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Explosive emission cathodes for high power microwave devices: gas evolution studies

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EXPLOSIVE EMISSION CATHODES FOR HIGH POWER MICROWAVE DEVICES

by

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# Explosive Emission Cathodes for High Power Microwave Devices; Gas Evolution Studies

**Abstract**

Present-day high power microwave devices suffer from a lack of reliable, reproducible cathodes for generating the requisite GW-level electron beam in a vacuum. Standard explosive emission cathode pulse durations have been limited to 10’s or 100’s of ns due to the expansion of cathode-generated plasma and the ensuing impedance collapse that debilitates microwave output. Traditional thermionic cathodes do not suffer from this drawback of plasma generation, but have not yet been able to provide the required emission current densities explosive emission cathodes are capable of. It is expected that if the plasma could be made cooler and less dense, explosive emission would be more stable. Cesium iodide (CsI) has been found to slow the impedance collapse in many explosive emission cathodes. Herein we will experimentally examine diode impedance collapse, gas production, and cathode conditioning in an effort to perform an evaluation of explosive cathode performance in a typical thermionic electron gun environment. These results will then be used to help demarcate the parameter space over which these CsI-coated carbon fiber cathodes are viable candidates for the electron beam source in next-generation high power microwave devices.

**Subject Terms**

- High Power Microwaves
- Cathodes
- Electron Beam
- Vacuum
- Explosive Emission
- Plasma
- Carbon Fiber

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**Supplementary Notes**

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.
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ABSTRACT

Present-day high power microwave devices suffer from a lack of reliable, reproducible cathodes for generating the requisite GW-level electron beam in a vacuum. Standard explosive emission cathode pulse durations have been limited to 10’s or 100’s of ns due to the expansion of cathode-generated plasma and the ensuing impedance collapse that debilitates microwave output. Traditional thermionic cathodes do not suffer from this drawback of plasma generation, but have not yet been able to provide the required emission current densities explosive emission cathodes are capable of. It is expected that if the plasma could be made cooler and less dense, explosive emission would be more stable. Cesium iodide (CsI) has been found to slow the impedance collapse in many explosive emission cathodes. Herein we will experimentally examine diode impedance collapse, gas production, and cathode conditioning in an effort to perform an evaluation of explosive cathode performance in a typical thermionic electron gun environment. These results will then be used to help demarcate the parameter space over which these CsI-coated carbon fiber cathodes are viable candidates for the electron beam source in next-generation high power microwave devices.
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I. INTRODUCTION

A. OBJECTIVES

Cathodes for generating vacuum electron beams have played a fundamental part in the development of the modern electronic society since the middle of the 19th century. They have found uses in many different areas of science and commerce, from television and vacuum tubes, to oscilloscopes and high energy particle colliders. Cathodes are an underlying elementary technology since they allow access to voluminous amounts of one of the fundamental particles that constitute our world, electrons. Being able to easily extract and manipulate these particles has led to changes in our theories about how our world works, which has led to advancements in computing and electronics that have completely changed the way we do science as well as how we live our lives. Continual research and advancements in the methods, construction, and employment of cathodes have shown we still have much to learn and many more uses for these devices.

Specifically the move from thermionic emission to explosive emission of electrons from cathodes has shown many advantages in power consumption, current densities and “life” of the cathode. Thermionic emission occurs when electrons are “boiled” off the cathodes surface by supplying enough energy to the cathode to exceed the cathode material’s work function. Explosive emission relies on quantum mechanical tunneling of electrons from materials, which can reduce the power required to emit electrons as well as minimize the temperature increase of the cathode. This second feature of explosive emission cathodes makes them very desirable since heating most materials to a point where they would emit electrons typically melts them first and hence only a few materials have been discovered that work well as thermionic cathodes. With explosive emission, practically any material can be used since the cathode remains in a relatively “cold” state. However, when choosing materials, research has shown that careful considerations must be made since the physics of high energy electron beams colliding with any material will cause neutral particles, electrons
and other contaminates to be ejected from the surface. These particle ejections can be a limiting factor in explosive emission cathodes if the materials are not chosen carefully.

The availability of high current densities as well as maintaining relatively cool cathode materials with the commensurate increases in cathode lifetimes has made explosive emission a prime candidate for use in high power microwave (HPM) devices. The use of explosive emission while bringing the previously stated advantages, also brings new and unique problems that must be thoroughly understood and compensated for or eliminated if explosive emission cathodes are to be considered effective in HPM devices. This thesis looks to understand and propose solutions to remedy these problems to bring explosive emission another step closer to being a useful mechanism in the employment of HPM devices.

