Repetitively Pulsed Electron Beam Diode Lifetime and Stability*

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Abstract

Repetitively pulsed vacuum beam diodes will be required for most projected inertially confined fusion systems. Yet data on the operation of diodes under repetitive pulsing is sparse. This paper discusses the operation of a 250 kV, 1.5 kA/cm^2 diode at repetition rates to 30 Hz for sustained runs. Short term stability is typically 3 percent (standard deviation). Longer term there is a drift toward higher impedance at the start of the pulse. Details on this drift and a comparison of this process for a rather blunt versus a sharp edged cathode are presented.

Introduction

The development of repetititvely pulsed vacuum beam diodes is crucial to most inertial confinement fusion (ICF) concepts whether the driver be electrons, light ions, or lasers. Typical pulse repetition frequencies (PRF's) being discussed are 10 Hz or less based on factors like the speed at which a reactor can be recycled between shots and the PRF needed to produce a reasonable power output (perhaps 1 GW) given a reasonable pellet yield (100 MJ). The rate limitation is not in general based on pulsed power considerations. Instead it is assumed that pulsed power systems can be developed to provide repetitively pulsed drivers of suitable PRF.

This paper addresses the operation of vacuum beam diodes in repetitive service. Problems specific to individual ICF schemes, e.g. repetitive extraction of pinched beams for particle beam applications or anode extraction foil survival in the case of laser diodes are not considered. Instead the subject is the general stability both short and long term of diode in the absence of the transport of anode material to the cathode (blowback).

Experimental Details

Data were taken with the RTF-I 100 Hz high voltage pulser (transformer driven, oil insulated, 9.5 Ω, 700 kV PFL[1]) attached to the diode shown in Fig. 1. At the left side of the figure is one side of the self-breaking gas output spark gap of RTF-I. Oil insulation ends in a diaphragm type vacuum interface designed to operate at pulse forming line voltages in excess of 1 MV. The cathode diameter is limited to 5 cm or less so that the beam area is at most 20 cm^2. Typical operating voltages are 200 to 350 kV; thus to match the 9.5 Ω PFL the anode-to-cathode (A-K) spacing as calculated from the space charge limited flow equation

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

is in the order of 0.5 cm. (The diode voltage V is in megavolts. A and d are the beam area and A-K spacing.) The anodes used were 0.3 cm thick aluminum plates backed by a water jacket. Calculation and experiments indicate that the anode should be able to survive beam heating rates corresponding to at least 30 Hz.

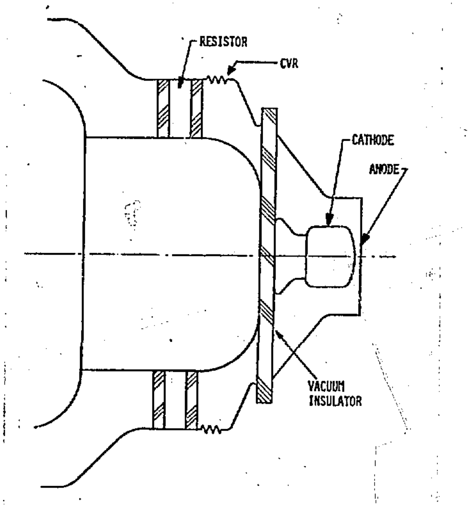

Fig. 1. Schematic of The RTF-I diode.

Diode voltage was measured with an integrated dV/dt monitor located at the output end of the high voltage gas spark gap. It reproduced the diode voltage waveform and could be consistently

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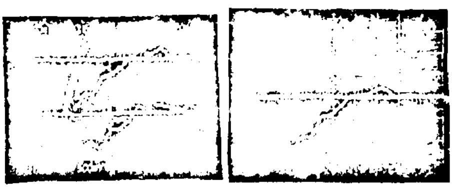
calibrated. However, in common with all integrated monitors it produced a low output voltage unsuited for input to the waveform digitizer to be discussed later. In contrast a resistive voltage monitor located in the annular water resistor shown in Fig. 1 reproduced the temporal shape of the diode voltage waveform but did not appear to maintain a consistent calibration. It was originally calibrated along with the dV/dt and a capacitive monitor measuring the PFL voltage using microsecond pulses at voltages up to 90 kV. All three monitors agreed on temporal shape and amplitude. For short (<50 ns) pulses the dV/dt was later found to read 50 percent higher than the annular resistor. Measuring the leading edge of an open circuit load shot, the dV/dt gave an output voltage equal to the PFL voltage but the annular resistor was 33 percent low. This implies that the dV/dt monitor is correct. Whenever resistive monitor waveforms are used their amplitude has been rescaled match the dV/dt monitor.

