PLASMA EROSION OPENING SWITCH DEVELOPMENT AT NRL

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Abstract

Plasma Erosion Opening Switch (PEOS) experiments are described covering a conduction time range from 35 ns on Gamble I to 2300 ns on Pawn. A microwave interferometer is used to estimate the plasma density for some of the experimental cases. The conduction current, conduction time, geometrical configuration and density are used to calculate the plasma center-of-mass displacement from JxB forces and to compare the conduction current with the bipolar limit of PEOS theory. At short conduction times, the conduction current agrees with the bipolar limit. As the conduction time increases, the conduction current is orders-of-magnitude less than the bipolar value, possibly the result of plasma displacement and/or compression by JxB forces. Eventually, the PEOS does not open; instead, the current is convected toward the load as in a plasma flow switch. The transition to conduction current much less than bipolar occurs when the center-of-mass displacement is a significant fraction of the plasma length.

Introduction

Plasma Erosion Opening Switch (PEOS) experiments have been performed since the early 80's on various pulsed power generators around the world.[1] This switch is capable of ~ TW pulse generation with ~ 10 ns rise time. One example is the Gamble II PEOS experiment, where a 4.5 MV, 3.5 TW, 10 ns pulse was obtained on a shot where the ideal, matched load power would have been 1.5 TW. This represents a power multiplication factor of 2.8.[2] In this experiment, the PEOS conducts ~ 1 MA rising in ~ 50 ns. A variety of experiments in this short conduction time regime indicate that the conduction current depends on the plasma parameters and the geometry but is independent of conduction time.

In more recent PEOS experiments, a fast capacitor bank drives current through the plasma, without the intermediate power conditioning of a large water line. Conduction currents of ~ 1 MA with ~ 1 μs rise time are typical of recent, high-power experiments.[3] High voltage, high power pulses have been obtained using this inductive storage approach. However, the longer conduction time experiments seem to be limited to opening times of ~ 100 ns instead of the ~ 10 ns opening times in the short conduction time experiments. Hydrodynamic displacement and/or compression of the current-carrying plasma may cause switching to occur at a current level much less than for the short conduction time case, resulting in slower opening.

In this paper, several experimental results are compared where the conduction time varies from 35 ns to 2300 ns, to evaluate the relative importance of bipolar current conduction and hydrodynamic effects. Two extreme cases are shown: 1) For short conduction time and low current, the plasma displacement is negligible and bipolar conduction is reasonable. 2) For very long conduction time, the current is convected toward the load as in a flow switch. The 1 MA, 1 μs regime is between these two extremes, where the conduction current is limited to values much less than bipolar, but the PEOS opens locally without convection.

Short Conduction Time Experiments

PEOS experiments with "short" conduction time, < 50 ns, have been performed since 1982 on Gamble I and Gamble II. A schematic drawing of these PEOS experiments is shown in Fig. 1. Plasma sources, either guns[4] or flashboards[5], inject a plasma composed primarily of C^{++} ions into the region between coaxial conductors. Current from the generator is conducted through the plasma as the current rises. During this "conduction phase," the load is completely isolated from the generator, and the PEOS looks like a short circuit as seen from the load. This is evident from the Gamble I waveforms shown in Fig. 2, where the (short circuit) load current is zero for 35 ns after the generator current begins. The plasma current decreases rapidly when the current exceeds 0.15 MA, and current is transferred to the load in about 10 ns.

