows one such configuration which demonstrates exceptional inflation. One issue identified through experiments is the property of surface stickage between the membranes. Especially in atmospheric tests, the onset of inflation can be difficult without a small initial separation between the membranes. Such concerns identified through experiments will help to guide the design of a space-based electrostatic inflation experiment and future space applications. The exploration of membrane shape possibilities is an on-going effort to determine optimal shapes, configurations and connections for applications of electrostatic inflation.

IV. Charge Flux Experiments

For application of the EIMS concept, it will be important to understand how the a charge flux from the local space environment interacts with a charged membrane structure. In particular, does the structure remain inflated and stable in the presence of a charge flux? To begin investigating the interactions, an experimental setup with an electron source was constructed. Here, the aim of the experiments is not to try to simulate realistic space plasma conditions, but to begin to understand the fundamentals of charged membrane structure and charged particle interactions. These experiments provide critical guidelines when developing analytical or numerical models to simulate the observed responses.

A. Charge Experiment Hardware Setup

The setup for the charge flux experiments includes an electron gun at one end of a vacuum chamber and a Faraday cup positioned behind a membrane structure at the opposite end of the chamber. The electron gun emits electrons and

Figure 6: Inflated structure in vacuum chamber

the Faraday cup measures the current, allowing observation of the flow of electrons around an EIMS structure and providing insight into how an EIMS structure can be used for radiation shielding. The EIMS structure is charged with a high voltage power supply system external to the vacuum chamber. The concept is illustrated in Figure 7, while photographs of the experimental setup are shown in Figure 8.

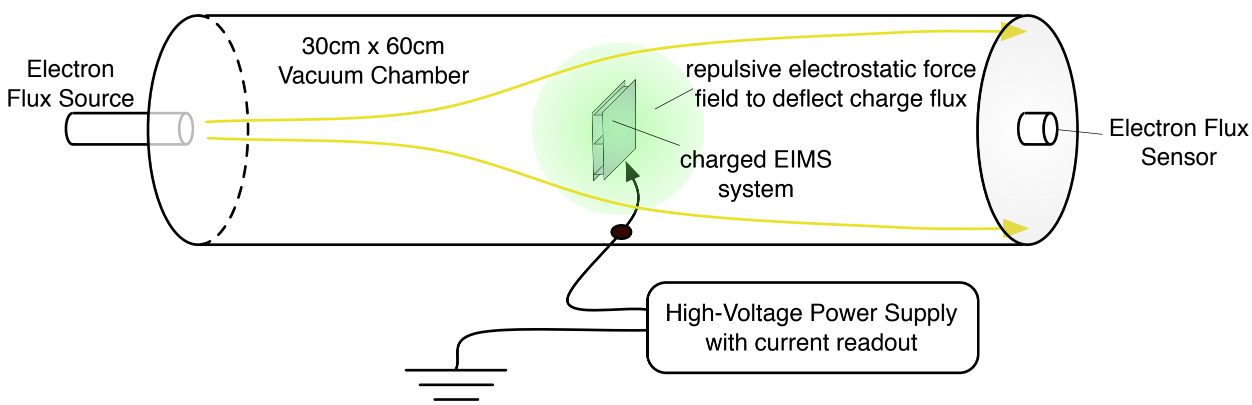
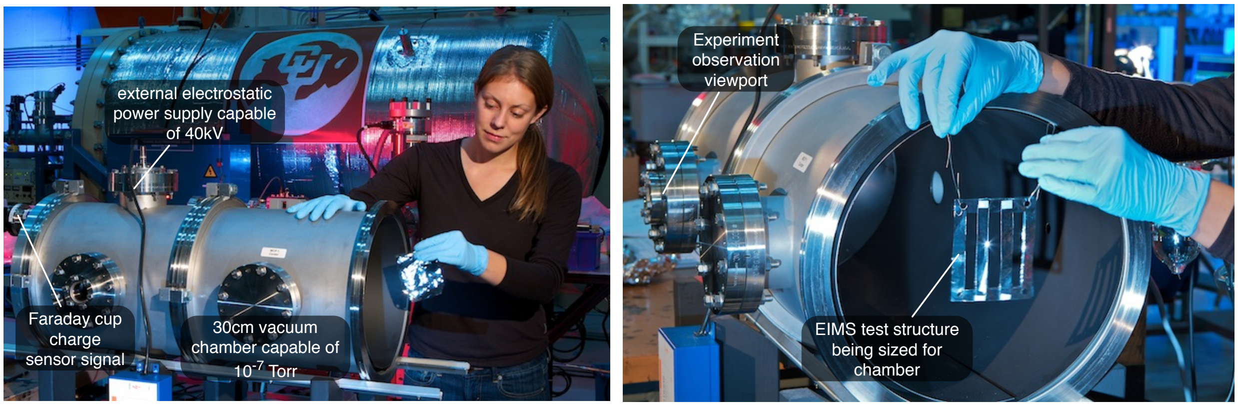


