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Novel cathode for field-emission applications

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A CsI salt-based cathode which is capable of producing a modest perveance, 10 s of A/cm² electron beam for several microseconds pulse lengths, and has little susceptibility to diode closure has been experimentally characterized. This explosive field-emission CsI-coated carbon fiber cathode has operated in modest 10⁻⁵ Torr vacuums at voltages up to 160 kV, and can easily be configured to provide space-charge-limited solid or annular electron beams in arbitrarily large diameter configurations. The CsI cathode has demonstrated negligible closure for 2 μs pulses, and has operated for 200 shots with no degradation in cathode performance. Data on the operating performance of this salt cathode, including effective gap time history and streak photographs demonstrating uniformity of the current density, are presented. A comparison of CsI cathode performance with a velvet explosive field emitting cathode used in electron-beam production is also presented. © 1995 American Institute of Physics.

I. INTRODUCTION

In the past fifteen years an increasing effort has been under way devoted to the application of pulsed-high current, mildly relativistic electron beams to high power microwave generation, high-energy laser pumping,¹ x-ray production,² and material response studies³ among other areas of research. In the case of high power microwave generation, electron guns capable of producing current densities in the range of tens to thousands of amperes per square centimeter of surface area are needed.

Explosive field-emission cathodes are used in most research where large total current is needed. Research has focused on beam emittance and brightness measurements⁴ as well as fast turn-on and uniform electron emission.⁵ Until recently the cathode emissive materials generally studied and reported on in the literature were high grade graphite, carbon felt, and velvet cathodes. Velvet cathodes have been shown to have superior turn-on times and beam brightness compared to smooth carbon cathodes^{6,7} or carbon felt cathodes.⁸ Cathode diameters of up to 5 cm have been tested.⁷ In addition, velvet cathodes show an improvement of emission uniformity during the pulse for pulse durations greater than 10 and up to 100 ns.⁸ Typical current densities for velvet cathode diodes are less than 50 A/cm². If current densities on the order of kA/cm² are desired, then smooth carbon cathodes are usually used. These cathodes can be used in systems where low beam emittance is a requirement if beam "scraping" techniques are used;^{4,9} however, they do suffer from beam uniformity deficiencies, especially for large surface areas.

Repetition rated experiments have been carried out on velvet cathodes. For short time scales, of about 40 ns, no adverse effects for velvet cathodes up to 40 000 shots have been observed.⁶ However, this test was done at the relatively low voltage of 30 kV. Other experiments done at a diode voltage of 135 kV and a pulse duration of 100 ns show a decrease in extracted total charge from velvet cathodes with time. The current density decreased by a factor of 2 after approximately 5 C/cm² of total integrated extracted charge.⁸

Even with extremely careful diode design, the available pulse duration for any of the cathodes above is usually limited by diode closure in which the cathode plasma expands across the diode gap at velocities of up to a few cm/μs. The diode gap closure velocity depends most critically on the nominal field strength at the cathode surface, the cathode emissive material, and magnetic field.¹⁰ In this work we discuss the development of carbon fiber cathodes that indicate constant impedance operation for up to 2.5 μs for current densities of tens of A/cm² at 150 kV diode voltage and cathode radius of 6.85 cm. Experimenters at UC Irvine have studied carbon fiber cathodes over the past twelve years¹¹ and most recently have conducted tests on the effect of CsI impregnation of velvet, carbon graphite, and carbon fiber cathodes.¹² Carbon fiber cathodes are very simple to construct and can operate satisfactorily in vacuums of 10⁻⁵ Torr. Carbon fiber cathodes can have fiber tips which are much smaller than tuft sizes of velvet emitter cathodes. Measurements indicate the dominant limitation to beam brightness of plasma field-emission cathodes is the size scale of the surface roughness.¹³ It is also likely that the smaller tip size can result in faster turn-on and more uniform emission for the