B. BACKGROUND

1. History and Developments

In order for explosive emission cathodes to be useful in an HPM, several physical characteristics of the system must be understood. In a typical HPM system, electrons are emitted from a pseudo-planar cathode surface and accelerated towards an anode some distance away. The energy in the electron beam thus generated is then extracted in the form of microwaves. At the high voltages (>100kV) and currents (>1kA) of an HPM device, the problem most frequently encountered is impedance collapse due to the closure of the cathode and anode (A-K) gap from plasma generated in the gap. The gases are presumed to evolve from primarily the cathode surface but can also come from anode surfaces which are typically metals that have high gas evolution rates. This gas and plasma evolution which can reach velocities from 1 to 10 cm/µs can quickly close the gap a few centimeters across and cause destructive arcing. This limits the pulse length allowed shot-to-shot in the HPM device which in turn limits the electron beam and total energy any HPM device could deliver [7].
Being able to control this gas and plasma evolution through better design and better materials is one focus of this thesis.

The selection of materials has been an on-going process in explosive emission with current trends focusing on carbon based cathode materials [1-13]. Previous materials were pure metal or metal based, but significant testing found that these materials self destructed quickly at the energies required, and had significant outgassing [10]. The desire for robust materials with good thermal characteristics, reasonable manufacturing processes, and ease of use drives current research to the use of carbon fiber cathodes. Several varieties of these cathodes are currently in testing, with some having carbon fibers attached with epoxy to metallic bases and others directly attached to carbon cathode stalks via a pyrobonding process [5]. Pyrobonded carbon cathodes were chosen based on this previous research and in particular to reduce the outgassing from the cathode surface to a point where other outgassing effects could possibly be observed and measured. These fully carbon cathodes can be baked at high temperature (400 °C) in order to drive off absorbed gases before testing. The practice of coating the carbon fibers with generous amount of Cesium Iodide (CsI) salt also has shown to reduce plasma propagation allowing greater pulse lengths and reduced gap closure occurrences, so this technique was also employed with each carbon cathode tested [3-7].

While the performance of the cathode is of primary importance to the focus of this thesis, the system as a whole must be evaluated to ensure other effects are considered when formulating conclusions about the data. In particular the anode performance is scrutinized as a source for neutrals and hence plasma that can lead to accelerated gap closure and impedance collapse. The ensuing arcing can damage the cathode and anode surfaces to the point that they become unusable due to continued localized field enhancements that can’t be conditioned away. Previous anodes used bare metal surfaces to absorb the electron beams with the result being significant outgassing at the anode surface. Research had showed that polishing these metals to very fine finishes could reduce this outgassing, but the resultant neutral production was still undesirable
Careful consideration of the design and type of anode used were evaluated to minimize its effects in the A-K gap, and to help reduce the neutral generation as well as extend the life of the high power diode.

The relatively free flow of electrons in the diode region required the use of a good vacuum system. Initial high power cathode tests had vacuums on the order of $10^{-4}$ to $10^{-6}$ torr, which were reasonable, but had too much background gas to deduce reasonable conclusions about the nature of the gasses and plasmas generated in the A-K gap region [9-10]. Recent research has shown that vacuums in the low $10^{-7}$ to high $10^{-8}$ torr are desirable to determine the number of neutrals as well as determine the type of constituent elements emitted from outgassing at the cathode and anode surfaces [7].

2. Theory

In order to understand the emission characteristics and physical limits imposed on explosive emission cathodes, two gentlemen, C. D. Child and I. Langmuir worked from 1911-1913 to develop a mathematical model that described the basic limits of electron discharge from an A-K diode in a vacuum. In their description of this electron discharge they came upon a fundamental physical limit which they called the space-charge limit. Although complex in three dimensions, the basic premise was that there are only so many electrons you can emit from a cathode before the volume of the A-K gap gets saturated with charge, the electric field is driven to zero at the cathode and the rate of electron emission reaches a steady state. This is the essence of space-charge limited flow. Their technique involved solving a non-linear, second order differential equation and is presented here to set the basis for understanding the real charged particle emissions seen in explosive emission cathodes.

The Child-Langmuir (C-L) limit considers the maximum current density that can be drawn in a vacuum between two infinite parallel plate electrodes. These plates are separated by a gap distance $D$ with a potential voltage $V$ between the two plates. Assuming an infinite supply of electrons at the cathode, C-L showed how much current could be drawn across the gap in steady state.
Since the plates are infinite, current density rather than total current is considered:

\[ J(z) = \rho(z) \ast v(z) = - J_{SCL} \]  

(1)

where \( \rho \) is the charge density and \( v \) is the charge velocity as a function of their position in the gap \( z \). Since the plates are infinite the \( x \) and \( y \) directions are removed to simplify the equation and all vectors can then be treated as scalars. Since charge is conserved \( J_{SCL} \) will not vary with \( z \) and is therefore equal to a fixed current density which is what we desire to obtain. The negative sign is introduced to show charged carried in the positive \( z \)-direction by electrons to match the standard definition of current flow. Considering the kinetic and potential energies in the conservation of energy equation leads us to see:

\[ \frac{1}{2} m v^2(z) - e \varphi(z) = K = 0 \]  

