# PROGRESS IN PLASMA EROSION OPENING SWITCH RESEARCH AT THE NAVAL RESEARCH LABORATORY†

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## Summary

The plasma erosion opening switch (PEOS) has many pulsed power applications. This paper describes experiments that have contributed to our understanding of the physics of the PEOS. The experimental results are in agreement with a theoretical model. Extending the PEOS to higher current, voltage, longer conduction, and faster opening should be possible.

## Introduction

The PEOS is an opening switch that can be used for many pulsed power applications. The PEOS can be used in an inductive energy storage system to produce voltage and power multiplication with fast risetime.[1] In experiments at the Naval Research Laboratory (NRL), the PEOS has conducted ~ MA currents for ~ 50 ns before opening into a parallel load producing > MV voltages in 10 ns. Our present understanding of the PEOS operation has grown from theoretical and experimental research over the last few years.

The general operation of the PEOS can be described with the aid of Fig. 1(a), which is a schematic of the front end of the Gamble I generator at NRL configured for inductive-store/pulse-compression experiments with a PEOS. Also shown is a more detailed view of the switch region [Fig. 1(b)]. Plasma is injected toward the cathode (inner conductor) through a screen anode. The plasma source consists of three carbon plasma guns[2] equally spaced in azimuth around the inner conductor. The generator is fired a time interval $\tau_D$ after firing the guns. Negative voltage is applied to the center conductor and current flows through the plasma, energizing the coaxial storage inductance. For the proper combination of plasma parameters the behavior illustrated in Fig. 2 is obtained for a short-circuit load. At some time during the pulse, the generator current $I_G$ is rapidly diverted ( $\simeq$ 10 ns opening time) to the load, as evidenced by the time history of the load current $I_L$. With the configuration illustrated in Fig. 1(b), the fastest openings at the highest currents for the Gamble I parameters occur when $\tau_D$ is such that the plasma injection speed is $\gtrsim$ 7 cm/ μs, and the switch plasma electron density is $n_e \simeq 3 \times 10^{13} cm^{-3}$. Here, the plasma is predominantly $C^{++}$ and the electron temperature is $T_e \simeq 5 eV$.

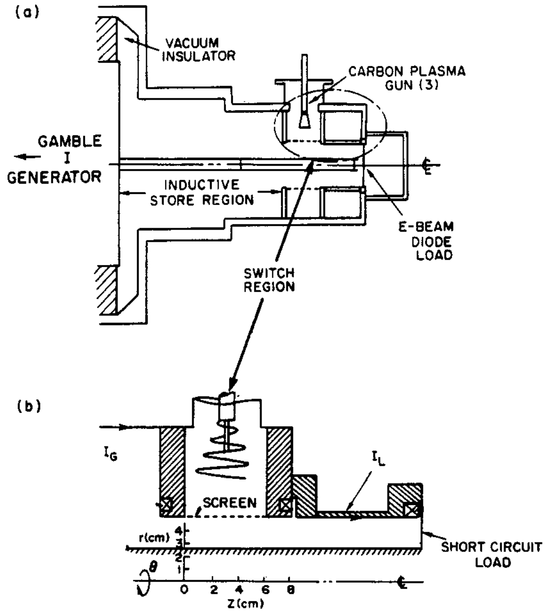

Fig. 1 a) Gamble I PEOS experiment with e-beam diode b) Close up of switch region with short circuit load.

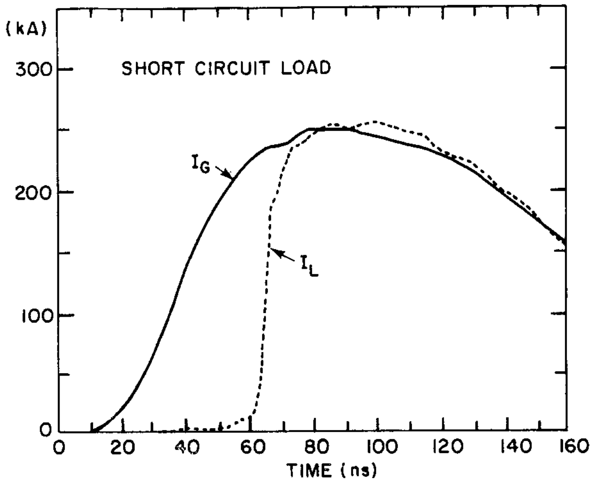

Fig. 2 Fast rising load current ($I_L$) produced by PEOS on Gamble I into short circuit load.

