

MEASUREMENTS OF IMPROVED CATHODE PERFORMANCE USING A CERAMIC HONEYCOMB SECONDARY EMITTER*

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Abstract

Experiments carried out on the Electra Laser main amplifier (500 kV, 100 kA, 100 ns, 5 Hz) show that inserting a slab of ceramic honeycomb in front of a large area cathode (2600 cm²) improves the electron beam emission uniformity, decreases the beam current rise and fall times, and maintains a more constant diode impedance. A more robust cathode that starts to emit at a higher electric field without a degradation in uniformity is achieved by using carbon fiber as the primary emitter. These qualities, the simplicity of design, and the low cost make the ceramic honeycomb cathode an interesting candidate for long lifetime use in the krypton-fluoride lasers proposed for inertial fusion energy.

I. INTRODUCTION

Krypton fluoride (KrF) lasers are an attractive driver for inertial fusion energy (IFE) due to their short operating wavelength (248 nm), excellent beam quality, and modular nature. Typical power plant beam-line designs envision counter-streaming, rectangular cross-section electron beams pumping laser gas at a repetition rate of 5 Hz for lifetimes approaching 3×10^8 shots [1]. Meeting the IFE goals will require cathode lifetime improvements of up to 4 orders of magnitude. For a 500 kV beam of 160 ns pulse width, we found that dielectric fiber (velvet) cathodes meet IFE requirements for uniformity, rise time, and gap closure but only at pulse repetition rates ≤ 1 Hz for up to a few times 10^4 shots. Carbon fiber and metal-dielectric cathode lifetimes have exceeded 10^6 shots but our studies indicate that their emission uniformity and slower turn-on times are questionable for KrF laser applications [2].

Experiments conducted on the Electra Laser [3] main amplifier (500 kV, 100 kA, 100 ns, 5 Hz) show that inserting a 2 cm thick slab of ceramic honeycomb in front of a large area cathode (2600 cm²) improves the electron

beam emission uniformity, decreases the beam current rise and fall times, and maintains a more constant diode impedance. Results indicated that, when used with a carbon fiber primary emitter, the ceramic honeycomb cathode could achieve a long lifetime while maintaining acceptable uniformity [4]. This paper reports on further experiments with a ceramic honeycomb cathode consisting of a 5 cm thick slab of honeycomb, coated with γ -alumina with a primary emitter made of carbon velvet [5]. Section II presents experimental results obtained to characterize the cathode perveance and emission uniformity and compares them with results obtained with carbon velvet alone and with a standard dielectric fiber velvet cathode. Section III details experiments done to examine the longevity of the ceramic honeycomb cathode. Section IV concludes the paper with a discussion of the implications of these experimental results vis-à-vis IFE requirements.

II. CATHODE CHARACTERIZATION

A 27 cm x 97 cm ceramic honeycomb cathode was constructed using a mosaic of 5 cm thick honeycomb tiles with 1 mm² pores at a density of ~ 50 pores/cm². The honeycomb is made of cordierite; $\epsilon_r = 6.3$ in the bulk material. It is coated with γ -alumina which increases the surface area of the ceramic by many orders of magnitude. γ -alumina behaves like a "reactive sponge" [6] essentially recycling adsorbed gases. The primary emitter was made of carbon fibers 6 μ m dia. x 1.5 mm long "flocked" onto 500 μ m thick aluminum sheet at a packing density of 2.2%. The flocking process binds the fibers to the aluminum sheet with a conducting epoxy, $\rho = 10$ -20 $\mu\Omega$ -cm. The gap between the primary emitter and the honeycomb was 3.0 mm. A drawing of the cathode is shown in Fig. 1. The performance of this cathode was compared with two other cathodes: one made only of carbon velvet and one made of dielectric fiber velvet [7] (18 μ m dia. fibers, 1.5 mm height, 4.4% packing density).

