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DEVELOPING FIELD EMITTER ARRAY CATHODE SYSTEMS FOR ELECTRODYNAMIC TETHER PROPULSION

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Abstract

Field Emitter Array Cathodes (FEAC) are a new technology being developed for spacecraft charge control. Instead of a single hot (i.e. high powered) emitter, or a gas dependant plasma contactor, FEAC systems consist of many (hundreds or thousands) of small (micron level) cathode/gate pairs printed on a semiconductor wafer that effect cold emission at relatively low voltage. Each individual cathode emits only micro-amp level currents, but a functional array is capable of amp/cm^2 current densities. This provides a robust, low power, relatively inexpensive technique for the high level of current emissions that are required for a tether propulsion mission. (Tether propulsion is a achieved by flowing current through a conducting tether, using the ionosphere as a current return path, thus requiring electron emission.) This paper covers research in progress at the University of Michigan to develop FEAC systems for electrodynamic (ED) tether propulsion. Problems for a FEAC system in the ED tether environment relating to space charge limits and ionospheric effects will be presented. Possible solutions via electrical and geometric configurations of FEAC systems, and the PIC and vacuum chamber tests being used to develop those solutions are discussed.

Nomenclature

ED = electrodynamic
FEAC=field emitter array cathodes
Vgt = gate tip voltage
?$_0$: permittivity of free space
e: electron charge [C]
m_e: electron mass [kg]
T_o: electron emission energy [eV] (tens of volts)
D: gap spacing (.01) [m]
V: gap voltage (1) [V] equal to spacecraft bias w.r.t. the plasma
W: emitter width
r_b: emitter radius
A: emitter area (0.01) [m^2]
s= sheath size [m]
$J_{CL}(N)$ = N dimensional Child-Langmuire current limit

Introduction

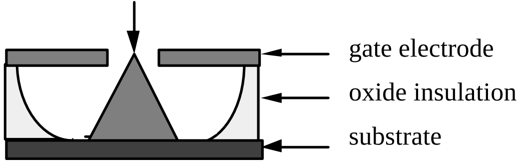
Space electrodynamic (ED) tethers offer the opportunity for in-space “propellantless” propulsion and power generation around planets with a magnetic field and an ionosphere (e.g., Earth and Jupiter). In general, moving a conductor across a magnetic field generates an electromotive force (EMF) to drive current through the conductor if a means to “close the circuit” is available. For example, using gravity gradient stabilized space tethers around Earth, it is possible to have kilometer-scale structures that move across the geomagnetic field at rapid velocities generating 50–250 V/km EMF in an eastward-moving system at a mid- to low-latitude orbit inclination. Current flow through the tether is enabled by collecting electrons from the ionosphere at or along one end of the tether and, at the opposite end, either injecting electrons back into the ionosphere or collecting ions. Electron injection is necessary to achieve the highest possible currents given the low mobility of ions. [Gilchrist, 2000]

The focus of this paper is electron injection via FEAC systems. FEAC systems emit charge with an initial velocity depending on the gate-tip voltage, and the voltage of any other associated acceleration or protection grids. As charge leaves the cathode into free space, or a plasma, each charge emitted experiences a field created by the charges before it. If the emission density is too high, this effect will decelerate the charge and, in the limit, reverse the flow and reflect current back on the emitter. One way of describing this effect is that a compression wave forms in the emission stream, with the crest propagating backwards towards the emitter. Pulses of charge buildup return, causing the emission current to vary sinusoidally with time. Another description is that a virtual cathode forms at a varying distance from the emitter, and emitted electrons see this cathode and are repelled back from it.

This space charge limitation is perhaps the most significant limitation to FEAC and other charge emission systems. The implications of this limitation and techniques for mitigating it are being studied at the University of Michigan. The approach and results to date of these studies will be presented below. This paper will also cover some of the other issues facing FEAC systems in ED tether propulsion.

FEAC Systems

The figure below shows a typical FEAC system. The scale is sub micrometer.



