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Title: Plasma Flow Switch Experiment on Procyon

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PLASMA FLOW SWITCH EXPERIMENT ON PROCYON

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We report here results obtained from a series of plasma flow switch experiments done on the Procyon explosive pulse power generator. These experiments involved switching into a fixed inductance dummy load and also into a dynamic implosion load. The results indicated that the switch did fairly well at switching current into the load, but the results for the implosion are more ambiguous. We compare these results to calculations and discuss the implications for future plasma flow switch work.

Introduction

The purpose of a plasma flow switch is to work as an opening switch in an inductive storage pulse power device. A good opening switch will convert the long rise time typical of these devices into the shorter current rise times required for z-pinch experiments designed to produce high intensity radiation sources. The motivation for this type of pulse power machine is that it is less expensive to build. The difficulty has always been in getting the switch to work as well as one would like.

A detailed discussion of plasma flow switches is given by Turchi;¹ In simple terms it consists of an annular conductive plasma across the inner and outer electrodes in a coaxial transmission line. The magnetic force in the coax then pushes the plasma down the transmission line. The mass in the plasma flow switch is fixed so that the plasma reaches the load region at the desired time in the current pulse. The plasma then rapidly flows across the load region, incorporating this region into the circuit and switching the current into the load. There was a significant amount of work done at the Air Force Weapons Lab(AFWL) to develop this switch. They were able to get very good switching into an implosion load and significant radiation output from that implosion.² More recent efforts at reproducing this work on the Pegasus machine at Los Alamos have not met with the same success.³ This we believe is due to a variety of effects which may not have been a problem on the Shiva Star machine at AFWL. One of these effects has to do with a plasma boundary layer which forms on the walls of the electrodes as the plasma flows down the coaxial transmission line. It was concerns about this particular problem that led to a redesign of the plasma flow switch for experiments on Procyon.

Plasma Flow Switch Design for Procyon

The typical plasma flow switch design seeks to create a plasma density profile which varies as $1/r^2$ to match the radial dependence of the magnetic force. Thus, if there were no other effects, the plasma would move down the coax in a planar manner without tilting. Because of the boundary layer that forms, a significant amount of plasma can be dragged across the load, preventing good switching. This was seen to be the case on the first experiments done on Pegasus⁴ and was reduced significantly by using a trap for this plasma. Preliminary calculations for Procyon showed that the trap did not do much good and the boundary layer prevented the switch from working properly. It was then decided to try a different mass profile to reduce the effect of this boundary layer. The profile decided upon was a $1/r$ mass profile. With this profile, the acceleration on the plasma at the inner radius is greater than at the outer radius, thereby pushing the plasma on the inside down the coax faster. This leads to a "gating" effect, where the plasma flow switch tries to open from inside out like a swinging gate. Preliminary calculations indicated that this worked much better and so this was tried on Procyon with a dummy load. The results from this experiment, called PSS-7, were presented at the last pulsed power conference.⁵ The switch worked, but not in the predicted manner as it opened at a much earlier time. This turned out to be due to a wall instability that occurs that causes a region of plasma near the wall to thin out. The magnetic field then pushes this region out, popping out of the plasma like a bubble. This bubble popping causes the switch to open and current to transfer to the load.

This design was fired three more times on Procyon. The first of these shots used a fixed inductance dummy load but with a higher inductance than the previous shot. The results of this shot were consistent with the PSS-7 shot until the switch opened. At that time a breakdown occurred in the power flow channel which prevented the switch from working properly. The next experiment used a 30 mg aluminum foil as an implosion load. In this case the vacuum insulator broke down at the beginning of the current pulse and so very little current reached the switch. There was therefore no significant results from that shot.

The last shot fired, designated PC-3, was a successful shot. The machine performed as expected and there were no unexpected breakdowns in the power flow channel to weaken the performance of the switch. We will focus on results of this shot and compare these results to the results from PSS-7 and to calculations.

Description of the PC-3 Experiment

The PC-3 experiment consisted of the standard Procyon generator which has been described in detail by Goforth.⁵ We used a plasma flow switch which consisted of an aluminum foil and a Mylar barrier film. The foil had a total mass of 130 mg and this mass was distributed with a $1/r^2$ dependence. The mass of the barrier film was 60 mg and the total combined mass distribution was $1/r$. The load for this experiment was an aluminum foil with a mass of 32 mg. The foil had an initial radius of 5 cm. and was 2.0 cm. in height.

