HIGH DENSITY PLASMA OPENING SWITCH EXPERIMENTS ON HAWK[+]

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ABSTRACT

Previously, plasma opening switch (POS) experiments[1] on Hawk have shown fast opening (< 100 ns) into electron-beam diode loads, generating 1-2 MV after 0.5-1 μs conduction time. The plasma density measured in these experiments was in the 10^{15} - 10^{16} cm^{-3} range. Plasma thinning by $J \times B$ forces during conduction[2] reduces this density, ultimately leading to gap formation in the low density region. The Hawk experiments described here were designed to investigate this switching phenomenon with higher initial densities, in the 10^{17} cm^{-3} range, to determine whether fast switching and high voltage could be sustained. This scaling is important for POS applications on future, higher energy generators. Experiments were performed with a relatively small center conductor radius (1.27 cm) and small plasma length (3 cm or 8 cm). Either 36 or 12 cable gun plasma sources were used to inject plasma into the coaxial switch region. The anode structure was varied to investigate techniques to increase the voltage when the switch opens. High voltage (1.5 MV) switching was observed at ~ 0.9 μs conduction time when the radial gap between the inner and outer conductors in the switch region was reduced from 7 cm to 2 cm. Two techniques that improved switching on the DPM1 experiment[3] at conduction times < 600 ns were investigated on Hawk: (1) removing the physical connection on the anode through the switch plasma, and (2) varying the radius of the anode conductor on the load side of the switch. These changes had no noticeable effect on the switch voltage for the longer conduction time scale of Hawk. The number of plasma sources had little effect on the voltage. These experiments demonstrate that, at least for some geometrical configurations, POS operation at 10^{17} cm^{-3} density is similar to operation at one or two orders-of-magnitude lower density. Presumably, the plasma thinning mechanism results in a similar gap in all cases.

INTRODUCTION

Long conduction time (~ 1 μs) plasma opening switches (POS) are the subject of intense research for pulsed power development. Successful implementation of such switches will enable inexpensive, compact pulsed power generators without water lines. The Hawk generator at the Naval Research Laboratory (NRL) is a testbed for long conduction time POS development. Hawk consists of a 250 kJ Marx with typical output voltage of 640 kV and a vacuum inductor, initially shorted by a POS as shown schematically in Fig 1. The current through a short circuit at the POS location is a sine wave with 750 kA amplitude and a quarter period of 1.2 μs. In previous POS experiments on Hawk, the injected plasma density was in the 10^{15} - 10^{16} cm^{-3} range, resulting in 0.5-1.0 μs conduction times and voltages as high as 2 MV.[1]

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUL 1995	**N/A**	-

4. TITLE AND SUBTITLE	
High Density Plasma Opening Switch Experiments On Hawk	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Pulsed Power Physics Branch, Plasma Physics Division Naval Research Laboratory, Washington, DC 20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
Previously, plasma opening switch (POS) experiments1 on Hawk have shown fast opening (< 100 ns) into electron-beam diode loads, generating 1-2 MV after 0.5-1 J.1S conduction time. The plasma density measured in these experiments was in the 101s- 1016 cm"3 range. Plasma thinning by J x B forces during conduction2 reduces this density, ultimately leading to gap formation in the low density region. The Hawk experiments described here were designed to investigate this switching phenomenon with higher initial densities, in the 1017 cm"3 range, to determine whether fast switching and high voltage could be sustained. This scaling is important for POS applications on future, higher energy generators. Experiments were performed with a relatively small center conductor radius (1.27 em) and small plasma length (3 em or 8 em). Either 36 or 12 cable gun plasma sources were used to inject plasma into the coaxial switch region. The anode structure was varied to investigate techniques to increase the voltage when the switch opens. High voltage (1.5 MV) switching was observed at~ 0.9 f.LS conduction time when the radial gap between the inner and outer conductors in the switch region was reduced from 7 em to 2 em. Two techniques that improved switching on the DPMl experiment3 at conduction times < 600 ns were investigated on Hawk: (1) removing the physical connection on the anode through the switch plasma, and (2) varying the radius of the anode conductor on the load side of the switch. These changes had no noticeable effect on the switch voltage for the longer conduction time scale of Hawk. The number of plasma sources had little effect on the voltage. These experiments demonstrate that, at least for some geometrical configurations, POS operation at 1017 cm"3 density is similar to operation at one or two orders-of-magnitude lower density. Presumably, the plasma thinning mechanism results in a similar gap in all cases.