A typical array is a semiconductor wafer with hundreds of thousands of individual tips per square centimeter. Typical operating voltages are in the range of 50-100 V, and typical currents are on the order of tens to hundreds of mA/cm^2.

The advantages of FEAC systems over alternative electron emission devices are power, consumables, and environmental tolerance. Hollow cathode contactors, which operate by generating a plasma plume and exchanging electrons with the ionosphere across the surface of that plume, are low power (though a heater is necessary) and require relatively low operating voltages, but a consumable gas is required to maintain the plume. Electron guns require higher voltage and power than FEACs, and are sensitive to pressure gradients. While FEAC systems are sensitive to ion bombardment and neutral gas damage (though coatings can mitigate this), the system is inherently hugely redundant, whereas an electron gun typically depends on the survival of a single filament. Various arc suppression techniques as will be discussed in the next section can prevent even the complete destruction of one or many tips from significantly reducing the functionality of the entire array.

FEAC protection schemes

The very small scale of FEAC devices makes the concern of arcing (due to excessive pressure, ion bombardment, defects, etc...) significant for individual tips. One technique to reduce the risk of arcing is resistive layers- an extra layer added to the semiconductor wafer can drop the gate-tip voltage of an arcing tip before the arc current runs away. [Levine, 1996] Another technique is called VECTL, and consists of building FET topology beneath the tips, such that the excessive current of an arc automatically causes the current to be pinched off, without a drop in voltage during normal operation. [Takemura, 1997] Another technique is tip coating. ZrC and BN coatings can give stable low work functions to facilitate emission, while improving robustness to ion bombardment and poor vacuum environments. [Mackie, 1998].

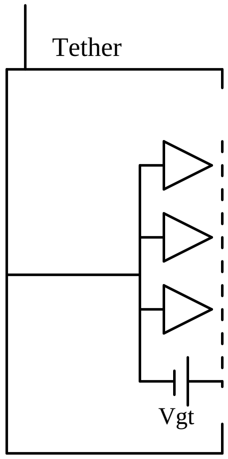
These techniques are being developed by researchers interested in FEAC systems for a wide variety of applications (from flat screen display to ion thruster charge neutralization). Testing of various solutions to environmental problems, arcing, etc... will be performed as part of the FEAC research being done at the University of Michigan, but such developments are not the primary focus.

FEAC Electrical Configuration

For a downward thrust (de-orbit) mission, energy for electron emission comes directly from the tether. For upward thrust it must come from solar cells or other onboard energy sources. In both cases decisions must be made as to how to connect the FEAC (gate and tips) to the spacecraft. How the gate and tip are biased relative to the spacecraft result in various advantages and disadvantages to the system overall.

A factor in this decision is that the spacecraft potential may vary widely. The bottom of the tether will be biased by it's motion through the earth's magnetic field (this is how ED tether propulsion works), possibly as much as thousands of volts negative. As the FEAC operates, however, it can bring the spacecraft up to neutral bias and even above, if the FEAC's current provision capability exceeds the tether/upper spacecraft's current collection capability. Therefore care must be exercised in how the tip is biased relative to the gate and spacecraft.

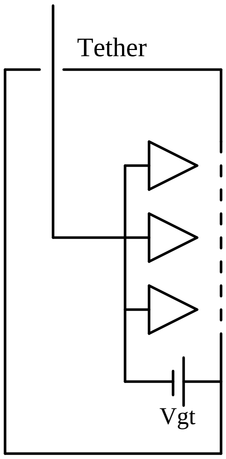
The figure below illustrates the grounded tip configuration:



Basic Grounded
Tip Configuration

Advantages of this configuration include stability and low return current. One disadvantage is that the emitted electrons must move away from a gate biased positive relative to the plasma (assuming the spacecraft is close to the plasma potential) and this will act as a decelerating force, increasing space charge limitations.