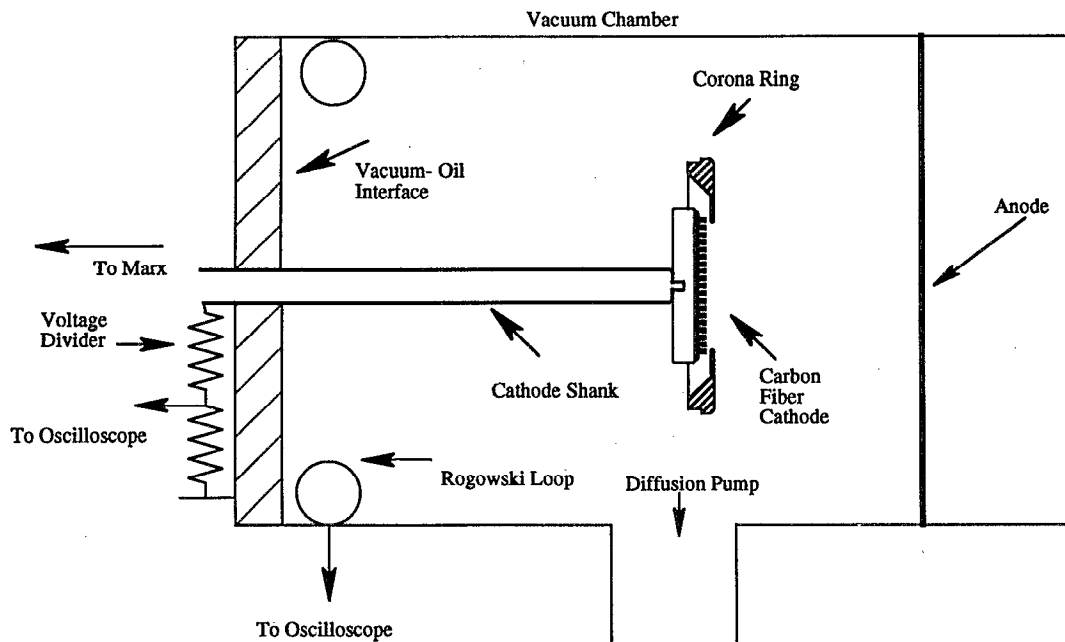


FIG. 1. Schematic of the experimental apparatus.

carbon fiber cathodes. CsI was chosen as an impregnant because it has a high mass, it is a good insulator, and it is known to be a good UV and x-ray photocathode. We speculated that the combination of high Z and good photoemission properties would produce the following effects: (1) slow the plasma motion across the AK (anode-cathode) gap and (2) turn the cathode on at relatively low fields since UV produced from any initial plasma production would turn on the primary cathode sites of emission.

II. APPARATUS AND EXPERIMENTAL RESULTS

The electron-beam generating system utilized for the cathode testing consists of a low inductance Marx generator which energizes a vacuum diode. The Marx is capable of producing a 200 kV output for full charge and has an erected capacitance of 75 nF. A $7\ \Omega$ CuSO_4 water resistor is connected in series with the diode to protect the Marx capacitors in case of diode shorting. Diode voltage is monitored on the output side of the $7\ \Omega$ resistor by a calibrated resistive divider and the total Marx current is monitored by a Pearson probe placed between the first spark-gap switch and ground. A Rogowski loop placed inside the vacuum chamber was used to monitor diode current. The Rogowski loop and Pearson probe signals correlated well, indicating that most of the Marx current was delivered to the diode. Due to the limitations of the Marx charging system, approximately one shot every 5 min could be fired at diode voltages of 150 kV and about 1 per min at 90 kV.

The vacuum diode consisted of a 9 cm radius stainless-steel anode screen of 75% transparency and either a 4.6 or 6.85 cm radius cathode. AK gaps for the experiments could be varied by moving either the cathode or anode and were between 2 and 4 cm. All the cathode tests were carried out

with a base pressure of at most 2×10^{-5} Torr and without an external magnetic field. Figure 1 is a schematic of the experimental apparatus.