(2)

where \( m \) is the electron mass and \( e \) is the electron charge. \( \varphi(z) \) is the potential field in the A-K gap. We set the equation equal to zero since electrons are initially at rest in the grounded cathode. The potential \( \varphi(z) \) must follow Poisson's equation:

\[ \nabla^2 \varphi(z) = \frac{- \rho(z)}{\varepsilon_0} \]  

(3)

with \( \varepsilon_0 \) equal to the permittivity of free space. Substituting Equation 1 and 2 into Equation 3 to eliminate \( \rho(z) \) and \( v(z) \) gives us Equation 4:

\[ \frac{d^2 \varphi}{dz^2} = \frac{J_{SCL}}{\varepsilon_0} \sqrt{\frac{m}{2e}} \frac{1}{\sqrt{\varphi(z)}} \]  

(4)

which is second order and non-linear. The solution is not readily apparent but is solved through normal manipulation.
An initial integration of Equation 4 can be performed by multiplying the equation by \( \frac{d\varphi}{dz} \):

\[
\left( \frac{d\varphi}{dz} \right)^2 = \frac{4J_{SCL}}{\varepsilon_0} \sqrt{\frac{2e}{m}} \sqrt{\varphi(z)} + K = \frac{4J_{SCL}}{\varepsilon_0} \sqrt{\frac{2e}{m}} \sqrt{\varphi(z)} + \left( \frac{d\varphi}{dz} \right|_{z=0} \right)^2
\] (5)

where we substitute the square of the electric field for \( K \) which is found at the cathode surface and is a result of the boundary condition at the cathode where the potential is zero (\( \varphi(0) = 0 \)). Assuming no initial space charge in the gap, the electric field \( V/D \) will accelerate electrons from the cathode to the anode. The vacuum electric field starts to change as electrons enter the gap due to their charge. Eventually the electron density is high enough to cancel out the applied electric field at the cathode surface and no further electrons are accelerated across the gap. It is at this point that the A-K system has reached its space charge-limit where any additional electrons introduced would be driven back toward the cathode surface due to the electric repulsion of the electrons already in the gap. In a steady state situation electrons enter the gap from the cathode at the same rate they leave the gap at the anode which gives rise to the space charge-limited current density \( J_{SCL} \).

With the electric field set to zero at the cathode surface we can integrate Equation 5 to give the potential in the gap:

\[
\varphi(z) = \left( \frac{3}{2} \right)^{\frac{4}{3}} \left( \frac{J_{SCL}}{\varepsilon_0} \right)^{\frac{2}{3}} \left( \frac{m}{2e} \right)^{\frac{1}{3}} \frac{4}{3} \frac{z^3}{3} + K
\] (6)

with the constant of integration set to zero due to the boundary condition \( \varphi(0) = 0 \). In order to obtain the space charge-limited current density, we need to apply the boundary condition of fixing the potential at the anode, \( \varphi(D) = V \), which then allows us to solve for the current density \( J_{SCL} \):

\[
J_{SCL} = \frac{4}{9} \varepsilon_0 \sqrt{\frac{2e}{m}} \frac{V^2}{D^2}
\] (7)
This solution presents a very straightforward way of looking at the current density in the gap since the only varying parameters are V and D [1-2].

However, this solution only takes into account electron emission in the gap. Real world testing has shown plasma formation and gap closure leading to the conclusion that most explosive emission cathode systems have other charged particles emitted from the cathode as well as possibly the anode. Additional charged particle emission will lead to higher observed current densities than those observed in C-L. Steady-state bipolar current flow, where the current is effectively doubled ($\sim 1.8 \times J_{SCL}$) due to positive ions in the A-K gap screening negative charge allowing more electron current to flow, is one possibility for higher current than the C-L theory. Also, even higher, though unstable, current densities can be observed if other mechanisms are emitting charged particles not directly attributed to the cathode and anode surfaces [4]. Emission from gas still present in the vacuum chamber, and emission from the cathode and anode mountings may contribute as well, leading to currents that can be several multiples of those predicted from C-L theory. Excessive current may then lead to an unstable arc condition. An arc, with its extremely low impedance, is no longer a useful source of energy for generating microwaves and must therefore be avoided.
II. EXPERIMENTAL SETUP

A. THRESHOLD CATHODE TEST FACILITY

The design and setup of the Threshold Cathode Test Facility (TCTF) was based on previous work conducted at the Air Force Research Laboratory (AFRL). The original TCTF tested at AFRL was designed for 250 kV, 100 Ohm, 1 μs duration pulses at a rate of up to 1 Hz. The new TCTF designed for this research operates at lower voltages (20-200 kV), lower impedance (50-100 Ohms), variable pulse lengths (200-2000 ns) and has both single and multi-shot modes of operation. Other improvements were made to the vacuum system allowing an order of magnitude increase in vacuum from $10^{-6}$ torr to $10^{-7}$ torr so that gas evolution from the cathode and anode materials can be more readily observed and studied.