A schematic of the experiment is shown in figure 1. This figure shows the physical structure of the power flow channel and the load region. The aluminum graded foil plasma flow switch and the barrier film are shown at their initial position as is the 32 mg load foil. The main diagnostic used for the plasma flow switch were magnetic probes. These probes were put along the outside conductor in the power flow channel and along the glide planes in the load region. The positions for these probes and their labels are shown in the figure. We also had faraday rotation sensors and rogowski coils to measure the current in the machine and in the load region.

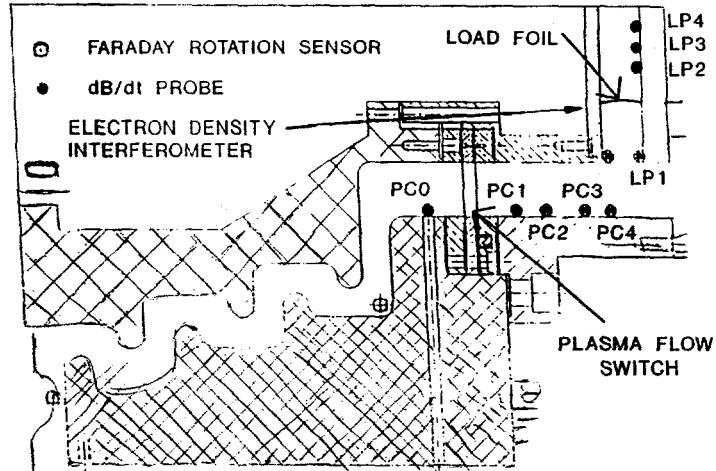


Figure 1. Schematic of Plasma Flow Switch Region for PC-3.

To diagnose the pinch, we had two sets of x-ray diode(xrd) detectors looking radially at the pinch and one set looking axially. We also had a set of bolometers looking radially and a visible framing camera looking radially. A time-integrated x-ray pinhole camera looking at the few kev photon energy was also used to image the pinch.

Results

The Procyon generator went off nearly as expected, producing the current drive we anticipated for the shot. There was a problem with some of the switching in the generator and so the timing of the current was off by a microsecond. In figure 2 we show that signal from a faraday rotation sensor for this shot compared to a previous Procyon shot. The PC-2 signal has been moved about 1 μ s early in the figure, and we see that the signals are very reproducible.

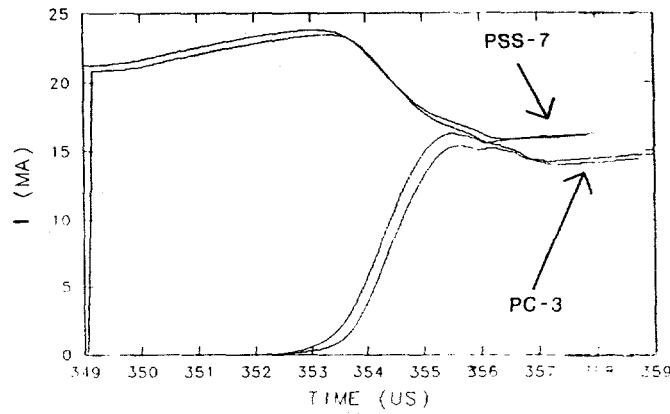


Figure 2. Comparison of the Storage and Load Current for PSS-7 and PC-3.

In figure 3, we have plotted the signals from the magnetic probe measurements down the power flow channel. These signals show the movement of the plasma flow switch down the channel and then the opening of the switch

due to the wall instability occurring at the time of 356.6 microseconds. Since the downstream probes are on the outside electrode, the plasma can be shielding these probes and so the field they measure is not due to the full current flowing in the machine.

