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EXTENSION OF HPM PULSE DURATION BY CESIUM IODIDE CATHODES IN CROSSED FIELD DEVICES

James N. Benford
David Price
William DeHope

Microwave Sciences, Inc.
1041 Los Arabis Lane
Lafayette, CA 94549

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Thomas A. Spencer, DR-III
Project Manager

FOR THE COMMANDER

Eileen M. Walling, LtCol, USAF
Chief, High Power Microwave Division

R. Earl Good, SES, DAF
Director, Directed Energy Directorate

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James N. Benford, David Price, William DeHope

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13. ABSTRACT *(Maximum 200 Words)* When explosive emission cathodes are used in higher power (>100 MW) devices, microwave pulse shortening occurs because of motion of the cathode plasma at speeds 1 to 5 x 10^6 cm/sec. This limited duration in turn can limit present-day high power microwave (HPM) sources to a few hundred joules. The introduction of cathodes made from Cesium Iodide-coated (CsI) carbon fiber has shown plasma speeds reduced by factors of a few from uncoated carbon fiber, but previous work was at low diode fields of a few 10's of kV/cm. We have demonstrated reduced CsI plasma speed for macroscopic electric fields of 265 kV/cm, sufficient for the diodes of GW microwave sources. Carbon fiber coated with CsI in saturated solution gives plasma speeds at these high electric fields of ~0.6 x 10^6 cm/sec, about three times less than the bare carbon fiber. The apparatus had oil-free high vacuum conditions and the cathode was baked both before assembly at atmospheric pressure and in vacuum after assembly, to temperatures of >600 °C. A residual gas analyzer showed burnout of the water; base pressure was ~10^{-6} Torr. The diode current and voltage traces are substantially more reproducible than with bare carbon fiber. This may be because CsI emits copious UV, lighting up the surface much more uniformly. With this reduced plasma velocity, CsI cathodes should produce an extension of the HPM pulse length and an increase in pulse energy in sources now limited by low-Z contaminant, cathode plasma motion.

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1. Executive Summary

•• For macroscopic electric fields of up to **285 kV/cm,** sufficient for the diodes of GW microwave sources, the plasma closure speed measured from a statistically significant sample is:

- CsI on carbon fiber: **0.59±0.16 cm/μsec**
- Bare carbon fiber **2.08±0.71 cm/μsec**

The ratio of these two speeds is **3.5.**

•• The data fits well Child's Law scaling with:

- area given by the sum of carbon tuft cross-sections,
- no radial plasma motion until late in the pulse, and
- monopolar flow (no ion flow)

•• The apparatus had **oil-free high vacuum conditions** (metal seals, glass insulator) and the cathode was baked both before assembly at atmospheric pressure and in vacuum after assembly, to temperatures >600 °F. A residual gas analyzer showed **burnout of the water**; base pressure was ~10^{-6} torr.

•• A benefit of the CsI coating is that the **diode current and voltage traces are substantially more reproducible than those for bare carbon fiber.** The statistical spread in measured plasma speeds is also much lower. This may be because CsI emits copious UV, lighting up the surface much more uniformly.

•• It is clear from the above that **cleaning the cathode gives better performance by ridding the material of volatiles.** By pursuing this line of inquiry with other materials we may be able to reduce closure to speeds <0.1 cm/μs, ushering in a new regime in intense beam diodes and HPM.

•• It's also clear that CsI cathodes should be introduced to increase energy per pulse in HPM sources. **We expect a factor of 3.5 extension of the pulse duration and the pulse energy** at high power with properly cleaned cesium iodide coated cathodes. Good source candidates are the relativistic magnetron and the MILO. We recommend that the Air Force have us use the results of this experiment to demonstrate microwave pulse extension by this large factor.

2. Apparatus and Experimental Procedure

We used the 450 kV, 500 ns, 50 Ω modulator shown in Figure 1. The principal parameters are shown in Table 1.

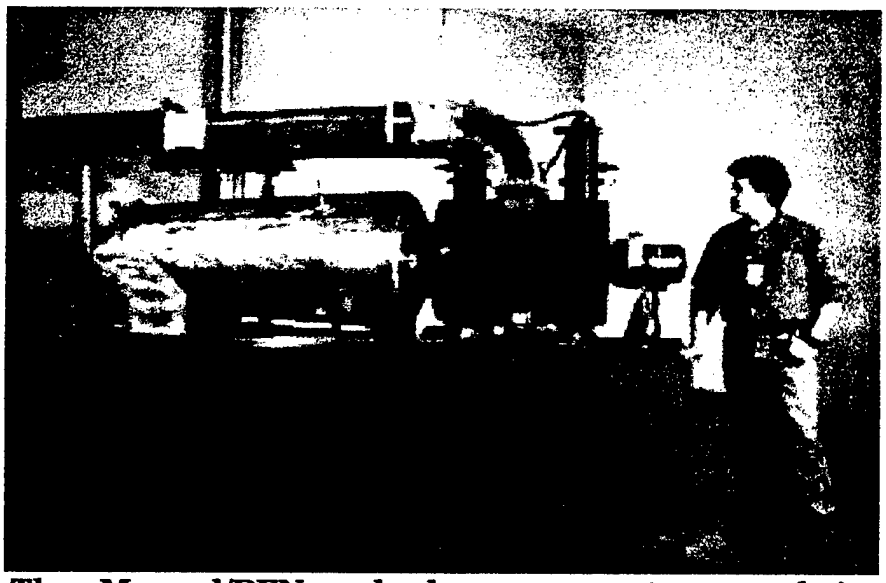


Figure 1. The Marxed/PFN pulsed power system used in the CsI experiments. The pulser can be operated repetitively, useful in this study to provide a large measurement sample.

The insulator is connected to a coaxial stainless steel MITL with inner radius 1.27 cm and outer radius 10.2 cm approximately 50 cm long. The vacuum volume is evacuated to the ~ 10^{-6} torr range with an 8" cryo-pump. The in-situ baking is done with a 500 W halogen lamp extended through gland seal on centerline. Diagnostics are a Rogowski current monitor just upstream from the anode, a resistive voltage divider ~1 m upstream from diode, and a residual gas analyzer (RGA) at the far downstream end of the vacuum chamber. The voltage is not inductively corrected because the effect is small to negligible due to the high impedance and the flatness of most of the pulse.