Figure 7: Concept illustration for the radiation shielding experimental setup

Figure 9(a) shows the constructed electron emitter. The filament is heated and electrons accelerated off by the electrostatic field between the biased filament and the grounded wire mesh. The filament is constructed of 5mil coiled Tungsten wire with length of 3.8cm, as limited by the melting point of the wire. The current emitted from the tungsten coil can be tuned by the AC current level passing through the wire. The higher the AC current supplied to the coil, the higher the temperature, thus more electrons are thermionically emitted and can be accelerated toward the grid. The high voltage power supply providing the DC bias to the coil is current-limited at 5 mA, therefore the maximum

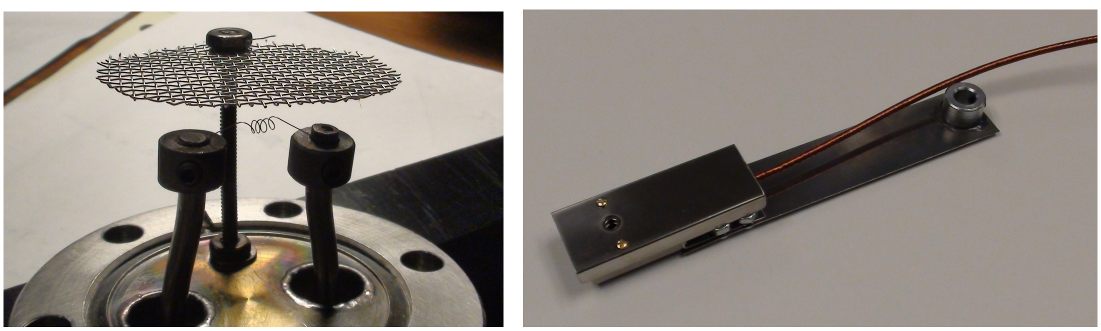


a) Vacuum Chamber Setup **b)** Open Chamber Illustration

Figure 8: Charge Flux Experiment Configuration.

emission current is 5 mA.

The FC-70 Faraday cup is chosen as the device to detect current within the vacuum chamber. The detector has a small aperture into which electrons can flow to measure the ambient current. The FC-70, shown in Figure 9(b) is mounted onto a rotatable vacuum feedthrough probe. The rotatable probe allows the Faraday cup to sweep through an angular range of approximately 120^o, thus providing positioning both behind and to each side of the membrane structure. The output of the Faraday cup is connected to a digital multimeter with DC current resolution to picoAmperes. A battery is located in the path between the nano-ammeter and the Faraday cup. The battery is a combination of the two 9 Volt batteries connected in series to bias the Faraday cup by 18 V. This small voltage helps to eliminate low-energy secondary electrons from entering the aperture of the Faraday cup.



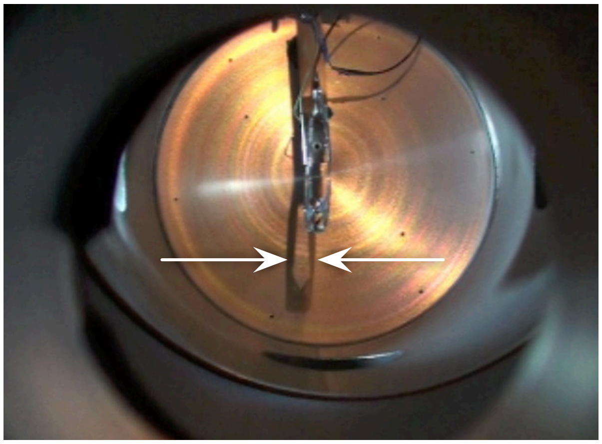
a) Electron gun filament and grid **b)** Mounted faraday with collar for attachment to vacuum feedthrough

