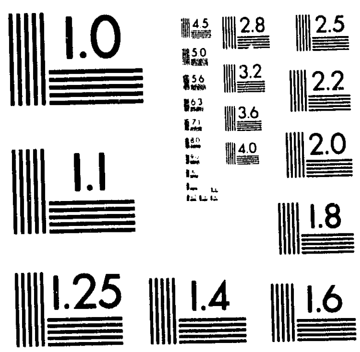
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REPETITIVE, ELECTRON-BEAM DIODE DEVELOPMENT*

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Abstract

We constructed a stacked-Blumlein pulse generator that can deliver pulses of nearly 200 kV to an electron beam diode load. This pulse generator has an output impedance of 100 Ω and a pulse width of 80 ns. It can operate continuously at pulse repetition rates as high as 500 Hz.

We discharged the pulse generator into two diodes. One had a 2.9 cm diameter sintered bronze cathode, and the other had a 4.0 cm diameter graphite cathode with points machined into it. The sintered bronze cathode turned on completely with a peak, macroscopic field of 100 kV/cm. The graphite cathode required a peak, macroscopic field of 150 kV/cm in order to operate reproducibly. Nevertheless, only about 10% of the area of the graphite cathode emitted.

The bronze cathode operated at 30 Hz, and it exhibited heat damage. Specifically, it melted in places. Conversely, the graphite cathode, operated at 50 Hz, exhibited little damage: principally, minor erosion around the perimeter.

Introduction

The Repetitive, High-Energy, Pulsed-Power (RHEPP) project[1] has the goal of producing a high-average power, short pulse accelerator, based on pulsed-power technology. The planned accelerator will operate at a pulse repetition rate of 120 Hz and an average output power in excess of 400 kW. Each individual pulse will have a width of 70 ns and peak output voltage and current of 2.5 MV and 25 kA, respectively.

Using this generator to power an electron beam diode has a number of potential applications: infectious waste sterilization, waste water treatment, food disinfestation, smoke stack gas treatment, and hazardous waste transmutation. Nevertheless, in order for such an accelerator to be commercially viable, it must have a long mean life between failures. We believe that the accelerator should be able to run for at least 10^8 shots before requiring any major maintenance.

The RHEPP project is divided into several subprojects. This paper reports on the effort to develop a long-lived diode for the RHEPP accelerator. The primary thrust so far has been toward finding an explosive emission cathode that will run repetitively for 10^8 shots. The diode subproject consists of two parts: (1) a 100 Ω output pulse generator designed to deliver 250 kV pulses with a FWHM of 80 ns to a diode load and operate at repetition rates as high as 500 Hz and (2) a vacuum chamber and electron-beam diode assembly.

Pulse Generator

The pulse generator consists of four Blumlein transmission lines charged in parallel and discharged in series. Our pulse generator is similar to one built by Davenloo *et al*[2], except that ours uses coaxial cables, and theirs uses strip lines. Figure 1 schematically depicts the pulse generator. Each Blumlein consists of two bundles of four, 25 ft long pieces of RG-218/U cable. The four cables in each bundle are connected together at each end. Therefore, each bundle has an effective impedance of 12.5 Ω and a length of 38 ns. Since each cable bundle has a low impedance, the pulse generator as a whole has a comparatively low output impedance of 100 Ω.

A 50 kW D. C. power supply charges a 5 μF, primary energy storage capacitor. A command charge switch (a large number of silicon controlled rectifiers (SCR's) in series) connects the primary storage capacitor to the pulse generator through a large inductance. The primary storage capacitance is much larger than the pulse generator capacitance; therefore, the charged cables in the pulse generator ring up to twice the primary voltage, and the primary capacitor maintains a nearly constant charge voltage.