Figure 2a (upper trace) shows the annular resistor output for a typical event. It compares well with the dV/dt waveform of Fig. 2b. Diode current as measured by a 0.135 Ω low inductance resistive shunt (CVR) is shown in the lower trace of Fig. 2a. The diode has a definite "turn on" phase during which the emitting cathode plasma is forming. It is characterized by a voltage spike and a delay to significant current flow. After emission has begun the voltage drops to a plateau value which uniquely specifies the diode impedance (Z) through the relation

$$V_{PLATEAU} = \frac{Z}{Z + Z_o} V_{PFL} \qquad (2)$$

where Z_o and V_{PFL} are the PFL characteristic impedance and voltage respectively. Inductive corrections are insignificant at this point because dI/dt is small. If V_{PFL} is measured as the maximum diode voltage for an open circuit shot, Z may be computed from Z_o and the ratio $V_{PLATEAU}/V_{PFL}$ which is independent of the probe calibration. In practice the impedance thus measured was used together with the measured diode voltage to calibrate the current measurement.



(a) (b)

Fig. 2. Waveforms from a relatively new roll pin cathode.
a. Voltate (upper trace, 120 kV/div) current (lower trace, 15 kA/div) 20 ns/div.
b. V voltage (20 ns/div, 120 kV/div).

A second voltage plateau (and an associated second current plateau) occurs when the voltage reflected from the diode during the turn on phase returns from re-reflection at the transformer end of the PFL. For a new cathode, as in the lower photograph of Fig. 3, the two plateaus are well defined. As the cathode ages due to repetitive pulsing the turn on phase takes longer and the leading voltage spike widens and destroys the first plateau (upper photo). The second plateau becomes longer with the net effect that the total energy delivered to the load remains relatively constant (to about 10 percent). This is presumed to be a consequence of the fact that there is nowhere for the energy originally stored in the PFL to go on a nanosecond time scale except into the diode. Energy reflected from the diode early in time will ultimately return and be converted into beam.

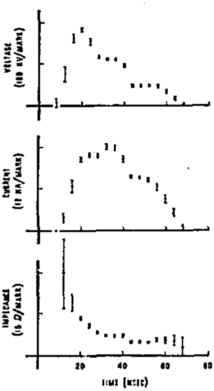
(a) (b)

Fig. 3. Waveforms for a ring cathode.
a. Aged cathode waveform (20 ns/cm, upper trace voltage at 120 kV/div, lower trace current at 15 kA/div).
b. New cathode, same scales as a.

To follow the aging process and to get a good measure of shot-to-shot stability requires the analysis of many events. Processing a sufficient number of photographs to properly diagnose a repetitively pulsed diode run is time consuming and the most interesting events, e.g. those immediately preceding diode failure, may be completely lost. Therefore, a waveform digitizer capable of recording voltage and current waveforms at PRF's in excess of 100 Hz was developed. Each waveform is split into 24 repetitive signals using high fidelity resistive splitters. These 24 waveforms are staggered in time by 4 ns using cable delays and a small (<4 ns) time slice of each is digitized using 24 fast sampling analog-to-digital converters (ADC's). Each waveform is sampled at the same real time thus because of the staggering of the waveforms the points actually sampled are separated by 4 ns from waveform to waveform. The first sample is taken 12 ns prior to the waveform; so the first three ADC's sample baseline. Thereafter up to 80 ns of waveform may be digitized. Because the ADC's sample only negative signals any positive afterpulse is lost. The raw data from each event is stored on magnetic tape for subsequent analysis. A fraction of the data are also analysed online to monitor the progress of the experiment. The ADC's require input signals of several volts amplitude (after a 24:1 division) thus forcing the use of the resistive monitor output for the voltage waveform.