Figure 9: Charge deflection experiment hardware

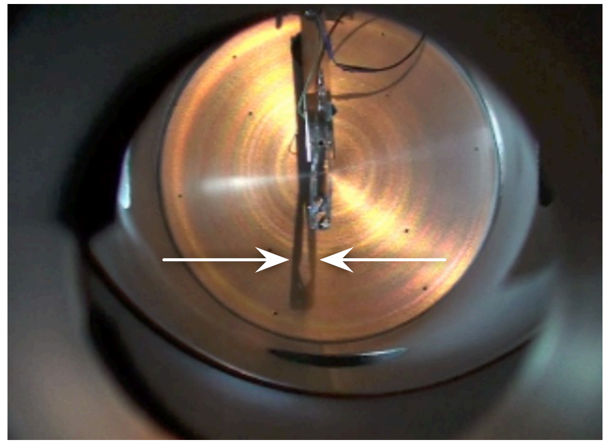
B. EIMS Vibrations due to Charge Flux Coupling

One of the purposes of the vacuum charge flux experiments was to identify any interesting structure and charge flux interactions. The experiments show that the structure is stable, in the sense that it does not collapse or undergo major shape changes, in all of the ranges of particle flows created (up to 5mA emission current and energies up to 5keV). Interestingly, small structural vibrations were discovered when the structure is charged and the electron gun is emitting a flow of electrons. These vibrations are seen at both very low currents and the currents near the maximum of 5mA. The vibrations, however, are not seen through the full sweep of currents. Rather, at particular charge flux and electrostatically inflationary pressure combinations a resonance-like vibration appears. If the EIMS voltage is change upwards or downwards, the vibrations can cease until new critical conditions are achieved. Similar patterns are seen for the full range of membrane structure voltages (0 to 10 kV) and electron energies (0 to 5 keV).

Figure 10 is shown to convey the magnitude of vibrations in the structure. It is difficult to capture the small oscillations, but a difference can be seen in the membrane shadows of Figure 10. The vibrations are of small magnitude, and ripple across the membrane structure.



a) Slightly expanded position during vibration



b) Slightly deflated position during vibration

Figure 10: Video snapshots to illustrate magnitude of structural oscillation; As shown by arrows, difference enhanced in shadow

The cause of these isolated vibration conditions in inflated membrane structures subject to a charge flow remains a key question for electrostatic inflation. A stroboscope was used to determine the approximate frequency of the observed vibrations. Often, there were several different vibration frequencies present across the EIMS prototype at a given instant. This indicates a complex ripple of vibrations is present as small shape changes occur, not just a single standing vibration. The primary frequencies measured were around the 4 Hz range.

Several potential sources of such vibrations were investigated and eliminated. First, it is possible that the deflected charge flux imparts a sufficiently large momentum exchange with EIMS to cause this rippling. To investigate this possible cause, experiments with a single membrane sheet were performed. None of the single-sheet experiments, charged or not charged, showed any visible vibrations, even sweeping through all feasible electron energies and all electron currents. These results suggest that the vibrations are un-likely caused by a transfer of momentum. Otherwise, vibrations or deflections would have been seen with single sheet experiments.

Secondly, the electron flux itself could be a source of these vibrations if the electron gun emitted flux is not steady, but has frequencies near 4Hz. To investigate this possible vibration cause, the electron flow output signal from the emitting gun is studied with an oscilloscope. The Fourier transform function of the oscilloscope is used to determine frequencies present in the driving current signal. The only significant frequencies present were the power line frequency of 60 Hz and a very high frequency in the kiloHertz range. Neither of these frequencies are in the 4Hz range of the observed structure vibrations.

Thirdly, fluctuations in the EIMS external power supply performance could cause EIMS vibrations. In essence, if the actual EIMS voltage is not held steady, but cycles in the presence of the external charge flux, then these voltage variations would directly results in the electrostatic inflation pressure varying. As a result, the EIMS structure would slightly deflate and inflate. An oscilloscope is used to examine the output of the power supply which charges the membrane structure. The power supply has an internal feedback loop to ensure a digitally commanded reference voltage level is maintained. The measure output signal provides a measurement of how well this voltage is being held constant. It was speculated that the power supply may be overcompensating as the external charges from the electron gun change the charge on the structure. It was found, however, that the power supply output frequencies, with and without the EIMS vibrations present, showed no significant difference. In fact, the power supply fluctuations were very small, barely observable, and more than an order of magnitude larger than the observed EIMS vibrations. Thus, it is concluded that the power supply did not provide first order contributions to the EIMS vibrations. Otherwise, output power variations during EIMS vibrations would leave a unique fingerprint.