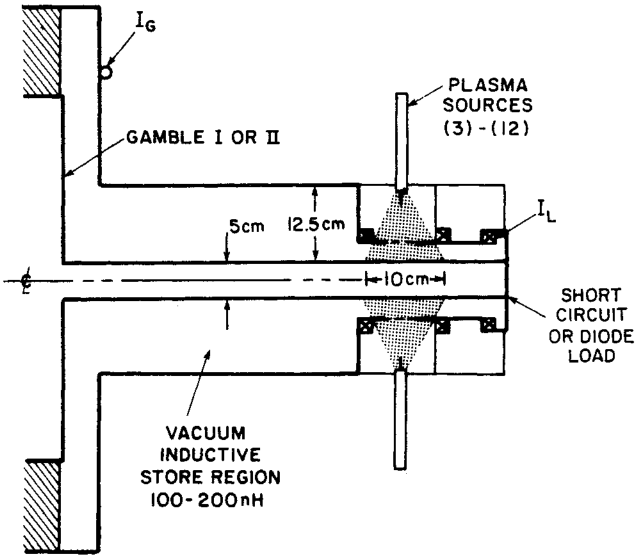

Figure 1 Schematic diagram of PEOS configurations used on Gamble I and Gamble II.

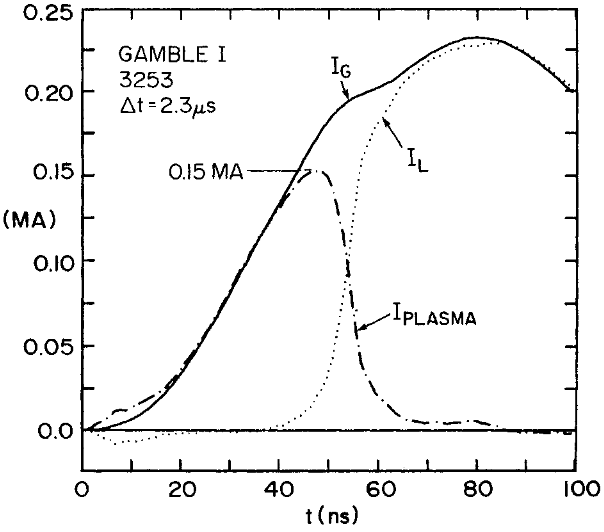

Figure 2 Currents measured on the generator side (I_G) and load side (I_L) of the PEOS in Gamble I using 3 guns and a time delay of 2.3 μs with a short circuit load.

PEOS theory[6] predicts that switching occurs when the current exceeds a limit determined by bipolar electron emission at the negative electrode, in this case the inner conductor. The bipolar current limit, I_{BP}, is given by:

$$I_{BP} = (M_i/Zm_e)^{1/2} (2\pi a l)(n_e e v), \qquad (1)$$

where M_i (m_e) is the ion (electron) mass, Z is the ion charge state, a is the cathode radius, l is the plasma length, n_e is the electron density, e is the electronic charge, and v is the average ion flow velocity to the cathode.

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14. ABSTRACT
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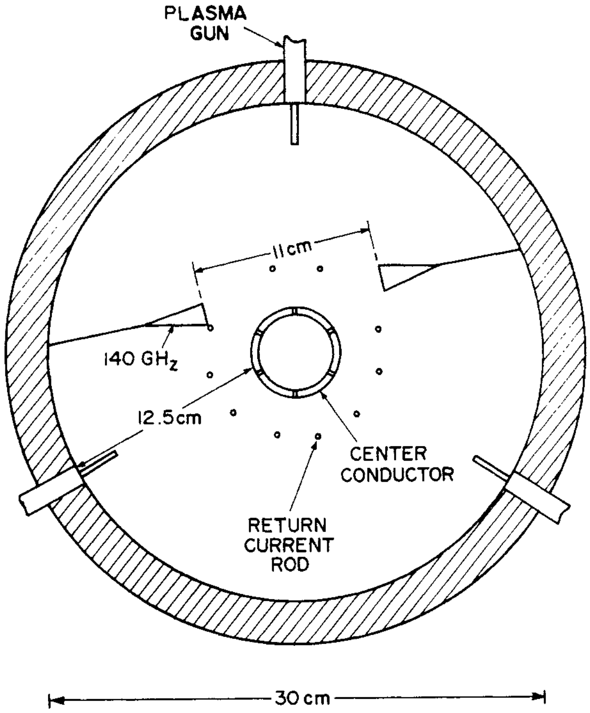

Figure 3 Cross section of the Gamble I PEOS experiment showing the line-of-sight of the microwave interferometer.

