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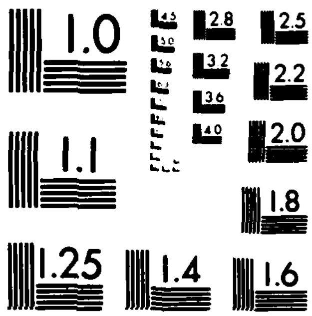
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 5037	2. GOVT ACCESSION NO. AD-A126 268	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) VACUUM INDUCTIVE STORE/PULSE COMPRESSION EXPERIMENTS ON A HIGH POWER ACCELERATOR USING PLASMA OPENING SWITCHES		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. A. Meger,* R. J. Commisso,* G. Cooperstein, and Shyke A. Goldstein*		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 47-0875-0-3
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Nuclear Agency Washington, DC 20305		12. REPORT DATE March 31, 1983 13. NUMBER OF PAGES 20
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

*Present address: JAYCOR, Inc., Alexandria, VA 22304
This work was supported by the Defense Nuclear Agency under Subtask T99QAXLA, work unit 00038 and work unit title "Nuclear Weapons Effects."

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Plasma opening switch
Pulse compression
Voltage multiplication
Inductive storage

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A new type of an opening switch which operates in vacuum and opens on a nanosecond timescale at voltages > 1 MV is described. This Plasma Opening Switch (POS) is able to conduct several hundred kiloamperes for ~ 50 nsec while a vacuum inductor is charged, then to open in < 10 nsec, delivering a large fraction of the stored energy to an electron-beam load. Preliminary experiments are described and a simple model of the POS operations is presented.

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CONTENTS

VACUUM INDUCTIVE STORE/PULSE COMPRESSION EXPERIMENTS ON A HIGH POWER ACCELERATOR USING PLASMA OPENING SWITCHES

1. Introduction

The use of inductive energy storage for pulsed power production is of great interest to accelerator designers. Inductive storage offers the significant advantage of 10 - 100 times higher energy density than conventional capacitive storage systems, thus making more compact and economical generators possible[1]. Energy can be stored in an inductor at low voltage, relaxing insulator design requirements and extracted on a shorter time scale at a higher power level. Present opening switch technology involves the use of explosively activated circuit breakers,[2] wire fuses,[1,3,4] electron-beam (e-beam) controlled diffuse discharges,[5] and various injected plasma schemes.[6] In this paper we report experiments with a new type of opening switch which operates on a nanosecond timescale. These Plasma Opening Switches (POS's) are used in conjunction with a vacuum inductor and open on a <10 nsec timescale. Similar techniques have been used previously for suppression of prepulse and steepening of pulse risetime on high-power generators[7,8,9,10] as well as in plasma filled diode experiments.[11] The work discussed here is directed at storing energy in a vacuum inductor and then extracting this energy on a shorter time scale through a low inductance, high impedance load thereby pulse compressing and increasing the output power level. Results show the switch remains closed for up to 70 nsec as the vacuum inductor is charged. The switch then opens in <10 nsec and most of the energy in the inductor is delivered to an e-beam diode load. Voltage pulse compressions of a factor of 3 and power multiplications of up to a factor of 4 over non-POS shots have been measured. A model of the switch opening is described which qualitatively agrees with the data.

Manuscript approved January 5, 1983.

2. Apparatus

In these experiments the Gamble I accelerator[12] was used to charge a coaxial vacuum inductor section. A 66-kV charging voltage was used to provide a negative 1-MV, 60 nsec full-width-at-half-maximum (FWHM) sinusoidal open circuit voltage waveform with an effective 2-Ohm source impedance. Figure 1a is a schematic of the inductor section as mated to the Gamble I accelerator. Figure 1b is an equivalent circuit diagram of the system. The experimental hardware consists of three main components: a 40-cm long, 100-Ohm coaxial-vacuum inductor; a switch section; and an e-beam diode section. The ~ 140-nH, high impedance vacuum inductor section and the ~ 30-nH insulator region combine to produce the storage inductance $L_S \sim 175$ nH . The 2.5-nsec electrical length inductor looks like a high impedance lumped element load to the 2-Ohm output impedance accelerator, limiting the energy transferred into the inductor. At 66-kV charge Gamble I can store 250 kA or 6 kJ in the inductor. To the right (downstream) of the inductor in Fig. 1a is the opening switch region. Three plasma guns[13] located 12 cm off axis inject carbon plasma through a 10-cm diam. brass screen toward the inner 5-cm diam. cathode support stalk surface (see Fig. 1a). The plasma strikes the cathode surface over a ~60 cm^2 area. The measured plasma density distribution has a peak density of ~ $5x10^{12}$ cm^{-3} and moves with a drift velocity of 7.5 cm/μsec.[14] Measurements of the density distribution have shown spatial fluctuations as high as 25% for these guns. The gun plasma has been reported[13] to be comprised of C^+, C^{2+}, C^{3+}, C^{4+} and H^+ with C^+ and C^{2+} dominating. Also, a neutral carbon component with a velocity of ~ 1 cm/μsec has been observed in the switch region arriving after the plasma. No allowance for plasma stagnation near the outer screen and on the