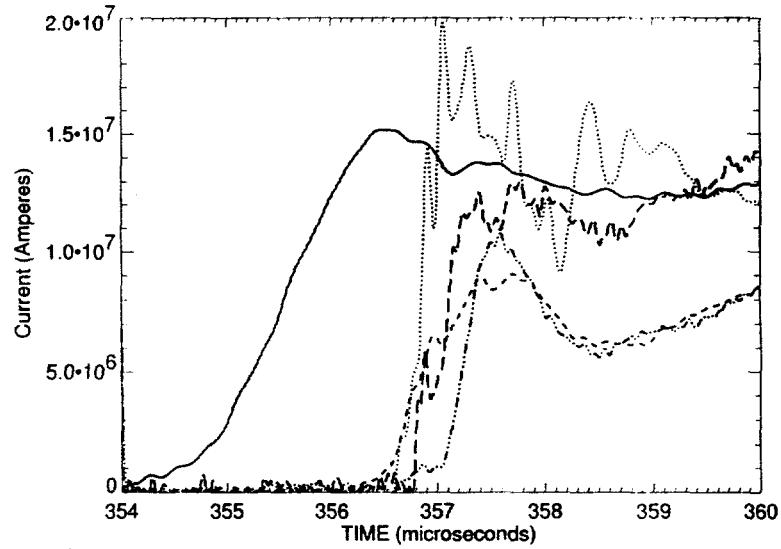


Figure 3. Magnetic Probe Measurements for the Power Flow Channel Region. (— PC0, - - - PC1, - · - PC3, - - - PC4, - · · - PC6).

Figure 4 shows a comparison of probe pc3 with the same probe from the PSS-7 shot which used the same plasma flow switch with a fixed dummy load. These signals are very similar and we believe the plasma flow switch has functioned similarly in both cases.

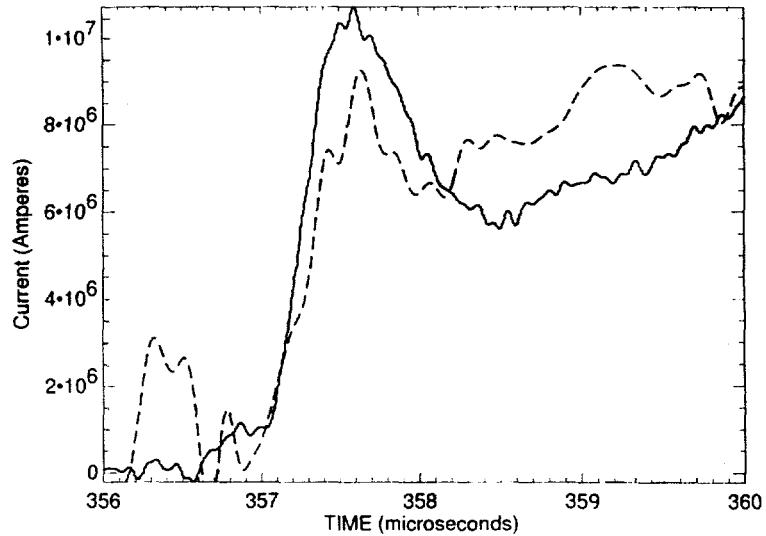


Figure 4. Comparison of Probe PC3 With the Similar Probe From PSS-7. (— Shot PC3, - - - Shot PSS-7.)

The load probes also indicate that this current caused the load to pinch. Signals from these probes are shown in figure 5.

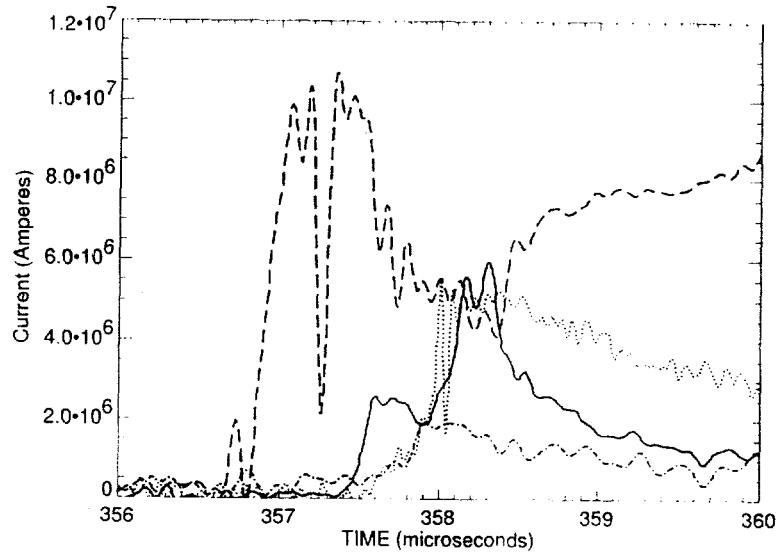


Figure 5. Magnetic Probe Measurements for the Implosion Load Region.
 $(--\text{LP1}, -\text{LP2}, \cdots\text{LP3}, -\cdots\text{LP4})$.