Table 1. Parameters of the Pulsed Power Driver

• **Operating Parameters**	
V (matched load)	450 kV
Z_{load}	50 Ω
Flattop	± 10%
Pulse Width	500 ns
Risetime	50 ns
Repetition Rate	10 pps
I_{peak}	9 kA
Average Power Output	20 kW
Pulse Energy	2 kJ
Burst	5 sec
PFN Enclosure Dimensions	67" long 30" diameter
PFN Weight	350 lbs.
HV Interface	Pyrex

• **Design**
- Marx/PFN
- ± 50 kV bipolar charge in up to 2 atm SF_6- Spark gap switches
- Type C Guilleman circuit
- 9 stages, secured by cantilevered torlon rods
- Each stage composed of five 1.7 nF TDK capacitors, a 95 nF CSI capacitor and tuned inductors

Diode Region

The region around the cathode, shown in Figure 2, consists of the anode and the downstream region beyond it. The anode is a mesh of copper 50-mil (0.127 cm) wire, 80% transmissive. Immediately behind it is an anode from an L-band relativistic magnetron, made of ~300 pounds of stainless steel. The halogen lamp is inserted toward the anode along the axis from the downstream end.

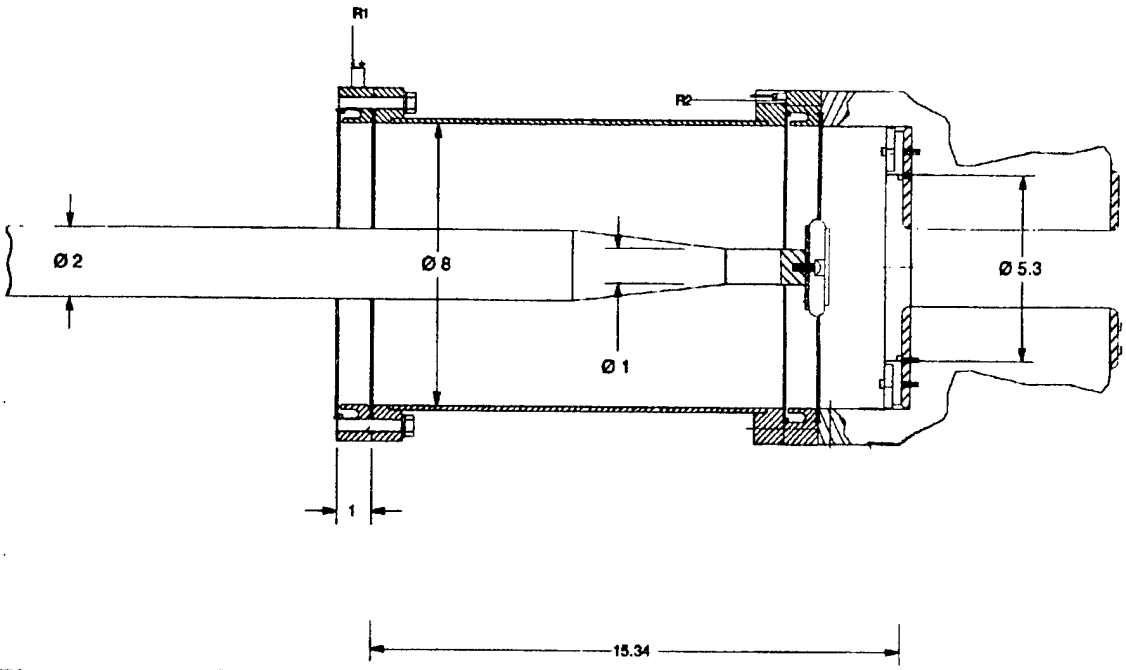


Figure 2. Diode region of the experiment shown to scale. Dimensions are in inches.

The electric field on the 2 inch diameter main cathode shank is 115 kV/cm for 400 kV peak voltage applied. The field reaches 154 kV/cm at the smaller diameter immediately behind the cathode face, which is sufficiently large to intercept any electrons emitted from shank. Fields in the main gap, which was varied from 1.4 to 2.0 cm, were 200-285 kV/cm. No virtual cathode formation occurs since the diode impedance is >100 Ω ($i_D < 4i_{scl}$, i_{scl}(285 kV) ≈ 3.4 kA). Likewise beam pinching doesn't occur ($i_D < i_c$, i_c(285 kV) ≈ 29 kA).

Cathode Assembly

Components of the cathode are shown in Figure 3. The cathode base, shown in Figure 4, is of POCO graphite, 8.0 cm diameter, 0.635 cm thick with full radius. To avoid contamination, no cutting fluid was used during the machining. The cathode tip assembly is made entirely of components compatible with high-vacuum operation--metals, no plastics.

The carbon fiber is made of 4 mm high, Ceylonese, Cellon 6000, assembled into bundles, effectively 0.25 cm dia. on 4 mm centers. After threading the fiber bundles into the cathode plate, a gapping fixture is clamped on and a uniform 4 mm height achieved with cuticle scissors and a beard trimmer.

The CsI coating is applied to the carbon fiber using a 50/50 volumetric mix CsI and H_2O (salt from Aldrich Chemical Corporation). This mix is heated (~130 °F) until a super-saturated solution is attained. The cathode is dipped in the solution, giving a uniform coating. CsI coating is applied over the cathode front surface and the outer, radiused edge.

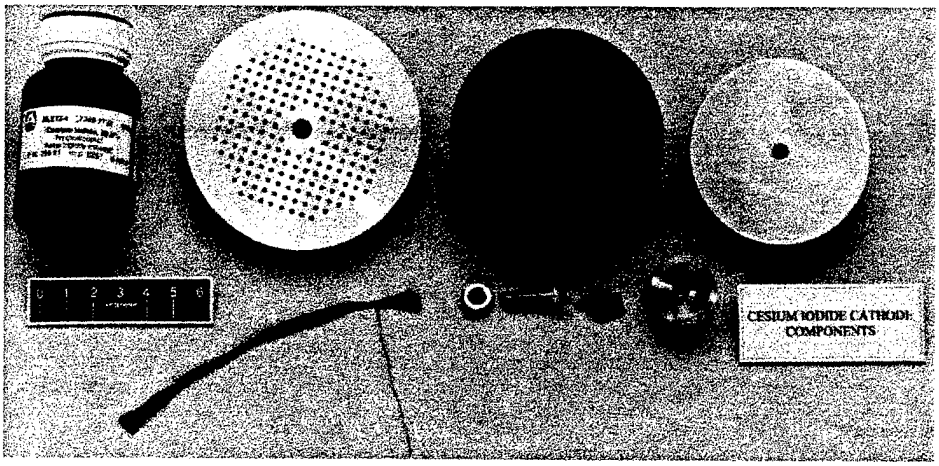
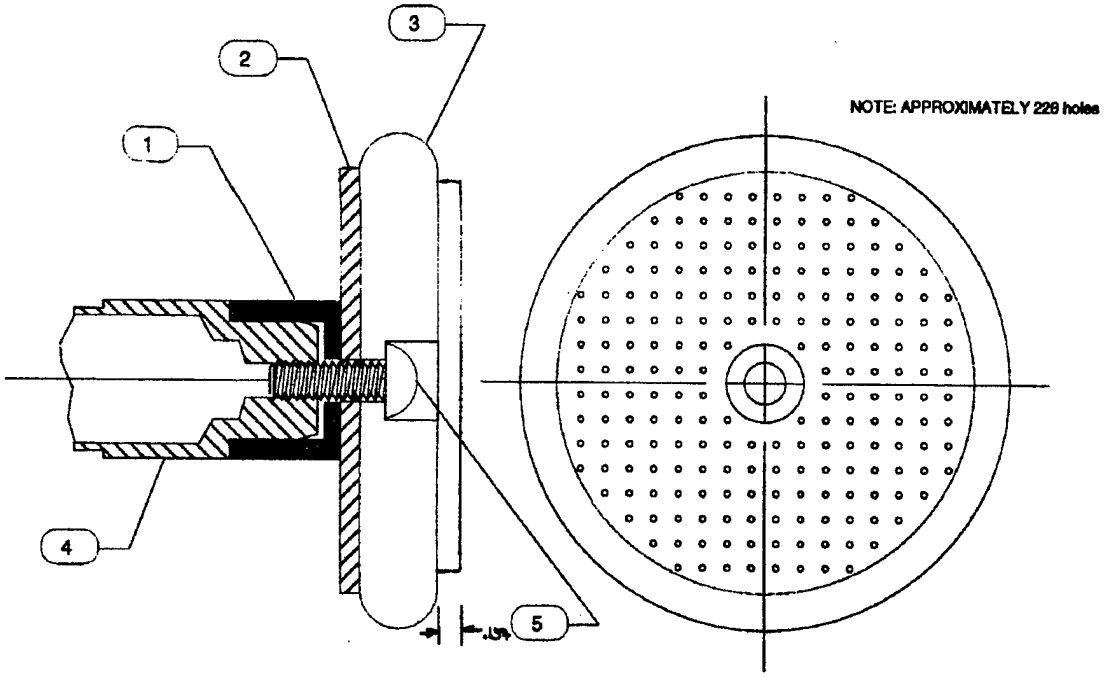