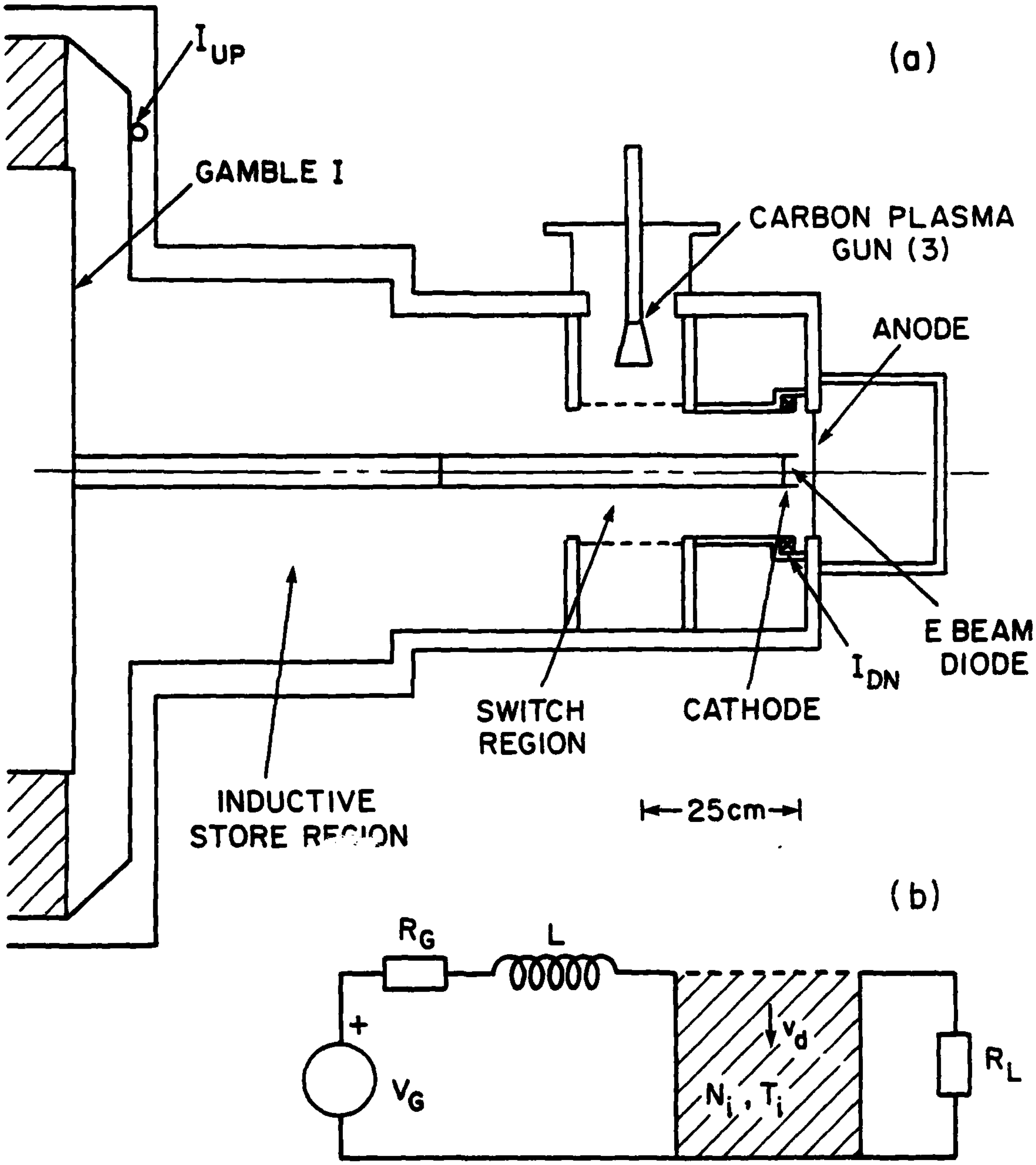

Fig. 1 — (a) A schematic of the Gamble I plasma opening switch experiment. (b) Circuit of the experiment. V_{OC} is the open circuit voltage waveform, R_G is the 2 ohm accelerator impedance, L_S is the inductor, and R_L is the load impedance.