This theory is based on the premise that cathode emission dominates processes occurring in the plasma body, such as JxB forces. One measure of the relative importance of JxB forces is the displacement of the plasma center-of-mass at the end of the conduction time (while the load current is zero). For a current that rises linearly in time, the center of mass displacement, Δz, is given by:

$$\Delta z = \{\mu Z \ln(b/a) I_0^2 \tau^2\}/\{48\pi^2(b^2-a^2)M_i n_e l\}, \qquad (2)$$

where $\mu = 4\pi \times 10^{-7}$ H/m, b is the outer conductor radius, I_0 is the conduction current, and τ is the conduction time. This quantity gives an estimate of bulk plasma motion, independent of the current distribution in the plasma. The shortcoming of this formula is that it does not describe the plasma distribution after displacement, nor does it predict the radial plasma displacement or any 3D effects, such as pinching. However, without detailed information about the current and density distributions, Δz is the only quantity that can be calculated from the available measurements.

As an example, the waveforms in Fig. 2 show a conduction current of 0.15 MA and conduction time of 35 ns. The plasma density for this shot is estimated from separate measurements using a 140 GHz interferometer, as shown in Fig. 3. The line-average density along the chord is computed from the measured phase shift. The result is plotted in Fig. 4 as a function of time after firing the gun capacitor bank. For the shot in Fig. 2, the current begins to flow through the plasma 2.3 μs after the guns are fired. For this time delay, the measured density is about 2×10^{13} cm^{-3}. The plasma displacement can be calculated from Eq. (2) using a = 2.5 cm, b = 5 cm, l = 10 cm, and assuming the plasma is mostly C^{++}. Δz is then 0.14 cm, negligible in comparison with the axial plasma length. The bipolar current limit formula (Eq. 1) requires an average ion collection velocity. This quantity is estimated very roughly as the ratio of the distance from the guns to the cathode, 12.5 cm, divided by the time delay, 2.3 μs, or $v \simeq 5$ cm/μs. Eq. (1) then predicts a current limit of 0.25 MA, in relatively close agreement with the measured value of 0.15 MA considering the uncertainties in the values used for v and n_e. In Gamble I, switching begins when the current reaches the bipolar limit, and the JxB displacement of the plasma is negligible in the sense discussed above. This is not always the case, as described in the rest of this paper.

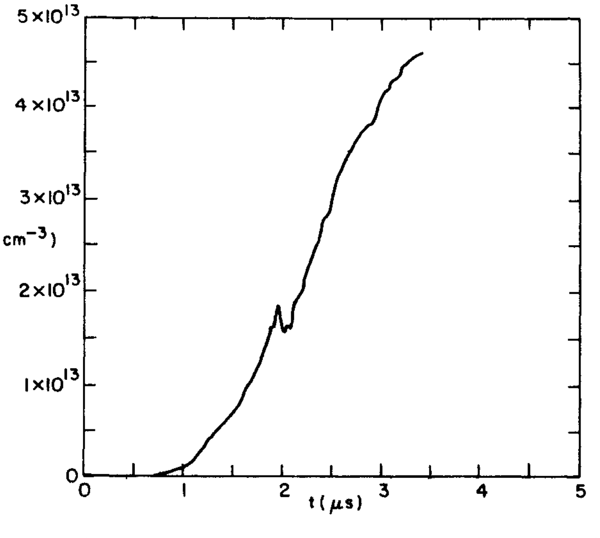

Figure 4 Line-average electron density in the configuration of Fig. 3. The diagnostic is limited in this case to densities less than 5×10^{13} cm^{-3}.