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6</td><td rowspan="2">19a. NAME OF RESPONSIBLE PERSON</td></tr>
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Prescribed by ANSI Std Z39-18

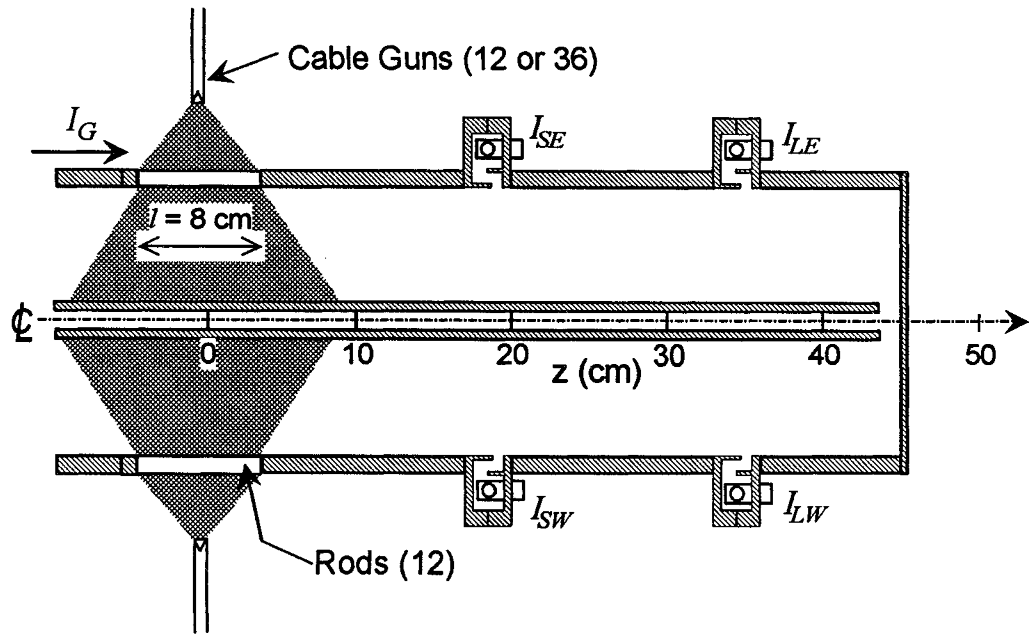

Figure 1. High density POS experiment on Hawk.

The fast switching in these experiments is believed to be related to a "plasma thinning" mechanism, where the plasma is redistributed by $J \times B$ forces during conduction resulting in a low density region where gap opening can occur, by a combination of erosion and magnetic pressure. The physical size of the gap calculated from simple magnetic insulation relations is about 2-3 mm. The density reduction during conduction has been observed in some experiments using laser interferometry.[2] The density, averaged along an axial line of sight, becomes smaller than the sensitivity of the instrument (about 10^{14} cm^{-3} $\times$ 10 cm) at the time of opening. This density reduction by more than two orders of magnitude is probably required to obtain high voltage switching. Without this density decrease, the POS would conduct the generator current and eventually propagate axially to the load as a plasma flow switch.

POS operation may limited at higher density. If the plasma thinning mechanism only decreases the initial density by a fixed factor, the density prior to opening may be too high to allow vacuum gap formation, resulting in low voltage generation. If, on the other hand, higher density allows higher conducted current *density*, the plasma thinning may be expected to continue until vacuum gap formation occurs, similar to that obtained in the lower density cases. The conditions for productive plasma thinning are not well known, and may depend on many factors including the plasma distribution and the electrode shapes. In the Hawk experiments reported here, high density (~10^{17} cm^{-3}) POSs were investigated for several anode configurations, showing that at least for one configuration, high voltage (1.5 MV) can be obtained after 0.9 μs conduction time.

HIGH DENSITY POS EXPERIMENTS ON HAWK

The POS plasma sources shown in Fig. 1 are cable guns, constructed from semi-rigid coaxial cable with an inverted cone drilled into the end. Current from a capacitor is discharged across the insulator (Teflon, C_2F_4), creating a plasma that flows into the region between the inner and outer