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The cathodes were tested on Electra using a diagnostic anode plate that allowed access for electron beam measurements. Radiachromic film monitored time-integrated beam uniformity; a 4-frame, micro-channel plate intensified, gated optical imager (GOI) gave time resolved uniformity; and an array of Faraday cups measured beam current density and rise-time. The diode voltage and current were measured with capacitive probes and Rogowski coils, respectively. A 25 μm thick, aluminized Kapton foil, which is transparent to electrons of energy greater than ~ 20 keV, served as an anode foil in front of a 6 mm thick graphite plate. The cathodes are recessed 1 cm into a conducting frame which smooths the electric field discontinuity at the cathode edge and suppresses the high current density beam halo. The AK gap was 5.5 cm to the emitter and the applied external magnetic field was 0.14 T in all cases. Figure 2a compares a typical, normalized beam current for each of the cathodes. Insertion of the ceramic honeycomb in front of the carbon velvet improves the 10-90 rise-time by a factor of 2. This is nearly 15 ns faster than the standard set by the dielectric velvet cathode. The deleterious fall time of the carbon velvet cathode is eliminated in the honeycomb cathode case where the fall time is equivalent to that of the velvet. The current density in all cases was ~ 29 A/cm². The perveance, $P(t)=I/V^{3/2}$ is plotted for each cathode in Fig. 2b. With the 5 cm, γ -alumina coated honeycomb slab inserted, the perveance is nearly constant and reaches its equilibrium value much earlier in time than in the carbon velvet alone case.

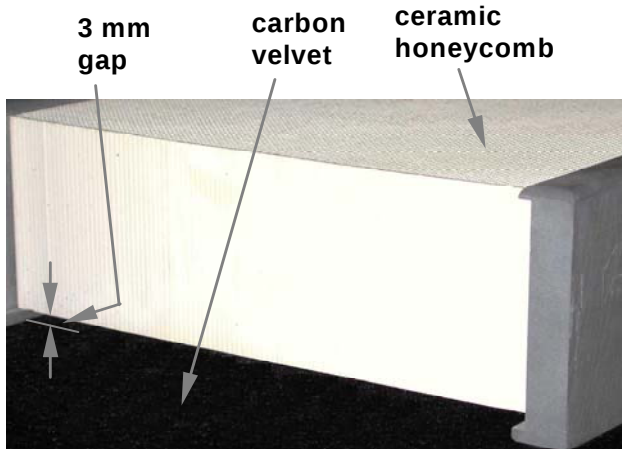


Figure 1. Essential elements of the ceramic honeycomb cathode.

Table 1 compares emission uniformity measurements for the dielectric velvet cathode and the ceramic honeycomb cathode. Radiachromic film measurements of time-integrated emission uniformity showed variations of about 8% with the honeycomb. These measurements were slightly higher than previous measurements done with 2 cm, uncoated honeycomb [4]. Variations of 4.2% were seen with the dielectric velvet. Note that previous measurements with the carbon velvet alone showed

variations of $\sim 15\%$ [2]. Time-resolved emission uniformity measurements were obtained with the GOI. The nominal 500 kV beam electrons are stopped in a 100 μm thick tantalum convertor located at the anode and the resulting x-rays are then converted to optical light using a 2 mm thick, fast scintillator (EJ-212) sandwiched against the tantalum. The spatial resolution is 6 pixels/mm; the gate width (6 ns) and gain for each frame used in the analysis are the same. The table shows an average velvet uniformity variation of 11.8% at the start of the current flat-top (refer to Fig. 2a) but evolves to a more uniform emission (4.2% variation) 42 ns later. The ceramic honeycomb emission is more constant over the same interval which seems to follow the trends seen in the perveance. Note that the later time measurements in both cases are consistent with the time-integrated uniformity obtained with radiachromic film.