The cathode emissive material was either velvet or carbon fibers and emissive materials were tested both with and without a CsI surface coating. Two different carbon fiber cathodes of 4.6 and 6.85 cm radius were tested. The carbon fiber cathodes are constructed as follows. Referring to Fig. 2(A) (schematic) and 2(B) (photograph), a 5 mm thick disk of poco grade graphite was drilled with an array of 1 mm diameter holes uniformly spaced 6 mm apart. Depending on the cathode geometry, the hole pattern was either 4.6 or 6.85 cm in radius. Carbon fiber, consisting of Celion 12000, available from Celanese Corporation, is threaded through the holes, and secured to the rear of the graphite disk using quick setting (15 min) epoxy. All fibers are cut to uniform length after the epoxy cures. The graphite disk adheres to an aluminum cathode backing plate with cyanoacrylate. The aluminum plate/graphite disk-carbon fiber brush assembly is then securely fastened to the corona ring by set screws. The corona ring had a high-field-emission threshold, glyptol coating (DEM-KOTE 4X592B, Dayton Electric Manufacturing Co., Chicago, IL) and was used in all the experiments, regardless of cathode emissive material. This corona bushing effectively eliminated any emission from the electrostatically shielded cathode edge; thus these tests are typical of the bulk material itself rather than potentially from enhanced emission from the edge of the cathode, as might possibly occur if no bushing was used.

Preparation of the velvet cloth or carbon fiber cathode with the CsI salt was done by applying a saturated solution of CsI to the material using a fine brush. After drying, the emissive surface of the cathode assembly was baked overnight at 100–120 °C. Because the CsI is hygroscopic, and

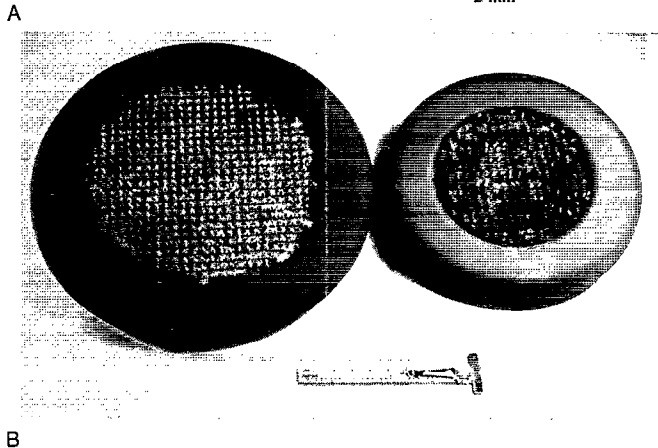
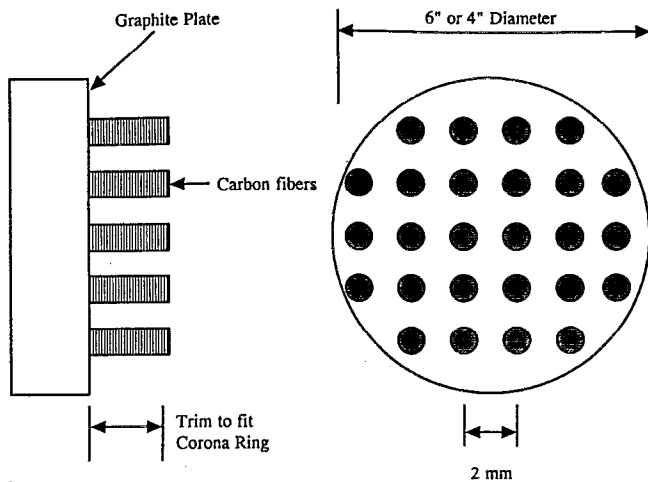


FIG. 2. (A) Schematic of the carbon fiber cathode. (B) Photograph of the 6.85 (left) and 4.6 cm radius CsI cathodes used in this work, with outer corona bushing attached.

because of the large area available to the bristles to absorb water, it is very important that the cathode assembly be placed under vacuum as soon as possible after this bakeout period.

