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OPERATION OF A REPETITIVELY PULSED 300 kV, 10 kA ELECTRON BEAM DIODE*

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Introduction

Repetitively pulsed diodes will be required for most of the proposed inertially confined fusion systems, yet little information is available on the operation of vacuum beam diodes under repetitive conditions.[1-4] Most data are relevant to laser exciter/sustainer diodes operating at low current density (< 1 A/cm^2) for long pulses. As such they are of marginal value for estimating the properties of repetitive high current density diodes such as will be required for particle beam and some gas laser fusion drivers.

To examine the operation of high current density diodes (~ 1 kA/cm^2) at moderate voltages (200-350 kV), data have been obtained from a small area (~ 20 cm^2) beam from a diode attached to the RTF-I high voltage pulser.[5] RTF-I uses a transformer-driven, oil insulated, 10 Ω coaxial pulse forming line (PFL) to produce 350 kV, 30 ns pulses at a maximum rate of 100 Hz. The space charge limited diode impedance is

$$Z = \frac{137\pi}{\sqrt{V}} \frac{d^2}{A} \qquad (1)$$

where Z is in ohms, V in megavolts, d is the A-K (anode-cathode) gap spacing and A is the beam area. For Z = 10 Ω, V = 0.25 MV, d/r (r is the radius of the cylindrical beam) is 0.2. Typical A-K gaps are 0.36 to 0.5 cm with cathode radii being 1.8 and 2.5 cm. In each case the A-K gap was adjusted to give resonable impedance match to the PFL. Diode current was measured with a low inductance 0.124 Ω shunt (CVR). Voltage was measured with an integrated dV/dt monitor (a capacitive voltage probe with a small resistance leading to ground) and with a resistive divider mounted in the annular water resistor shown in Fig. 1. This annular resistor served the dual purposes of monitoring and prepulse suppression. The dual-resonance charging of the PFL in RTF-I produces a 5.6 μs bipolar charging waveform. Thus prepulse can be a severe problem and a rather low resistance (typically 50 to 150 Ω) is needed in parallel with the diode at small A-K spacings to prevent premature plasma formation resulting in a shorted diode. Since a significant amount of power is deposited in this prepulse resistor it must be cooled. Tap water (resistivity 2000-3000 Ω-cm) proved to be a convenient resistive medium as it may be freely discharged to dissipate the heat load. The anode for all runs was a 0.3 cm thick aluminum plate backed by a water jacket. Aluminum was chosen because its relatively high specific heat capacity and thermal conductivity more than offset its low melting point in determining maximum allowable beam loading.

Results

Data are presented from three runs of more than 10,000 consecutive shots each. Consecutive is understood to mean without major diode repairs or modifications. All of the runs were suspended at intervals to inspect the diode or perform other tests as detailed below.

Figure 2a shows data from a 17,000 shot run at 500 kV on the RTF-I PFL. A 3.5 cm diameter cathode with cross hatching to provide some field enhancement was found to produce a reasonably uniform beam. Figure 3

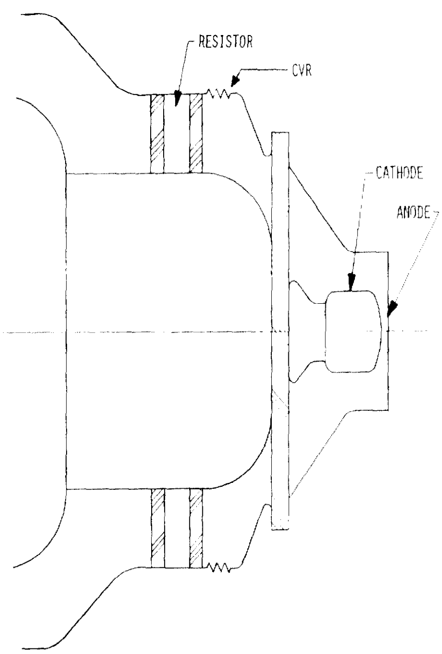

Fig. 1. Diagram of the RTF-I diode.