One can see that although the initial current into the load slot appears to reach about 10 MA, that this level drops as the load implodes. In fact the probes indicate that only 2 MA reaches 1.0 cm radius. This may be a somewhat pessimistic measurement as these probes do not measure the field far away from the glide planes but at a position only 2 mm from the wall. We have seen before that these implosions often leave material along the wall which could shield the probes. Simulations which were done for this experiment predict that more of the current should reach the center. Figure 6 shows a plot of the predicted current levels into the load region. These simulations predict that for the curves shown we expect a radiated output of 500 kJ with a blackbody temperature of 60 eV.

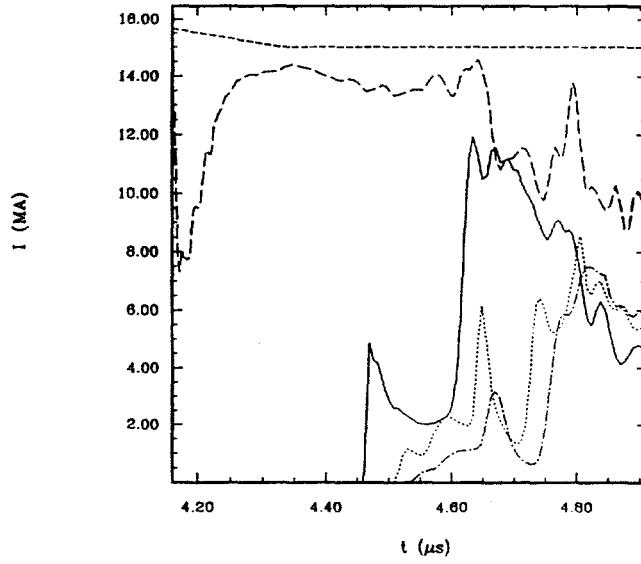


Figure 6. Predicted Probe Measurements for the Implosion Load Region From the Simulations.
 $(--\text{LP1}, -\text{LP2}, \cdots\text{LP3}, -\cdots\text{LP4})$.

Figure 7 shows the output of the xrd's which looked radially at the source. The size of these signals and the spectrum indicate a much cooler radiation source and the estimates of the total radiated energy from the xrd's is only 90 kJ.

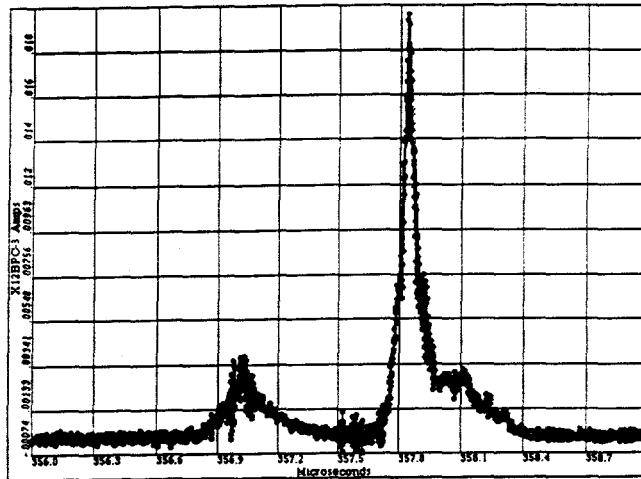


Figure 7. X-Radiation Output From a Carbon Filtered X-Ray Diode.

The bolometer signals were also much lower than expected and indicate a radiation output of 35 kJ. This would seem to indicate that there was not a good implosion on this experiment, but if one looks at the dI/dt for the machine, it shows that something occurred in the load region after the current switch which pulled a significant amount of energy out of the machine. This signal is shown in figure 8 and there is clearly a second large change in dI/dt after the switch opens. If we assume this is due to an implosion in the load region, one can calculate the amount of energy which is supplied to this implosion. Doing this gives a figure of 900 kJ. We have used this technique to compare this amount to the amount of radiated energy for some direct drive shots and find that this amount typically overestimates the radiated energy by 40%.⁶ This would then indicate a radiated output of 650 kJ.