We found the following break-in procedure useful, and followed it regardless of emissive material: allow the cathode to be under vacuum for at least 24 h before firing and begin operation at the minimum voltage required to initiate the emission. After a few tens of shots, the gas pressure rise should be reduced about a factor of 5 or more compared to the first shots. Raise the diode voltage by between 10 and 15 kV, again observing the pressure rise reduction after tens of shots. Repeat until the desired diode voltage is attained. This procedure gave reliable, relatively flat current versus time characteristics for diode voltages over 120 kV. A typical voltage and current trace for the 6.85 cm radius carbon fiber cathode is shown in Fig. 3.

We began initial testing on a nominal 6.85 cm radius untreated velvet cloth cathode. At a diode voltage of 55 kV and for a 2 cm AK gap, a maximum diode current of 3 kA was recorded. At diode voltages up to 70 kV we did not see diode shorting. Increasing the AK gap to 4 cm resulted in a peak diode current of 2.1 kA at 150 kV diode voltage. It was noted during disassembly of the velvet cathode diode that

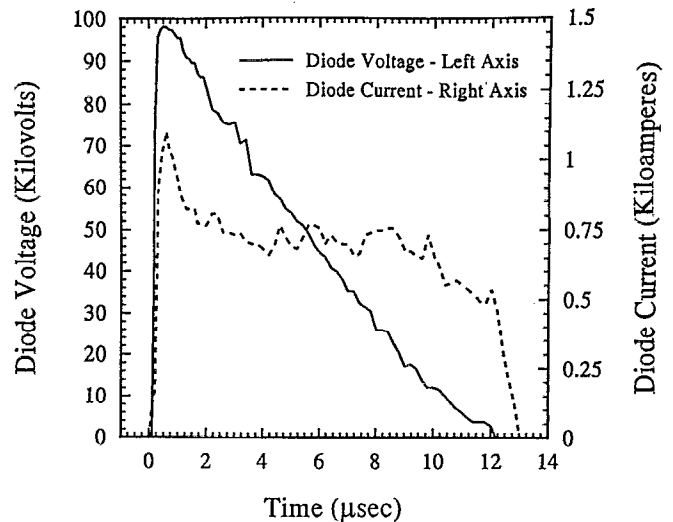


FIG. 3. Voltage (solid line, left axis—98 kV peak) and current (dashed line, right axis—1.1 kA peak) for the 6.85 cm radius CsI-coated carbon fiber cathode.

after approximately 50 shots the velvet cloth became discolored and browned as if burned.

The observed gap closure rates for the velvet cathode over a period of 7 μ s were 0.55 and 0.74 cm/ μ s for the 4 and 2 cm AK gaps, respectively. Here and in the discussion that follows, the gap closure rate is determined by assuming the emission is space-charge limited so that the current I is given by the Langmuir-Child result

$$I \propto V^{3/2} / [d(t)]^2,$$

where the proportionality constant is determined by the measured AK gap, $d(t=0)$, the measured emission area, and the voltage and current traces (V, I traces) at time $t=0$. A plot of $d(t)$ can be made from the voltage and current traces and the effective gap as a function of time can be calculated. The closure rate is then found from the slope of the $d(t)$ curve. This overestimates the gap closure rate since any increase in measured current is attributed to a decrease in the AK gap due to plasma expansion across the gap and does not take into account the possibility of radial plasma expansion.

Application of CsI to the velvet cloth surface decreased the gap closure rate by approximately 7% for the 4 cm AK gap. It is not clear why the CsI coated velvet cathode does not show any substantial improvement in the gap closure rates compared to bare velvet. However, it should be noted that the CsI coating tested did not completely cover the velvet surface of the cathode. That is, there was some direct line of sight to the velvet surface as well as the CsI coating. Perhaps during ignition of the cathode surface significant amounts of plasma from the velvet surface was generated, resulting in similar gap closure rate to the base velvet cathode.