shows this type of cathode. Although it does not produce the perfectly uniform cylindrical beam which is the basis for the space charge limited flow equation 1, the overall impedance follows that equation well as illustrated by the horizontal dashed line on the experimental waveform in Fig. 2a. After the diode turn on phase (the falling impedance region) the diode impedance curve flattens out near the theoretical value. This impedance waveform was calculated from the current and voltage waveforms of Fig. 2b. These were taken at a repetition rate of 20 Hz, each trace being a composite of approximately 10 shots. The shot-to-shot stability of RTF-I and its diode is apparent. In addition, since the two sets of traces were taken approximately 5000 shots apart, their similarity indicates a long term stability.

During this 17,000 shot run 4000 events were taken at a rate of 10 Hz or less, 5000 at 20 Hz, and 8000 at 30 Hz. The run was terminated by multiple arcs across the diode vacuum interface on the oil side, probably as the result of air bubbles. The interface ruptured destroying diode vacuum. At this point the anode was still intact although considerable mass had been removed. Most was deposited on the cathode immediately opposite the damage site, but a fine aluminum powder was deposited throughout the vacuum diode. These deposits did not adversely effect the diode performance to an observable degree.

To further examine the effect of this debris another run with equivalent electrical parameters was performed. During this run a computer based waveform analysis system was introduced which monitored the current and voltage at 4 ns time intervals and computed the impedance for all shots, thus allowing charges in operating parameters to be carefully followed. This run lasted 20,000 shots at a repetition rate of 10 Hz. Failure followed a puncture of the anode, which is shown in Fig. 3. Arcing in the region of the puncture is responsible for the majority of the damage seen; however, there is a lattice of damage spots on the

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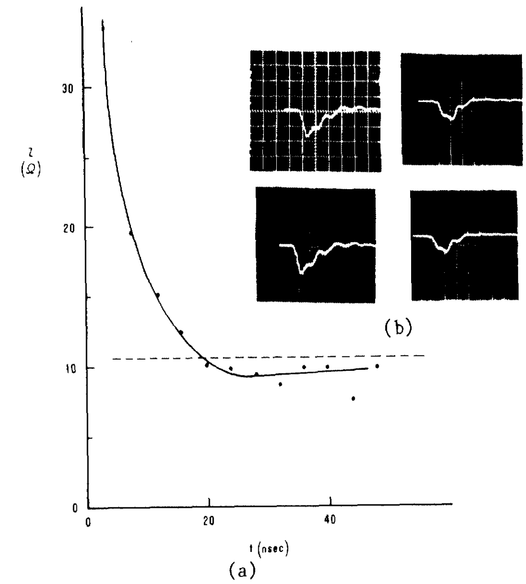

Fig. 2. a. Impedance waveform 17,000 shot run.
b. Voltage (left, 160 kV/div.) and current (right, 8 kA/div.), 20 ns/div.

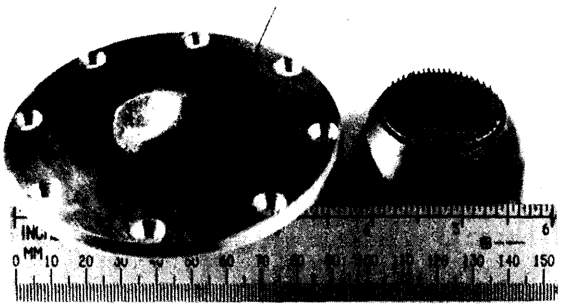

Fig. 3. Anode (left) and cathode (right) 20,000 shot run.

