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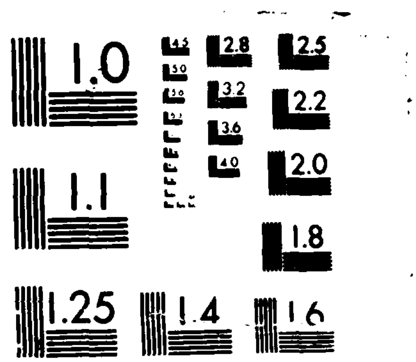

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High Voltage, High Power Operation of the Plasma Erosion Opening Switch

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A Plasma Erosion Opening Switch (PEOS) is used as the opening switch for a vacuum inductive storage system driven by a 1.8-MV, 1.6-TW pulsed power generator. A 135-nH vacuum inductor is current charged to ~750 kA in 50 ns through the closed PEOS which then opens in < 10 ns into an inverse ion diode load. Electrical diagnostics and nuclear activations from ions accelerated in the diode yield a peak load voltage (4.25 MV) and peak load power (2.8 TW) that are 2.4 and 1.8 times greater than ideal matched load values for the same generator pulse.

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High Voltage, High Power Operation of the Plasma Erosion Opening Switch

A Plasma Erosion Opening Switch (PEOS) can be coupled with a vacuum inductor to modify the output pulse of a pulsed power generator[1-6]. During the closed phase of the switch, energy from the generator accumulates in the vacuum inductor. When the switch opens, this inductively stored energy and the balance of the generator pulse can be delivered to a load. For prepulse suppression[1], the switch opens at low current, and little energy is stored inductively. For risetime sharpening[4], a moderate current is carried by the switch until it opens, leading to a faster risetime of current into a normal load. The most demanding application of the PEOS[2,5,6] is when a substantial portion of the generator pulse energy is stored in the inductor, then the switch is opened into a load impedance which is significantly larger than the characteristic impedance of the generator. This mode of operation can deliver a pulse with voltage and power higher than ideal matched load values, and a current near the matched load value. However, the pulse must be of shorter duration than the normal generator pulse for energy conservation.

In this letter, we report on experiments that demonstrate high voltage and high power operation on the Gamble II generator at the Naval Research Laboratory (NRL). The PEOS conducts until ≈750 kA is stored in 135 nH of vacuum inductance, whereupon 700 kA is transferred to a ~6-Ω inverse pinch ion diode load[7]. Electrical and nuclear diagnostics yield a peak load voltage $\geq$ 4.25 MV and resulting peak load power $\geq$ 2.8 TW. These values are 2.4 and 1.8 times larger than the ideal matched load case.

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A theoretical model[8] for the operation of the PEOS has been developed. Briefly, the current the PEOS can carry before opening is determined by the flux density of injected plasma at the cathode, and the area of the cathode exposed to the plasma. The plasma can carry the generator current without voltage appearing on the load until the ion current required to satisfy the bipolar Child-Langmuir law[9] at the cathode sheath can no longer be supplied by the plasma. A sheath then begins to open at the cathode by erosion, at a rate determined by the one-dimensional Child-Langmuir law, until the sheath is large enough for electrons from the cathode to undergo magnetic bending. This inhibits the electron current, and greatly enhances the ion current, which then rapidly opens the sheath until the electrons are magnetically insulated. Substantial voltage is developed across the switch in this enhanced opening phase, and current begins to flow to the load, assisting in the magnetic insulation of the cathode electrons. This model has been coupled to a transmission line code[10] to allow comparisons of the model with experimental data.

Experiments were performed on the NRL Gamble II generator to achieve high voltage and high power operation of the vacuum inductor/PEOS system. For the operating conditions used in these experiments, Gamble II would deliver a 60-ns, 1.8-MV, 1.6-TW pulse to an ideal 2-Ω matched load. The experimental setup is shown in Fig. 1. A coaxial vacuum inductor was added to the generator, giving a total inductance of 135 nH from the generator voltage monitor to the PEOS. In the switch region, the radius of the cathode (inner conductor) was 2.5 cm, and the radius of the anode (outer conductor) was 5 cm. The PEOS plasma was provided by three flashboard plasma sources[11], located 10 cm from the cathode, each driven by a 0.6-μF, 25-kV capacitor. The plasma filled an annular region about 10-cm long. The inverse pinch ion diode was located 5 cm downstream (load side) of the switch, with a 5-cm cathode tip radius. The diode was operated as an ion diode by using a 0.32-cm thick acrylic anode to provide a plasma from which to accelerate ions. These ions were readily accessible to diagnostics. Current into the vacuum inductor (upstream current, I_G) was measured by a current shunt in the generator and by a magnetic probe in the vacuum inductor. Current to the load (downstream current, I_L) was measured by a Rogowski coil located in the outer conductor between the switch region and the load. Voltage was measured by a voltage divider in the generator, and an inductive voltage correction was made to obtain the voltage at the switch or at the load.