The TCTF system with all attached support equipment has a total internal volume of $50 \pm 2$ liters. Manufacturer specifications and the general uncertainty of the exact dimensions of the assembled parts made determination of volume by manufacturer specifications difficult. Therefore, total volume was determined using the Ideal Gas law. The existing vacuum system and pressure gauges made this process straightforward. A gas flow meter was used and dry nitrogen was flowed into the evacuated chamber. Pressure and flow measurements were taken at time increments of 30, 45 and 60 seconds. Using the difference in initial and final pressures and the measured gas flow, the volume was determined. This process was repeated and showed a deviation between runs of less than 5%. The calculated estimate of the volume using manufacturer’s internal dimensions was approximately 47 liters, which is in good agreement with the volume as measured above.

The new TCTF vacuum chamber is 30 cm in diameter and has six copper gasket-seal flanges. All other seals are copper except for an elastomer based seal for the main access door to the vacuum chamber and elastomer based seals on two independent gate valves used to isolate attached pumps from the chamber. In order to achieve high vacuum multiple stages of pumps are used.
The system is started with an oil-free scroll pump to achieve initial vacuum, followed by a turbine pump to get vacuum to the $10^{-6}$ torr level and lastly an ion pump to achieve the $10^{-7}$ torr and high $10^{-8}$ torr vacuum levels needed for gas evolution analysis. Pressure measurements are taken at the turbine pump and in the test chamber using convection gauges with ranges from atmospheric to the millitorr range. Cold cathode inverted magnetron gauges with ranges from a few millitorr to the ultra-high vacuum regime ($<10^{-7}$ torr) are used to monitor pressures during normal cathode testing operations. A 600 W quartz heating lamp is also installed to assist in outgassing the internal surface area, and to reduce water absorption during cathode and anode change-outs when the chamber is brought back up to atmospheric pressure. This layout allows pumpdown of the system from atmospheric to $10^{-7}$ torr in two to three hours, and $10^{-8}$ torr with quartz lamp heating over 12 to 18 hours [12].

In order to test cathodes, mountings were fabricated to allow easy change out of materials for both cathode and anode surfaces. Rogowski-based profiles were selected due to their ability to provide a uniformly decreasing electric field as a function of radius along the cathode and anode surfaces [12].
1. Cathode Selection and Coatings

The decision to use carbon fiber cathodes stems from previous research at AFRL as well as several other studies showing the advantages of using carbon to reduce outgassing and improve design lifetime of the cathode surface [1-12]. Carbon has many traits desirable to explosive emission. Because the cathodes can be manufactured in fiber form, they in essence are thousands of localized field emitters. This allows fast turn on due to highly enhanced fields at each fiber. The addition of a Cesium Iodide coating is also thought to promote rapid flashover due to photoelectron emission which quickly “turns on” the whole cathode surface. These properties are desirable since they have demonstrated generally uniform current distribution over the cathode surface during the duration of the voltage pulse.

The carbon fibers 3500 °C sublimation point can clearly withstand the maximum transient temperatures of around 2500 °C in the TCTF, but carbon fiber failures do occur due to the rapid emission of electrons from its surface. The carbon fibers do not melt and form blunt ends, but rather fracture and
splinter forming additional sharp points which are field enhancement areas. This effect has not shown any performance degradation since the overall cathode enhancement area is generally unaffected [13].

Previous cathodes were manufactured with a metal base for mounting with the carbon fibers attached using an epoxy to glue the two materials together [13]. This design had problems due to the degradation of the epoxy in the high electric fields encountered in explosive emission systems. This resulted in fiber detachment from the cathode surface which caused the cathode to fail with cascading fiber detachment due to increased fields at the remaining fibers. Energy Science Laboratories Inc. (ESLI) were contracted to manufacture a pure carbon cathode, with a carbon mounting stock as well as carbon fibers. The fibers are pyrobonded to a POCO™ graphite stock allowing continuous carbon cathodes with no discontinuities that could lead to premature fiber separation or unwanted field enhancement. The cathodes were manufactured with 2.0% area coverage with the majority of the fibers at \( \sim 1.5 \text{ mm} \) height and sparsely mixed were fibers at \( \sim 2.0 \text{ mm} \) height. Addition of the 2.0mm fibers is thought to promote faster turn-on and lower required voltage for emission. The longer fibers have stronger field enhancement since they rise above the neighboring 1.5mm fibers; the 2.0mm fibers emit first which then turns on the 1.5mm fibers in a cascading fashion.