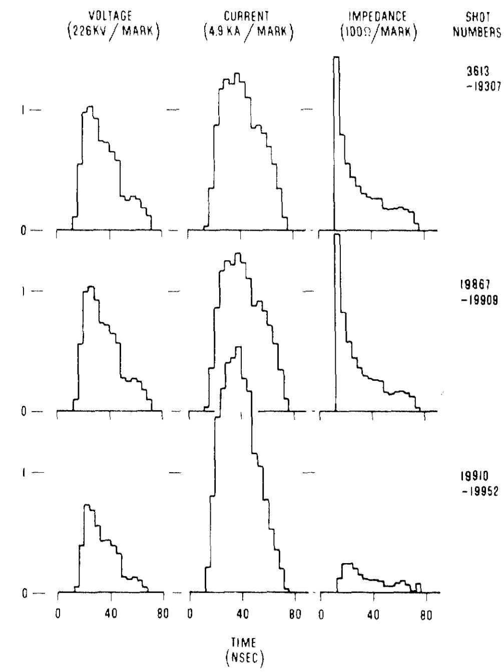

Fig. 4. Computer waveforms from 20,000 shot run.

anode opposite the heavily damaged region. These were observed to have occurred halfway through the run. This lattice mirrors the cathode cross hatching and indicates the formation of beamlets at the corners of the cathode structure. These beamlets do not diverge significantly in crossing the A-K gap as the damage spots are small compared to that spacing. The outer beamlets are bent inward by the self-magnetic field of the total electron beam and penetrate into the anode at their angle of incidence which is approximately 35° to the normal. This is illustrated by the needle mounted in one of the beamlet holes in Fig. 3. These beamlets result in a nonuniform loading of the anode which explains its rapid destruction. Nevertheless, as the anode material is being deposited throughout the diode, the operating characteristics are remaining relatively unchanged. A series of data points stretching over the entire run are shown in Fig. 4. Note that voltage, current, and impedance remain stable until virtually the end of the run at which point the diode shorts. The first triplet of waveforms show the voltage, current, and impedance for most of the run. The middle set shows the last 43 stable events. The 43 events of the lowest 3 traces indicate a nearly short circuit condition. The run was stopped manually 3 shots later, the final 3 shots being completely short circuited. Clearly the diode remains stable prior to its catastrophic failure. Because the lowest three waveforms are an average over 43 events, it is possible that the waveforms remain stable until the anode ruptures destroying the vacuum and that these waveforms deviate from the norm because they average good shots with short circuit events.

For studies of stability over a longer term, it was necessary to produce a more uniform and diffuse beam. The larger (2.5 cm diameter) cathode with rings (to avoid the corners that form beamlets) pictured in Fig. 5 was used with an A-K spacing of 0.4 cm. In this geometry a data sample of 157,000 shots was taken at 450 kV on the PFL. The sample contains 20,000 shots at 10 Hz, 87,000 at 20 Hz, and 50,000 at 33.3 Hz.

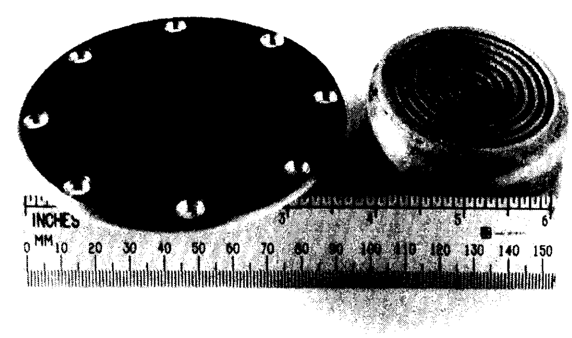

Fig. 5. Anode (left) and cathode for 157,000 shot run.

Anode damage, also illustrated in Fig. 5, was found to be insignificant at rates below 30 Hz. After 50,000 shots at 33.3 Hz there was just sufficient damage to replicate the cathode pattern on the anode.

That diode parameters do change during the course of so long a run is illustrated in Fig. 6. Voltage, current, and impedance waveforms are presented which are averaged over the number of shots given in the figure. These are online data, consequently, it is impossible to determine which shots were analysed. The number in parenthesis is the last shot of the analysed data. The upper and middle triplets of waveforms are separated by 15,700 shots, an interval similar to the total interval of Fig. 4. They illustrate the diode's stability over a run of this duration. The repetition rate in this case was 20 Hz.