The remainder of this paper is a discussion of the importance of the plasma parameters and switch geometry on PEOS performance. A brief summary of the theoretical model is given, to compare with experimental results. Experiments on Gamble I show how PEOS response depends on plasma parameters, polarity and load impedance.

## Theoretical Model

The theoretical model of the PEOS is described in detail by Ottinger, et al.[3] This description is a blend of theoretical ideas and experimental observations. It describes the observed quantitative behavior of the PEOS and has been successfully used to make qualitative predictions. The PEOS physics is briefly summarized here for comparison with experiments.

The operation is most easily described as a sequence of four phases illustrated in Fig. 3: conduction, erosion, enhanced erosion, and magnetic insulation. The last three phases constitute the switch opening. The plasma is injected into the switch region and voltage applied to the cathode. The conduction occurs through a gap at the cathode in a bipolar space-charge-limited fashion with the

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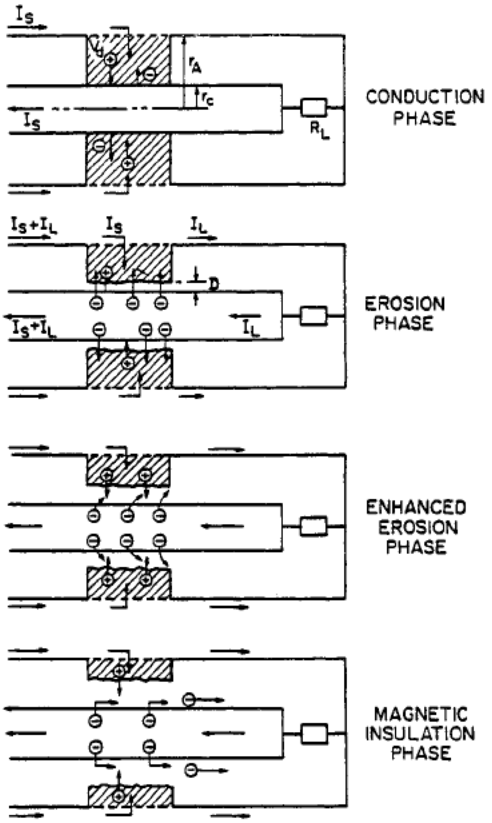

Fig. 3 Theoretical model: four phases of PEOS operation.

electron component emanating from the cathode and the ion component provided by the injected plasma. As long as the switch current remains below a predictable value, $I_0$, the plasma acts as a short circuit. $I_0$ is the bipolar space charge limited current given by:

$$I_0 = 2\pi r_c \ell n_i Z e v \sqrt{M_i/Zm_e} \ , \tag{1}$$

where $r_c$ = cathode radius, $\ell$ = axial plasma length, $n_i$ = ion density, $Ze$ = ion charge, $v$ = ion drift velocity, $M_i$ ($m_e$) is the ion (electron) mass. When the switch current becomes high enough that the bipolar space-charge condition cannot be satisfied by the ions from the injected plasma, the gap widens, providing more ions. This is called the erosion phase. When the switch current increases to the point where the average electron Larmor radius is comparable with the gap size, the electron lifetime in the gap increases and as a result the space-charge condition is modified in such a way that even more ions are required. This is called the enhanced erosion phase and it is during this phase that the substantial fraction of current is diverted to the load. The switch is totally open when the magnetic insulation phase is reached. This occurs at a value of current for which the average Larmor radius is less than the gap size and all the current reaches the load.

## Gamble I Experimental Results

This section is a brief description of Gamble I PEOS experiments and comparison with theory.

### a. Gun-generator time delay

Figure 4 shows load currents obtained on different shots where the delay time between the gun firing and the generator firing is varied. The load for these shots is a short circuit as shown in Fig. 1(b). The plasma guns are located 10 cm from the inner conductor (cathode) surface. The solid curve is a typical current measured on the generator side of the PEOS and would be equal to the load current without the PEOS. The conduction time increases with delay time, $\tau_D$ , as shown. Optimum switching occurs for $\tau_D$ = 1.6-1.8 μs. As the delay time is increased, the load current risetime is degraded, and ultimately the PEOS shorts out the entire Gamble I current pulse and never opens.