In the case of the 6.85 cm radius cathode, we initially tested the cathode configured with the carbon fiber 1 cm in front of the plane of the corona ring. Without the CsI coating and at a 4 cm AK gap this cathode generated 2.76 kA at 85 kV, corresponding to a current density of 18.7 A/cm². At

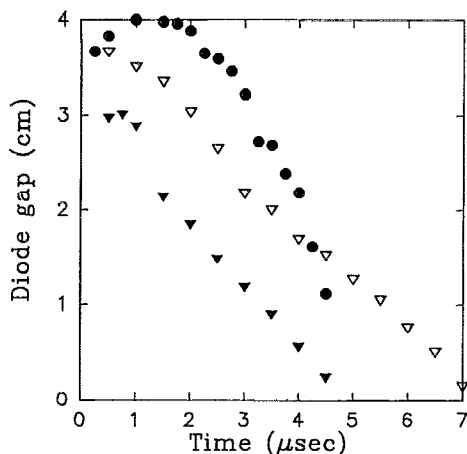


FIG. 4. Time dependence of the AK gap for the velvet and CsI-coated carbon fiber cathodes. Open triangles—velvet cathode, $r=6.85$ cm radius, physical AK gap $d(t=0)=4$ cm, peak diode voltage $V=150$ kV, peak diode current $I=2.11$ kA; closed triangles—carbon fiber with CsI cathode, $r=4.6$ cm, $d(t=0)=3$ cm, $V=152$ kV, $I=2.43$ kA; closed dots—carbon fiber with CsI cathode, $r=6.85$ cm, $d(t=0)=4$ cm, $V=157$ kV, $I=2.2$ kA.

diode voltages greater than 95 kV arcing occurred regularly. The gap closure rate for the carbon fiber cathode using this geometry was approximately 1.33 cm/ μ s. The addition of CsI to this cathode decreased the gap closure rate by about a factor of 3 to 0.46 cm/ μ s. The gap closure rate with the CsI was comparable to the velvet cathode closure rate. However, in the case of the velvet cathode, the current density was only 6 A/cm².

With the fiber tips 1 cm in front of the corona ring and the outermost carbon fibers about 6 cm from the vacuum vessel wall, the corona ring cannot effectively shape the field near the tips of the fibers. It is likely that enhanced emission from the edge of the cathode occurs. Therefore the cathode fibers were trimmed so that the tips were flush with the corona ring. At a diode voltage of 157 kV and for an AK gap of 4 cm, the gap remains approximately constant for about 2.5 μ s. The current drawn by the diode during the initial 2.5 μ s period was 2.2 kA. Using the same cathode but at 89 kV diode voltage and 1.1 kA diode current, no significant gap closure occurs in the diode for 4 μ s. This diode routinely provided electron emission, without arcing for durations of 12 μ s.

We also tested this cathode configuration for over 200 shots carried out over a duration of approximately 35 h. This testing was done at 85 kV diode voltage and its main purpose was to determine if any degradation in performance or the CsI coating itself might occur. Typically, 1 kA of emission was observed for between 6 and 12 μ s, with the total pulse length increasing as the testing period progressed. No observable mechanical degradation of the CsI coating could be detected at the end of this 200 shot test.

The 4.6 cm radius CsI coated carbon brush cathode, when tested near 80 kV voltage, provided long pulse operation typically between 7 and 9 μ s. For these shots the AK gap was 4 cm and the resulting diode current was 0.7 kA. In order to increase the total current of the diode, we increased the diode voltage and decreased the AK gap to 3 cm. At 152