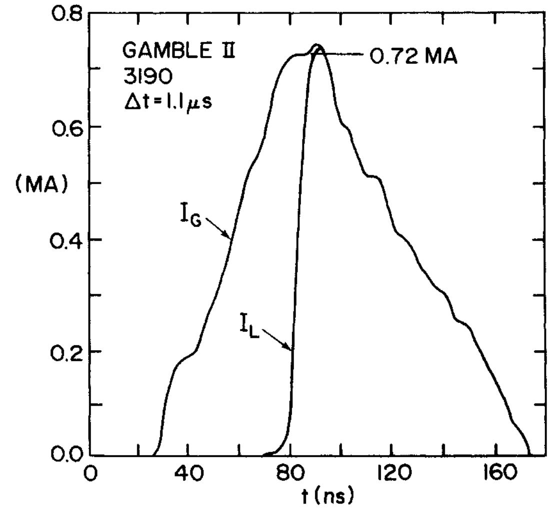

Figure 5 Measured currents for Gamble II shot 3190. Three flashboards are used as the plasma source, 10 cm away from the center conductor.

Gamble II experiments used the same PEOS configuration as Gamble I at higher current, ≃ 1 MA. The plasma sources used in these experiments are flashboards that produce a higher density plasma than the guns. Data from a shot using a diode load (instead of a short circuit) are shown in Fig. 5. The density was measured in the configuration shown in Fig. 6. The measured density is shown in Fig. 7 for different pulses of the flashboard. The pulse numbered "8" is typical of experiments, but it must be noted that the density is not necessarily reproducible, nor is this measurement a precise value for simulating experiments. Rather, it is a value that should be used for order-of-magnitude estimates and relative comparisons between different experiments.

The time delay for the Fig. 5 data was 1.1 μs, which corresponds to an approximate density of 4×10^{13} cm^{-3}. The conduction current, 0.72 MA, and conduction time, 50 ns, indicate a plasma displacement of $\Delta z \simeq 3$ cm, a significant fraction of the plasma length, (≃ 10 cm). The bipolar current limit is estimated using $v \simeq 10$ cm/1.1 μs ≃ 9 cm/μs, resulting in $I_{BP} \simeq 0.9$ MA, close to the measured value of 0.7 MA. In this case, the bipolar limit is reached even though significant plasma motion occurs.

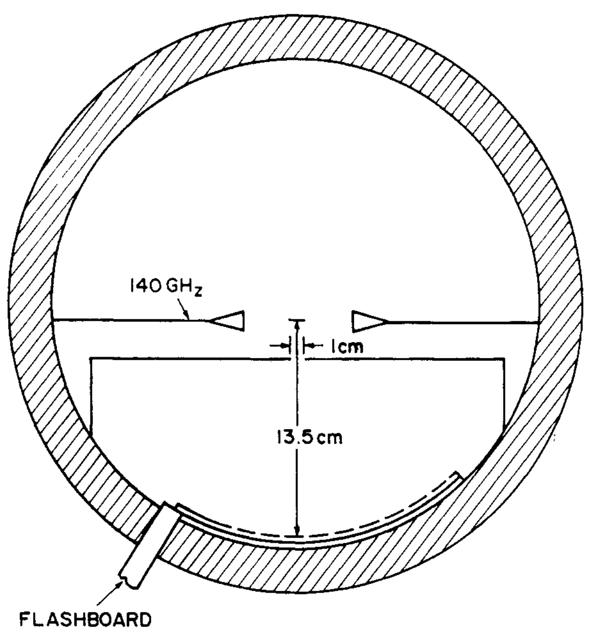

Figure 6 Experimental configuration for flashboard density measurements. The plasma length is restricted to 1 cm to reduce refractive bending of the probe beam.