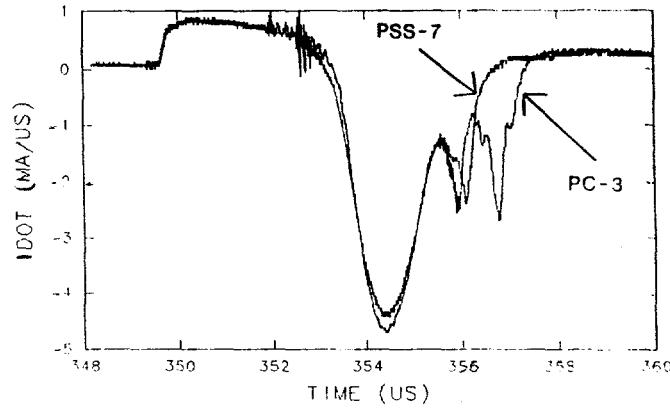


Figure 8. Measurement of $Idot$ in the Storage Inductor for PC-3 and PSS-7.

A possible explanation for this inconsistency comes from the simulations of the experiment. In these simulations, a significant amount of plasma flow switch mass has moved across the load slot and in the way of the x-ray detectors. We show this in figure 9, which is a density contour plot of the plasma flow switch at the window which the detectors look through.

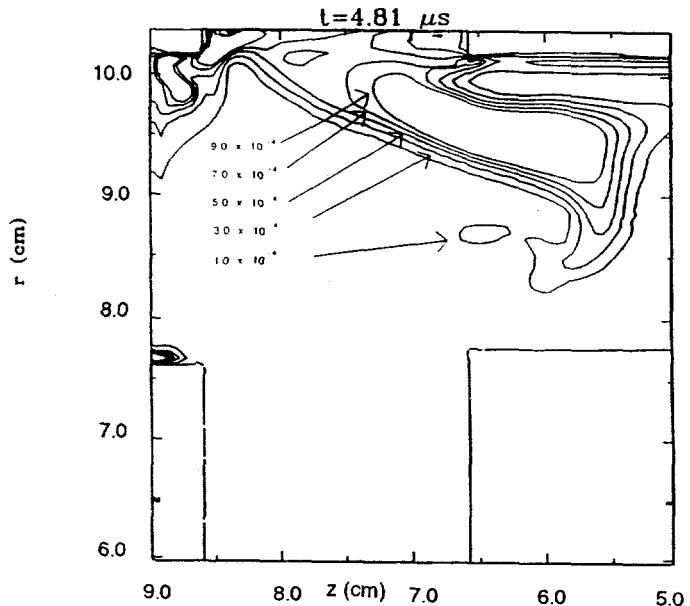


Figure 9. Calculated Density Contours for the Plasma Flow Switch Mass at the Time of Peak Radiation.

The plasma flow switch material, which consists of carbon, hydrogen, oxygen, and aluminum, has a mass density of about $5 \times 10^{-4} \text{ g/cm}^3$ and has a temperature of 12 eV. Using opacity estimates for aluminum and oxygen from the Sesame library⁷ we find that this material represents an average optical depth of 2.5 for a 50 eV blackbody radiator. We therefore would expect 92% of the radiation emitted radially to be absorbed. This energy would then be reradiated by the absorbing plasma, but at a much lower temperature which would be undetectable. This absorption would then predict that the radiation emitted by the source would be 12.5 times higher than measured, or 1.1 MJ for the xrd's and 440 kJ for the bolometers. The second number is more consistent with the simulations and the current measurements. The only problem with this interpretation is the lack of a large signal on the axial xrd's. We have noted on previous direct drive shots that we do not get very high signals axially, while many other machines do get good axial signals. One difference is that the pinches that seem to give good axial signals all have short time scales, i.e. < 1 microsecond. On the machines that have long time scale implosions it seems that material has time to begin filling up the viewing region before the pinch occurs and reducing the radiation output seen from the pinch. This could be the explanation here, but we do not know this for sure.

Conclusion

We have fired a $1/r$ mass profile plasma flow switch on Procyon with an implosion load. The performance of the switch is consistent with previous experiments on Procyon and there are indications that a moderately good implosion occurred. However, very little radiation output was measured from this implosion. We believe the reason for this low output was that a significant amount of the plasma flow switch mass moved across the load slot at the time the radiation was emitted, thereby blocking the radiation and preventing it from being measured. The implication of this is that the plasma flow switch performed nearly as predicted and did drive a relatively good implosion, but that the present design does not allow the radiation to escape and be used for some other experiment. In the future the issues of getting the radiation out and preventing the plasma flow switch mass from getting in the way must be resolved.

Acknowledgements

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