Figure 3. Cathode components shown clockwise from upper left: 1) CsI supply; 2) aluminum winding mask; 3) 8-cm dia., 0.635 cm thick POCO graphite cathode, with full radius and with 60-mil holes drilled on 0.4 x 0.4 cm grid; 4) stainless steel backing plate; 5) shank extension hardware; and 6) carbon fiber strand, 40-mil diameter Cellon 6000.



ASSEMBLED CATHODE TIP

(SCALE: FULL)

Figure 4. Mechanical drawing of assembled cathode.

Bake-out Procedures

Initial bake-out is done at atmospheric pressure in a 250 °F oven for 15 hours. The still-hot cathode is installed in the pulser within 2 minutes of removal from the oven, the vacuum chamber having been flushed with dry nitrogen prior to installation to reduce water contamination. Rough pumping proceeded for ~2 minutes; and the cryo-pump attained ~10^{-5} Torr ~5 minutes later. The 500 W halogen lamp was positioned ~16 cm from the anode on centerline. Light shone through the 80% transmissive anode mesh, heating the entire diode region, including the cathode. Heat was applied for ~ 4 hrs. Pyrometric measurements gave an interior surface temperature of > 600 °F; the outside temperature (of the anode "block") attained 202 °F with the vacuum pressure steady at 2×10^{-6} torr. During shooting, which followed immediately, the block cooled slowly, due to the large thermal inertia of the 300 pound block, so the diode region stayed heated. The RGA registered a large amount of water when heating began and a steady decline in water as the bakeout proceeded.

On the day on which the CsI-coated cathode was tested the shooting started with the outside wall temperature at 147 °F. At the end of the testing the final outside wall temperature was 130 °F, which is above the boiling temperature of water under vacuum. Moreover, whenever the beam fired, ~300 joules was deposited in the walls from each shot, maintaining temperature. During bursts at 3 shots/sec, the wall heating is ~1 kW, about the same as the halogen lamp.

Therefore, no water re-condensation could occur on the cathode surface between shots or bursts. In these conditions the ambient base pressure consisted mainly of water and nitrogen. Figure 5 shows an RGA measurement of gases taken about one minute after a burst of 20 shots with the CsI coating. The outside temperature of the anode block was 136 °F and pressure was 2×10^{-6} torr. The clearly identifiable molecules are hydrogen, water, nitrogen, carbon dioxide and perhaps hydrogen iodide (128).

3. Modeling and Data Analysis

We collected the data digitally, then used a custom model for reduction of the data. We wanted to quantitatively compare the data to a variety of diode physics models to ascertain their correctness and relevance. This is in contrast to the normal practice of simply measuring the slope of the impedance vs. time and declaring this the closure velocity. We found that careful comparison of the data to models gave much more insight to the cathode physics processes.

The basic model for diode closure is derived from Child's Law

$$j_{CL}\,(\mathrm{kA/cm^2}) = 2.33\,V(\mathrm{MV})^{3/2}/d(\mathrm{cm})^2. \qquad (1)$$