inner cathode surface was made in these experiments. The plasma density in the switch region can be varied by changing the radial location of the gun and the timing relative to the accelerator as well as by changing the screen transmission.

Downstream of the switch region is a 10-cm long, 42-Ohm transmission line segment with inductance L_1 ~14 nH followed by the e-beam diode load. The diode consists of a 6-mm thick rounded edge, hollow cylindrical aluminum cathode opposite a 1.6-mm thick carbon coated aluminum anode. The diode has a critical current impedance of ~ 12 Ohms for the 1-cm anode-cathode (AK) gap used in this experiment.

Diagnostics on this experiment consisted of a voltage monitor upstream (to the left in Fig. 1a) of the Gamble I insulator, a dB/dt current monitor in the inductor section labeled I_{UP} in Fig. 1a and a Rogowski type current monitor downstream of the switch region labeled I_{DN}. In addition, a photodiode with a pilot-B scintillator was located on axis 35-cm downstream of the anode to provide time resolved bremsstrahlung measurements from the e-beam diode.

3. Experimental Measurements

Shown in Fig. 2 is experimental data from two shots, one with the POS and one without. The shots had nearly identical peak accelerator voltage pulses of -960 kV across the inductive store section as measured by the voltage monitor. The accelerator pulse arrived at the inductor 0.5 μsec after the peak of the plasma density as measured by a Faraday cup at the (inner) cathode surface. The currents in the inductor upstream of the switch, I_{UP}, and downstream in the e-beam load section, I_{DN}, are shown in Fig. 2a. The two cases differ dramatically. Without the POS the accelerator sees the full