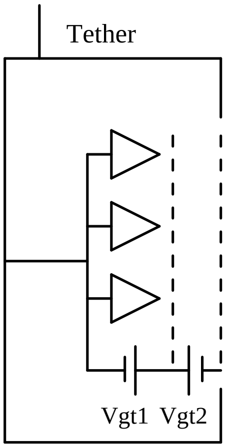
The following diagram illustrates the grounded gate configuration:



Basic Grounded
Gate Configuration

The advantage of this configuration is that electrons leave through a screen at the same potential as the plasma, no decelerating fields will exist. (if the spacecraft is biased negative, a beneficial accelerating field will be present). One major disadvantage is that the gate-tip voltage can be directly effected by swings in the tether voltage. This becomes an especially significant concern when the tether is connected and disconnected for mission propulsion reasons-potentially resulting in huge spikes that the gate tip supply must suppress to avoid sparking the entire array.

Combinations of these techniques are possible as illustrated below. One advantage of a multiple gate configuration is that the second gate could be shaped to defocus the emitted electron beam, further mitigating space charge effects because the effective density is reduced (see space charge limits below).



Multiple Gate
Grounded Tip
Configuration

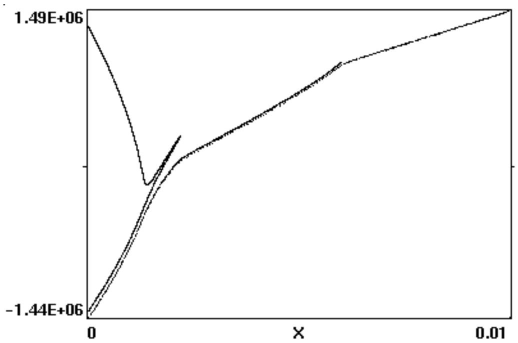
Space Charge Limits

Charge control can be described as two major steps- 1) create charge, 2) get the charge away. FEAC systems create charge with low power and voltage, thanks to the small scale of the tip-gate geometry. But regardless of the voltage required to pull electrons free of the tips, they must leave the FEAC with enough energy to get away and stay away from the spacecraft. This is where space charge limitations come in.

The first step of space charge limitation is in the sheath region, the plasma depleted area immediately surrounding the spacecraft. Plasma accommodation is of little assistance here, while the emitted electron density is the highest. Some believe that this is the most critical region. However it is also the region where the electron velocity is the highest, and barring large spacecraft biases, the sheath will only be on the order of centimeters wide. Others believe that the primary space charge limitations will occur in the plasma where electrons must travel a large distance until they are accommodated, i.e. the emitted electron density becomes trivial compared to the background density. The beam is lost in the noise, so to speak. Where exactly the most critical limitations occur probably depends on the spacecraft bias, electron emission density, and ambient ionospheric density and the solution to this question is one of the primary focuses of this research.

Basic Space Charge Limitations

The following figures show results of one dimensional PIC simulation in the space charge limited regime. XPDP1 simulates particle activity between two plates- with each particle representing a sheet of charge (thus the 1D nature). The first plot is of velocity versus position of the individual electrons in the simulation (the apparently continuous line is actually individual electron dots in close proximity). The center of the plot is zero velocity. Electrons are emitted with a relatively high energy (equivalent to 60v), but space charge effects decelerate them until they reverse direction and travel back towards the emitter. When enough electrons have reversed, space charge effects are alleviated and forward motion resumes. Thus the plot below is not a steady state solution but rather a continually shifting distribution. Figure two shows the time variation.



1 dimensional charge emission, with buildup and reflection near the emission point (left side).

The following plot of current versus time reflects the process of electron bunch and spreading when emission occurs in the space charge limited regime.