Assuming the anode-cathode gap d closes at a constant speed v,

$$d(t) = d_0 - vt, \qquad (2)$$

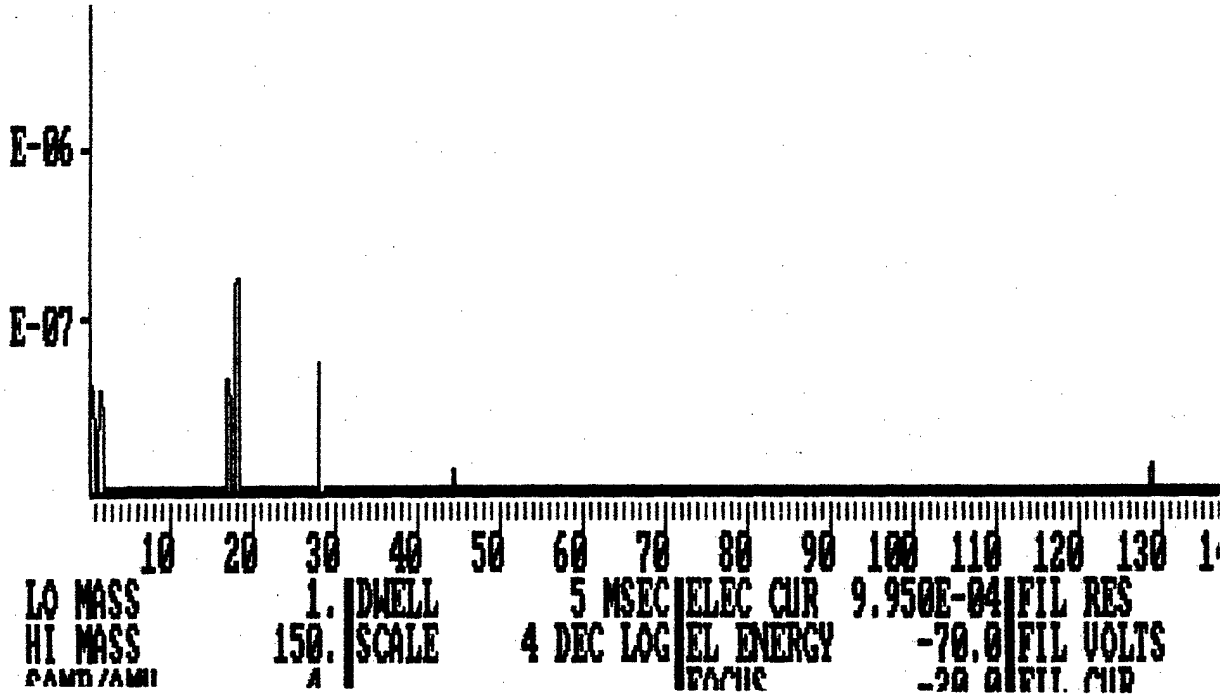


Figure 5 RGA measurement of gases taken moments after a burst of 20 shots with the CsI-coated carbon fiber. Outside temperature of the anode block was 136 °F and pressure was 2 x10^{-6} torr. Clearly identifiable molecules are hydrogen, water, nitrogen, carbon dioxide and perhaps hydrogen iodide (128).

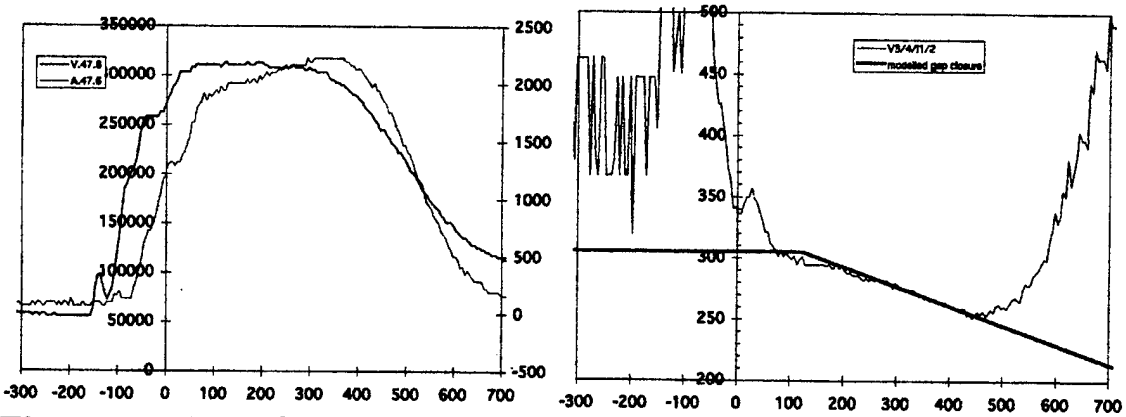


Figure 6. V(t) and I(t) for a CsI shot (tenth in a burst of 20 at 3 Hz) on the left. On the right are the inverse square root of perveance and the modeled gap (Eq. 2) vs. time, using the data on the left.

$$d_{CL}(t)=2.33\,\pi\,r_c^2\,V^{3/2}/I. \qquad (3)$$

Using the V(t) and I(t) from the diagnostics, we calculate $d_{CL}(t)$. Assuming a closure speed we use the simple model (2) to calculate a time dependence of the gap. Then we compare the two graphically, as in Figure 6.

The diode physics modeling uses an effective emitting area model area of CsI tufts through an effective cathode diameter,

$$D_e = D_t N^{1/2} \quad (4)$$

where D_t is the diameter of the tuft and N the number of tufts. This reflects the fact that Child's Law applies to the local current density, and so only applies at the tips of the fiber tufts. For this cathode D_t is 0.25 cm, the number of tufts is 192, so D_e is 3.457 cm.

Cathode radial plasma motion can be invoked in the model through a speed with magnitude and time of on-set of motion chosen by the user. The time of plasma turn-on can be varied. Bi-polar flow (factor of 1.86) can be invoked or suppressed (toggled on or off)in the model. Fringing of electron flow can be toggled on or off through an effective gap,

$$d = d_o / [1 + d_o/r_c] \quad (5)$$

which models flow at the cathode edge at an angle of 45°.

4. Experimental Results

Operations

We first conducted a study of the bare carbon fiber cathode, then coated the cathode and repeated. Vacuum was broken only to change over to the CsI-coated cathode. Vacuum base pressure remained in the range 1-2 x 10^{-6} torr. There were 99 shots with bare carbon, mostly single shots, a few repetitive at 3 Hz, taken over three days. There were 145 shots with CsI-coated carbon, most collected repetitively at 3 Hz in bursts of 20 shots, all shots taken in a single day.

Electrical Performance

Diode current and voltage traces for the CsI-coated cathode are substantially more reproducible than those for the bare carbon fiber cathode. A typical burst is shown in Figure 7. The CsI diode is clearly more repeatable, with less "hash"—short-time fluctuations. The effect on diode impedance is great, as shown in Figure 8. The coupling between the 50 Ω driver and the ~125 Ω diode load varies as the diode impedance fluctuates. This matters because microwave generation depends sensitively on the electron beam. Higher levels of noise in the flow gives fluctuating microwave power levels. This beneficial effect may be because CsI emits copious UV, lighting up the surface much more uniformly, eliminating jets or flares of emission.