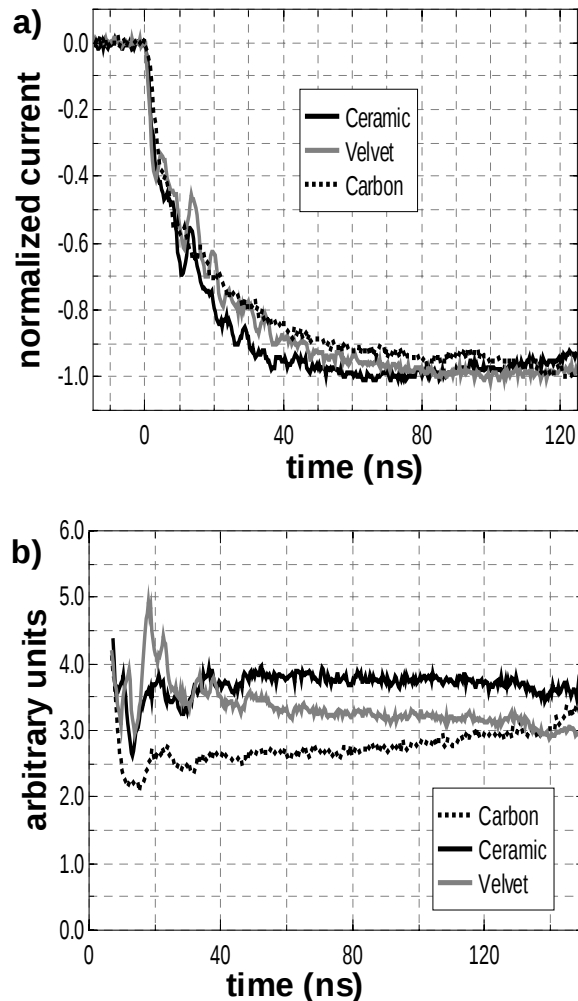


Figure 2. Comparison of the a) beam current rise-time and b) beam perveance for carbon velvet, dielectric fiber velvet, and ceramic honeycomb cathodes.

III. CATHODE LONGEVITY

To examine cathode longevity, the diagnostic anode plate was replaced with a water-cooled, stainless steel anode plate (beam dump). The ceramic honeycomb and dielectric velvet cathodes were tested for five consecutive 10,000 shot runs each. The pulse repetition rate for each run was 1 Hz. At this rate, interaction between the anode and the cathode is minimal (i.e. anode plasma formation and ion back scattering onto the cathode are not factors). Two 4000 l/s cryogenic pumps established an initial diode pressure of 2×10^{-6} Torr as measured by a cold cathode gauge. Samples of evolved gas were taken at various intervals during operation and analyzed with an RGA to determine the constituents. The uniformity of emission was measured after 10 shots and at 10,000 shot intervals thereafter using radiachromic film positioned 3 mm in front of the anode with an in-vacuum scrolling mechanism. Diode vacuum was “broken” only after 50,000 shots were complete. Figure 3 plots the diode voltage pulse at three points during the ceramic honeycomb cathode run. The pulse shape and amplitude was very reproducible throughout the entire 50,000 shot run. Radiachromic film scans of ceramic honeycomb emission uniformity at the 10,000 shot intervals were consistent but differed from the $\sim 8\%$ variation measured after 10 shots, particularly along the bottom half of the cathode. This was due to the failure of the conducting epoxy that held the carbon fibers of the primary emitter. Many of the carbon fibers became loose and piled up in the 3 mm gap between the primary emitter and the honeycomb making a connection between the two sometime during the first 10,000 shots. This changed the emission dynamics of the cathode. A possible mechanism for the failure of the epoxy is the high temperature (150-200 °C) that the ceramic may reach during operation at 1 Hz. The ceramic honeycomb itself was unaffected by the temperature and proved to be very robust. The diode operating pressure climbed to $2\text{E-}4$ Torr by the 10,000th shot but then gradually decreased to $5\text{E-}5$ Torr by the 50,000th shot. RGA analysis of diode gas samples taken at 10,000 shot intervals show air and water components declining in partial pressure as the shot count was rose, while observable hydrogen increased 50-100 times. Effects of melting epoxy were not evident in the gas samples.