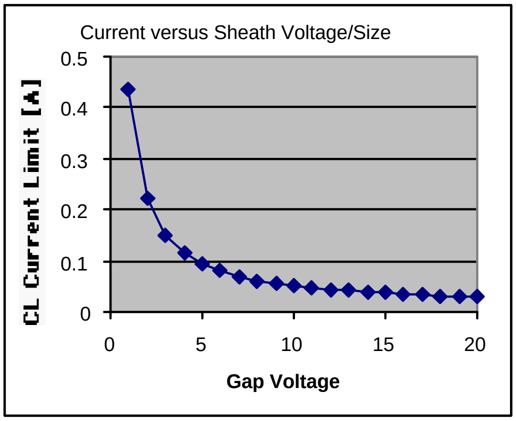
figure 2: emitted current in the space charge limited regime.

This simulation represents the approximation where the sheath is considered to be the only region of interest- i.e. that any electrons managing to cross the sheath are effectively absorbed by a virtual anode (the ionosphere) and need no longer be considered. This simplest version of the problem has been solved analytically and the equation is given below. The maximum current density that can be transmitted across a one-dimensional planar gap is given by the one dimensional classical Child-Langmuir Law [Luginsland, 1988].

$$I_{CL} ?1?? \frac{4?_o}{9e}\sqrt{\frac{2}{m_e}}\frac{T_o^{3/2}}{D^2}\begin{matrix}??\\??1?\\??\end{matrix}\sqrt{1 ? \frac{eV}{T_o}}\begin{matrix}??\\??\\??\end{matrix}^{3} A$$

With the A term added to describe the area of the emitter [Gilchrist & Jensen, 1999].

The following plot shows the resulting current emission capability as a function of sheath size/voltage.

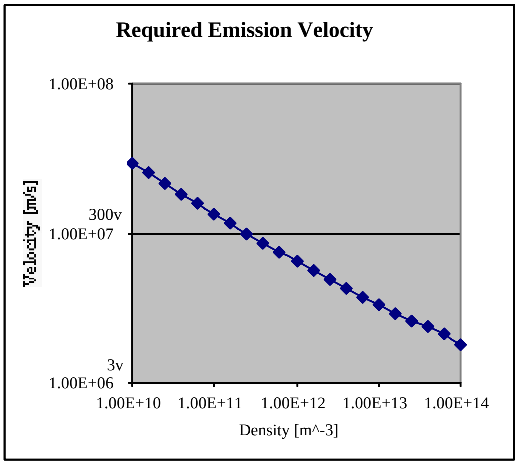


With the relationship between sheath size and voltage as:

$$s \approx \left(\frac{2\varepsilon_0 V}{e n_s}\right)^{1/2}$$ [Lieberman & Lichtenberg, 1994]

Note that while an increase in bias voltage does improve the ability to emit electrons because the electrons are propelled away from a negatively biased spacecraft, this effect is overbalanced by the fact that the sheath which the electrons must successfully cross gets larger at the same time.

Another related space charge limitation approximation is to consider a FEAC operating facing into the ram direction of spacecraft motion. Electrons will react to the spacecraft bias regardless of spacecraft velocity, but ion motion will be largely static, ion mass being too large to allow them to react to a sheath before they strike the spacecraft (unless the sheath is large, or the space charge limited buildup of electrons is large). Ion flow across the sheath will assist in electron flow in the opposite direction, and the greater the density of ions, the greater the possible non-space charge limited electron flow. The following plot illustrates the results of XPDP1 simulations of this approximation.



As illustrated, the energy required to avoid space charge limits increases as the ion density being emitted towards decreases.

Higher Dimensions

Space charge limits are a function of emitted charge density. Therefore the more the emission beam is spread, the less the space charge limitations. Higher dimensions allow for larger current emission. The following equation shows the increase in space charge limited current for two dimensions as opposed to one [Luginsland, 1996]:

$$\frac{J_{CL}(2)}{J_{CL}(1)} = 1 + \frac{0.3145}{W/D} - \frac{0.0004}{(W/D)^2}$$

An additional improvement is allowed by the transition to three dimensions, as calculated by [Humphries, 1990]:

$$\frac{J_{CL}?3?}{J_{CL}?1?} ? \frac{?r_b^2 ? ?D/2?^2?}{r_b^2} ? ?1 ? ?D/2r_b?^2 ?$$

PIC Simulations

Additional 1 dimensional analysis accounting for sheath dynamics and other factors is still to be done. In addition, confirmations of the above higher dimensionality equations as they apply to this application will be done with XOOPIC (2dimensional PIC) and other codes in 2, 2.5, and 3 dimensions.