Finally, the question remains, what is driving these EIMS vibrations under particular electron flux and electrostatic inflation pressure conditions. The hypophysis is that the membrane surface vibration is a result of local surface charge density variations causes by the charge flux. As the charge density σ varies, then the local electrostatic inflation also changes. Since the EIMS system is in an equilibrium between the 1-g gravitational forces attempting to compress the structure, and the electrostatic pressure inflating the structure, a small change in electrostatic pressure will negate this equilibrium and result in a local shape deformation, outward or inward. This shape change, in return, will cause a change in the surface normal electrostatic field which impact the near-surface charge flux.

To consider how mathematically such interactions can occur, consider the following mechanism where a charge flux will impact the local surface charge density σ. The electrostatic inflationary pressure on a general shape is a function of σ. The stronger the charge density, the stronger the inflation pressure will be. Assuming a conducting surface, the electric field magnitude, E, at the surface is related to σ through

$$E = \frac{\sigma}{\epsilon_0} \tag{1}$$

where ϵ_0 is the permittivity of free space. Note that the electric field is defined by taking the gradient of the local potential function $\Phi(\boldsymbol{r})$ through

$$\boldsymbol{E} = -\nabla_{\boldsymbol{r}}\Phi(\boldsymbol{r}) \tag{2}$$

In the laboratory experiments, the external power supply is holding a fixed potential during the inflation tests. In a vacuum, this would dictate a corresponding E-field, and thus charge distribution, on the EIMS surface. However, including an electron flux will cause a change of the surface local E-field. As a result, through Eq. (1), the local σ will change, and thus the resulting electrostatic pressure. With the pressure-gravity equilibrium disturbed, the surface shape will change assuming negligible stiffness of the micron-thick membrane foil. The change in surface curvature and location changes the local E-field, and cyclic reaction could result. This hypothesis matches the observed experimental results in that the vibrations never appeared with single-membrane charging experiments. The vibrations are only seen if two charged membranes are repelling each other into an inflated shape equilibrium configuration with particular EIMS voltage and charge flux energy levels.

An alternate method to illustrate how a charge flux impacts the EIMS charge distribution is to look at the Debye shielded potential field about a sphere. Assume the sphere radius is R, while V is the potential of a perfectly conducting surface. The potential $\Phi(r)$ that exists outside the sphere surface R is given by

$$\Phi(r) = k_c \frac{q}{r} = \frac{VR}{r} \tag{3}$$

where q is the net charge on the sphere. The E-field off the surface is thus

$$E(r = R) = \frac{V}{R} \tag{4}$$

This equation assumes the sphere is in a perfect vacuum. If the sphere is in a plasma with an effective Debye length $\hat{\lambda}_D$,[19] then the partially plasma shield potential field about the sphere is approximated through[20]

$$\Phi(r) = \frac{VR}{r} e^{-(r-R)/\hat{\lambda}_D} \tag{5}$$

The resulting E-field off the sphere surface is now given by

$$E(r) = -\nabla_r \Phi(r) = \frac{VR}{r^2} e^{-(r-R)/\hat{\lambda}_D} \left(1 + \frac{r}{\hat{\lambda}_D}\right) \tag{6}$$

Note that the E-field off the surface is now

$$E(r = R) = \frac{V}{R}\left(1 + \frac{R}{\hat{\lambda}_D}\right) \tag{7}$$

The plasma Debye shielding causes the potential field Φ to drop off sharper. As a result, the gradient of Φ is larger, and thus E is larger off the surface. As discussed in detail in Reference 20 and 21, the plasma presence will increase the capacitance of a metallic object in space, and thus impact the local charge density σ.

Analytical or numerical proof of this hypothesis is still being investigated. However, thus far, all experimental results support a dynamic coupling between the charge flux and the local charge distribution, resulting in the observed small magnitude vibrations. Further, note that this hypothesis requires the structure shape to be in an equilibrium between competing electrostatic pressure and compressing gravity forces. This raises the question if such EIMS vibrations would manifest if the structure were in space. If the electrostatic pressures are sufficiently large, here the shape inflation is not limited by gravity, but by internal support structure and membrane surface tension.[7] Thus, a loss in pressure will not result in a shape change until the pressure is less than an externally compressing perturbation. In the absence of gravity, a gravity-like perturbation must still be considered if the structure is accelerated through an orbital maneuver.