Table1. Time resolved and time-integrated measurements of emission uniformity variation.

	dielectric velvet	ceramic honeycomb
t=56 ns	11.8 %	10%
t=98 ns	4.5%	8.4%
time-integrated	4.2%	8%

The same longevity test was conducted with the dielectric fiber velvet cathode. Again the voltage pulses were very consistent throughout the 50,000 shot run. Emission uniformity was the same at each 10,000 shot interval and approached the $\sim 4.2\%$ variation measured after 10 shots. After 50,000 shots, texture and color changes of the velvet were obvious; however, it is unknown at what point during the run they took place. Closer inspection under a microscope revealed various degrees of melting and/or burning of the dielectric fibers. The diode operating pressure reached $3\text{E-}5$ Torr after 1,000 shots and changed only slightly to $2\text{E-}5$ Torr after 50,000 shots. Gas sample analysis showed essentially a constant pressure of all constituents throughout the run with some small changes in partial pressure at higher charge to mass ratio (AMU) lines (perhaps due to chemical changes in the dielectric fibers).

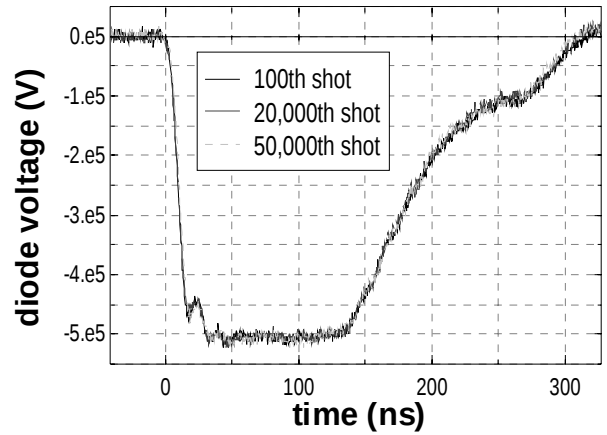


Figure 3. Sample of diode voltage pulses taken during the 50,000 shot run with the ceramic honeycomb cathode.

It should be noted that, during the velvet longevity run, an unintegrated B-dot monitor showed a much higher RF signal than in any previous experiment on Electra. An FFT of the signal revealed a very high amplitude component at 4 GHz indicating the presence of the transit-time instability [8]. The primary difference in the present experiment was the 1 cm recession of the cathode into its frame that suppresses the high current density beam edge. During the ceramic honeycomb cathode run however, the raw RF noise amplitude was a factor of 1000 lower and spread over many frequencies.

IV. DISCUSSION

From the measurements presented above, it is clear that inserting a 5 cm ceramic honeycomb cathode with γ -alumina in front of a carbon velvet primary emitter improves the electron beam emission uniformity, decreases the beam current rise and fall times, and maintains a more constant diode impedance than a cathode made of carbon velvet alone. Indeed it out-

performs the dielectric velvet cathode with a rise-time that is ~ 15 ns faster and with a perveance profile that reaches its equilibrium value earlier and is more constant throughout the pulse. Although the late-time emission uniformity of velvet is better, the ceramic was more uniform earlier in the pulse and the 8% variation ultimately reached is still within the IFE standard of 10%. The time resolved uniformity measurements loosely follow the trends in the perveance profiles and later time frames show variations that are in close agreement with the time-integrated radiachromic film measurements. The perveance and rise time characteristics of the 5 cm γ -alumina coated honeycomb were very similar to the previously tested 2 cm uncoated ceramic honeycomb cathode [4]. Again, the only difference was an insignificant change in uniformity variation. Thus the γ -alumina coating doesn't affect the emission qualities of the ceramic cathode which is fortuitous because the coating showed promise in increasing the longevity of the cathode by essentially acting as a reservoir for adsorbed hydrogen. Although the primary carbon velvet emitter was compromised by higher temperatures, the ceramic honeycomb was unaffected and the voltage pulses produced were still very consistent through 50,000 shots. The presence of the ceramic in the diode vanquished the transit-time instability, which was present when testing the velvet cathode. Similar to loading a planar waveguide with a dielectric, the TEM waves that couple to the beam electrons were not generated and the instability was not initiated [9]. The next test of the ceramic honeycomb cathode will use a primary emitter that is made of pure carbon fibers that are painstakingly woven through many small diameter holes in a support plate. This structure should be unaffected by temperatures below 300°C, which is the anticipated temperature of the ceramic cathode at 5 Hz operation. It is expected that the ceramic honeycomb cathode with the pure carbon fiber primary emitter will show increased lifetime while maintaining IFE-acceptable rise time, gap closure, and uniformity characteristics.

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