An additional step was taken to prepare the carbon cathodes for use in explosive emission. The cathodes were coated with a fine mist of a supersaturated Cesium Iodide (CsI) salt solution. This technique has shown favorable results in slowing the propagation of the plasma generated at the cathode surface, possibly due to heavier ions compared to hydrogen. This reduces gap closures speeds allowing for microsecond pulses to be used and reduces the possibility of arcing in the A-K gap. Minimizing or eliminating this arcing minimizes any damage that may occur to the cathode and/or anode surfaces which extends the life of the materials.
Figure 2.  Bare carbon fibers at 14x (l) and 230x (r) magnification  
(Photos courtesy of Qiong Shui at the University of Southern California)

Figure 3.  Bare carbon fibers at 914x (l) and 3000x (r) magnification  
(Photos courtesy of Qiong Shui at the University of Southern California)

Figure 4.  CsI coated carbon fibers at 14x (l) and 228x (r) magnification  
(Photos courtesy of Qiong Shui at the University of Southern California)
2. Anode Selection

Previous studies [3] have showed that pure metal anodes were effective in high power devices, but due to the outgassing and the damage to the anode surface from the high energy electrons, this type of anode would be undesirable for experimentation. Two types of anodes were used due to their ability to trap the incoming electrons and reduce possible outgassing and bipolar effects in the A-K gap.

The first anode used was a molybdenum mesh. It was constructed to fit the Rogowski-based anode profile and was chosen due to its high strength, stiffness, and melting point which was deemed desirable at the power levels encountered in the TCTF system. The reasoning behind the mesh arrangement was to allow electrons to pass through the mesh thereby minimizing impacts to the anode surface, while still maintaining the electric field necessary for the diode to work properly. Allowing the electrons to pass through the mesh and collect farther downstream from the anode surface will reduce bipolar effects and outgassing in the A-K gap since electron impacts wouldn’t occur in the gap region.
The second anode used was a carbon fiber anode designed and fabricated similarly to the cathodes, except all fiber heights were 1.5mm. The reasoning behind this arrangement was to take advantage of the reduced outgassing characteristics of carbon as well as use a different mechanism to hopefully reduce the effect of energetic electrons at the anode surface. With many thousands of individual fibers at the anode surface, electrons crossing the A-K gap will generally impact at oblique angles to the carbon surfaces. This should reduce the likelihood of the impact leading to gas generation and thereby reduce the positive ion bipolar effect as well. The durability of the carbon anode is also desirable since even if gap closure and arcing do occur, the robustness of this material minimizes the damage to the system, leading to longer life of the diode.

Installation into the TCTF was straightforward with cathodes threading into the Rogowski-based cathode holders, anodes inserted or threaded into the
Rogowski-based anode holders and both cathode and anode holders threaded onto the mounts in the TCTF system.

Figure 7. Carbon fibers and threaded carbon stock with CsI coating

Figure 8. Carbon cathode with fibers projecting slightly (0.2mm) above the stainless steel cathode holder surface
Figure 9. Fully installed cathode (lower) and anode (upper) showing Rogowski-based profiles

B. PULSED POWER SYSTEM

In order to deliver adequate electrical power to the A-K diode, a robust, fast and flexible power system had to be designed. A circuit diagram is provided in Figure 10 outlining the major parts and specifications of the system. Maximum design output voltage is 200 kV with output amperage in the 1-10 kA range depending on diode impedance which varies by A-K gap distance and applied voltage.
The system uses two General Atomics CCDS power supplies rated at 50 kV and 8 kJ/s. In order to achieve 200 kV the system uses capacitors in parallel with one pair charged with the positive power supply and the other pair charged with the negative power supply. Reaching maximum voltage requires one pair of capacitors to be charged to positive 50 kV and the other pair charged to negative 50 kV. Then using the spark gap switches, the system is discharged in series to give an effective voltage output of 200 kV. The system can vary the voltage to
the capacitors so that a voltage range from 20 kV to 200 kV can be employed. Typical rise times of the current from 10% - 90% of peak value are around 65 ns. Having a fast rise time is important since slow rise times will cause difficulties in obtaining full cathode “turn-on” during the voltage pulse and can limit output current.
III. DATA AND ANALYSIS

A. VOLTAGE, CURRENT AND PRESSURE PERFORMANCE

1. Mesh Anode

The first round of testing the new TCTF started with using the mesh anode. This anode was expected to produce space charge limited flow and also show very little neutral production in the A-K gap since electrons were expected to impact far (several cm) downstream from the A-K gap. Simulation had shown that at a gap distance of 1.27 cm, over 80% of the electrons would not impact the solid part of the anode in the gap and the electric field would be primarily concentrated in the gap region.

