Lowered Plasma Velocity With Cesium Iodide/Carbon Fiber Cathodes At High Electric Fields*

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We have demonstrated reduced CsI plasma speed for macroscopic electric fields of up to 285 kV/cm with cesium iodide-coated (CsI) carbon fiber cathodes, sufficient for the diodes of GW microwave sources. Plasma speed is 0.6 x 10^6 cm/sec, 3.5 times less than the bare carbon fiber. The apparatus had oil-free high vacuum conditions (metal seals and glass insulator) and the cathode was baked both before assembly at atmospheric pressure and in vacuum after assembly, to temperatures sof >600 ºC. A residual gas analyzer showed burnout of the water; base pressure was ~10^{-6} Torr. An unexpected benefit of the CsI coating is that diode current and voltage traces are substantially more reproducible than with bare carbon fiber. With reduced plasma velocity, CsI cathodes should produce an extension of the HPM pulse length and an increase in pulse energy by a substantial factor in sources now limited by low-Z contaminant cathode plasma motion.

When explosive emission cathodes are used in higher power (>100 MW) devices, microwave pulse shortening can occur because of motion of the cathode plasma at speeds 1 to 5 x 10^6 cm/sec, which can limit present-day high power microwave (HPM) sources to a few hundred joules. In previous work[1-5] 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 extended the CsI cathode to much higher fields, such as occur in HPM sources of the GW class.

We used a 450 kV, 500 ns, 50 Ω modulator. The cathode base 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 region around the cathode 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 inactive L-band relativistic magnetron, made of ~300 pounds of stainless steel. A halogen lamp is inserted toward the anode along the axis from the downstream end.

The cathode was baked both before assembly at atmospheric pressure and in vacuum after assembly, to temperatures of >600 °C. 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 residual gas analizer registered a large amount of water when heating began and a steady decline in water as the bakeout proceeded. No water re-condensation could occur on the cathode surface between shots or bursts.

We first conducted a study of the bare carbon fiber cathode, then coated the cathode and repeated. Diode current and voltage traces for the CsI-coated cathode are substantially more reproducible than those for the bare carbon fiber cathode. The CsI diode is clearly more repeatable, with less "hash"—short-time fluctuations, compared to bare fiber. With bare fiber, 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.

In Figure 1 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. For bare carbon fiber the average value of this turn-on field is 67 kV/cm. For CsI-doped carbon fiber it is 124 kV/cm. Previous workers quote ~50 kV/cm for CsI-doped carbon fiber[1-5]. 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 1. 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 vs. time, using the data on the left.

Figure 2 shows that 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/μs. With the bare carbon fiber the magnitude and the shot-to-shot variation is much larger For bare fiber, closure speed is 2.08±0.71 cm/μs. Note that the ratio of speeds is 3.5, and the 1σ data spread varies by a factor of 4.4.

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.

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

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

Therefore

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

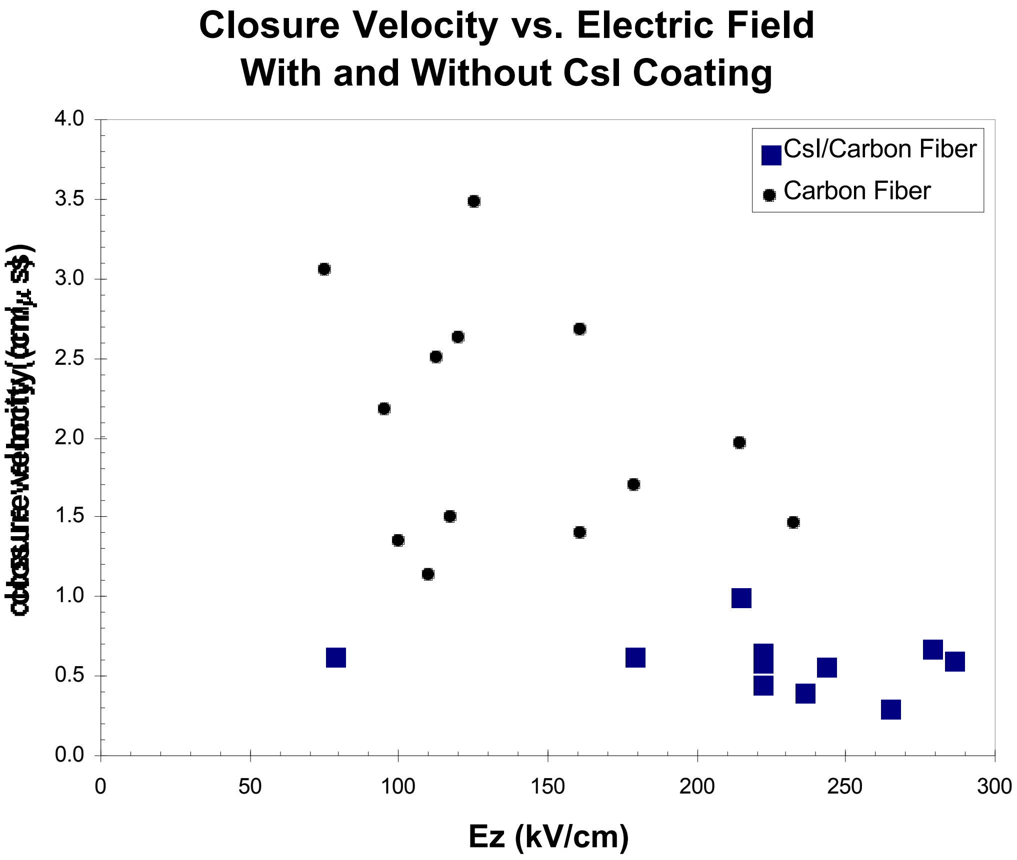

Figure 2. Closure rate with bare carbon fiber and CsI-coated fiber.

where m_f is the mass of whatever ion determines the closure speed with bare carbon fiber. The simplest interpretation is that heated bare fiber still contains hydrogen, 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:

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

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[6].

Note we found that baking under vacuum removed copious amounts of water from the CsI cathode, which had already been baked at atmosphere. 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.)

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1. R. Prohaska and A. Fisher, "Field Emission Cathodes using Commercial Carbon Fibers", Rev. Sci. Instrum. **53**, pg. 1092, 1982.

2. R. J. Adler, G. Kiuttu, B. Simpkins, D. Sullivan and D. Voss, "Improved electron emission by use of a cloth fiber cathode", Rev. Sci. Instru., **56**, pg. 766, 1985.

3. E. Garate, R. MacWilliams, D. Voss, A. Lovesse, K. Hendricks, T. Spencer. M. C. Clark and A. Fisher, "Novel Cathode for Field-emission Applications", Rev. Sci. Instru., **66**, pg. 2528, 1995.

4. K. Hendricks et. al., "Recent Results on Pulse Shortening of GW Class HPM Sources", APS Plasma Physics Mtg., Denver, CO, 1996.

5. R. B. Miller, “Repetitive pulse operation of reltron tubes”, SPIE 3158, pg. 2, 1997.

6. D. D. Hinshelwood, “Cathode Plasma Formation in Pulsed High Current Vacuum Diodes”, IEEE Trans. Plasma. Sci., PS-11, pg. 188, 1983.