V. Charge Deflection Experiments

Next, the capability of an inflated EIMS system to deflect charge is investigated. The resulting wakes will impact LEO EIMS concept deployments, as well as applications such as radiation shielding. Radiation shielding is an important design criteria for any deep-space mission, especially those involving human space explorers. Lightweight structures for active radiation shielding are an attractive option to create safe habitation zones. An example of this is charged membrane structures deflecting the harmful radiation ion-flux as seen in Figure 4. The EIMS concept is envisioned as a lightweight structure which provide the required large capacitors needed to deflect MeV and GeV ions from solar flares and cosmic radiation.

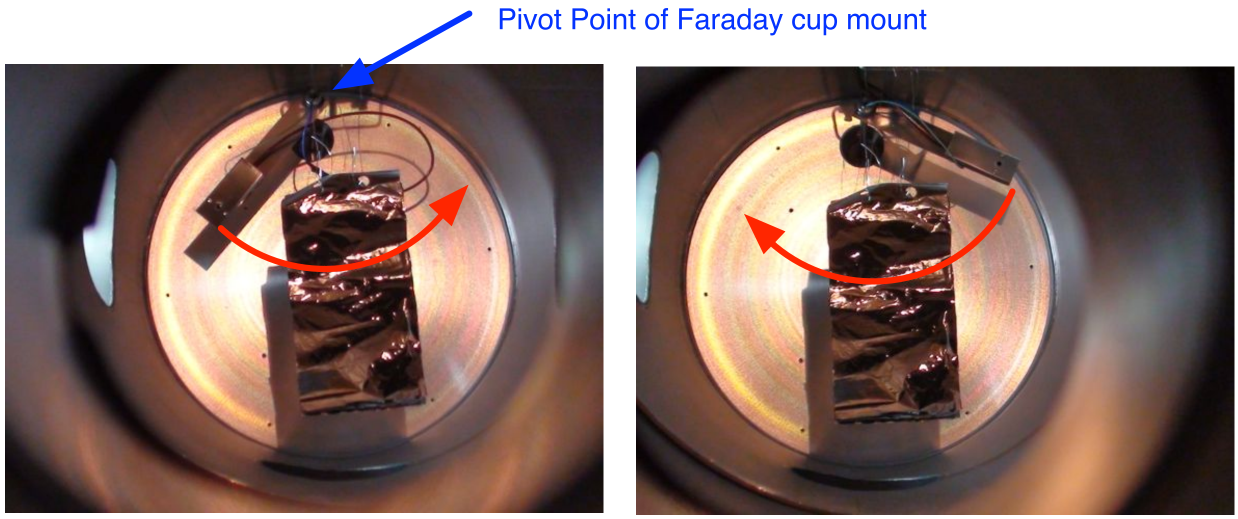


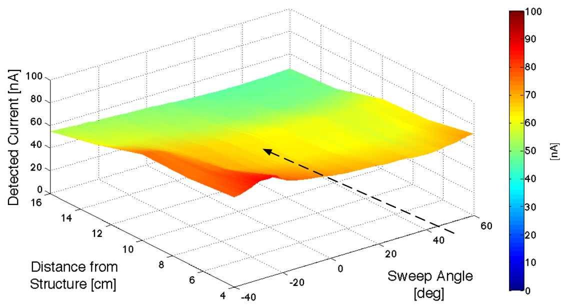
Figure 11: Rotation of the Faraday cup around the membrane structure

A. Low Energy Charge Deflection

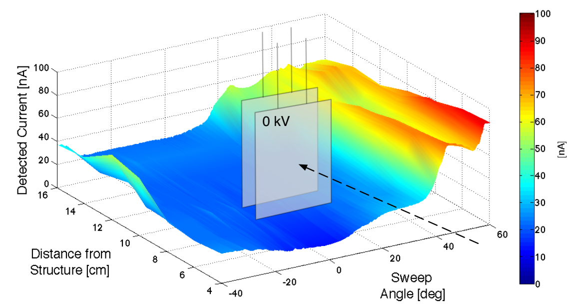
Experiments with a charged structure in the electron stream were performed to understand the charge flow patterns around the electrostatically inflated membranes and also to study the charge deflection capability of low energy electrons. A Faraday cup position is rotated within the chamber to obtain a sweep of charge flux measurements down-stream of the EIMS. The probe on which the detector is mounted allows for rotation through approximately 120 degrees. Measurements of detected current are recorded as the probe and detector are swept through the physically feasible angular range. The rotation of the detector is illustrated in Figure 11.