![A-K simulation showing electron trajectories (white lines) and electric field strength (green = high, purple = low)](image)

Figure 11. A-K simulation showing electron trajectories (white lines) and electric field strength (green = high, purple = low)

Experimental results never showed stable space charge-limited emission at any gap distance. Simulation and experiment have shown extra emission can come from the carbon cathode/cathode holder interface, causing additional electrons to be emitted from this area in order to drive the electric field to zero at the cathode surface. This led to electrons impacting the anode holder surface outside of the molybdenum mesh and caused neutral gas and ion production at the anode which contributed to the additional current observed.
Voltage and current traces were compared with predicted values from the simulations. The simulation predicted 129 A of current with a 2.54 cm gap at 100 kV. Comparisons with several shots taken at these parameters showed values of current were always above those predicted for space charge-limited flow.
Since the raw data made initial analysis of current values hard to visualize, a smoothed plot of values was constructed over the duration of the voltage pulse. Using the smoothing algorithm in DAAAC 4.0 software replaces each point with the average (no weighting) of the points in the smooth region. Figure 15 shows that initial current is above space charge-limited and quickly rises to about 3x that at its peak. Average current was calculated using data points at 100 ns time intervals for the duration of the voltage pulse. The average current over the duration of the pulse is 276 amps which is 2.1x space charge-limited. This average is close to bi-polar flow (1.8xSCL) but the system, even after conditioning, always showed currents above space charge-limited and bipolar flows.
Figure 15. Smoothed current at 2.54 cm gap and 100 kV

Figure 16. Pressure burst at 2.54 cm gap and 100 kV

Dropping the gap distance to 1.27 cm pushed the output current even further ahead of the predicted space charge-limit. Simulations expected a value of 418 amps at 1.27 cm and 100 kV. The raw and smoothed current analysis in Figures 18-19 show that current equating to bipolar flow is initially seen at cathode turn on, but quickly proceeds to 1850 A at peak which is 4.4x SCL and averages 1425 A which is 3.4x SCL. Extra emission from the edge of the cathode and ions generated from neutral emission from the anode and cathode are possible causes for this extra current. Also seen at this gap distance was clear indication of plasma generation as the current trace no longer follows the
fast turn on and turn off of the voltage trace, but rather has a long time-scale decay.

Figure 17. Voltage trace at 1.27 cm gap and 100 kV

Figure 18. Current trace at 1.27 cm gap and 100 kV

Figure 19. Smoothed current at 1.27 cm gap and 100 kV
Analysis of the cathode and anode after removal from the TCTF showed the effects of the enhanced currents, enhanced emissions, and arcing. The cathode fibers were somewhat damaged but still intact with the cathode substrate and looked to be useable. The stainless steel surfaces were pitted and showed some of the harsh effects systems of this energy can have on these elements. The anode mesh in particular had a ~1 cm hole punched through it due to arcing in the chamber. This occurred during the 0.5 inch gap shots and is attributed to the high currents seen at this gap distance.

Figure 20. Pressure burst at 1.27 cm gap and 100 kV

Figure 21. Effects of ion impacts and arcing on cathode surface
2. Carbon Anode

After the relative “death” of the mesh anode, the carbon fiber anode was inserted into the TCTF to compare its performance to the molybdenum mesh. The mechanism for electron entrapment/absorption entailed glancing impacts from the electrons on the carbon fibers which was hypothesized to help reduce outgassing. In addition, ions that are generated deep inside the carbon fiber ‘forest’ are less likely to be accelerated out towards the cathode, so bipolar flow and/or arcing should be reduced. The carbon fiber anode was also expected to withstand the effects of arcing better than the mesh and allow continued useful performance even after many high energy arcs had occurred in the A-K gap. This projected performance was anticipated to allow voltage pulses to reach 160 kV which were attempted with interesting results.

Carbon anode performance was similar to mesh anode performance and initial voltage and current traces matched very favorably with mesh performance. Outgassing was slightly higher and was expected since now all of the electron impacts occurred near/in the A-K gap. However, the amount of outgassing was within the same order of magnitude as the mesh and was a clear indication that these anodes could be used with similar performance to the molybdenum mesh.
Figure 23. Voltage trace at 2.54 cm gap and 100 kV with carbon anode

Figure 24. Current trace at 2.54 cm gap and 100 kV with carbon anode
The voltage and current measurements using the carbon anode at 100 kV and 2.54 cm gap shown in Figures 23 and 24 were nearly indistinguishable from the mesh anode. The pressure burst shown in Figure 25 was higher than the mesh in Figure 16 but within the same order of magnitude. The pump valves were closed for this pressure measurement to get better data on the pressure burst, therefore pressure data during these shots does not show any decrease.

Decreasing the gap distance to 1.27 cm also showed similar results to the mesh. Pressure data did show higher values but again were within the same order of magnitude. Most notably during these pulses no visible damage was observed to the carbon anode or carbon cathode even with arcing present at lower gap distances and higher voltages through 100 kV. Late time current was observed during 100 kV pulses at 1.27 cm gap similar to the mesh anode.
Figure 26. Voltage trace at 1.27 cm gap and 100 kV with carbon anode

Figure 27. Current trace at 1.27 cm gap and 100 kV with carbon anode
Most notable in high voltage and short gap distance shots was the regular occurrence of a late time current of variable polarity. This clearly shows plasma generation in the A-K gap. The plasma current is long lived and its magnitude is likely due to the energy stored in the inherent capacitance and inductance of the TCTF system.