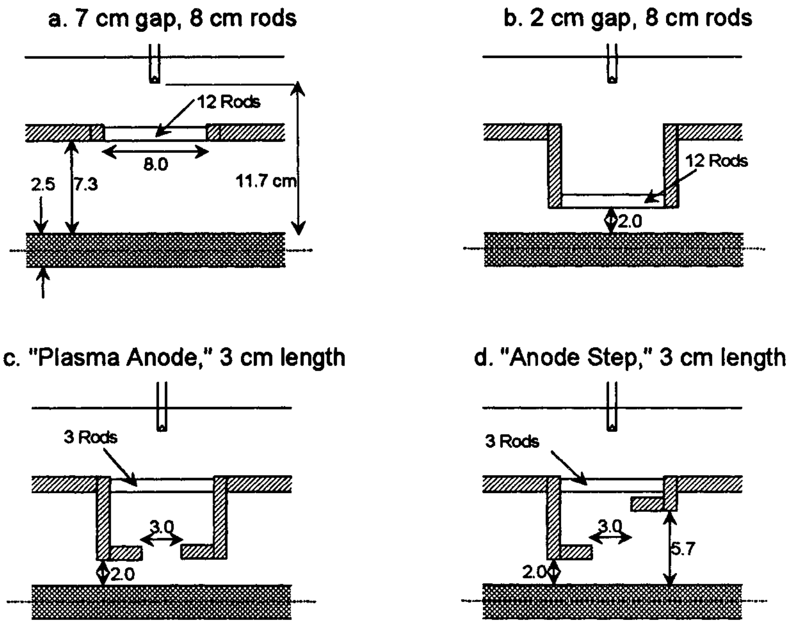

Figure 2. Anode variations used in high density POS experiments on Hawk: a) 8 cm length, 7 cm radial gap in POS region, b) 8 cm length, 2 cm radial gap in POS region, c) "plasma anode" configuration, where plasma connects the 3 cm long break in the anode in the POS region, and d) the "anode step" configuration, where the radial gap is increased on the load side of the POS to 5.7 cm.

conductors with a flow velocity of a few cm/μs. For these experiments, either 12 or 36 guns were arranged azimuthally in one ring to provide the high density plasma.

The density, n, required to conduct the Hawk current, $I(t)$, depends on the center conductor radius, r, and the plasma length, l,

$$n \cong \frac{1.6\times10^{20}}{r^2 l^2}\iint I^2 dt^2 \tag{1}$$

where cgs units are used except I(amps).[4] This scaling relation has been determined from other cable-gun and flashboard POS experiments on Hawk where the plasma density was measured during shots using a He-Ne laser interferometer. High density will be required when r and l are small. For the experiments reported here, the center conductor radius was 1.27 cm and the plasma length was either 8 cm or 3 cm.

The geometry of the outer (anode) conductor was varied as shown in Fig. 2. The two variations in the top half of Fig. 2 utilize 12, 8-cm-long rods to connect the two sides of the plasma injection region. These two configurations differ by the distance between the center conductor and the rods. The configurations in the bottom half of Fig. 2 depend on the injected plasma to connect the two sides of the anode, therefore the name "plasma anode." These two configurations differ on the load end, where the distances between the center conductor and anode are changed. The increased radial distance on the load side of the plasma injection region is called the "anode step." The distance between the guns and the center conductor was either 12 cm or 6 cm.

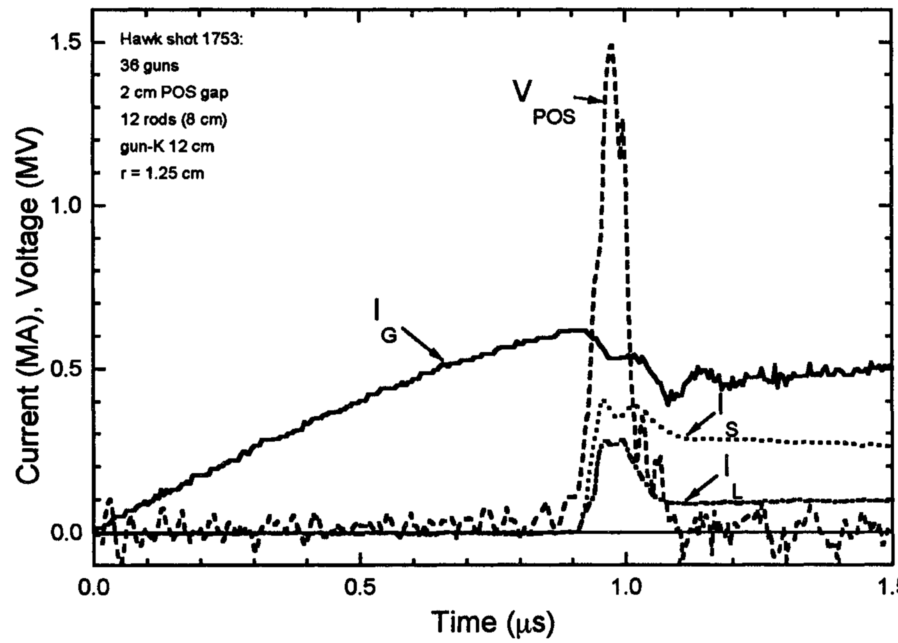

Figure 3. Electrical measurements for Hawk shot 1753, using the configuration shown in Fig. 2b. The conduction time is 0.9 μs on this shot. The voltage rises when the POS opens, with a maximum of 1.5 MV. The currents measured on the load side of the POS (I_S and I_L) indicate current loss in the POS-load region.