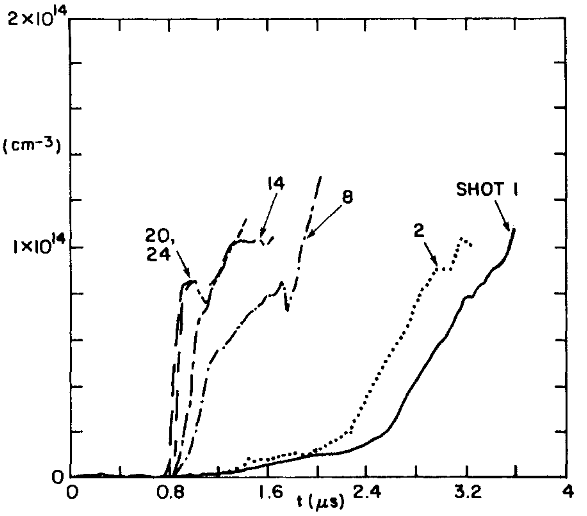

Figure 7 Measured density for different flashboard pulses. The measurement is limited to densities less than 1×10^{14} cm^{-3}.

Long Conduction Time Experiments

PEOS experiments have been performed on the Pawn generator[7] at NRL where the conduction time has been varied from 250 ns to 2300 ns. The configuration used for these experiments is depicted in Fig. 8. The load is a short circuit. Magnetic probes are used at different locations to determine the axial distribution of the current. The generator is a fused capacitor bank that is switched to the PEOS using a vacuum flashover switch (VFS)[8]. By varying the time the VFS closes, the rise rate of current into the PEOS can be varied by an order of magnitude.

Data from a 250 ns conduction time shot on Pawn are shown in Fig. 9. The load current signal is synchronized with signals from probes located between the PEOS and the load, indicating that the current is interrupted locally in the original plasma location. Switching begins when the plasma current is 0.23 MA. The density is estimated for this shot using Fig. 7 (pulse "8") and the time delay of 1.3 μs, for which $n_e \approx 6\times10^{13}$ cm^{-3}. Eqs. (1) and (2) give $I_{BP} \approx 2.5$ MA and $\Delta z \approx 2$ cm. Switching occurs at a current ten times less than bipolar. It is not surprising that the conduction current is less than I_{BP}; if the conduction current was equal to I_{BP} (and the conduction time ten times longer) the resulting Δz value would be 2×10^4 cm!

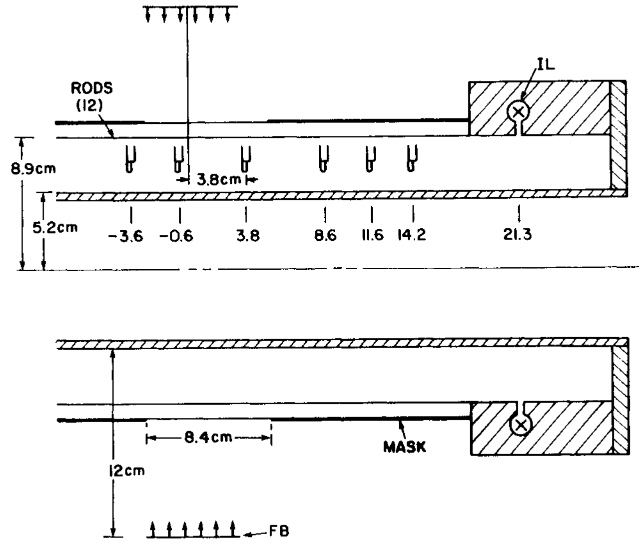

Figure 8 PEOS configuration used in Pawn experiments. Nine flashboards are used as the plasma source, 12 cm from the center conductor.