Results

Figures 4 and 5 show digitizer outputs for a new cathode and for one aged by 10^5 shots. The PRF was 20 Hz. These data were taken with a cathode made of roll pins (0.16 cm diameter hollow cylinders) mounted on a brass backing (Fig. 6). The array produced a beam 5 cm in diameter. The pins have sufficient electric field enhancement at their tip to turn on quickly but also wear out rather rapidly. The pins on the outer perimeter of the cathode melted back as much as 0.2 cm during the 10^5 shots between the data in Figs. 4 and 5. Erosion of the inner pins was less severe. The figures show the readjustment of the voltage and current waveforms during aging as previously discussed. Notice that the impedance late in time (beyond 40 ns) is virtually unchanged during the aging process. This late in time plasma has formed on the cathode and, since the driving voltage is unchanged, the impedance should be the same.



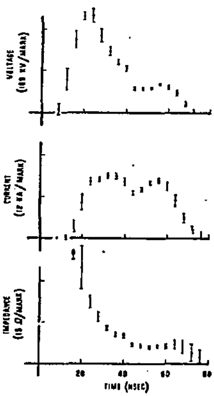


Fig. 4. Digitizer output waveforms for an a new cathode (left).

Fig. 5. Digitizer output waveforms for an aged cathode (right).

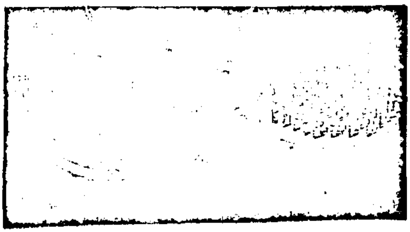


Fig. 6. Used roll pin cathode together with anode showing beam damage.

Figure 3 illustrates the aging process in another type of cathode, one without the large field enhancements present at the tips of the roll pins. This cathode emits from the edges of concentric rings cut into a brass block (Fig. 7). The waveforms are rather similar and the aging is qualitatively the same. Quantitatively the roll pin cathode ages somewhat more rapidly. If the impedance at the peak of the voltage waveform (normalized to the value at the outset) is plotted versus accummulated shots (Fig. 8), the roll pin impedance increases much more rapidly beyond 25,000 shots than the ring cathode impedance does. The roll pin impedance doubles in 50,000 shots but the ring cathode impedance requires almost twice as many.

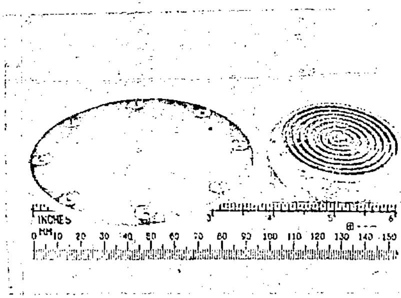


Fig. 7. Used ring cathode with anode showing beam damage.

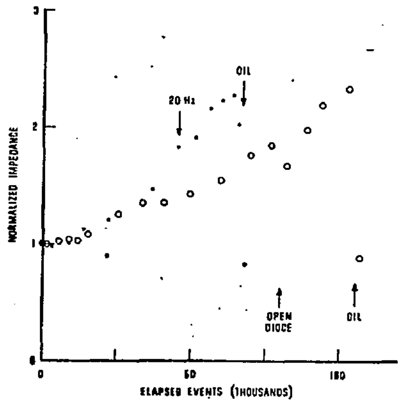


Fig. 8. Change in the diode impedance at voltage maximum vs. accummulated shots. The dots and downward pointing arrow refer to the roll pin cathode. Circles and upward arrows correspond to the ring cathode.