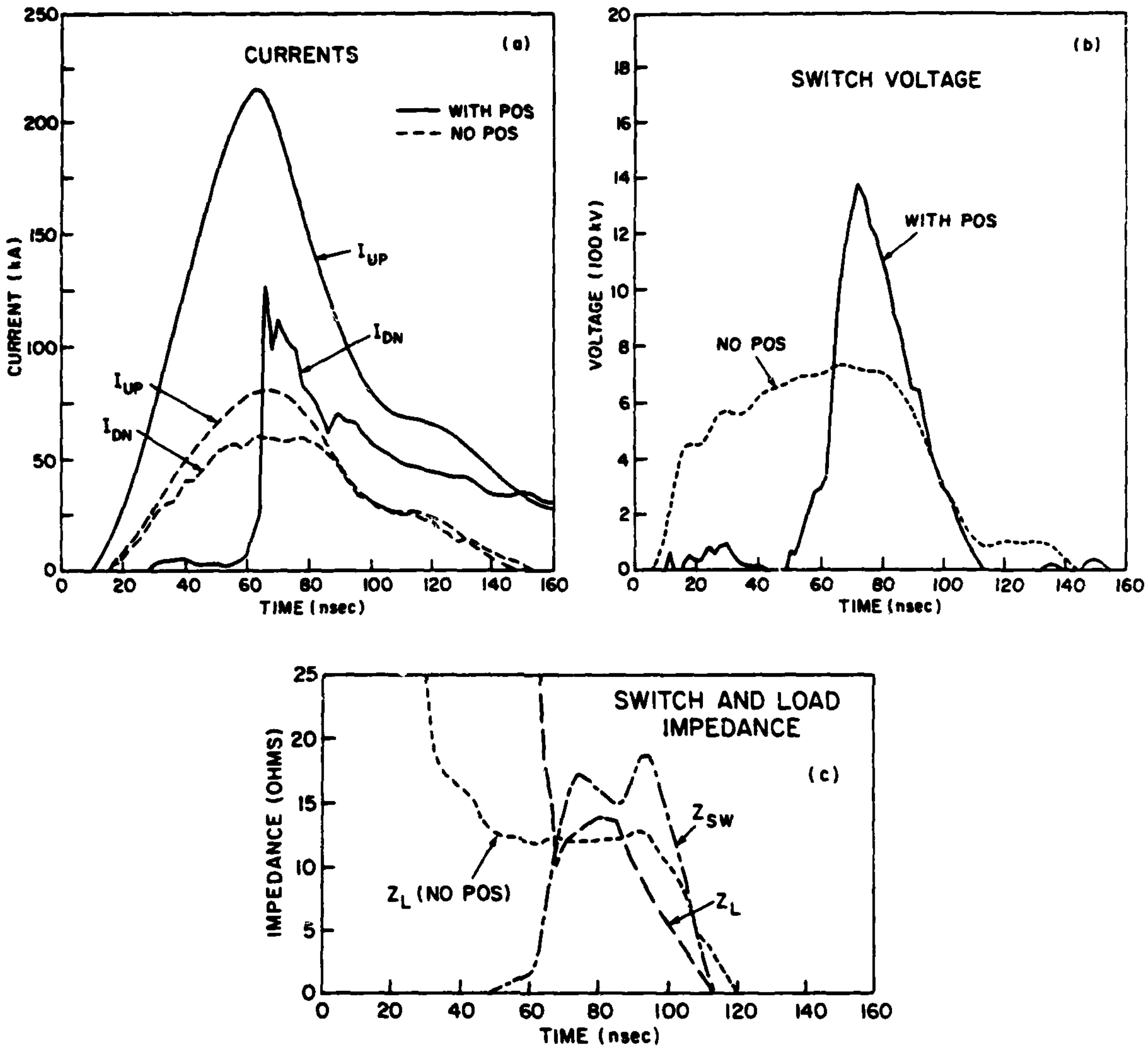

Fig. 2 — (a) Currents upstream I_{UP} and downstream I_{DN} of the switch region, with and without the plasma opening switch. (b) Voltages across the switch for the two cases. (c) Switch impedance Z_{SW} with the POS and load impedance Z_L with and without the POS.

190 nH inductance (inductive store plus transmission line) in series with the ~ 12 ohm e-beam load. Thus the current in the inductor is limited to ~ 80 kA . The downstream current I_{DN} follows the upstream current I_{UP} with some current loss due to cathode stalk emission. With the POS the accelerator sees a 175-nH load inductance into a short circuit for about half of the pulse duration. The switch is closed for the first ~ 50 nsec, as shown in Fig. 2a, during which time it acts as a short circuit, diverting up to 220 kA from the load. When the switch begins to open, the downstream current rises to ~ 130 kA in ~ 6 nsec . The downstream current risetime when the POS opens is ~ 2.2×10^{13} A/sec. An apparent loss of 90 kA occurs in the switch region. This loss is partially in the form of intense beamlets striking the outer conductor just downstream of the switch region and represents a shunt resistance even when the switch has opened. The loss may be related to the geometry of the short line downstream of the switch not properly retrapping the switch electron flow.

Voltages across the switch $V_{SW}=V_D-L_S dI_{UP}/dt$ were computed from the measured insulator voltage V_D and dI_{UP}/dt and are shown in Fig. 2b. The voltage across the load impedance is approximately the same as the switch voltage because $L_1 \ll L_S$. Without the POS the switch voltage peaks at ~ 790 kV and has an 85-nsec FWHM. With the POS the voltage is held near zero during the conduction phase, then rises to 1.4 MV in ~ 20 nsec. The FWHM of the pulse is ~ 25 nsec. The FWHM of the voltage pulse with the POS is reduced by a factor of three and the peak voltage is nearly a factor of two higher than the shot without the POS. The pulse compression and voltage multiplication is a result of the charging of the inductive store and the subsequent extraction of the energy on a shorter time scale. The effective switch shunting resistance $Z_{SW}\equiv V_{SW}/(I_{UP}-I_{DN})$ and the load resistance $Z_L\equiv V_{SW}/I_{DN}$ for the two cases are shown in Fig. 2c. Without the POS the load impedance is 12 Ohms for most of the pulse. With the POS, the switch looks like a short during the conduction phase, then rises to an effective shunt resistance of ~17 Ohms when the switch opens. The load impedance is ~ 13 Ohms during the output pulse.