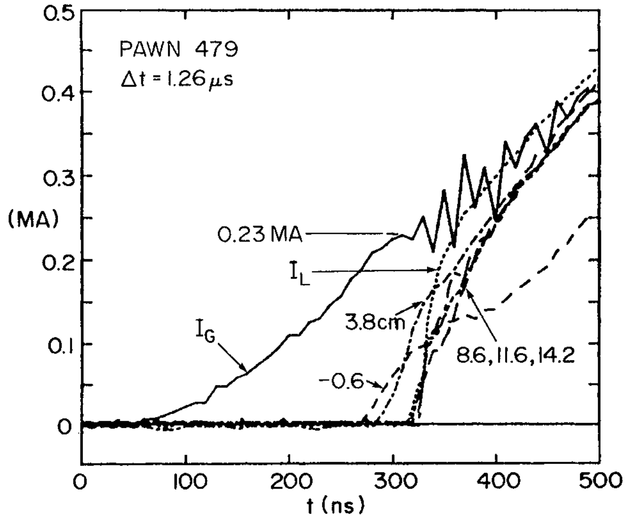

Figure 9 Measured currents and probe signals for a 250 ns conduction time shot on Pawn.

In order to conduct to the MA level on Pawn requires time delays of about 4 μs in this configuration. Data from such a shot is shown in Fig. 10. The conduction time in this case is 800 ns. This is the situation used for the highest power shots obtained to date on Pawn with diode loads.[9] The plasma density is not known for this time delay, as seen from Fig. 7, but is evidently much higher than 1×10^{14} cm^{-3}. The probe signals can be used to locate the current channel at the time the load current signal begins. At this time, the current has not reached the 8.6 cm location, and is centered near the 3.8 cm location. Assuming this is also the position of the plasma center of mass, Eq. 2 implies an initial plasma density of 4×10^{15} cm^{-3}. The bipolar limit is then 50 MA, 60 times higher than the conduction current of 0.9 MA. The $\approx$ 4 cm plasma displacement inferred from the probe signals is near the original boundary of the injected plasma.

Two other conclusions may be drawn from the probe signals on this shot. First, the plasma current is interrupted locally. This is evident because signals from the downstream

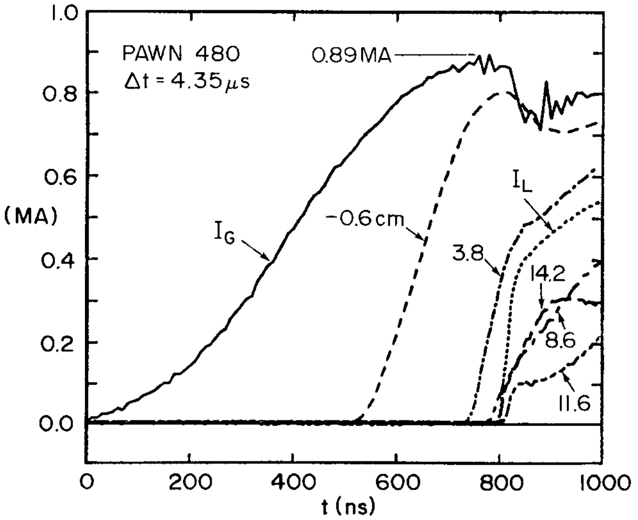

Figure 10 Measured currents and probe signals for a 0.9 MA, 800 ns conduction time shot on Pawn.

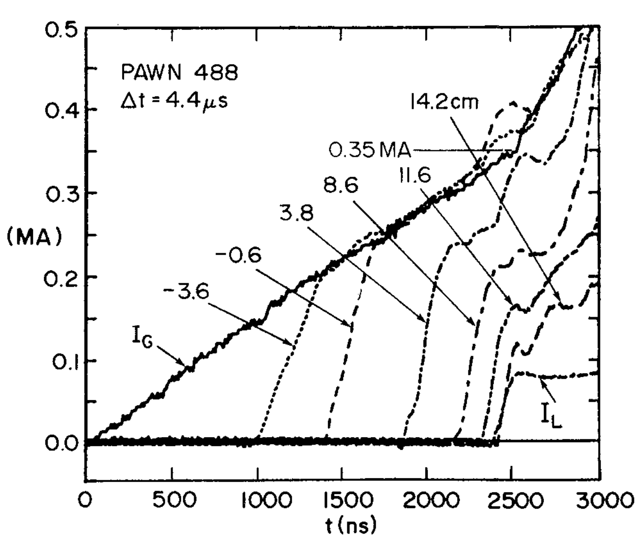

Figure 11 Measured currents and probe signals for a 0.35 MA, 2300 ns conduction time shot on Pawn.