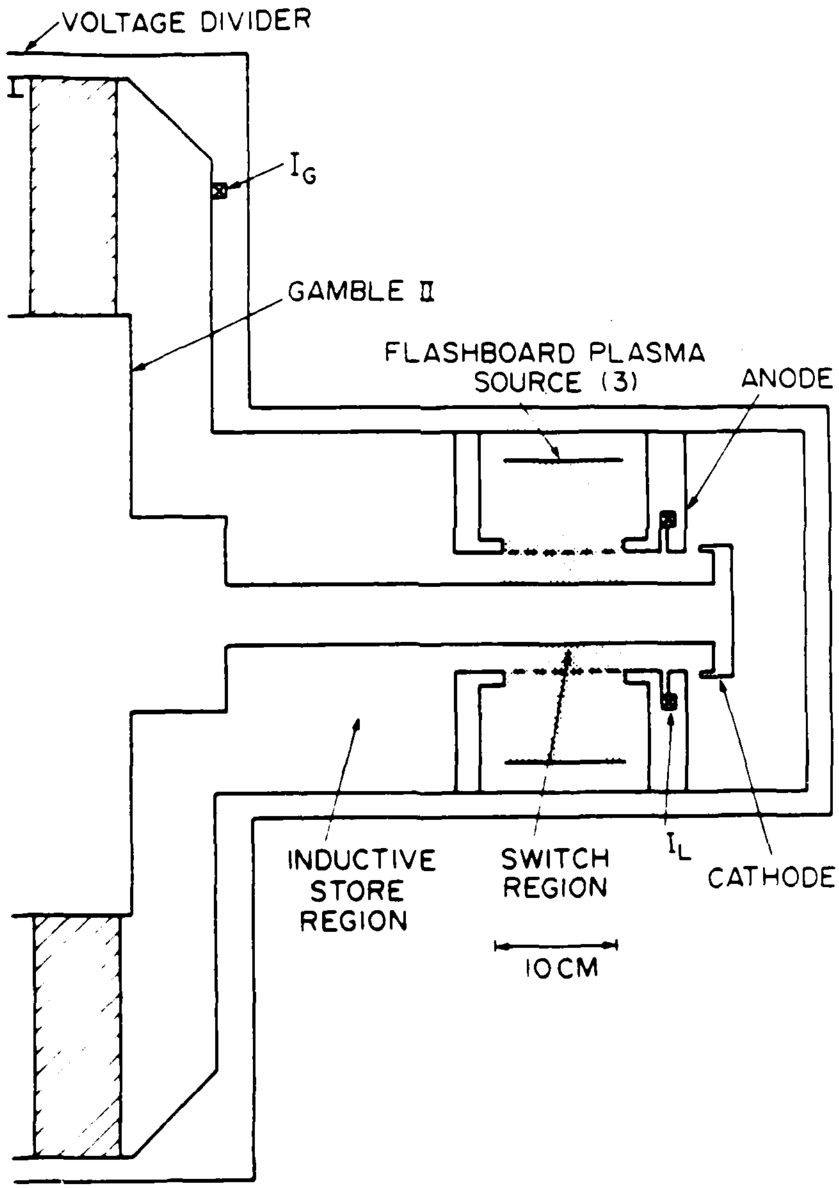

Fig. 1 — Experimental arrangement of the PEOS system and inverse diode on Gamble II