RESULTS

Sample electrical data from a high voltage, long conduction time shot are shown in Fig. 3. This shot used the anode geometry illustrated in Fig. 2b (2 cm gap, 8 cm rods). The generator current, I_G in Fig. 3, rises to 620 kA in 0.9 μs while the POS is "closed." The POS voltage, V_{POS}, increases to 1.5 MV when the POS "opens," beginning at t = 0.9 μs. Current measurements between the POS and the load, I_S and I_L indicate current losses that occur because the load impedance and POS-load inductance are higher than optimum for the POS. In principle, the POS-load inductance and load impedance could be reduced to optimize the power and energy delivered to the load.

The POS density inferred from Eq. 1 for the shot in Fig. 3 is 6×10^{16} cm^{-3}. For the same conduction time but a shorter length of 3 cm (as with the anode configurations in the bottom of Fig. 2), the required density is 4×10^{17} cm^{-3}. Therefore, the POS experiments with different anode configurations should be able to investigate POS operation with densities in the $\sim 10^{17}$ cm^{-3} range.

Results from the two configurations in the top half of Fig. 2 are compared in Fig. 4. These configurations have 8 cm rods located either 2 cm or 7 cm from the center conductor. The distance between the guns and the cathode was either 12 cm or 6 cm for the 2 cm gap case. The plot shows the maximum POS voltage as a function of conduction time. The highest point corresponds to the shot in Fig. 3.

The "best" configuration, from the point of view of voltage generation, is the 2 cm gap, 12 cm gun-cathode distance configuration. The voltage decreases abruptly for conduction times greater than 0.9 μs, possibly because the plasma dynamics during conduction are different, leading to smaller gap

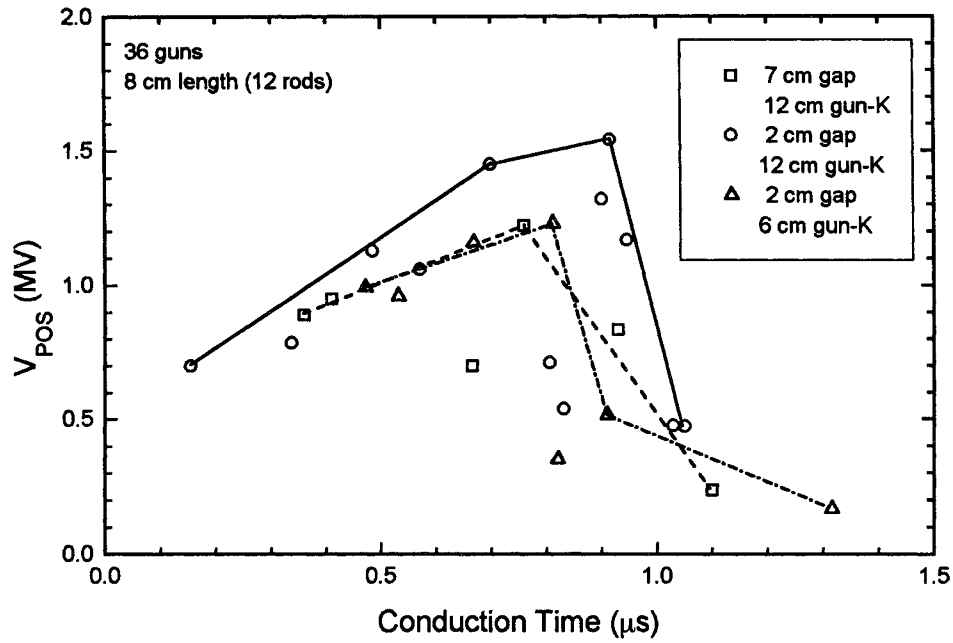

Figure 4. Maximum POS voltage is plotted versus conduction time for the three variations indicated in the plot. Decreasing the gun-cathode distance from 12 cm to 6 cm results in decreased voltage, as does increasing the distance between the cathode and the rods from 2 cm to 7 cm.

formation. The desirable high voltage performance is somewhat irreproducible as evidenced by the two low points at 0.8 μs conduction time.

