

PLASMA-FILLED ROD-PINCH DIODE EXPERIMENT ON GAMBLE II*

B.V. Weber, G. Cooperstein, D.D. Hinshelwood, D. Mosher, J.W. Schumer, S.J. Stephanakis, S.B. Swanekamp,** and F.C. Young**

Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375

Abstract

A plasma-filled rod-pinch diode, fielded on the NRL Gamble II generator, may represent a breakthrough in concentrating electron-beam energy into a small volume. Injected plasma connects the grounded cathode to the concentric tungsten rod anode. After a short-circuit phase lasting 10-30 ns, the impedance increases and a large fraction of the electron-beam energy is deposited on the tip of the rod, producing a small, intense x-ray source. As the injected plasma density increases, the current and voltage (at the time of maximum radiation) range from 260 kA and 1.8 MV to 770 kA and 0.45 MV. These parameters imply effective anode-cathode gaps of 130 to 7 μm , far smaller than can be achieved with metal electrodes without premature shorting. The physics of the plasma-filled rod-pinch diode differs from its vacuum analog [1, 2, 3]. Current can be convected to the rod tip by plasma translation instead of electron-beam propagation. When plasma is pushed beyond the tip of the rod, a gap can form there by erosion. The high current and voltage, combined with the small anode diameter, may produce record electron-beam power densities ($75 \text{ TW}/\text{cm}^2$) and high-energy-density plasma conditions at the rod tip. Potential applications include improved radiography sources, x-ray/matter interaction studies, and high-energy-density plasma generation.

I. EXPERIMENT

The setup of the plasma-filled rod-pinch diode experiment on the Gamble II generator is shown in Fig. 1. The positive-voltage center conductor is terminated with a small-diameter rod that extends through and beyond two grounded cathode plates. The cathode plates are planar, with circular holes concentric with the rod. Plasma is injected between the plates into the anode-cathode gap from six cable guns, arranged azimuthally around the axis and positioned 5 cm (or 2.5 cm on some shots) from the axis. The time delay between firing the plasma guns and Gamble II determines the initial plasma density and its distribution.

Several parameters were varied during the initial 16-shot experiment. The rod was usually tungsten, either 1- or 0.5-mm diam and extended 1.6 or 5 cm beyond the cathode plane. On one shot, a 0.5-mm diam carbon rod

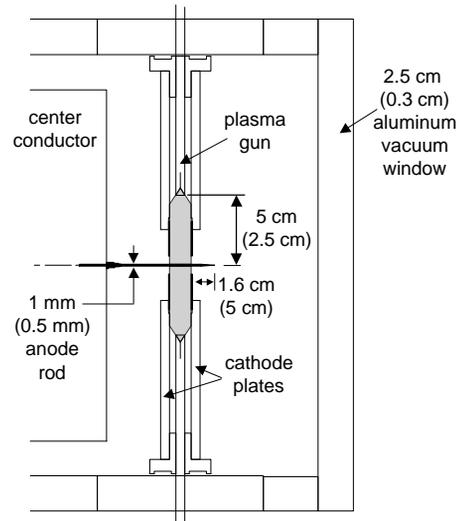


Figure 1. Setup of the plasma-filled rod-pinch diode on Gamble II. Plasma is indicated by the cross-hatched region.

was used to test the operation with a range-thin anode, and on one shot, a 1-mm diam brass rod extended through the cathode with a 0.25-mm diam tungsten wire extending 2.5 cm from the brass.

An x-ray pinhole photograph for a typical shot is compared with the electrode configuration in Fig. 2. X-ray emission is concentrated at the tip of the tapered 1-mm diam tungsten rod. Emission from the rod in the plasma-injection region is negligible. The bright white region is pinhole-limited in the radial dimension and

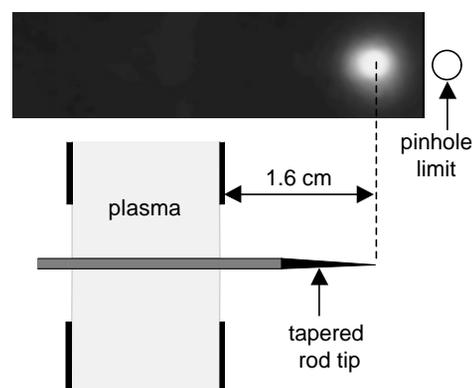


Figure 2. Time integrated x-ray image (above) compared with electrode setup (below) for shot 7802. The projection of a point source through the pinhole creates a 3-mm diam circle ("pinhole limit").