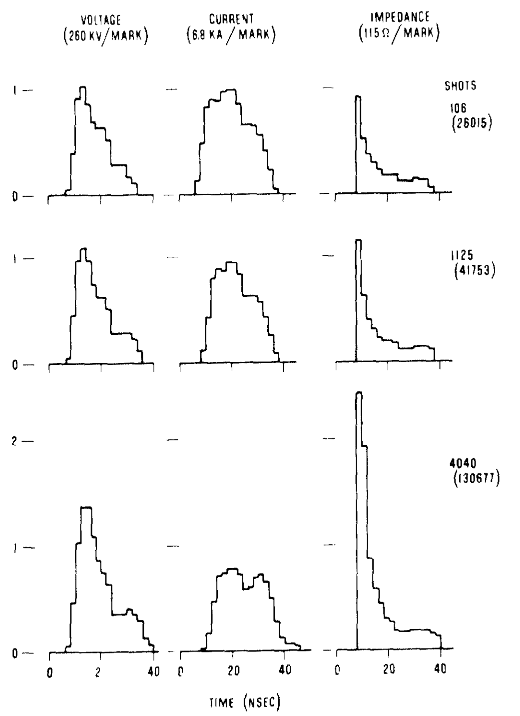

Fig. 6. Online waveforms from 157,000 shot run.

Going to the third triplet of waveforms 89,000 shots later, the initial voltage spike, during which the pulse from the RTF-I PFL reflects from a poorly emitting cathode, becomes larger, indicating that the cathode plasma is becoming increasingly harder to form. The flat portion of the voltage pulse disappears and a large current appears late in time. This current is due to the voltage reflected from the diode early in time which re-reflects from the transformer end of the RTF-I PFL and upon returning to the diode finds the emitting cathode plasma well formed. The impedance at the end of the pulse remains a constant 16 Ω. As the cathode ages, most of the PFL energy still goes to form beam but later in time than was the case before cathode aging.

The cathode may be returned to its original condition by a light surface coat of diffusion pump oil. Figure 7 shows two single shots following oiling of an aged cathode. Shot one is typical of an aged cathode whereas two is typical of a new cathode. Apparently for the first shot the oil acts to surppress emission. It is speculated that after the first shot the oil is carbonized which enhances cathode emission for the subsequent two shots. Coating the cathode with graphite improves its performance, but the coating ages rapidly. A graphite block cathode emits quite well, but its relatively high electrical and thermal resistivities lead to trouble in repetitively pulsed operation.

Conclusions

In conclusion, it has been shown that electron beam diodes can have opeating lifetimes of at least 150,000 shots and projected lifetimes in excess of 10^6 shots while operating in a 1000 A/cm^2 regime at 250 kV and 30 Hz. Diode RMS stability is no worse than 5 percent for short runs of 20,000 shots but operating parameters can vary over longer runs as the cathode slowly becomes a poorer emitter. Introduction of carbon on the cathode will return it to its original operating condition. Cathode changes result from a slow aging process and from accummulation of anode blow off. These two

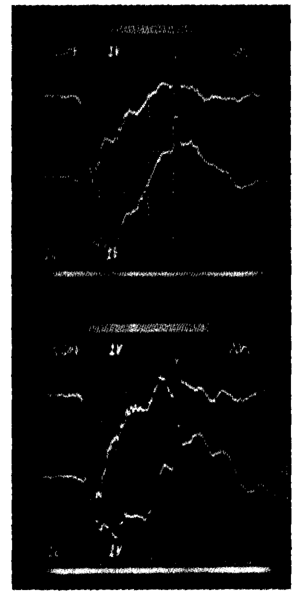

Fig. 7. Diode recovery after oiling, voltage (upper trace, 90 kV/div.) and current (3.8 kV/div.), 20 ns/div.

processes may be related. Provided blow off does not result in catastrophic damage, under the conditions of these experiments cathodes remain stable for tens of thousands of shots. It remains to be seen if these comments also apply to less roburst cathodes, such as the highly field enhanced foils used to generate low current density beams used to excite or sustain gas lasers.

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