An additional voltage measurement was performed using nuclear activation induced by ions accelerated in the diode[12]. The acrylic anode was coated with deuterated polyethylene (CD_2) to produce a source of deuterons which are accelerated by the diode potential. At the cathode, a portion of the accelerated beam was transmitted through a 0.64 cm diameter hole and propagated 6 cm onto a stacked foil nuclear activation diagnostic. The foil stack consisted of a 25.4-μm aluminum foil, followed by eight, 12.7-μm polyethylene (CH_2) foils. The aluminum removed low energy ions and radioactivity produced by deuterons elsewhere in the diode. Energetic deuterons (> 1.6 MeV) penetrate through the aluminum foil and induce activity in the polyethylene foils by the $^{12}C(d,n)^{13}N$ reaction. The ^{13}N undergoes positron decay with a 10-min. half-life. The initial activity of each CH_2 foil was determined after a shot using NaI γ-ray spectroscopy of the annihilation radiation associated with the positron decay. Deuterons with higher energy penetrate farther into the foil stack and induce activity in deeper foils. The yield of the nuclear reaction increases rapidly as the deuteron energy increases. For a given deuteron energy the activity in the stack decreases rapidly near the end of the deuteron range. In particular, the peak energy of the deuterons can be determined from the deepest foil activated, and from the relative activity of the deepest activated foils.

In the experiment, the plasma source was fired 1-2 μs before the Gamble II pulse was delivered to the vacuum inductor, to allow plasma to fill the switch region. A short delay time between firing the plasma sources and firing Gamble II lead to low switch current, while a long delay time lead to larger switch currents. For sufficiently long delay times, the full current (~900 kA) was conducted without opening. The delay was adjusted to give a switch current of 700-800 kA before opening. For this delay, the load impedance was varied to achieve large voltage and power gains. The results of a particular shot are given in Fig. 2, where the diode gap was 13 mm. Figure 2(a) shows the upstream and downstream currents. The peak switch current (difference of upstream and downstream currents) was 720 kA.

Figure 2(b) shows the inductively corrected voltage at the switch, compared with the calculated matched load voltage (into a 2-Ω ideal resistor) that would have been delivered on this shot. The larger, narrower voltage pulse is characteristic of voltage pulses obtained from a PEOS system. The inductively corrected voltage gives the voltage waveshape, but the accuracy is limited by electrical noise. The nuclear diagnostic was used to determine the peak voltage.

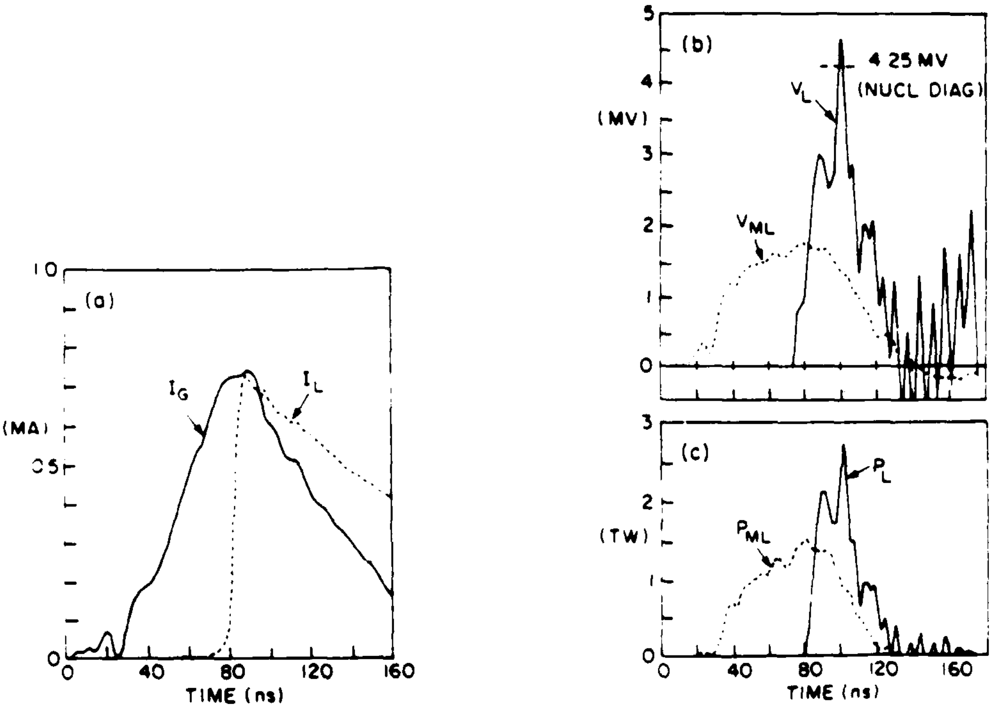

Fig. 2 — (a) Upstream (solid) and load (dashed) currents for shot 3190. (b) Inductively corrected switch voltage (solid) and matched load (dashed) voltage for shot 3190. Also shown is the peak voltage from the nuclear diagnostic. (c) Load (solid) and matched load (dashed) powers for shot 3190.