Experiments were performed with a membrane structure in the vacuum chamber as shown in Figure 7. This EIMS shape provided reliable inflation capabilities. Three-dimensional surface plots are used here to represent the resulting charge flux data down-stream of the EIMS for different charging scenarios in Figure 12. The Faraday cup probe is swept across the vacuum chamber at different distance behind the EIMS location to measure both nominal and deflected charge fluxes. Figure 12(a) provides a charge flux measurement experiment with no structure in the vacuum chamber. This provides a baseline result to illustrate the amount of current that is measured due solely to the electron source emitting into the chamber. Next, in Figure 12(b) the uncharged EIMS is added to the chamber, and subject to a similar charge flux. The multi-micron thick aluminum coated Mylar is too think for the 5keV electrons to penetrate. Thus, this result illustrates how much of the charge flux blocking is simply due to an uncharged EIMS. The electron flux directly behind the structure (approximately -20 to +15 degrees) drops from the 70 nA range down to the 25 nA range.

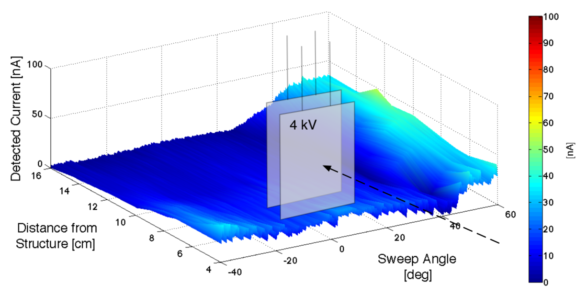
Next, the same data collection was performed with a charged structure at 4kV and 8kV. These two voltages were



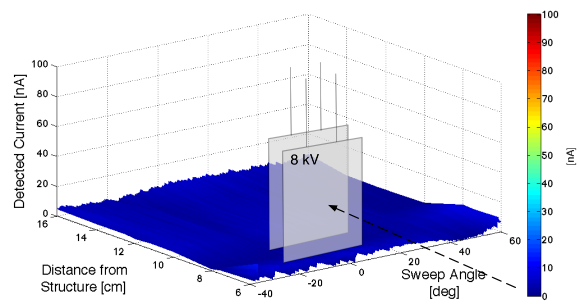
a) No Structure impeding electron flux (Baseline Flux Result)



b) Uncharged EIMS physically blocking electron flux (Baseline shielding result)



c) EIMS charged to 4kV



d) EIMS charged to 8kV

Figure 12: Electron Flux Wake Illustration behind charged and uncharged EIMS of size 8cm by 10cm.

chosen such that one voltage was below the energy of the electron gun (5 keV) and one above. The surface plots are shown in Figures 12(c) and 12(d).

When the structure is at 4kV and below the electron energy, there is still current in the 20 nA range in the flux wake behind the structure. There is an overall drop, however, in the amount of current detected anywhere behind or to the side of the structure. This experiment illustrates that the EIMS will remain electrostatically inflated while deflecting a charge flux about itself. When the structure is charged to 8kV, there is another large drop in the current levels detected in the EIMS wake. Here the EIMS potential is larger than the current energy levels, and we would expect all charge flux in the neighborhood of the EIMS to be deflected. The experiments illustrates that the inflation is again maintained while this stronger charge deflection is achieved. All recorded currents are below 12 nA and are in the single digit nA range behind the structure.

B. Shape and Configuration Study for Charge Deflection

A range of membrane structures shapes were constructed from Aluminzed Mylar for further charge deflection experiments. Of interest is how different EIMS shape perform in blocking the charge flux while considering open and closed concepts and different orientations relative to the charge flow direction. Four different configurations are used for the shape-study experiments, including sheets with cutouts, and different orientations of membranes connected with membrane ribs or ties. The cutout structures are included to study how the electrostatic fields not including the materials itself can shield particles. Figure 12(b) illustrates how even this thin membrane material is enough to block the low-energy electrons. The cutout structure would offer further mass savings. Further, having large cut-outs in the structures illustrated robustness of the EIMS charge deflection concept to rips and tears from micro-meteorite of small space debris damage. Illustrations of each configuration tested are shown in Figure 13.