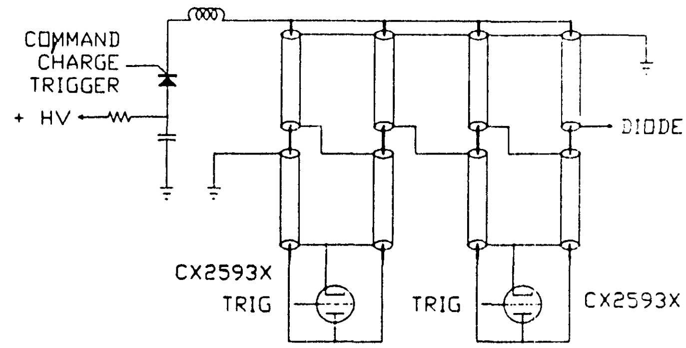

Figure 1. Schematic drawing of the pulse generator.

Two thyratrons, triggered simultaneously, comprise the primary switches for the pulse generator. Each thyratron switches two of the Blumleins, in parallel, and launches waves down the transmission lines. When the waves meet at the center of the pulse generator, the voltages add. Therefore, the pulse generator produces an output voltage of several times its charge voltage.

The pulse generator can operate at pulse repetition rates as high as 500 Hz. Furthermore, it can operate at that frequency continuously for extended times. To date, the shot rate limit has been set by the diode and not the pulse generator. The only time the pulse generator has not been able to run indefinitely at 500 Hz has been when one or more of its components were malfunctioning.

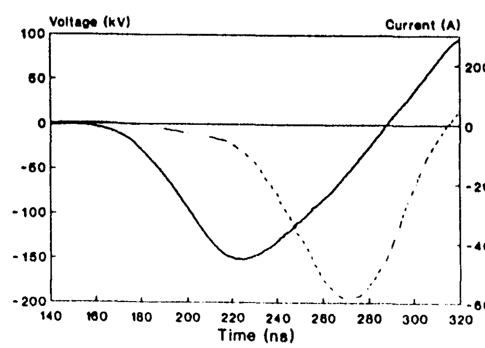

Figure 2. Output voltage from the pulse generator (solid line) and diode current (dashed line).

Figure 2 depicts the output voltage of the pulse generator and the diode current. These data represent an average over about 100 shots. The diode represented by these data had an impedance of about 200 Ω: double the 100 Ω output impedance of the pulse generator. The pulse generator has produced peak output voltages as high as 200 kV.

Diode

Figure 3 depicts a cross sectional view of the vacuum chamber and diode. The chamber has a diameter of 76 cm and a length of 61 cm. Two cryogenic helium, vacuum pumps connect to the side of the chamber through separate gate valves. These pumps operate completely

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independently, and the entire vacuum system is operated remotely from outside the experimental cell.

The chamber has two Rogowski coils: one located in the base plate, and one located in the face plate. The coil located in the base plate detects charge flowing downstream in the chamber, and the coil in the face plate detects charge reaching the anode. A comparison of the signals from the two Rogowski coils indicates how much charge fails to reach the anode. We have found that nearly all the charge entering the chamber reaches the anode. Moreover, all the charge reaching the anode appears to originate from the cathode face.

A $\dot{V}$ probe, located in the oil tank and connected between the output of the pulse generator and the tank wall, measures the dV/dt at the pulse generator output. We numerically integrate the output from the $\dot{V}$ probe and apply a voltage correction[3] to calculate the voltage at the diode.

The chamber base plate has a 38 cm diameter hole for the cathode shank. An insulator stack extends from the back of the base plate into the oil tank. The stack consists of five 2.5 cm thick acrylic plastic insulating rings and four steel grading rings. The grading rings have a much smaller inner diameter than the insulating rings. This helps to prevent diode debris from settling on the insulators. Moreover, the large grading ring area provides more uniform field grading across the insulator stack. Electrostatic field calculations[4] indicate that with an applied voltage of 250 kV, the highest field at any point on the insulators is 40 kV/cm. This conservative design should be reliable, even after a very large number of shots.

The cathode shank, attached to the back of the insulator stack, extends nearly to the anode. It supports the cathode near the anode.

The anode consists of a .076 cm thick tantalum plate. The tantalum plate also forms the anode vacuum window. We cool the anode by flowing water directly on it. We inject the water into the center of a volume on the outside of the tantalum plate and remove it at the perimeter of the tantalum disk, and water flows from the center of the anode disk to the outside. This ensures the best cooling possible with a water flow.