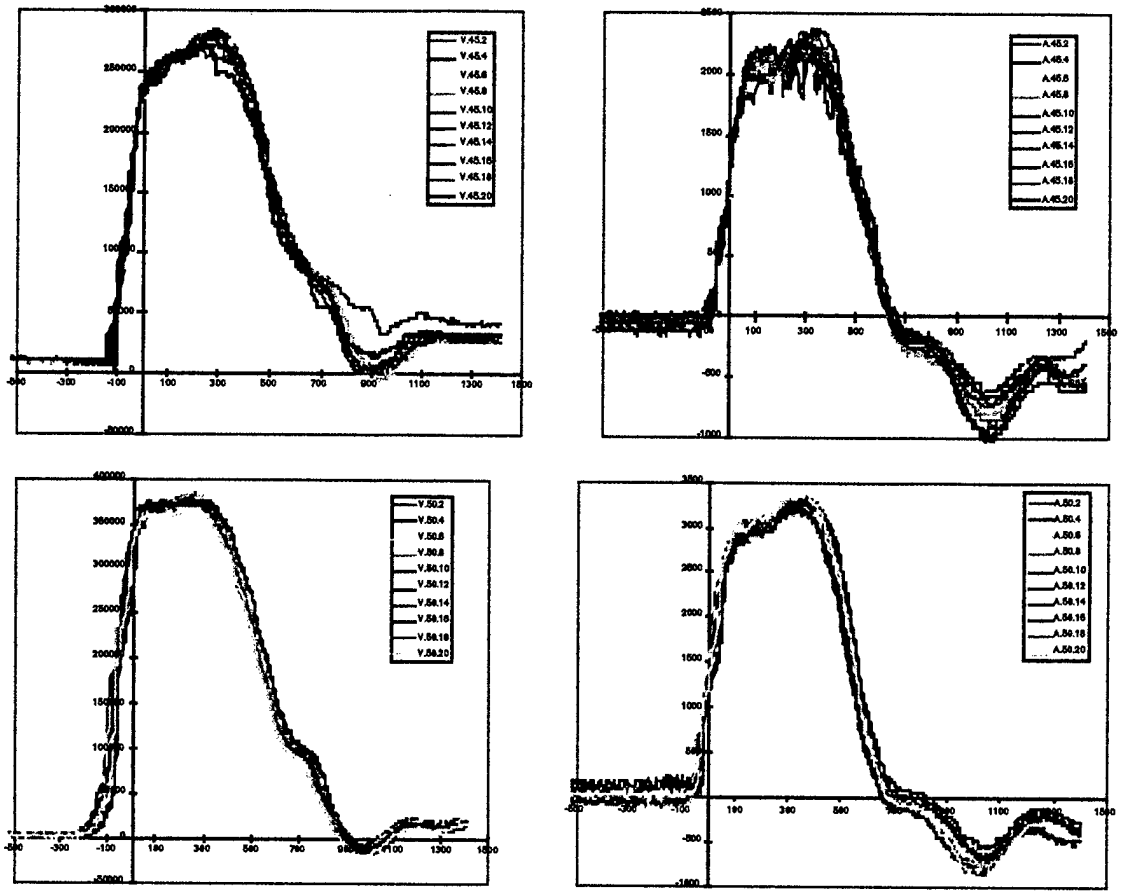


Figure 7. Voltage (left) and current (right) for bare carbon fiber (above) and CsI-coated fiber (below). In both cases these are ten even-numbered pulses from 20-shot bursts.

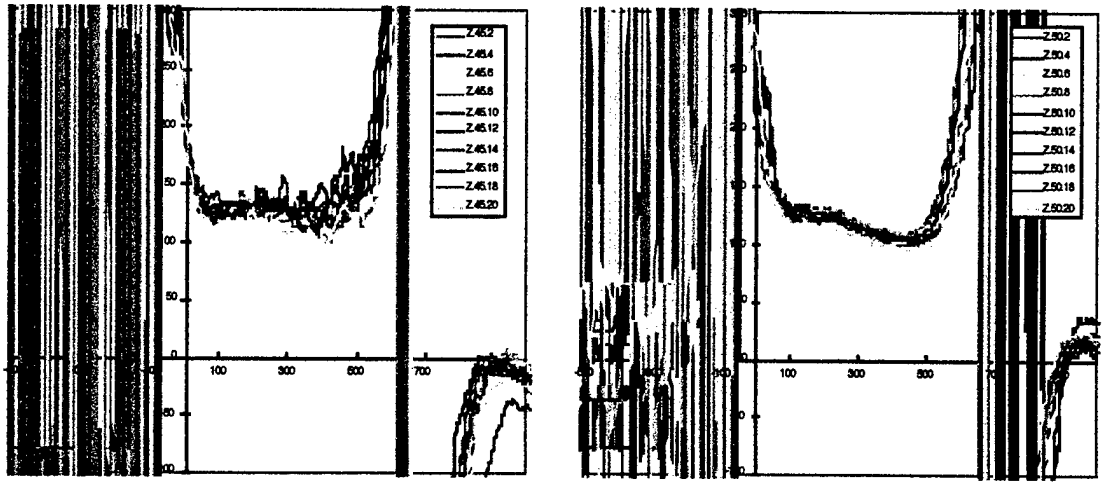


Figure 8. Impedance histories of the 20 shots in Figure 7.

Diode Physics

A general conclusion from data analysis and modeling is that there is good quantitative agreement with Child's Law with the effective area given by the tuft area. Note the close agreement of the simple constant-closure model (Eq. 2) with the gap calculated from Eq. 3 using V(t) and I(t).

In general, comparison with the model shows that radial motion doesn't occur until late in the pulse (see below). There is no evidence of bi-polar flow, i.e., no ions from the anode to increase the current by a factor of 1.86. This is expected because this flow requires that the anodes receive ~300 J/gm front surface dose. This experiment doesn't reach such levels in the 500 ns pulse. The best fit to the data is minimal fringing of the flow as the beam crosses the diode.

Turn-on Field

Note that in Figure 6 the current begins at ~25 ns, when the voltage reaches ~290 kV across the 1.4 cm gap. The voltage drops momentarily, loaded by the beginning of emission, then resumes its rise. Therefore, the field at which emission turn-on begins is ~200 kV/cm. For bare carbon fiber the average value of turn-on field is 67 kV/cm. For CsI-doped carbon fiber it is 124 kV/cm. The ratio of turn-on fields is 1.85. Previous workers quote ~50 kV/cm for CsI-doped carbon fiber. We shall see in section 5 that previous work on carbon fiber may well have been essentially dominated by water and other volatiles so the lower turn-on field was characteristic of the volatiles, not the fiber.

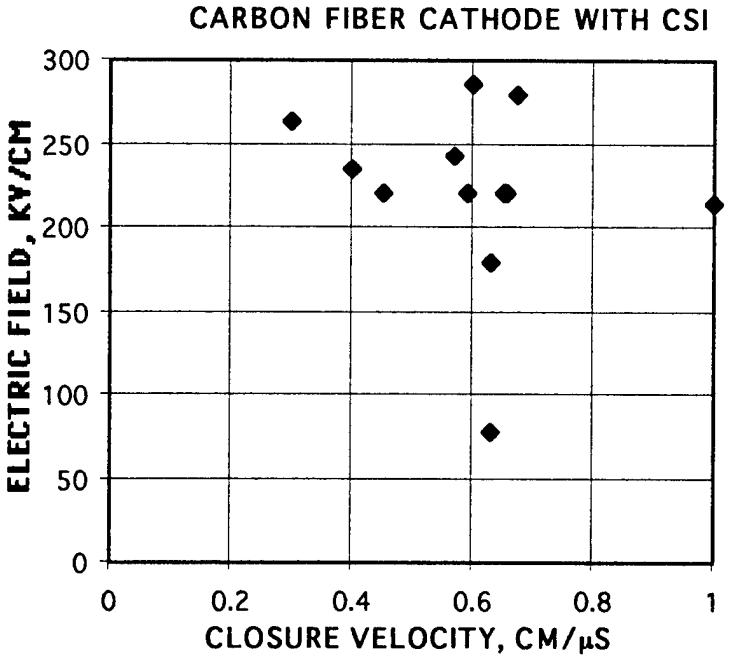


Figure 9. Closure speed with CsI-covered carbon fiber is low at high diode fields.