probes located at 8.6, 11.6, and 14.2 cm from the flashboard begin simultaneously with the load current signal. Second, current is conducted in the region between the switch and load after opening. Only half of the current is measured at the load. This loss of current indicates the presence of low density plasma in this region. Subsequent measurements with an electric probe showed that a density in the 10^{13} cm^{-3} range appears in this area several μs after firing the plasma sources. Improved plasma localization may prevent this current loss.

Data from another shot on Pawn are shown in Fig. 11. This shot used the same time delay as the shot in Fig. 10. The VFS was triggered at low voltage, resulting in the slow current rise rate to 0.35 MA in 2300 ns. No switching is evident in this case; instead, the current simply convects toward the load. At the time the load current signal begins, the current is centered between the probes located at 8.6 and 11.6 cm from the flashboard. Taking this to be the plasma displacement, $\Delta z \approx 10$ cm, Eq. 2 implies $n_e \approx 2\times10^{15}$ cm^{-3}. This density value agrees within a factor of two with the value calculated for the previous case with the same time delay. The bipolar current estimate for this case is $I_{BP} \approx 25$ MA, a factor of 70 higher than the peak PEOS current on the shot.

Summary and Conclusions

Table I summarizes the data and results given in this paper. For each shot, the table lists the measured quantities: τ, I_0, and opening time (10-90% load current rise time). Computed values of I_{BP} and the ratio Δz/l are also listed. Entries indicated in parentheses use density values inferred from the location of the current channel.

Shot	τ(ns)	Opening time(ns)	I_0(MA)	I_{BP}(MA)	Δz/l
GI 3253	35	10	0.15	0.25	0.01
GII 3190	50	10	0.72	0.9	0.3
Pawn 479	250	25	0.23	2.5	0.2
Pawn 480	800	40	0.89	(50)	(0.5)
Pawn 488	2300	--	0.35	(25)	(1.2)

Table I Summary of data and calculations.

The conduction current is determined by the bipolar formula (Eq. 1), to a good approximation, if the current reaches this level before JxB forces displace the plasma center-of-mass by a significant fraction (Δz/l = .2-.3) of the switch length. The conduction current can be orders of magnitude less than I_{BP} if Δz/l is significant before the current reaches I_{BP}. This is illustrated by contrasting Gamble II shot 3190 and Pawn shot 479. Both shots should have similar displacement and/or compression from JxB forces since Δz/l is similar in both cases. The difference is that Gamble II reaches I_{BP} during the conduction time while Pawn switches at only 9% of I_{BP}.

Fastest opening, highest power PEOS operation occurs when the conduction current is bipolar. In this case, the dominant opening mechanism is believed to be enhanced erosion resulting from a sudden increase in ion current when the flow of emitted electrons is impeded by the magnetic field near the cathode.[6] In cases where the conduction current is much less than I_{BP}, opening is much slower. The opening mechanism could be different in these cases, or could be erosion modified by bulk plasma motion during the conduction time. Eventually, switching does not occur locally and the current is convected toward the load for conduction times > 2 μs.

Improved switching in the MA, μs regime on Pawn and similar generators may be improved by some combination of plasma parameters and geometry that limits Δz/l to values << 0.5 during the conduction time. Using a high flow velocity plasma is one possibility. The plasma can cross from the outer to the inner conductor in 1%-10% of the conduction time, so the JxB forces act on a plasma ion only during a small fraction of the conduction time. Improved PEOS performance in this regime will be the subject of experimental work on Pawn in the near future.

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