The anode and cooling assembly are mounted on a plate that is attached to the chamber face plate through a steel bellows. The anode mounting plate rides on three threaded rods. Therefore, the anode mounting plate can be moved in or out by adjusting nuts on the threaded rods. Consequently, the anode-cathode (A-K) gap can be adjusted while the chamber remains under vacuum.

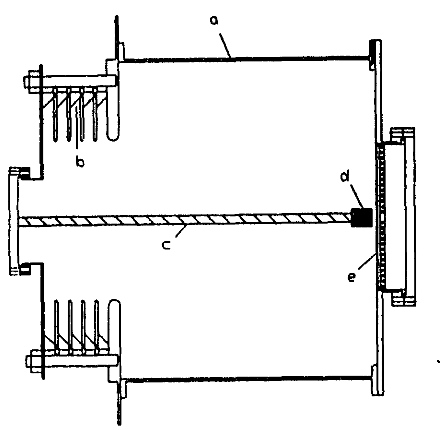

Figure 3. Cross sectional view of the experimental hardware: (a) Vacuum chamber, (b) Insulator stack, (c) Cathode shank, (d) Cathode, and (e) Anode.

In this paper we report on two types of cathode. The first is a solid cathode made of sintered bronze. The sintered bronze consists of a mixture of copper (87.5% to 90.5%), tin (9.5% to 10.5%), carbon (1.75% max), and iron (1% max). This type of sintered bronze has interconnected pores and a grain size on the order of a few microns. It has a density of 6.6 g/cm^2. The bronze slugs were machined into cylindrical cathodes having a diameter of 2.9 cm and a thickness of 1.3 cm. The machinist used only distilled water as a lubricant while machining the cathodes. He used no hydrocarbon fluids, such as cutting oil.

The second type of cathode is "sculptured" graphite. They are made of ATJ graphite and have a diameter of 4.0 cm and thickness of 3.6 cm. The sculpturing refers to a cross-hatch pattern machined into the face of the cathode. This pattern consists of a square array of 1.0 mm square points separated by 1.0 mm deep valleys.

Experimental Results

Figure 4 depicts the diode impedance at peak power for one of the sintered bronze cathodes. We set the initial A-K gap to 1.0 cm. Then we fired the pulse generator nonstop into the diode at a shot repetition rate of 30 Hz until we had accumulated 100,000 shots. At higher shot rates, the bronze cathodes melted.

The cathode ran reliably for the entire 100,000 shots. It maintained a relatively constant impedance and good shot-to-shot reproducibility. Nevertheless, it operated with a low impedance (~50 Ω), and it loaded the pulse generator. Consequently, the diode voltage was low (~100 kV peak). We found that if we increased the A-K gap to 1.2 cm, the cathode would not turn on well, and the shot-to-shot reproducibility became very poor.

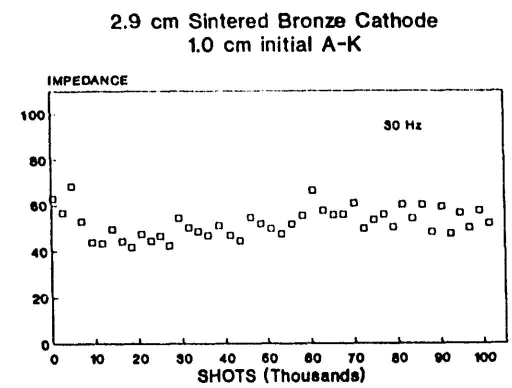

Figure 4. Diode impedance for a sintered bronze cathode calculated at peak diode power.