For a fixed electron energy and emission current, a sweep of voltages on the membrane structure was performed up to 5 kVs. For each structure voltage, the current detected by the Faraday cup was recorded for a single location behind the structure. This doesn't show the three-dimensional charge wake as in Figure 12, but does provide a convenient single-point measurement to study the percentage of charge blocking. This procedure is repeated for different electron energies, from 1 to 5 keV. There is a clear trend of decreasing current detected behind the membrane structure as the

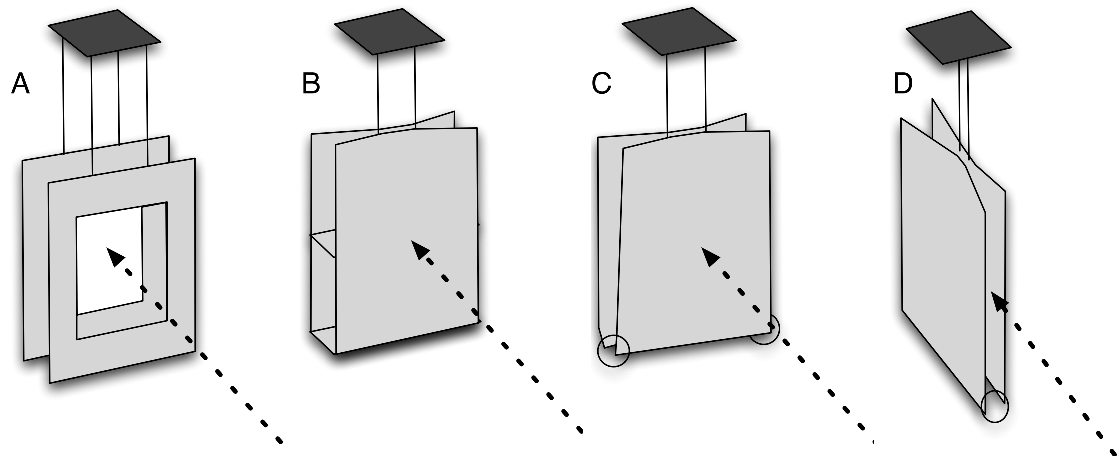


Figure 13: Four membrane structure configurations A–D used for experiments. The incoming charge flux direction direction is shown through the dashed arrow.

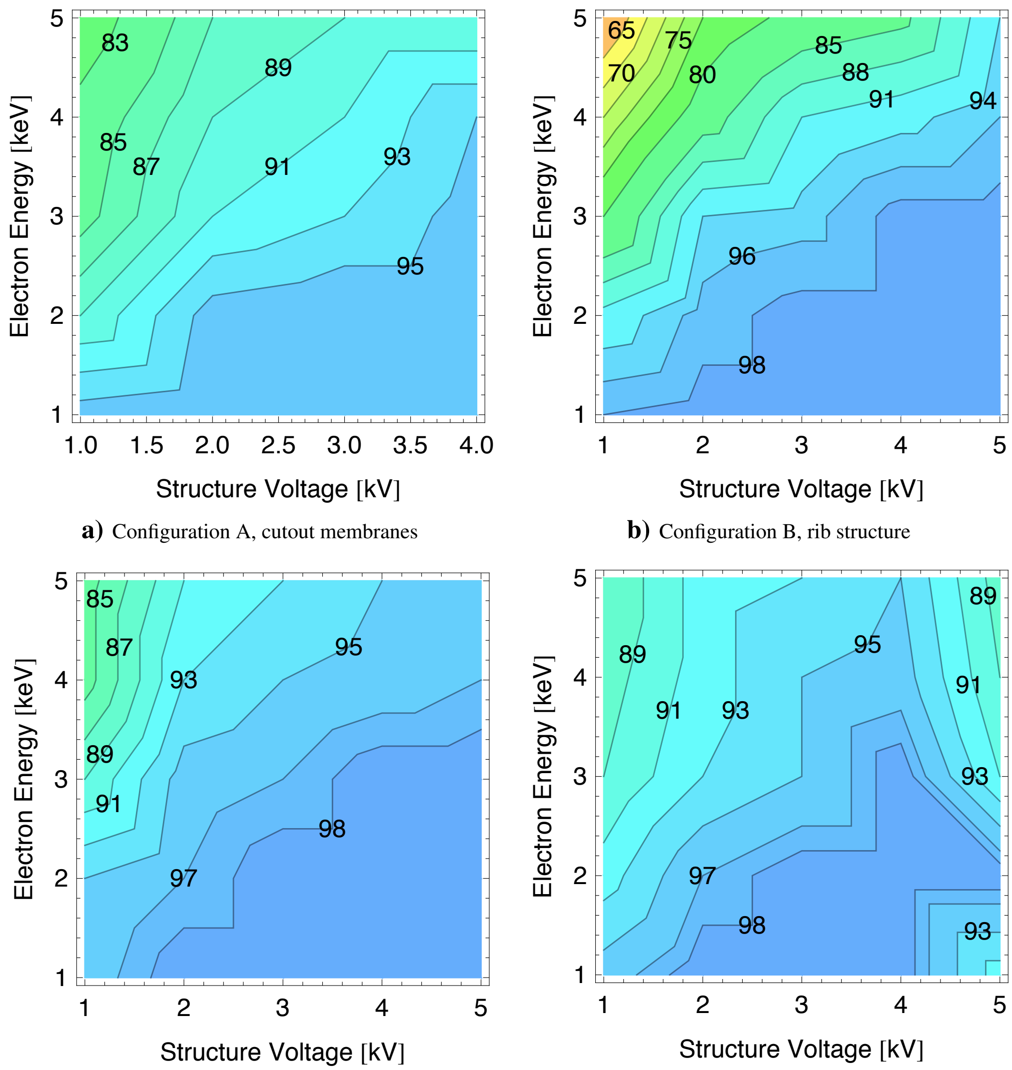
structure voltage is increased. This can be seen in Figure 14(a) for the cutout membranes (configuration A), in Figure 14(b) for the ribbed structure (configuration B), and in Figures 14(c) and 14(d) for the two configurations C and D of the tied structure. In these plots, the percentage of current detected relative to the current detected with an uncharged membrane is expressed by contours.