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** Jaycor, Mclean, VA

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14. ABSTRACT

A plasma-filled rod-pinch diode, fielded on the NRL Gamble II generator, may represent a breakthrough in concentrating electron-beam energy into a small volume. Injected plasma connects the grounded cathode to the concentric tungsten rod anode. After a short-circuit phase lasting 10-30 ns, the impedance increases and a large fraction of the electron-beam energy is deposited on the tip of the rod, producing a small, intense x-ray source. As the injected plasma density increases, the current and voltage (at the time of maximum radiation) range from 260 kA and 1.8 MV to 770 kA and 0.45 MV. These parameters imply effective anode-cathode gaps of 130 to 7 mm, far smaller than can be achieved with metal electrodes without premature shorting. The physics of the plasma-filled rod-pinch diode differs from its vacuum analog[1, 2, 3]. Current can be convected to the rod tip by plasma translation instead of electron-beam propagation. When plasma is pushed beyond the tip of the rod, a gap can form there by erosion. The high current and voltage, combined with the small anode diameter, may produce record electron-beam power densities (75 TW/cm²) and high-energy-density plasma conditions at the rod tip. Potential applications include improved radiography sources, x-ray/matter interaction studies, and high-energy-density plasma generation.

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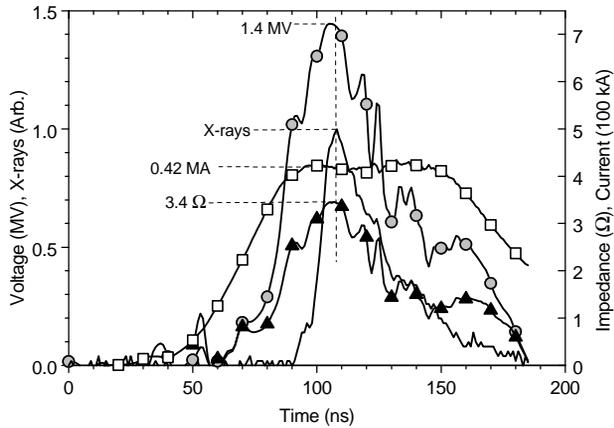


Figure 3. Electrical and x-ray waveforms for shot 7802: voltage (circles), current (squares), impedance (triangles) and x-rays (no symbol). Values of the parameters at the time of maximum x-ray signal are indicated.

slightly larger in the axial dimension. This x-ray image has shorter axial extent than a vacuum rod-pinch diode.[3]

Electrical operation of the diode for shot 7802 is shown in Fig. 3. The current starts before the voltage, indicating that the plasma is initially a short circuit. The impedance increases to 3.4Ω at peak x-ray emission. At this time, the voltage is 1.4 MV and the current is 0.42 MA.

The impedance of the plasma-filled rod-pinch at peak radiation is determined primarily by the injected plasma density, which increases with the plasma delay time. The current, voltage and impedance at peak radiation are plotted versus delay time in Fig. 4. As the delay increases from 0.9 to $3.6 \mu\text{s}$, the current increases from 0.26 to 0.77 MA, the voltage decreases from 2.0 to 0.4 MV and the impedance decreases from 6.9 to 0.5Ω . The total energy coupled to the load is $33 \pm 3 \text{ kJ}$ and is nearly independent of time delay and impedance. The electrical characteristics do not depend strongly on the rod diameter, rod extension, or rod material for this range of parameters.