**B. GAS ANALYSIS**

Gas generation in the A-K gap is the most serious problem encountered in explosive emission cathodes due to the plasma that rapidly forms and begins to short out the A-K gap. Gas analysis was not possible during the voltage pulse since the Stanford Research Systems Residual Gas Analysis (RGA) communications would fault out due to the E-M pulse. A method was devised to get data immediately following the pulse and compare. RGA data was taken after a fixed time interval when no shots were taken so that a baseline comparison could be conducted. The same time interval was used when one or more shots were taken so that this data could be compared against the baseline. The non-shot data showed measurements of gases which naturally migrated from the stainless steel and carbon materials in the TCTF vacuum chamber. The shot data measurements quantified the types and amounts of gases liberated in the explosive emission regime. The following data shows that previous work in
gas emission was not contradicted here, but a better base vacuum allowed more discrete analysis of each gas emitted and its behavior during explosive emission testing.

Figure 29. Normal leak up of gases in vacuum chamber when valves are closed

Figure 29 shows that normal outgassing occurs in the TCTF chamber when the pumps are closed off by valves. Hydrogen and nitrogen are the two most apparent contributors to the outgassing with carbon dioxide also apparent.

Figure 30. Gas emission after one shot fired at 80 kV and 2.03 cm gap

Figure 30 shows significant hydrogen generation after a typical explosive emission shot. Carbon dioxide partial pressure has risen as well but is showing decreasing behavior which was not expected. An analog scan measuring each of the gases emitted before and after the pulse was also taken to more clearly
show the type and amounts of gases released in a typical explosive emission pulse. Figures 31 and 32 show the before and after gas analysis.

Figure 31. Normal partial pressures of gases in vacuum chamber when valves are closed. H₂, N₂ and CO₂ dominate the spectrum.

Figure 32. Partial pressure increase after one shot fired at 80 kV and 2.03 cm gap. H₂ and CO₂ have significant increases, with a slight rise in what appears to be CH₄. N₂ has little change.

Neutral production at the cathode and anode surfaces was expected to follow one of two models. The first was a purely ballistic interpretation of neutral production where the neutrals generated were directly proportional to the coulombs of energetic electrons present in the shot represented by Equation 8.

\[ N \propto \int ld\tau \]  

(8)
where $N$ is the number of neutrals, $I$ is the current and $dt$ is the change in time. The other model for neutral production relied purely on heating where neutrals were generated due to the energy absorbed by the anode. This is represented in Equation 9.

$$N \propto \int V \cdot Idt$$

where $V$ is the voltage. Initial assumptions were that the neutral production would follow the electrons with ballistic impacts causing the gas emission and that the voltage would generally not play a part in that mechanism.

Integrating the current over the fixed pulse time denoted by the 50%-point at the beginning and end of the voltage pulse allowed calculation of the total coloumbs and hence electrons emitted for each shot. Multiplying the voltage trace and current trace and then integrating the result over the time from zero voltage and current to the 50% point at the end of the voltage pulse gave the total energy of the system. DAAAC software provided tools to do these manipulations directly to the waveforms allowing all data to be incorporated in the integrations. Neutral generation was determined from the pressure difference seen in each shot. Using the ideal gas law, pressure difference was converted into the number of neutrals using Avagadro’s number and the system volume.

Charts of the gas generation were made with the number of neutrals generated calculated from the pressure changes seen and the total volume of the TCTF. This was plotted against the total electrons injected into the diode as well as the total input energy. The tabulated data is presented in Figure 33. For 80 kV and 100 kV shots blue triangles are associated with the number of electrons and pink squares are associated with the number of joules; we can see that the performance of these are very similar. Pressure bursts in this voltage range are on the order of 1 μtorr and liberate around $10^{15}$ neutrals over this range of the input electrons and energy. Once the voltage is doubled to ~150 kV, which is the data presented by the pink squares farthest to the right in Figure 33, we see 3
orders of magnitude increase in the neutrals generated in the system with little change in the total input electrons or energy.

Figure 33. Gas generation plotted against input electrons and input energy. Data farthest to the right is at ~150 kV.