This plot also illustrates several other points about cathode aging. It is not strongly rate dependent. The roll pin data to 45,000 shots were taken at 10 Hz. After a change to 20 Hz the data continued along the same line. The aging process can be reversed by a light application of diffusion pump oil to the cathode surface as indicated for both cathode types. The ring cathode photographs of Fig. 3 show voltage and current for a single shot immediately after oiling an aged cathode (upper) and for the second shot after oiling (lower). The first shot is equivalent to an aged cathode event, the second to a fresh cathode. In fact, as illustrated in Fig. 8 after oiling the cathode becomes a better emitter than it was at the start of the run.

As regards shot-to-shot stability, Fig. 4 and 5 demonstrate that it is quite good. The "error bars" on those waveforms mark one standard deviation variances about the mean values. They are in general at the level of 3 percent, during the flat portion of the pulse and somewhat larger on the rising and falling edges. The voltage is slightly more stable than the current. Measurements of very stable calibration pulses have standard deviations below 1 percent even on the leading and trailing edges. Thus the jitter due to the digitizer is negligible (it adds quadrature with the diode jitter to produce the observed result). The data show that diode stability does not change as the cathode ages. There is apparently some variation in the rate at which cathode plasma is produced which creates the variability of the leading edge. This is reflected in a change in the overall pulse length reflected in the trailing edge jitter. This may account for the variations through the center of the pulse as well.

Runs on the roll pin and ring cathodes lasted 100,000 and 157,000 shots respectively. The roll pin data were distributed approximately equally between 10 and 20 Hz. The ring cathode data were at 20 and 30 Hz. Anode damage with the roll pins was worse at 20 Hz than was the damage from the ring cathode at 30 Hz, but in neither case was the run stopped by diode failure. The data of Fig. 8 clearly indicate the need to continue runs to the point where the aging terminates or becomes catastrophic. Such data will be taken in the near future.

Conclusions

Vacuum beam diodes have been shown to operate stably for at least 10^5 shots at current densities of 1 to ? kA/cm^2. Shot-to-shot stability of 3 percent implies power and impedance stability of 4 percent, which in turn implies a stability for the total efficiency of conversion of PFL energy to beam energy of the same level. Long term, the diode impedance early in time drifts upward resulting in more beam being delivered in the form of afterpulse. Depending upon the application this may or may not pose a problem. For example in this configuration an old cathode produces a rather square current pulse of decreasing voltage which could be useful for some purposes.

As to the origin of the aging, two mechanisms immediately suggest themselves. It could result from the destruction of cathode whiskers whose explosion is thought to produce the cathode plasma. This would be a process equivalent to the breaking in of DC vacuum insulators. In that case the DC voltage is raised slowly while the insulator is separated from the power source by a high impedance. Very low current discharges occur which do not damage the electrodes but do remove the major whiskers so that the hold off voltage increases with each discharge. In this way the hold off voltage is slowly brought to the desired value. In the present case the discharged current is not constrained to be small and electrode damage does occur. Nevertheless over tens of thousands of shots whisker removal may occur.

Aging could also result from the destruction or "covering over" of whiskers by anode blowback. To distinquish these two possibilities there are several options. One can look for whiskers before and after aging in an attempt to detect any net gain or loss. This may be a difficult task to perform. One may attempt to change the blowback to change the aging as for example by changing anode material or beam current density. To the extent that blowback is increased with increasing repetition rate Fig. 8 argues against its being the cause of aging because the aging process was not rate independent. Finally an examination of the extent to which blowback debris covers the emitting areas of the cathode could determine whether blowback can eliminate a significant fraction of the cathode whiskers. All the above options are currently being explored.

If the aging problem results from anode blowback it could be significant to pinched beam diode operation in where blowback may be severe even with a nominal plasma anode. The present experiments are so remote from such a diode that no conclusions should be drawn. However, if the aging is a result of whisker loss, sharp edged emitters (with relatively fewer emission sites) should age faster than blunt cathodes. Thus sharp edged emitters such as the foils used in laser diodes may change their emission characteristics quite rapidly in long term service and may require either a breaking in period or periodic maintenance.

References

1. M. T. Buttram and G. J. Rohwein, "Operation of a 300 kV, 100 Hz, 30 KW Average Power Pulser", Proc. of the 13th Pulse Power Modulator Symposium, Buffalo, NY (1978).