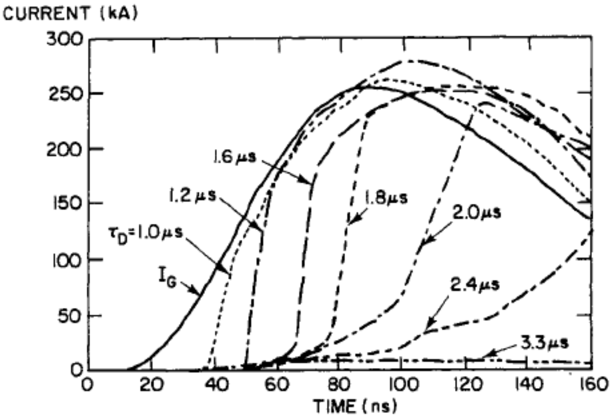

Fig. 4 Load current dependence on gun-generator time delay, $\tau_D$.

This behavior is consistent with the theoretical model and the known characteristics of the plasma guns. For early time delays, $\tau_D$ < 1.6 μs, the plasma density is low and the directed velocity toward the cathode is high. The product nv is such that the PEOS conducts to the current level given by Eq. 1 and opens quickly when $I_G$ increases. For $\tau_D$ > 1.8 μs, the density increases and drift velocity decreases with increasing nv. The increasing ion flux allows higher current conduction but slows the opening. When $I_0 > I_G$, the PEOS shorts out the generator pulse. The plasma parameters at the time the generator is fired determine the PEOS response.

### b. Vary number of plasma sources.

The dependence of conduction current on ion flux is demonstrated by varying the number of plasma guns. The delay time is kept constant, $\tau_D \simeq$ 1.6 μs. The switch current, $I_s = I_G - I_L$, is shown for 1, 2 and 3 guns in Fig. 5. The maximum switch current is proportional to the number of guns. The switching is best for 3 guns, perhaps because of the improved azimuthal symmetry of the current through the plasma. This scaling with ion flux has been extended on Gamble I to 6 guns and 300 kA switch current.

### c. Current Distribution

The distribution of current in a PEOS plasma was determined from magnetic probe measurements.[4] The results are shown in Fig. 6. The probe locations are indicated by solid dots. The generator and load currents are shown, and the current streamlines are drawn at four times during the discharge: during the conduction phase ( t = 16

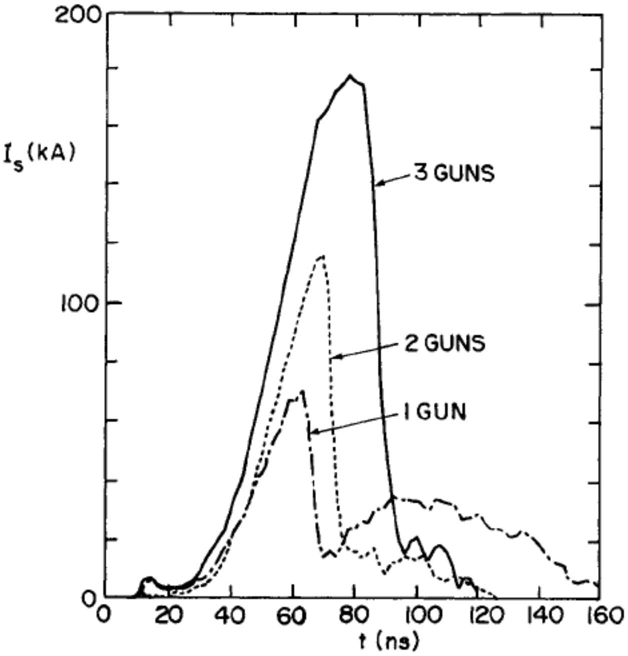

Fig. 5 Switch current dependence on number of guns for constant $t_D$.