Figure 34. Pressure burst at 4.57 cm gap and 150 kV w/ carbon anode

Specific analysis of the number of neutrals generated per electron and per unit of energy were constructed to get a picture of the performance of the mesh and carbon anodes. This data is shown in Figures 35 and 36.
Figure 35. Comparison of neutrals generated per electron

Figure 36. Comparison of neutrals generated per joule of energy
IV. CONCLUSIONS AND FUTURE RESEARCH

A. CONCLUSIONS

Space charge-limited flow predictions from simulation were always exceeded soon after the initial turn-on of the cathode. One of the reasons for this excess was the constraint in the simulation that all the electrons emitted were coming solely from the carbon cathode surface with no background plasma being present. We've seen this is not the case. In addition, even with the hollow mesh anode to allow for transporting the beam far downstream of the A-K gap, we see in simulation that about 18% of the electrons do impact the solid stainless steel portion of the surface of the anode at 1.27 cm gap and that this percentage increases with gap distance. Clearly bipolar or higher flow was normally seen after the first few tens of nanoseconds and this can be attributed partially to the impacts at the anode surface which liberate gas that can be readily ionized. Figure 12 shows very clear physical evidence of this behavior. Even with these impacts, it was found that the system was very well behaved and did not produce any arcs as long as the gap distance remained at or above 2 cm and in the 80 kV to 100 kV voltage range. Neither the mesh nor carbon anode showed any damage or signs of distress while operating in this regime which demonstrated that this system was capable of giving kiloamp-level current output with good reliability. Reducing the gap further tended to allow gap closure; arcing became a regular problem as the distance closed to within the scale needed for ions to cross during the microsecond pulse. Use of the molybdenum mesh at smaller gap distances did not work since the arcing energy in the system very quickly damaged the mesh and changed the electric field behavior in an unpredictable fashion which decreased diode performance. Using carbon fiber anodes has shown a clear advantage in withstanding these arcing effects, and has allowed voltage increases to double without showing any signs of performance degradation. If future systems can increase pumping rates to handle the higher outgassing and neutral emission from the carbon fiber anode, this arrangement should afford HPM systems longer life, higher reliability and more consistent
shot-to-shot electric field characteristics needed to generate narrow bandwidth microwaves.

Gas generation analysis looked for an answer to the ballistic versus energy emission question. What was found during testing was neither and both. A voltage dependence has been discovered on neutral production which can be most readily seen in Figure 33 when the voltage was increase from 100 kV up through 150 kV. This caused the neutrals produced to increase from one to three orders of magnitude higher than that seen at 80 and 100 kV which is the larger cluster of data at the far left of Figure 33. Several 120 kV shots were taken which showed long pulse duration (> 2μsec). These pulses had significant late time current and also showed pressure burst around 50 μTorr which are seen as the data points immediately left of the largest neutrals burst in Figure 33. Since late time current went off scale, the total number of electrons could not be accurately calculated. However, energy was calculated and was plotted against the total number of neutrals to show the higher neutral generation these higher voltage shots produce. It should be noted at the highest voltage tested, 150kV, the TCTF had several shots where there were some abnormal discharges in the vacuum chamber. In one such instance it was determined that most of the energy was discharged in a region other than the A-K gap since cathode current was very high, but anode current was low. Most likely the energy, which approached 1kJ, discharged into a non-conditioned area of the vacuum system and liberated a substantial amount of gas.

The higher voltage shots with significantly higher neutral generation leads to the conclusion that there is a voltage dependence on neutral production that cannot simply be explained by the linear ballistic or linear heating models as either Equation 8 or Equation 9 would predict. What was realized is that the system scales as some non-linear function of the voltage and follows the relationship formulated in Equation 10.

\[ N \propto \int f(V) dt \quad (10) \]
Previous work at different fixed voltages showed that the neutral emission at 100 kV and 300 kV tended to be ballistic in nature [3-7]. Data generated using a wide range in the applied voltage tells a different story, and has not been known to be explored before. With the neutrals generated varying as a non-linear function of the voltage what is seen is some sort of effective cross-section for neutral liberation, where neutral production follows ballistic models at each specific voltage but varies with voltage due to the change in an electron’s impact depth and its ability to liberate neutrals as it traverses this surface region of the anode.

B. FUTURE RESEARCH

A clear determination where these neutrals are produced was not discovered during testing. Whether these neutrals originate at the cathode in the form of plasma, the anode in the form of liberated gases (which become plasma), or both is a matter for further research. Both mechanisms have been shown to be at play in the explosive emission regime and distinctions between the two were beyond this experiment’s ability for analysis.

Future experiments look to quantify the outgassing at both anode and cathode surfaces by using a gated laser operating at hydrogen’s peak absorption wavelength, since hydrogen was the dominant gas produced during test. Measuring received laser intensity after traversing the cathode-anode gap should give a clear indication of where hydrogen, and hence the largest amount of outgassing, is coming from in the A-K gap.

Revisions to the cathode and anode profile will also assist in reductions in outgassing. A new Pierce Gun arrangement is being looked at to ensure all electron impacts occur past the A-K gap and deep inside a nearly field-free region so that any ions produced are not accelerated towards the A-K gap.
Additionally, widening the diameter of the anode hole in the present arrangement is also being considered with additional larger mesh anodes to demonstrate space charge-limited flow at microsecond pulse durations.
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