Closure Speed

Varying the charge voltage on the Marx from 24 kV to 38 kV and the gap from 2.0 to 1.4 cm varied the electric field in the gap from 47 kV/cm to 286 kV/cm. From shots like that in Figure 6 the dependence of closure speed on electric field can be graphed (Figure 9). For macroscopic electric fields of up to 285 kV/cm, sufficient for the diodes of GW microwave sources, closure speed for CsI on carbon fiber is 0.59±0.16 cm/μsec.

With the bare carbon fiber the magnitude and the spread--shot-to-shot variation-- is much larger (Figure 10). For bare fiber, closure speed is 2.08±0.71 cm/μsec. The ratio of speeds is 3.5, and the 1σ spread varies by a factor of 4.4.

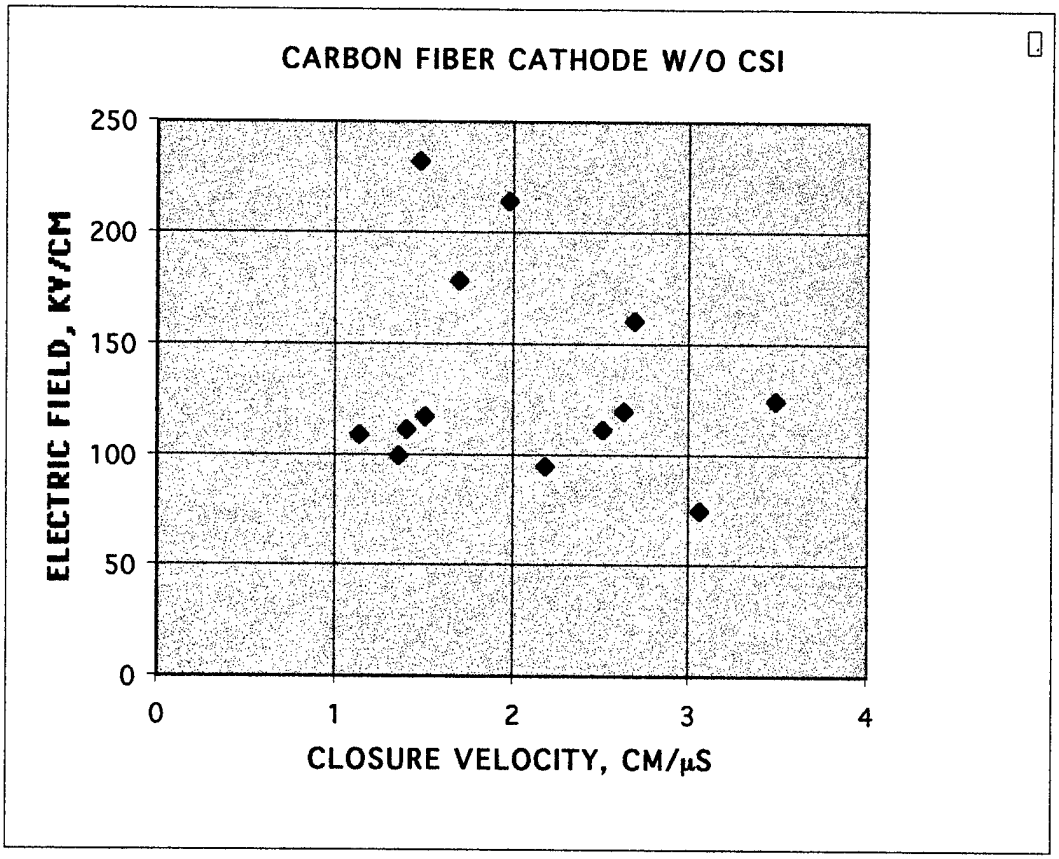


Figure 10. Closure speed with bare carbon fiber is high with large spread.

Wall Temperature

As the block cooled down, eventually reaching room temperature, closure speed didn't appear to vary, as shown in Figure 11.

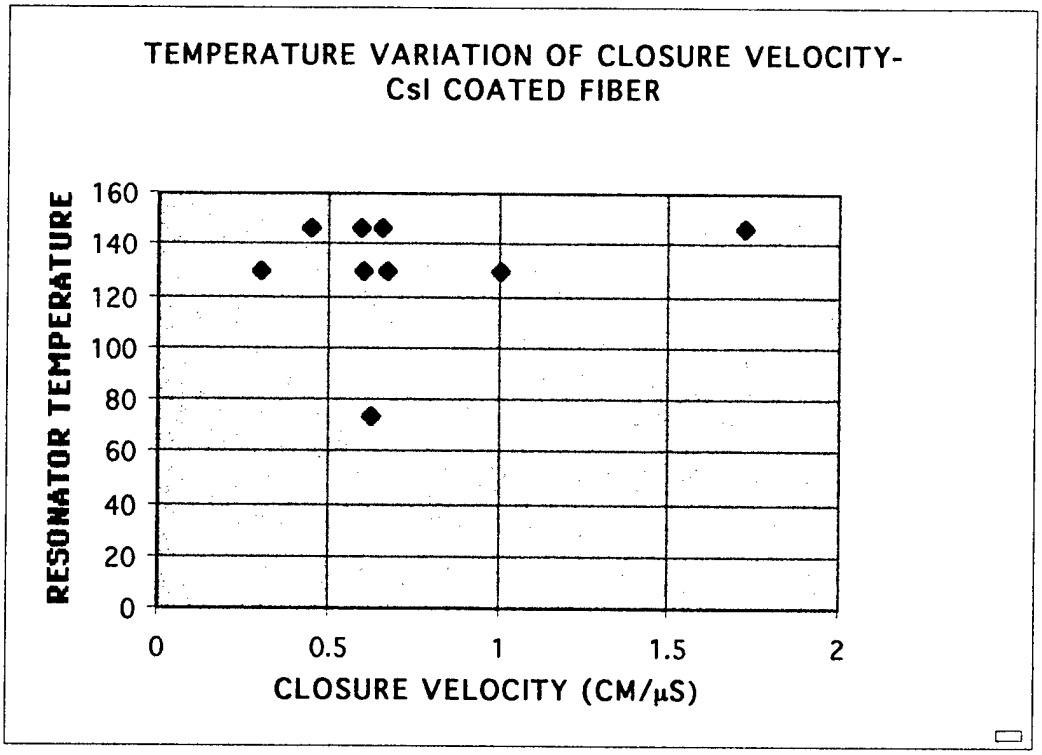


Figure 11. Closure speed with CsI-covered carbon fiber as a function of the temperature of the outer wall of the anode block. Room temperature is 75 °F.

Radial Motion and Very Slow Axial Motion

Figure 12 shows evidence for two effects. The first is an extraordinarily slow closure in the first part of the pulse. This occurs in a minority of the shots, starts at the beginning of emission and its duration changes from shot to shot. The fitted model in Figure 12 has an axial closure speed of 0.052 cm/μs throughout. Discussion of this remarkable result is deferred to Section 6.