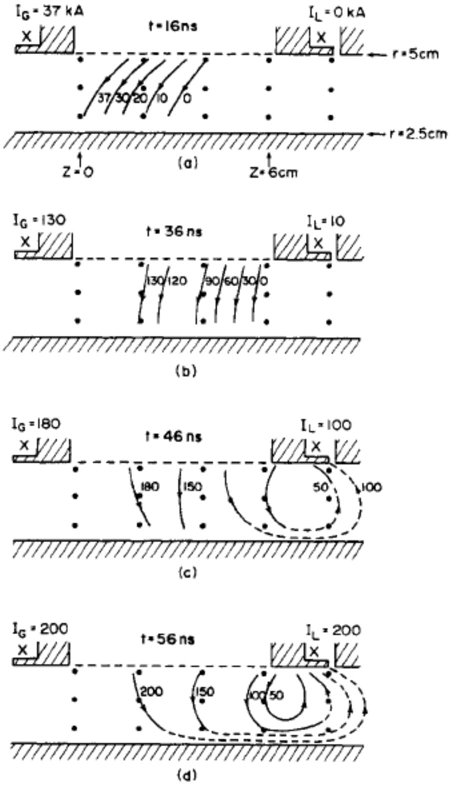

Fig. 6 Current distribution in the PEOS plasma.

and 36 ns), during the opening phase (t = 46 ns) and after opening (t = 56 ns).

The current channel through the plasma broadens rapidly during the conduction phase. The current channel width is consistent with the bipolar current density limit of Eq. (1), where the current increases at (roughly) constant current density,

$$\ell(t) = \frac{I(t)}{2\pi r_c n_i v e}\left(\frac{m_e}{Z M_i}\right)^{1/2} \tag{2}$$

The switch opening begins when the current channel reaches the load end of the plasma. The switch current is interrupted at the cathode side of the PEOS. These observations agree with the theoretical model of the PEOS. The physical mechanism responsible for the current conduction in the PEOS plasma is the subject of present research.

### d. Polarity

The importance of controlling the direction of plasma injection has been demonstrated by varying the polarity of the electrodes and the injection geometry. Data taken with Gamble I configured as in Fig. 1(b) along with illustrations of the specific plasma injection geometry and electrode polarity are shown in Fig. 7. The data represent optimized opening switch performance. The PEOS behavior is severely degraded for inward radial injection toward the anode [Fig. 7(b)] compared with the case of inward radial injection toward the cathode [Fig. 7(a)]. Using a flashboard source, outward radial injection toward the cathode was achieved. This recovers the fast opening behavior of Fig. 7(a), as illustrated in Fig. 7(c).

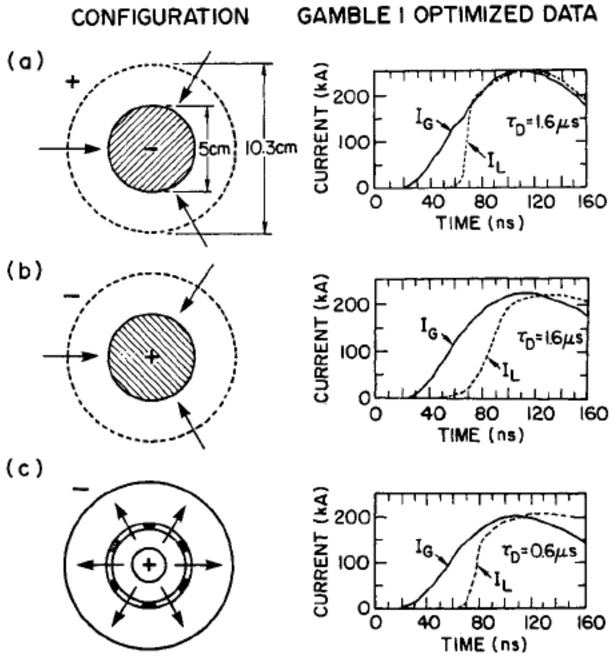

Fig. 7 Comparison of positive and negative polarity PEOS operation with inward and outward radial plasma flow velocity.

### e. Load coupling

The PEOS system shown in Fig. 1(a) has an e-beam dide load. The "pinched beam" impedance of the diode is proportional to the anode-cathode gap. The current delivered to the load from the PEOS-inductive store system decreases as the load impedance increases, as shown in Fig. 8.