Emission Diameter

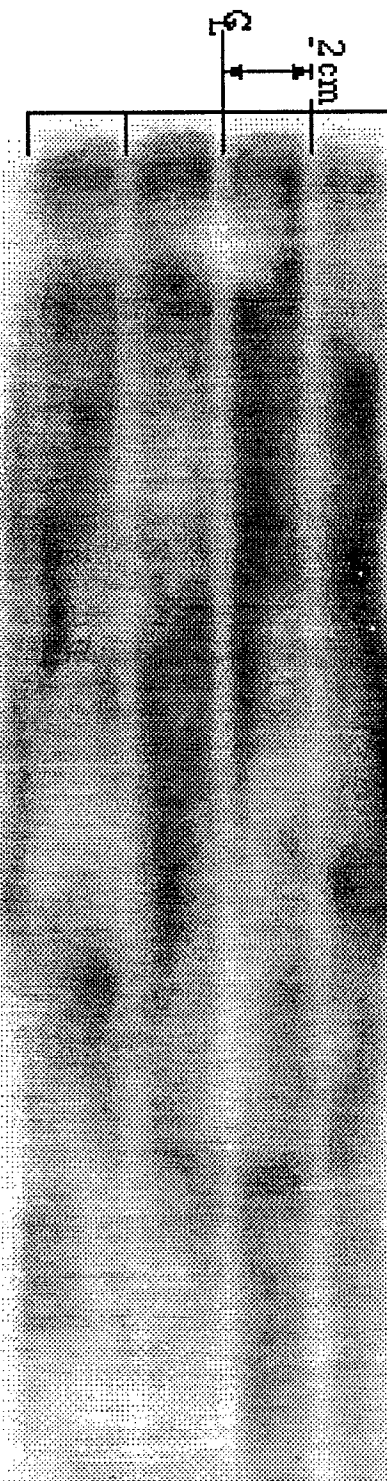


FIG. 5. Streak photograph showing the emitted beam diameter from a 4.6 cm radius CsI-coated carbon fiber cathode, with the emitting surface recessed 12 mm behind the front plane of the corona bushing and an applied voltage of 140 kV. Total streak record shown is 1 μ s. The short period at the beginning of the discharge where emission is suppressed is due to the usual overshoot and ringing associated with the pulse power driver.

kV diode voltage the total current drawn by the diode was 2.4 kA. The diode impedance and therefore diode gap remained essentially constant for the first 1 μ s of the pulse and then the gap closure averages 0.75 cm/ μ s for the next 4 μ s. Figure 4 is a comparison of the effective gap as a function of time for the velvet and carbon fiber cathodes.

Additional comparison tests were performed on the Sandia CDS pulser, a gas insulated five-stage Marx generator which was operated at voltages up to 160 kV. An important purpose of these tests was to provide streak photograph observations of the emitted electron-beam radial uniformity. In this work a Lucite scintillator was placed about 2 cm downstream of the anode and the scintillator light imaged on a Hammamatsu streak camera. The streak camera was typically operated to provide 0.5 or 1 μ s records. Although the light emission from the Lucite scintillator is not quantitative in this work, since we have not performed the appropriate calibrations, the gray scale of these streak camera photos is a qualitative indicator of uniformity of current density. On the Sandia CDS pulser, velvet cathode tests showed gap closure rates of about 2 cm per microsecond for a field stress near 40 kV/cm, based on the usual pulse-power data. Streak photographs suggested that current emission started at a "hot spot" and had an effective area about 3.6 cm in radius rather than the 4.6 cm radius of the entire cathode surface.

The 4.6 cm radius CsI-coated cathode was tested on the Sandia CDS pulser with the carbon fiber surface either flush or recessed 12 mm behind the front face of the surrounding corona bushing. This was done to see if reducing the line of sight from the cathode surface to the front surface of the corona ring might produce a better defined radial current profile. There was the possibility that the cathode surface might be creating electron emission from the corona ring front face via UV-driven secondary electron emission. The streak photograph in Fig. 5 shows the emission area is comparable to, but slightly less than, the geometric radius of the emitter when the emission surface is recessed, and remains

that way for the microsecond pulse lengths of interest. We attribute the reduction beyond geometrical to the greatly reduced macroscopic electric field on the outer diameter portions of the emitting surface when recessed. The figure also shows that at about 0.5 μ s into the pulse, the effective emitting diameter briefly increases, although it rapidly returns to the initial diameter of the cathode. In the case of fibers which were not recessed, we typically found that the effective emitting diameter monotonically increased from its initial nominally geometric value during the pulse until it typically encompassed the entire corona bushing portion having a line of sight to the cathode (about 2 cm in radius beyond the initial nominally emitting area). This streak camera data is consistent with the notion that UV light is driving emission from the corona bushing in the nonrecessed geometry, although it does not eliminate the possibility that the apparent emission at larger diameters is driven by particle bombardment of the bushing or simply radial plasma expansion of the cathode plasma.

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