The second phenomena is a radial motion beginning in mid-pulse. In Figure 12 the model of radial speed is zero till 250 ns, then of equal magnitude to the axial speed (0.052 cm/μs) beginning at 250 ns. Axial motion alone does not give a good fit, measured in terms of least-mean-squares. The onset of this radially-moving plasma is likely caused by the beginning of emission from the cathode edge. Recall that the CsI does not extend down the entire axial extent of the cathode plate, so perhaps the graphite base lights up later in the pulse.

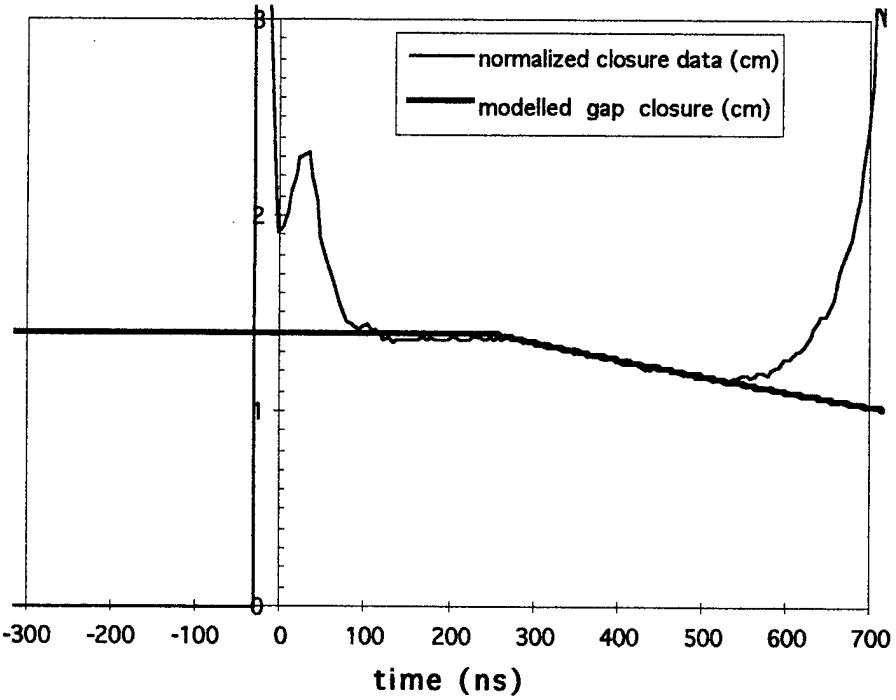


Figure 12. Very low axial motion and delayed radial motion with a CsI cathode.

5. Review of Previous Work

Table 2 shows a comparison of this work with previous work on both carbon fiber and CsI-coated carbon fiber. Here our work is assigned a current density of 110 A/ cm^2, which is 3.2 kA with the 29.2 cm^2 basic cathode area, not the tuft area, 9.4 cm^2.

CsI cathode work follows on from the carbon fiber cathode studies in the U.S. and Soviet Union in the 1980's. The first work, by R. Prohaska and A. Fisher[1], used carbon yarn, at fields of 10-30 kV/cm. They produced current densities of 1-10 A/cm^2. Burtsev, et. al.[2] reported a "graphite multiple point cathode" with uniform emission into a BWO generating 15 MW for 3 μs, claiming a closure velocity reduced by a factor of a hundred, but quantitative values were not given. Adler, et. al.[3] found that carbon tuft cathodes gave closure velocity < 1 cm/μs, as opposed to 2-3 cm/μs from carbon cloth cathodes. They used the carbon fiber cathode in a vircator and demonstrated reproducible and repetitive operation in a 40,000 shot, 6 Hz pulse train.

The CsI cathode was introduced in this field by Garate, et. al.[4]. The rationale is that CsI will produce a heavy ion to slow closure while emitting UV copiously. The UV may cause uniform emission. They demonstrated reduction of closure velocity from 1.33 cm/μs with carbon fiber to 0.46 cm/μs when coated with CsI, a factor of

Table 2. Summary of Carbon Fiber and CsI Experiments

Experiment	Material	E_o, (kV/cm)	v_p, (cm/μs)	Turn-on field, (kV/cm)	Vacuum (torr)	Baked?	Current Density (A/cm^2)
Benford, Price & DeHope, 1998	C CsI	240 285	2.08±0.71 0.59±0.16	67 124	10^{-6} 10^{-6}	yes, 200 °F atmos, 600 °F vac	110
Miller, 1997	CsI C	20-50	0.3-0.5 0.2	20-35	10^{-5}	no	40
Hendricks, et. al., 1996	CsI	225	-	-	10^{-5}	no	-
Garate et. al., 1995	C CsI	21	1.33 0.46	-	10^{-5}	yes, at atmosphere	18.7
Hendricks, et. al., 1993	CsI	40	0.3-0.4	-	10^{-5}	yes, at atmosphere	-
Kosai & Fisher, 1990	CsI	80	-	>10	10^{-4}	no	175
Adler, et. al., 1985	C	300	<1	-	-	no	<500
Prohaska & Fisher, 1982	C	10-30	-	10-30	10^{-5}-10^{-6}	no	1-10

three. The field was 21 kV/cm and current density was 18.7 kA/cm^2. In this paper a very low closure speed for 4 μsec is reported for CsI, but not quantified, which may be the very low speed seen occasionally in this experiment.

Recent work by Garate and the group at Voss Scientific has expanded the parameter space[5]. In a linear foilless geometry a CsI cathode driven at 500 kV again gave improvement of at least a factor of two compared to carbon fiber in a Marx-rundown pulse extending over a microsecond. Spectra from the cathode reveal that good performance corresponds to low emission of Hydrogen (low H_α). This indicates that surface cleanliness may aid CsI performance by greatly reducing low mass contaminants.

A more recent result is from use of carbon coated CsI in an HPM device, the RKO, by Kyle Hendricks, et. al.[6]. The RKO resonance requires that, after the beam current reaches the start current, beam impedance variation must be limited to less than 5%. This condition was not met with carbon cathodes. With the carbon coated CsI at a field stress of ~225 kV/cm the diode shows little impedance collapse over 200 ns of the 300 ns pulse, so the microwave pulse shows no pulse shortening.

The most recent result is from Bruce Miller[7]. He used an admittedly dirty CsI-covered carbon fiber and got mixed results, probably due to contamination.