The plasma-filled rod-pinch can couple efficiently to the 2- Ω Gamble II generator. In contrast, the vacuum rod-pinch on Gamble II operates in a 20-50 Ω impedance range, requiring parallel dummy loads to shunt most of the generator current.[4]

Thermoluminescent dosimeters fielded on axis close to the rod tip measure the dose. For shot 7802, the total dose from the rod tip scaled to 1 m is 9 rad(Si) through a 2.5-cm-thick aluminum vacuum window. This dose is about five times larger than that for vacuum rod-pinch shots on Gamble II with the same peak voltage, pulse duration and configuration, but with ten times smaller current. This implies a factor-of-two decrease in efficiency (dose/charge) for the plasma-filled diode, probably related to increased current losses to ions and electrons that are not deposited in the rod tip. The x-ray dose is relatively independent of rod diameter, but is about two times greater for 1.6-cm extensions than for 5-cm extensions, based on the limited statistics available.

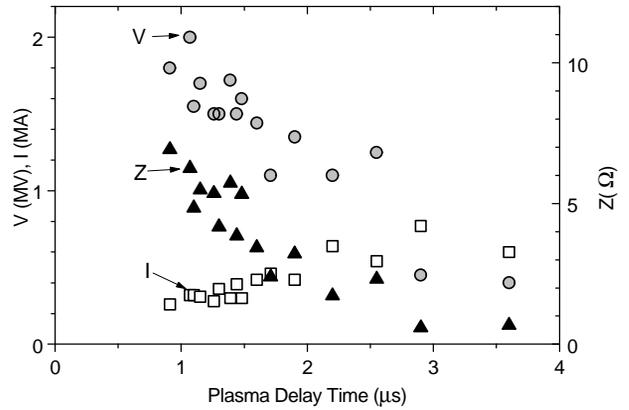


Figure 4. Current (squares), voltage (circles) and impedance (triangles) at the time of maximum x-ray signal as a function of plasma delay time.

The x-ray data in Fig. 5 are from a shot with a 0.5-mm diameter tungsten rod extending 5 cm beyond the cathode. Two time-integrated x-ray images are above the sketch of the electrode configuration. The intensified image shows strong emission from the tip (with exaggerated spatial extent due to blooming) and weaker emission from the aluminum holder. The un-intensified image shows that the emission from the tip is pinhole-limited in the radial dimension and slightly larger in the axial dimension. A set of four PIN diodes collimated to record x-rays from 2-cm long sections along the rod, measure time-dependent x-ray emission. The signals indicate little radiation from the plasma-injection region (PIN3) or just downstream of this region (PIN2). The signal from the tip (PIN1) is largest, but radiation from the holder (PIN4) is a significant fraction of the total radiation. On some shots,

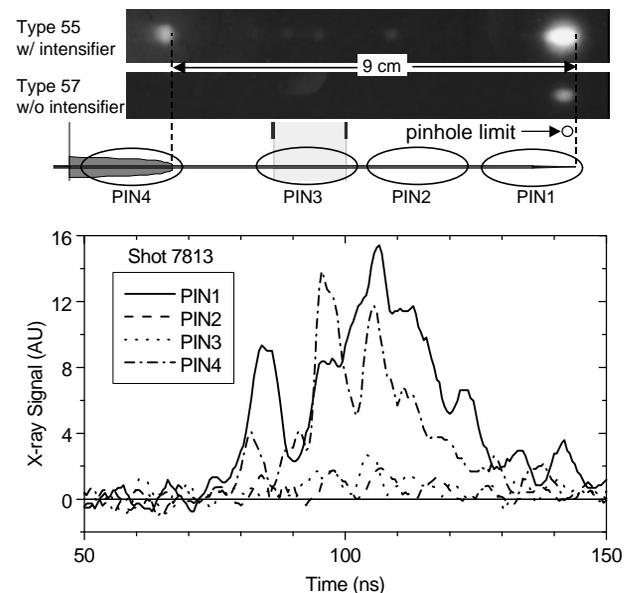


Figure 5. Side-on x-ray pinhole camera images, electrode configuration, and PIN diode signals for shot 7813.

radiation from the holder is as much as 50% of the total radiation.

A shot with a 0.5-mm diam carbon anode extending 1.6 cm from the cathode also resulted in intense radiation from the rod tip. The CSDA range of 1-MeV electrons in carbon is 2.5 mm, five times the rod diameter. For comparison, the range in tungsten is 0.4 mm, 0.8 times the rod diameter. The plasma-filled rod-pinch diode can therefore couple energy to the rod tip even when the rod diameter is a small fraction of the electron range.