The voltage decreases noticeably when the gun-cathode distance is decreased to 6 cm. This result is probably related to the change in plasma distribution. The results with a larger gap between the center and outer conductors are similar to those with the decreased gun-cathode distance.

Results from the "plasma anode" and "anode step" configurations are compared with the 2 cm gap results in Fig. 5. The plasma anode configuration results in lower voltage than the other configurations. The anode step results in somewhat increased voltage, but is significantly lower than the 2 cm gap configuration. These configurations differ in both the density required to conduct the generator current and the plasma length. Both of these changes may contribute to the decreased voltage generation for these configurations.

CONCLUSIONS

Experiments have been performed on Hawk to explore POS operation with plasma densities in the 10^{17} cm^{-3} range, one to two orders of magnitude higher than in previous Hawk experiments. Parameters that influence the voltage generated when the switch opens include the plasma source locations and the outer conductor configuration. Of the four outer conductor configurations investigated, one is superior in the sense that the voltage generated (1.5 MV) is highest at the longest conduction time (0.9 μs). Configurations using the "plasma anode" and "anode step" configurations, similar to those that proved superior on the DPM1 experiment,[3] resulted in lower voltage than the best configuration, an 8-cm long aperture connected with rods, located 2 cm from the cathode.

In order to design an optimum POS configuration for a given generator (or, to design an optimum generator for a given POS) requires a model that explains these results. Future work has this

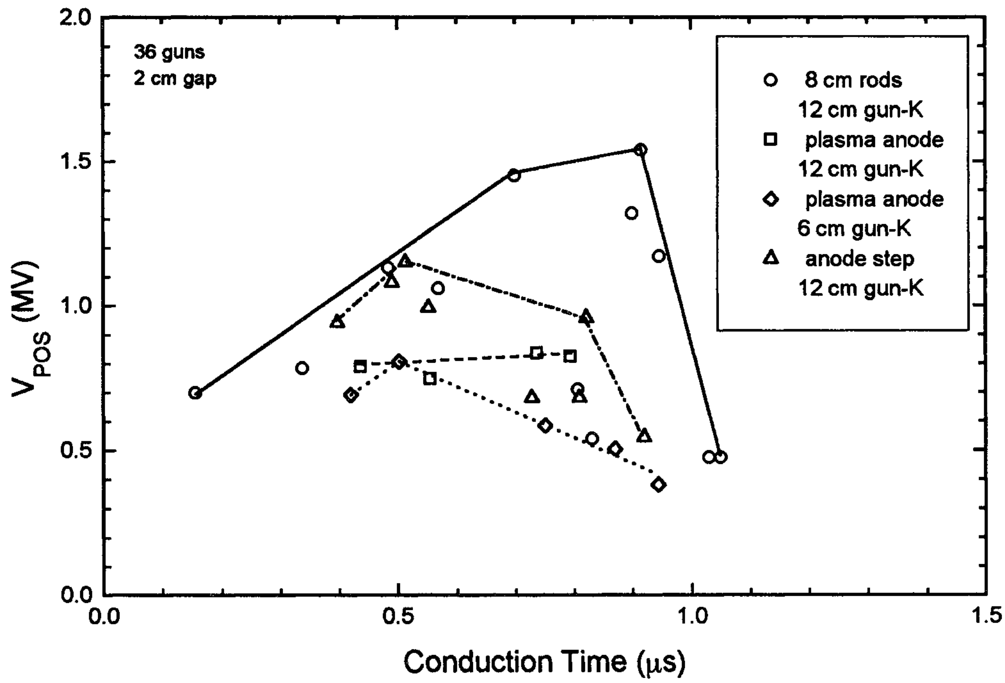

Figure 5. Maximum POS voltage versus conduction time are compared for the best configuration in Fig. 4 and the plasma anode and anode step configurations. The plasma anode and anode step configurations result in decreased voltage relative to the 8 cm rods, 2 cm gap case.

objective, using experimental measurements of plasma dynamics and combined MHD/Hall modeling of the conduction phase coupled with particle modeling of the opening phase.

ACKNOWLEDGMENTS

The authors are pleased to acknowledge the support of Dr. J. Rowley of the Defense Nuclear Agency. The Hawk experiments were performed with the expert technical assistance of M. Sucy.

+ Work Supported by DNA

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