Time resolved x-ray signals for both cases are shown in Fig. 3. Without the POS a ~ 35-ns FWHM, 25-V peak photodiode signal is measured compared to a 13-ns FWHM pulse and ~225 V peak with the POS. The shape of the x-ray signal and the factor of 8 signal increase agrees with an $I_{DN}(V_{SW})^{2.8}$ scaling of the data.[15]

The increased current and the higher voltage are corroborated by damage to the anode in these two cases. Without the POS the anode damage is confined within a 6-cm diam. circle opposite the cathode. With the POS the anode damage is confined within 4-cm diam. as would be expected from a higher current in the diode. The rear-surface anode spall is observed to be twice as thick for the POS case as without, which is consistent with a higher voltage.

The peak power into the switch and load combination is 0.065 TW without the POS and 0.28 TW with the POS. The four-fold increase in peak power results from the higher voltage and current in the switch. The higher voltage is due to the inductive energy storage and the fast opening action of the POS. With the POS the power pulse has been reduced to the decay time scale of the inductor through the parallel e-beam and switch load resistances. Another measure of power multiplication is to compare the peak power delivered by the Gamble I accelerator to a matched load to that delivered when an inductive store and POS are used. The open circuit voltage waveform was derived from the data in Fig. 2. A transmission line code[16] was used to reproduce the measured diode waveforms, then to compute output waveforms for a 30-nH, 2-Ohm