A shot with a 1-mm diam brass rod extending through the cathode with a 0.25-mm diam tungsten wire extending 2.5 cm beyond the brass resulted in an intense source at the end of the wire, and weaker emission from the brass-to-tungsten transition and from the aluminum holder. This shows that extremely small x-ray sources may be created using this technique.

The source size was measured more accurately on some shots by imaging a 1-m radius tungsten-alloy rolled edge onto x-ray film. The rolled-edge tangent was aligned with the axis of the rod (end-on). The film images were analyzed to characterize the radial distribution of the source.[4] Typically, the full width at half maximum (FWHM) of the line-spread function (LSF) was less than the rod diameter. For example, on shot 7806 the FWHM of the LSF was 0.53 mm for a 1-mm diam tungsten rod tapered to a point over the last 10 mm. Radial wings in the x-ray image extend beyond the rod diameter, possibly due to holder emission or to hydrodynamic expansion of the rod material.

II. PHYSICAL MODEL

The physics of the plasma-filled rod-pinch diode differs significantly from its vacuum analog. The injected plasma provides a zero-resistance anode-to-cathode connection so the current increases without the need for space-charge-limited emission. This short circuit phase lasts for 10's of ns and may be beneficial for coupling to generators by establishing magnetic insulation at the start of the pulse. The $\mathbf{J} \times \mathbf{B}$ force accelerates the current-conducting plasma axially toward the rod tip. The axial component of the magnetic force is greatest near the rod, because $\mathbf{J} \times \mathbf{B} \sim 1/r^2$. If the plasma connection moves beyond the tip, a vacuum gap can form there, perhaps by an erosion mechanism[5] in the remaining low-density plasma. High-energy electrons are magnetically prevented from striking the rod except at the tip. If they have sufficient angular momentum to miss the rod, they may orbit along the rod to the holder.[3]

The notion of a vacuum gap can be used to compare the plasma-filled rod-pinch diode with a vacuum diode of similar electrode configuration. The maximum value for the vacuum gap occurs when the diode operates at the critical current, given by:

$$I_{crit} (kA) = 8.5\alpha \frac{\sqrt{\gamma^2 - 1}}{\ln(r_C/r_A)}. \quad (1)$$

Here, γ is the relativistic factor for electrons, r_C and r_A are cathode and anode radii, and $\alpha \sim 1.6$ when ions are present and when r_C/r_A is in the range of 1 to 2.[2] Applying Eq. 1 to the plasma-filled rod-pinch diode, the effective vacuum gap ($r_C - r_A$) is 7 to 130 μm , depending on the plasma timing and anode radius. This illustrates the impossibility of obtaining such low impedances from a vacuum rod-pinch diode with small diameter anodes.

III. EXPERIMENTAL VARIATIONS

Two variations were tested in subsequent Gamble II experiments: (1) the downstream cathode plate was removed to immerse the rod tip in plasma, and (2) a thin-wall (75 μm) aluminum tube with a 1-mm diam gold sphere attached at the end replaced the solid tungsten rod. The configuration with the downstream cathode plate removed is shown in Fig. 6. (The distance from the guns to the rod was also reduced from 5 cm to 2.5 cm for these shots.) In these experiments, the dose was found to be independent of polar angle from 0° to 60° . The one shot in this configuration with a 1-mm diam tapered tungsten rod set a dose record for a rod-pinch diode on Gamble II, 20 rad(Si) from the rod tip, at 1 m through a 3-mm thick aluminum filter. Radiation from the holder is about ten times weaker. The voltage and current at the time of maximum x-rays were 1 MV and 500 kA. A digitally-enhanced side-on x-ray image for this shot is shown on the left in Fig. 7. Intense emission is evident from the last 1.7 mm of the tapered rod. Much weaker emission is seen from expanding material at the tip and from a large fraction of the 10-mm long taper.