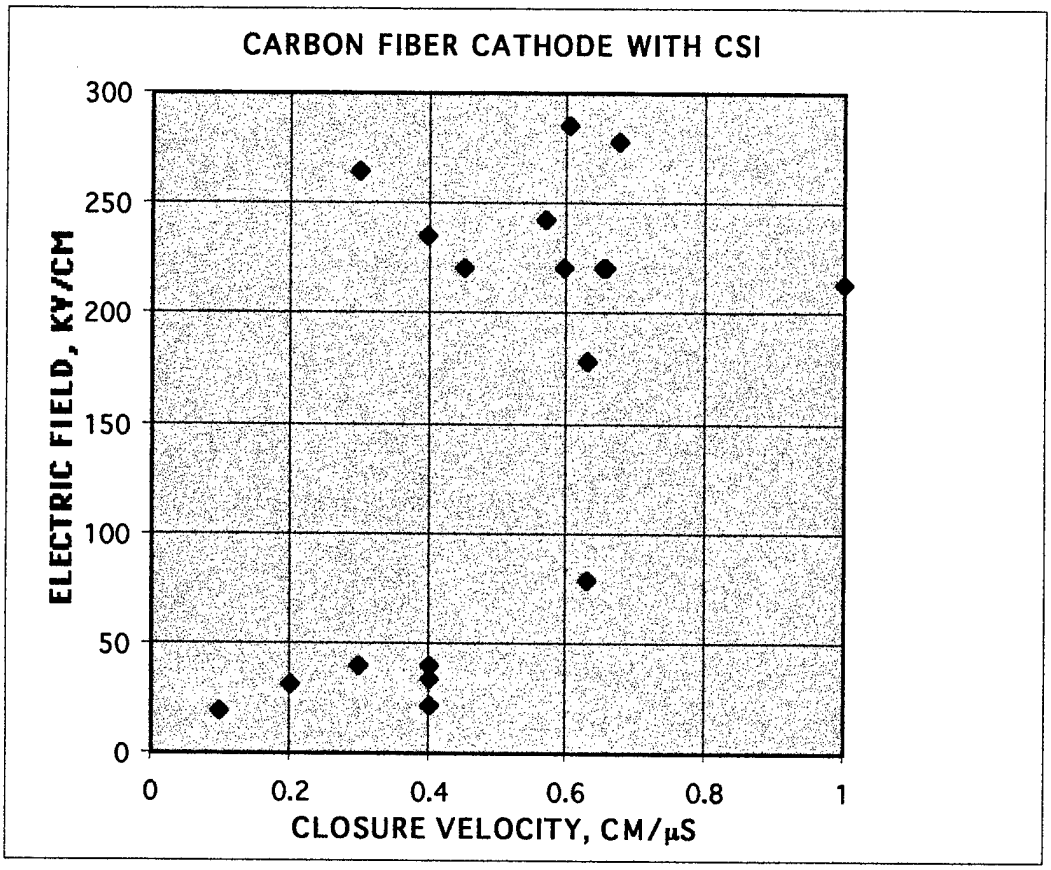


Figure 13. Comparison of closure from Hendricks, et. al. and in this experiment. Hendricks et. al. points are below 50 kV/cm and 0.4 cm/μsec.

6. Interpretation and Implications

The ratio of closure speeds with and without CsI is 3.5. Therefore, we expect a factor of 3.5 extension of the pulse duration and the pulse energy at high power with properly cleaned cesium iodide-coated cathodes. Good source candidates are the relativistic magnetron and the MILO. We recommend that the Air Force fund us to use the results of this experiment to demonstrate microwave pulse extension by this large factor.

When plasma motion is the mechanism causing closure (and, in microwave sources, shortening the microwave pulse duration):

$$\tau_\mu \propto v_p^{-1} \propto \sqrt{m_p} \quad . \tag{6}$$

The ratio of closure speeds with and without CsI is 3.5, therefore:

$$\frac{m_{CsI}}{m_f} = 3.5^2 = 12.25 \tag{7}$$

where m_f is the mass of whatever ion determines the closure speed with bare carbon fiber. The simplest interpretation is that bare fiber still has hydrogen in it, so $m_f = 1$. Therefore, $m_{CsI} = 12$, and expansion is evidently governed by the next lightest, available, ion: the carbon from the fibers or the substrate.

Our interpretation of the physics of bare carbon fiber is that the lightest, fastest ion, which determines the closure speed, is residual hydrogen from the fiber, probably from chemisorbed sources, not from water, most of which we boiled off under vacuum. As a check, recall that the plasma thermal velocity is:

$$v(cm/\mu s) = \sqrt{T(eV)/m} \tag{8}$$

where m is the mass relative to the proton. Then for hydrogen from the bare carbon fiber, T= 4 eV gives a speed of 2 cm/μs, as we observe. This fits, because we expect such collision-dominated cathode plasmas to have temperatures of a few eV[8].

Note we found that baking under vacuum removed copious amounts of water from the CsI cathode, which had already been baked at atmosphere. Recall that previous workers either did no baking or baked at atmosphere only. Therefore, we can explain most of the work preceding ours as basically water-dominated.

For CsI-covered carbon fiber, the hydrogen from the fiber or the water is captured by the process of covering it with CsI. Perhaps the hydrogen is bound up into hydrogen iodide, HI. (Note from Figure 5 the RGA detects a molecule with this mass). This leaves carbon as the lightest, fastest ion. To get the closure speed of CsI, assume the temperature remains about the same 4 eV, insert in Eq. 8 the carbon mass, 12, giving 0.6 cm/μs, fitting the observed 0.59 cm/μs. (Here we assume the density is high enough to give rough equivalence of electron and ion temperatures, which seems likely from comparison with the literature on cathode densities.)

The most intriguing result is the very slow 0.052 cm/μs shown in Figure 12. One interpretation is that this is due to the Cesium itself dominating the plasma closure speed, before heating at the surface releases carbon. Using Eq. 8, for 4 eV, cesium, mass 133, gives 0.17 cm/μs. So to fit this scenario, the cesium temperature must be lower, ~0.36 eV. Alternately, if a CsI ion dominated closure a temperature of ~0.7 eV would be required to match observations.

7. Conclusions

It is clear from the above that cleaning the cathode gives better performance by ridding the material of volatiles. By pursuing this line of inquiry with other materials we may be able to reduce closure to speeds <0.1 cm/μs, ushering in a new regime in intense beam diodes and HPM.

It's also clear that CsI cathodes should be introduced to increase energy per pulse in HPM sources.

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1041 Los Arabis Lane
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Official Record Copy
Dr. Thomas A. Spencer
AFRL/DEHE, Bldg. 326
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 10 cys

Dr. Barry Hogge
AFRL/DE
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Earl Good
AFRL/DE
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. William Baker
AFRL/DEH
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Kyle Hendricks
AFRL/DEHE, Bldg. 326
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Mike Haworth
AFRL/DEHE, Bldg. 326
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Moe Arman
AFRL/DEHE, Bldg. 326
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Kirk Hackett
AFRL/DEHA, HERTF
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Collins Clark
AFRL/DEHA, HERTF
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Bill Dungan
AFRL/DEHA, HERTF
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Robert Peterkin
AFRL/DEHE, Bldg. 326
3550 Aberdeen Ave, SE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Marc Litz
ATTN:AMSRL-WT-NH
Sources Physics Branch
Army Research Laboratory
2800 Powdermill Road
Adelphi, MD 20783 1 cy