From these figures several conclusions can be drawn. A clear trend exists of increased shielding with increased structure voltage for the first three configurations, where the pattern is seen for all electron energies and structure configurations. These figures appear to have roughly the same trend. For the ideal case of having electrons approach the center of a charged membrane with energies less than the EIMS potential, the electron should be deflected backwards. Thus, in this ideal scenario we should be measuring zero charge behind the structure if the EIMS voltage is above the electron energy voltage. However, these tests of similarly sized EIMS prototypes illustrate that this only approximately the case. The electron beam is not well focused and the current impacts and interacts with the vacuum chamber body itself. This can cause additional scattering of the charge flux, leading to the small currents detected behind such structures. Differences in the charge deflection amount were observed for different EIMS shapes. For example, the cut-out membrane structure (configuration A) provides only a small loss in charge deflection in contrast to the more solid membrane structures. This indicates that very open charged structures might provide very light-weight charge deflection capabilities.

An interesting deviation from the nominal charge deflection to EIMS voltage relationship is seen in Figure 14(d). Here, for the tied configuration with the edge facing the electron gun, the current begins to instead increase at the highest structure voltage. Below a structure voltage of 5 kV, the membranes are physically blocking the Faraday cup aperture. When 5kV is achieved, inflation of the two membranes creates an opening in front of the aperture. As there is theoretically no electrostatic field between two like-charged sheets, the shielding begins to degrade. This illustrates that the complex flexible shape interactions with the resulting electrostatic force field must be carefully considered when designing such active charge deflection systems.

VI. Conclusion

The focus of this paper is a study of the interactions between an electrostatically inflated membrane structure (EIMS) and a charged particle flux. A vacuum chamber environment is used to perform experiments with a low-energy electron flow around various electrostatically inflated membrane structures. The goal is to understand how these membrane structure shape will behave in the plasma environment, studying charging and shape stability. The results demonstrate an interesting, newly discovered phenomena of structural vibrations between a charged membrane structure and an electron flow. A series of diagnostic tests were performed to eliminate sources of the vibrations, leading to a hypothesis that the vibrations are caused by a coupling between the changing electrostatic fields surrounding the structure and the flow of electrons to and around the structure. Additionally, the application of EIMS for active charge deflection is addressed and low-energy electron energy experiments are described. The EIMS structures are shown as efficient in shielding electrons nearly 99 percent of energy levels below or equal to structure charge levels.



a) Configuration A, cutout membranes

b) Configuration B, rib structure

c) Configuration C, tied structure, face

d) Configuration D, tied structure, edge

Figure 14: Percentage of original detected current behind inflated membrane structure at different electron energies

Acknowledgments

This work was partially support through the National Science Foundation graduate fellowship, as well as a NASA Langley research grant No. NNX11AJ80G. Thanks goes to Dr. Sternovsky of LASP for providing access to his vacuum chambers and assisting with performing the vacuum chamber experiments, as well as Dr. Tripathi for the discussions on applying this work to active radiation shielding. Finally, we appreciate the technical support provided by Carl Seubert, Nicholas Zinner, Jack Mills and Paul Anderson with setting up and performing the EIMS electron flux experiments.

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