The solid rod was replaced with a thin-wall (75 μm) aluminum tube with a 1-mm diam gold sphere attached at the end. A side-on x-ray image for one of these shots is shown on the right in Fig. 7. The tube and sphere outlines below the x-ray image are positioned to show the location

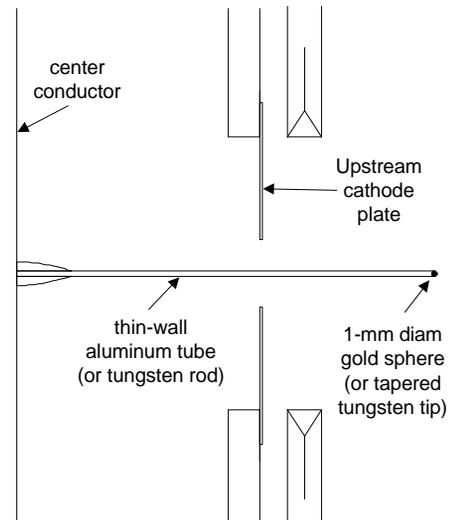


Figure 6. Plasma-filled rod-pinch diode with the downstream cathode plate removed.

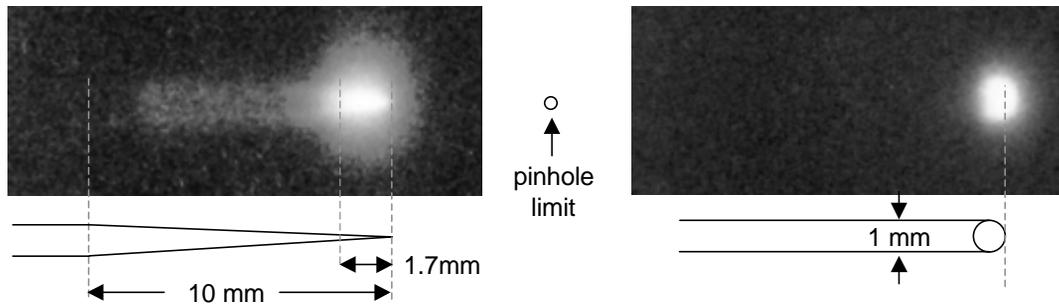


Figure 7. X-ray pinhole-camera images for shots without the downstream cathode plate: (left) 1-mm diam tungsten rod tapered to a point over the last 10 mm (shot 7956), (right) thin-wall aluminum tube with a 1-mm diam gold sphere at the end (shot 7957).

of the x-ray emission. It appears that the emission is primarily from the downstream half of the sphere. Radiation from the aluminum tube is negligible, although emission from the holder (not shown in Fig. 7) is about 5% of the total radiation. The 1.1-MV, 740-kA pulse produced 14 rad(Si) from the tip, at 1 m through a 3-mm thick aluminum vacuum window. This configuration is attractive for off-axis radiography because the source size remains small, even at large angles, in contrast to the vacuum rod-pinch. This configuration should also facilitate the use of multiple radiography sources along the same line-of-sight.

IV. SPECULATIONS AND APPLICATIONS

The low impedance and small anode diameter of the plasma-filled rod-pinch diode result in some impressive properties. If the generator current (200-800 kA) flows in a 0.5-mm diam rod, the magnetic field at the rod surface is 1.6-6.4 MG. If the electron current reaching the tip is 100 kA (one-half to one-eighth of the total current), the electron current density would be 50 MA/cm².

The measured x-ray dose from the tapered tungsten rod in Fig. 7 corresponds to 17 kJ of 1-MeV electrons absorbed in the last 1.7 mm. In 50 ns, the average electron power density at the tip is 75 TW/cm² (ignoring hydrodynamic expansion). This intense electron energy deposition could produce high-energy-density plasmas at the tip with temperatures exceeding 100 eV. These estimates provide incentive for exploring the properties of the plasma in the vicinity of the rod tip.

The vacuum rod-pinch diode is well suited for pulsed hydrodynamic radiography with 1- to 3-MV endpoint voltage bremsstrahlung.[4] The plasma-filled rod-pinch diode, described here, has several advantages for this application, including: larger dose, smaller source size, reduced axial source length, good electrical match to low-impedance generators, and the ability to couple energy to a high atomic-number sphere producing an intense x-ray source with a size that is independent of angle of observation.

More research (experiment and theory) is planned to improve the understanding of the particle flows in this diode and eventually to exploit it for radiography and other applications, such as x-ray/matter interaction studies and high-energy-density plasma generation.

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