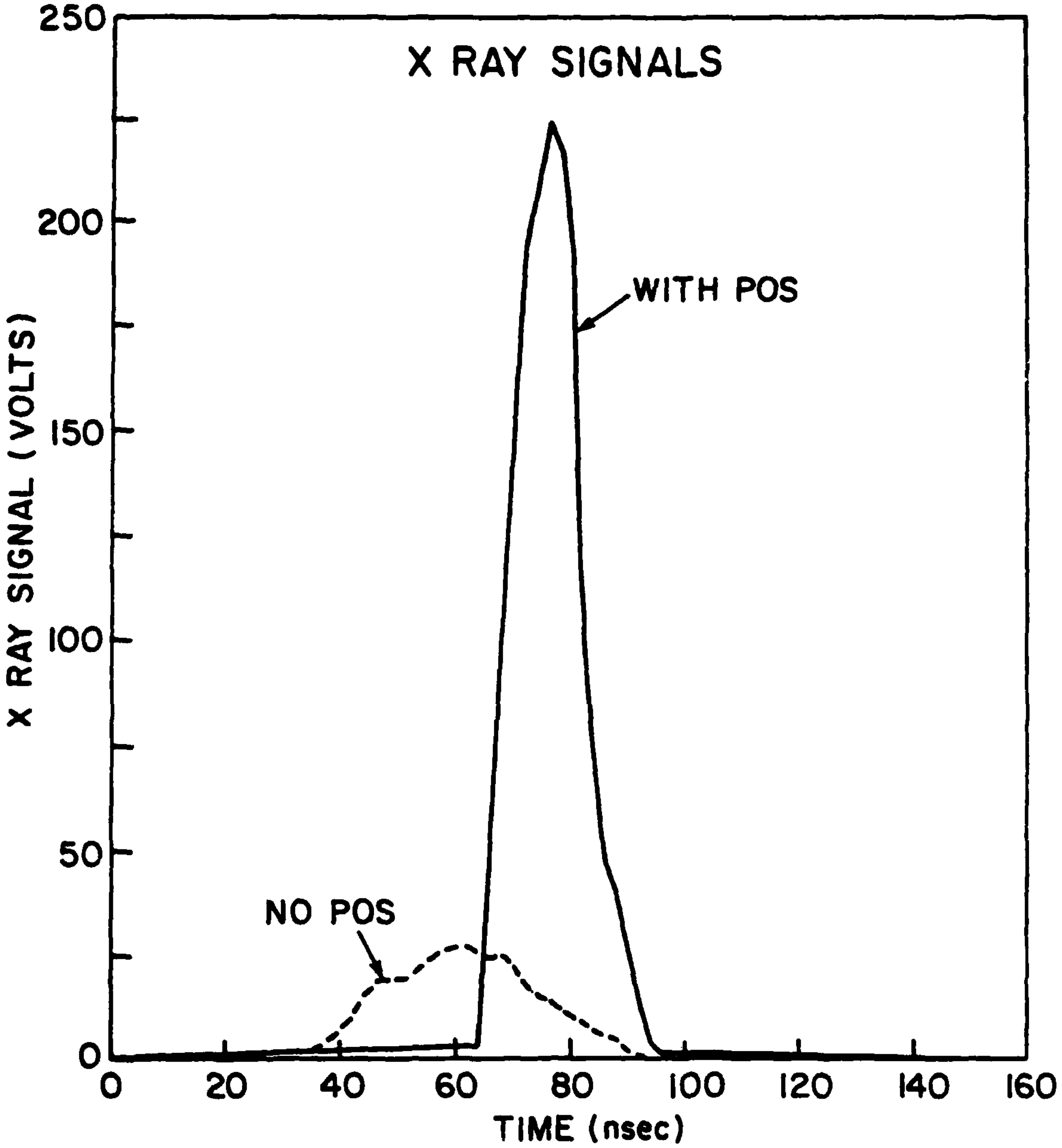

Fig. 3 — X-ray signals as measured by a photodiode with and without the POS.

load which represents the optimum Gamble I load impedance. Peak power for this idealized diode was 0.14 TW which is one-half the measured peak power with the inductive store and POS.

Many shots were taken with different plasma densities in the switch region and with different timing between the arrival of the plasma in the switch region and the arrival of the accelerator pulse. The switch opening was observed to be reproducible within the limits of the plasma gun and accelerator pulse reproducibility. The duration of the conduction phase was reduced if the plasma density in the switch region was decreased by either moving the guns further away from the inner conductor or by injecting the beam earlier in the plasma pulse. With such adjustments the switch could be made to divert only the leading edge of the accelerator pulse as desired for prepulse suppression or to divert as much as 250 kA with the switch still opening in $\sim$ 10 nsec. The conduction time could also be changed with apertures or attenuating screens in front of the guns. If the accelerator pulse was delayed more than one microsecond after the peak plasma density at the inner conductor or if too much plasma was injected, the conduction period increased and the opening time became slower. In the extreme case the switch diverted the entire pulse from the load. Reducing the accelerator voltage increased the switch conduction period. If the conduction time extended beyond the peak inductor current, the switch opening time increased to $\gtrsim$ 25 nsec. An extended parameter study is presently being performed on these variables.

4. Opening Switch Model

A simple model of the opening switch operation will be presented to explain the experimental results. The model is based on bipolar flow in a Child-Langmuir diode and includes magnetic field effects. The model consists of four phases, each of which is treated separately, but the switch progresses from one phase to the next as critical current levels are reached in the switch or load. The four phases are the conduction phase, a simple bipolar-erosion phase similar to previous models,[6,7] an enhanced-erosion phase, and finally a magnetic-insulation phase. The model ignores magnetic-field-pressure effects, surface-physics effects and neutral-background-gas effects.

Phase I of the switch operation begins with a plasma in the switch region of a known species, density, charge state, average drift velocity toward the cathode, and temperature. The switch plasma fills the region uniformly and strikes a finite area on the cathode surface. A schematic representation of the system is shown in Fig. 1b. A load resistance is located downstream of the switch. The accelerator is fired and a voltage appears across the inductor, driving current through the inductor and switch. As a finite voltage appears across the plasma, a sheath forms near the cathode. In this sheath the electrons are swept out producing a planar-diode-like gap with the cathode surface on one side and the edge of the plasma on the other. The gap adjusts itself such that the cathode surface becomes a space-charge-limited-electron emitter while the plasma supplies ions to the opposite side of the gap producing a bipolar current flow across the gap. The current driven through the plasma is limited by the accelerator output driving the entire system and by the series inductor. Ions enter the gap due to their drift velocity and the component of the ion thermal velocity normal to the cathode. In such a bipolar diode the ion flux necessary to maintain the current flow[17] is

$$j_i/j_e = (m_e/2M_i)^{1/2} (\gamma+1)^{1/2} \qquad (1)$$

where m_e, M_i and $\gamma\, m_e c^2$ are the electron rest mass, ion rest mass, and maximum electron energy, respectively, and c is the speed of light. The total bipolar current density is

$$j = j_e + j_i = (1 + j_i/j_e)\ 4.3\times10^{-6} V^{3/2}/d^2 \qquad (2)$$

where V is the voltage across the gap in volts and d is the gap thickness in cm. For example, according to Eq. (1) a C^+ plasma with a charge flux of 20 A/cm^2 as used in the experiments is sufficient to drive almost 3 kA/cm^2 in total current (electrons and ions) across the gap. If the accelerator current density through the switches is less than this level Eq. (1) is satisfied and the gap will not increase. In addition, if the switch plasma becomes resistive so that a finite electric field penetrates the plasma, ions can gain enough energy on the beam timescale to further increase the charge flux into the gap. This allows more current to be driven across the bipolar gap without affecting the gap size. Under these conditions the switch impedance remains low as observed experimentally during the conduction period of switch operation.