Figure 3 shows ratios of measured activations for CH_2 foils 8 and 7, and the ratios for combined CH_2 foils (7 & 8) to foils (5 & 6), as compared with calculated ratios based on monoenergetic deuterons. Deuteron energies on the lower scale are for ions arriving at the front of the polyethylene foil stack, while the upper scale is for ions at the front of the aluminum and polyethylene stack. The ratio, foil 8/foil 7, corresponds to a monoenergetic deuteron energy of 4.25±0.05 MeV, and the ratio, foil (7+8)/foil (5+6), corresponds to a monoenergetic deuteron energy of

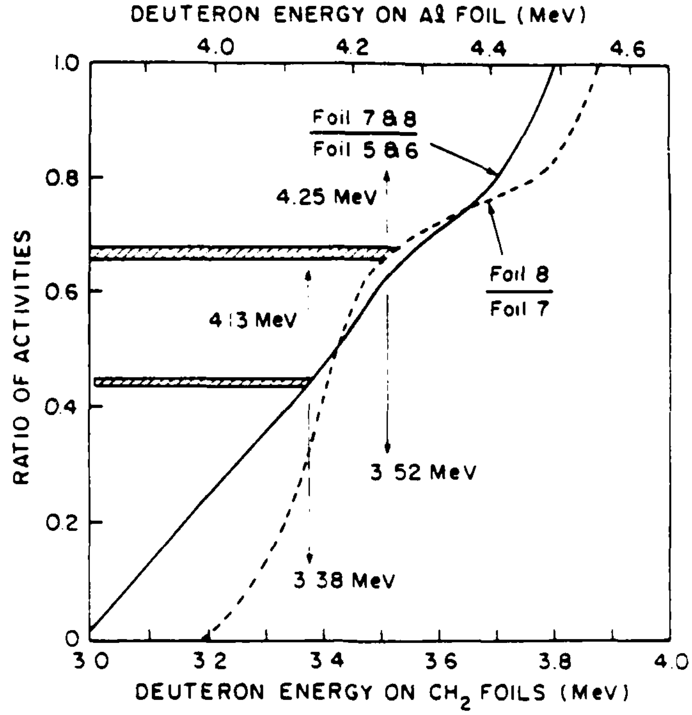

Fig. 3 — Comparison of ratios of measured ^{13}N activation (shaded regions) with calculated ratios for monoenergetic deuterons. The dashed line is the calculated ratio for foils 7 and 8, while the solid line is calculated for foils (7+8) and (5+6). The lower horizontal axis gives the deuteron energy at the front of the polyethylene foils, while the upper horizontal axis gives the deuteron energy at the front of the aluminum foil.

4.13±0.05 MeV. The energy for the second measurement is somewhat lower because the thicker foils sample more low energy deuterons. Results of this nuclear diagnostic indicate a voltage gain of 2.4 over matched load [Fig. 2(b)]. The nuclear result could be lower than the actual voltage due to 1) the averaging of ion yield over the 12.7-μm thick CH_2 foils; and 2) the assumption of monoenergetic ions used in the analysis of the nuclear data. Using the corrected voltage, Fig. 2(c) shows the load power compared with the calculated power to an ideal matched load, giving a power gain of 1.8 over matched load.

Comparison of this shot with the opening switch model, using the physical dimensions of the switch, is consistent with initial plasma densities of n_i=1-5x10^{13} cm^{-3}, and drift velocities, v=2-10 cm/μs, at a constant product of $n_i v$. These parameters are within the range of measured values for the plasma produced by the flashboard plasma sources[11]. The theoretical model is somewhat insensitive to the plasma parameters in this particular geometry, because the electrons are strongly insulated by the large magnetic field at the small cathode radius (60 kG at 750 kA).

The inductive storage/PEOS system on Gamble II has demonstrated substantial voltage and power gain over the matched load values that the generator would normally deliver. A load voltage of at least 2.4 times the matched load voltage was measured, leading to a power gain of 1.8 over the matched load value. Similar voltage and power gain on PBFA II[13] would lead to peak diode voltage in excess of 30 MV and peak power in excess of 150 TW, sufficient for investigating inertial confinement fusion physics.

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