The vertical axis is peak load current divided by the peak generator current. The switch current (determined by the delay time $\tau_D$) is ~ 150 kA for all data (X's) shown. The horizontal axis is the

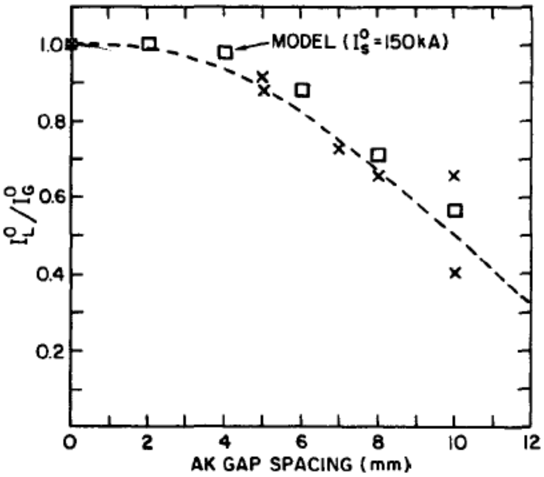

Fig. 8 Current transfer efficiency to diode loads with different anode-cathode (AK) gaps, comparison of experiment (X's) and PEOS code calculations (boxes).

diode anode-cathode gap in mm. The decrease in load current with AK gap is the result of incomplete magnetic insulation in the gap between the inner conductor and the plasma. This conclusion is based on the good agreement with theory (shown by boxes) where a computer code incorporates the PEOS model, the Gamble I generator and a diode load model. To improve the coupling to the load, the PEOS must be changed to improve magnetic insulation with high load impedance.

### f. Load voltage measurements

Direct measurement of the diode voltage was performed with an inductive voltmeter. The load for these measurements was an "inverse" diode, used to prevent electron pinching on the voltmeter. The goal of these measurements is to estimate the load voltage while the PEOS is "closed," and compare with the voltage after opening. An example of the results is shown in Fig. 9. $V_L$ is the inductive voltmeter signal, directly measuring the voltage between the anode and cathode of the diode. Some noise is evident on the voltage probe during the conduction phase between t = 20 and 80 ns where $V_L$ = 0 ± 20 kV. The load voltage increases to 1 MV in 15 ns beginning 60 ns after the start of the generator current. This data demonstrates the ability of the PEOS to act as a short circuit during the conduction phase.

This property of the PEOS is easily understood by considering the current distribution in the plasma (Fig. 6). The front of the current channel is the point where B = 0. The current-free plasma on the load side of the PEOS acts as a short circuit, shunting current until the current front reaches the plasma boundary on the load end. Until this time, the load is effectively isolated from the generator and inductive energy store.

## Summary and Conclusions

The PEOS has been studied theoretically and experimentally. the theoretical description of the switch conduction and opening is consistent with experimental observations. The conduction current is determined by the plasma density, flow velocity, and cathode area through the bipolar space charge limited current expression (Eq. 1). The switch opens when a gap erodes at the cathode side of the PEOS. Fast opening requires ion current enhancement resulting from current flow in the load. Efficient current transfer requires magnetic insulation in the switch gap, which becomes more difficult as the load impedance increases.

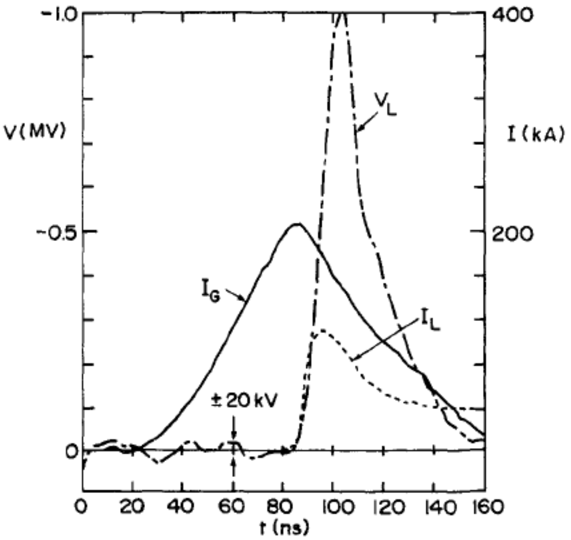

Fig. 9 Direct measurement of load voltage ($V_L$) with an inductive voltmeter & "inverse" diode load.

The PEOS has several properties that are ideal for inductive storage and other pulsed power applications: 1) the PEOS is a short circuit during the conduction phase; 2) current is switched to a parallel load very quickly, < 10 ns; 3) the switch can withstand high voltage after opening and 4) the properties of the PEOS can be adjusted by varying the plasma parameters and switch geometry.

The demonstrated properties of the PEOS and our theoretical understanding are encouraging for extension to higher currents and voltages, longer conduction times and faster opening. Specific examples of PEOS applications are given in the paper by Meger, et al., at this conference.

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