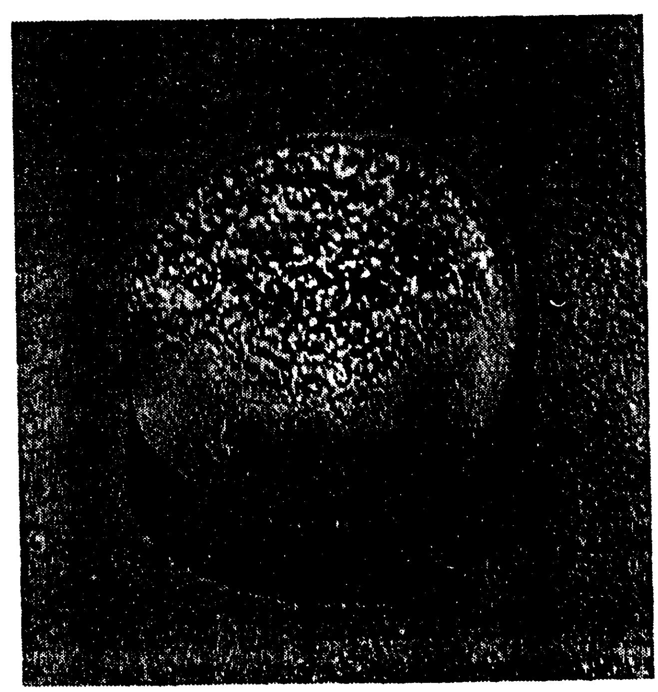

Figure 5. Photograph of a sintered bronze cathode after 100,000 shots.

Figure 5 is a photograph of the cathode after 100,000 shots. Even running at 30 Hz, the cathode suffered heat damage. Portions of the cathode melted and formed peaks and valleys.

Figure 6 depicts the impedance of the diode with a graphite cathode at peak power. Before we began the run, we set the A-K gap at 1.2 cm. After 200,000 shots we decreased the A-K gap to 1.0 cm. When we took these data, the pulse generator was not operating properly, and it limited the shot rate to 50 Hz.

With a 1.2 cm A-K gap, the diode exhibited poor shot-to-shot reproducibility. When we closed the gap to 1.0 cm, the diode operated reasonably reproducibly, but the impedance was rather high (~200 Ω). The peak output voltage at the diode was 150 kV.

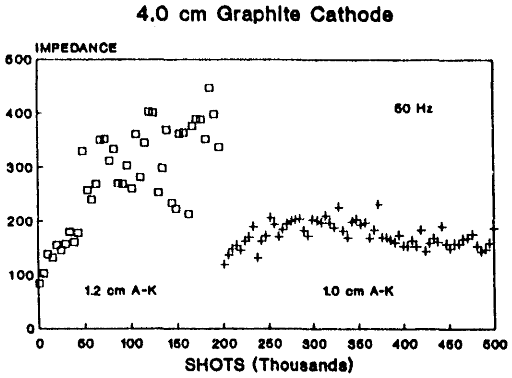

Figure 6. Diode impedance for a sculptured graphite cathode, calculated at peak diode power. Squares: 1.2 cm A-K gap. Plus signs: 1.0 cm A-K gap.

Figure 7 is a photograph of the graphite cathode after 500,000 shots. The graphite cathode sustained very little damage. It is somewhat eroded on the circumference, and it is slightly dished out in the center. Otherwise, it suffered no noticeable damage. Nevertheless, what will happen when the points are completely eroded away? Will new points evolve on the surface? These are questions to explore in future work.