To quantify parameters of electron charge emission into a space plasma, a typical tether propulsion mission operates in the low earth orbit environment, through the F and possibly as low as E regions of the ionosphere. From 100-1000km, ionosphere electron densities are typically within the outer extremes of N= 10^8 to 10^{13} m^{-3}. [Tascione, 1988]

For useful propulsion, tether currents (and therefore system emission currents) on the order of 1-3A are required at a minimum, with larger currents desirable. With limits in available spacecraft surface area, this implies an emission current on the order of 100mA/cm^2. In order to minimize the power drain of the system, either from internal power, or from the tether emf used for propulsion, it is desirable to minimize the emission velocities. Initial estimates indicate electron emission energies on the order of tens of volts, in the 30-60 V range. [Gilchrist & Jensen, 1999] Emission velocities in the hundreds or single volt ranges will not be considered.

With a tethered satellite system, the bias of the spacecraft with respect to the plasma could be quite large- on the order of tens of volts or higher depending on the efficiency of charge emission. Bias voltages ranging from about half a volt to tens of volts can be considered. The Debye length in a plasma is

$$?_D ? ??\frac{kT}{4?ne^2}??^{\frac{1}{2}}$$

Which, with a representative electron temperature of 0.03 eV [NRL, 1998] calculates out to 7mm to 2.2cm for the range of plasma densities being considered. A low voltage sheath can be estimated as being a few Debye lengths thick, while a high voltage sheath can be tens of Debye lengths thick. This dictates a sheath size ranging from about 1 cm to tens of centimeters. [Lieberman & Lichtenberg, 1994]

These parameters, and the parameters measured in chamber tests as mentioned below will be used in the PIC simulations.

Vacuum Chamber Tests

FEAC tests will be performed in the CTF vacuum facility at the University of Michigan.

Cathode Test Facility

The Cathode Test Facility (CTF) is a two meters long by 60 centimeters in diameter chamber that is pumped by a 135 CFM mechanical pump for roughing and a CVI TM500 (20 inch) cryopump with a measured xenon pumping speed of 1,500 l/s. Base pressure for the facility is 2 x 10-8 Torr. The facility consists largely of components either granted to PEPL by NASA Lewis Research Center or bought with funds from NASA Lewis Research Center and the Jet Propulsion Laboratory.

Test Plan

Unfortunately it was impossible to complete chamber tests before the conference, but the following tests are in progress.

Environmental tests of sample FEACs will be performed. FEACs will be subjected to a variety of neutral gas densities and constituents. Operational and survival limits will be determined for uncoated, ZrC coated, and other tips.

Space charge tests will be performed via a variable plasma density, and mobile anode (current collector). The ability to emit current across a limited gap will be compared to PIC simulation results, and the ability of a FEAC to emit charge into a plasma with no collector will be confirmed.

The test procedure will be automated insofar as possible, with GPIB devices and a Labviews controller. Measurements of the gate, tips, collector, and spacecraft simulator (a steel can) will be made. The bias of the various components will be varied, thus experimenting with the various electrical configurations as described above, and with the effect of sheath size. Plasma density measurements in proximity to the emitter will be made with multiple Langmuir probes and a mobile electron current density probe. Neutral pressure will be monitored with an ion gauge and residual gas analyzer.

Summary

FEAC systems are an enabling technology for ED tether propulsion. PIC analysis and chamber tests are being performed to characterize and mitigate the various technical issues facing FEAC systems in the ionospheric region. This research will lead to efficient and effective designs which will make possible a variety of ED tether and other missions.

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