Phase II begins when the accelerator current density exceeds the level where the ion flux into the gap is sufficient to maintain bipolar flow across the plasma-gap interface. An additional ion flux is provided by eroding the plasma thereby opening the gap. The increasing gap raises the effective resistance of the switch. With the series inductor the system acts like a constant current source, increasing the voltage across the switch impedance which in turn increases the erosion rate. This feedback process produces opening velocities of ~ 10 cm/μsec under the experimental conditions presented in this paper. This process starts the switch opening but can open the gap by only 1 mm in 10 nsec. Phase III begins when electron trajectories are altered significantly by the self-magnetic field associated with the current flow in the switch and the diode load. This field bends the electrons downstream and they travel along the plasma surface for the length of the switch plasma. This increases the electron space charge near the boundary and enhances the ion emission in a manner similar to a pinch-reflex ion diode.[17] This changes Eq. (1) into

$$j_i/j_e = (m_e/2M_i)^{1/2} (\gamma+1)^{1/2} L/d \ , \tag{3}$$

where L is the axial length of the plasma. For small gaps this L/d enhancement factor can increase the ion flux by a large factor. Opening velocities of ~ 10^2 cm/μsec are obtained so that a gap opening of 1 cm in 10 nsec is expected.

As the switch impedance increases to the load impedance and beyond, the load begins to conduct a larger fraction of the current. Phase IV begins when the diode current exceeds the current $I = I_c/\gamma = 8.5\times10^3 \ \beta R/d$ amp in the switch region, where I_c is the critical current and β is the electron velocity (normalized to the speed of light) at full voltage. The electrons then become magnetically insulated and travel downstream to the load. Since the electrons no longer cross the gap, the switch current becomes that of a single species Child-Langmuir diode pulling carbon ions out of the plasma. Its effective impedance is much higher than for the bipolar case which accounts for the rapid increase in the switch impedance.

The simple switch model described here has all the experimentally observed features. It allows for a conduction period before the switch current exceeds the ion flux criteria. It can explain the observed 10 nsec opening times and shows why the switch impedance increases when magnetic insulation in the switch is obtained. It does not explain the observed losses at the downstream end of the switch region. These losses most likely depend on the impedance mismatch between the opening switch and the downstream section of transmission line.

5. Conclusion

Experimental results have been presented which demonstrate the operation of a Plasma Opening Switch. The switch was shown to conduct current for ~ 50 nsec while a vacuum inductor was charged. Then the switch opened in an interval of ~ 10 ns producing a voltage in excess of 1 MV and delivering a large fraction of the inductively stored energy to an e-beam diode load. The rapid opening is attributed to enhanced erosion effects in the switch due to the beam's self-magnetic field. The output voltage pulse was compressed by a factor of three and increased by a factor of two. The power delivered to the load increased by a factor of four compared to measurements without the switch and by a factor of two compared to the accelerator's matched load peak power. In the closed state the switch successfully diverted > 200 kA of current. A current loss of 90 kA observed in the switch region may be related to electron losses downstream of the switch in the short section of the transmission line.

A simple model of the opening switch was presented which agrees qualitatively with the observed switch operation. This model suggests further experiments which will provide further insight into the operation and improved design of such switches.

The method described here is applicable to many pulsed-power accelerators. It offers a wide range of applications from prepulse suppression to compact inductive energy storage and power multiplication. The POS can lower the inductance between the final energy store and the load which limits the pulse risetime. Applications to multi-line accelerator systems to eliminate line to line jitter are envisioned as well as in other experiments requiring fast risetime, high power pulses. Future experiments will focus on scaling of the switch operation to higher currents and voltages and a better understanding of the opening process.

6. Acknowlegements

The authors would like to acknowledge the technical assistance of M. Sucy, A. Robinson, and J.R. Boller; useful discussions with P.F. Ottinger, R.J. Barker and J.D. Shipman, Jr.; and experimental help from F.C. Young and J.M. Neri. This work was supported by the Defense Nuclear Agency.

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