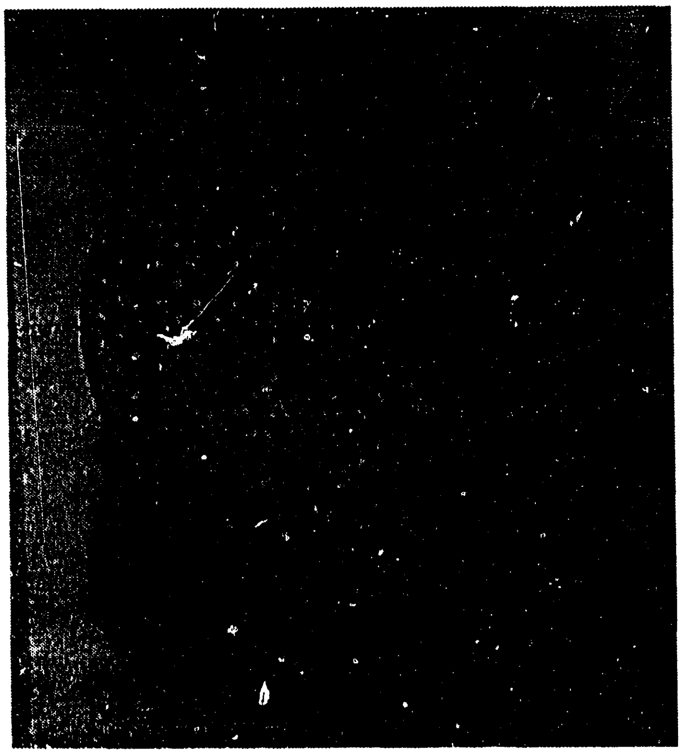

Figure 7. Photograph of a graphite cathode after 500,000 shots.

EGUN Simulations

We used the electron optics code EGUN[5] to simulate the diode experiments. Figure 8 depicts the results of one simulation: a 2.9 cm diameter cathode, a 0.6 cm A-K gap and voltage of 80 kV. For this simulation, we assumed a gap closure of 0.4 cm. This is consistent with a closure velocity of 5 cm/μs, which is typical for these experiments.

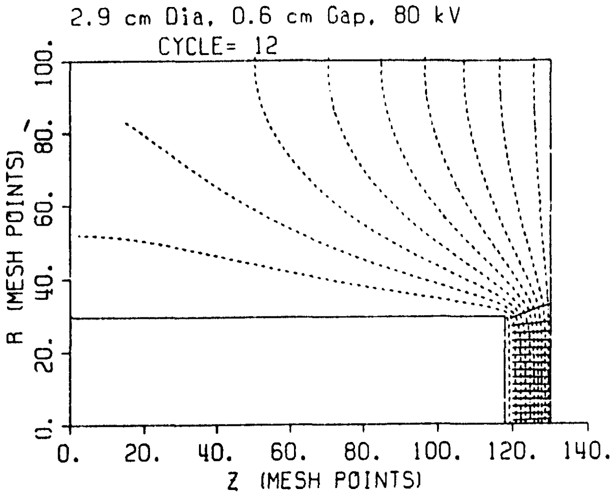

Figure 8. EGUN simulation of the electron trajectories for a diode with a 2.9 cm diameter cathode, a 0.6 cm anode-cathode gap, and 80 kV. The dashed lines represent equipotential surfaces. The mesh units correspond to 0.05 cm.

The simulations of the 2.9 cm bronze cathodes agreed well with the experiments; nevertheless, the simulations of the 4.0 cm graphite cathodes predicted far more current than we measured experimentally. We conclude that the bronze cathode turned on completely, while the graphite cathode turned on only partially.

Conclusions

The pulse generator operates with a peak voltage between 150 and 200 kV. We have made steady improvements, and we anticipate increasing that to 250 kV. It has a 100 Ω characteristic output impedance and an output pulse width of 80 ns. It will run continuously at pulse repetition rates as high as 500 Hz.

Sintered bronze cathodes turn on completely at peak macroscopic fields of 100 kv/cm. Nevertheless, they melt easily, and that limits the shot rate.

Sculptured graphite cathodes turn on incompletely at peak macroscopic fields of 150 kV/cm. A comparison of the data and the EGUN simulations indicate that about 10% of the cathode face emitted. Nevertheless, the graphite cathodes suffer little wear, and they can operate at significantly higher shot rates than the bronze.

Future Work

We are investigating larger diameter cathodes, both sintered bronze and sculptured graphite. Our immediate goal is to operate for extended times at shot rates of at lease 120 Hz and peak current densities on the anode of less than 25 A/cm^2. As we improve the output of the pulse generator, we will increase the A-K gap.

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4. J. O. Dritt, private communication.

5. W. B. Herrmannsfeldt, EGUN-An Electron Optics and Gun Design Program, SLAC-Report-331, (Stanford, CA: Stanford Linear Accelerator Center, 1988).

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