PROCYON EXPERIMENTS UTILIZING FOIL-FUSE OPENING SWITCHES*

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Introduction

The Los Alamos National Laboratory has applied the explosive magnetic flux compression generator (FCG) technology to the high-energy foil-implosion project, Trailmaster,[1] to reach energy levels unattainable by other methods under current budget constraints. A required component for FCG systems is a power-conditioning stage that matches the slow risetime of the energy source with the fast-risetime requirements of the foil-implosion load. Currently, the Trailmaster concept is based on a two-step process of combining an intermediate power compression stage with a plasma flow switch[2] (PFS) that will deliver energy to an imploding foil on the order of 100 ns. The intermediate power compression stage, which is the main emphasis of this report, consists of an energy storage inductor loaded by the FCG (the energy source) and an associated opening and closing switch. In our Procyon testing series, a subtask of the Trailmaster project, we have explored two approaches for opening and closing switches. One uses an explosive opening switch (EFF) and a detonator-initiated closing switch, the topic of another paper at this conference,[3] and the other a resistive fuse opening switch and a surface tracking closing switch (STS), the subject of this presentation. This latter concept was successfully tested last summer with a complete plasma flow switch assembly except the dynamic implosion foil was replace by a rigid passive inductive load. We present data on the performance of the fuse opening switch, the surface tracking closing switch, and the plasma flow switch.

System Operation

An operational schematic is presented in Fig. 1, giving the circuit parameters. The energy source is the Mark IX explosive flux compression generator that has a 7.2-μH initial stator inductance that decreases to less than 1-nH final inductance. Approximately 30% of the initial generator flux is transmitted to the 55-nH storage inductor, L_s, over a time period of 210 μs. For the experiment, L_s contained 13 MJ of stored energy. Delivering this energy into the PFS is the function of the opening switch, S1, and the closing switch, S2. The measured current waveforms in the experiment are shown in Fig 2.

Fuse Opening Switch

Computation of the fuse mass and resistance for optimum transfer of energy to the PFS for PSS3 was performed by the "CONFUSE" code.[4] This code accounted for the dynamics of the circuit elements and the PFS design. A previous test reported at an early conference,[5] was used to benchmark the code for the PSS3 operating regime. The PSS3 fuse was designed to develop a 20-kV voltage drop at 210 μs after generator startup at which time the STS flashes over and conducts current into the PFS. The design criteria were implemented by a copper fuse with an area of 2.8 cm^2 and a length of 30 cm. Actual construction of the fuse required seven turns of 1.4-mil copper foil around a 35-cm-diam mandrel as shown in Fig. 3. Between each layer of copper foil was inserted a 2-mil layer of polypropylene film. An overwrap of 10-mil polyethylene was used to tamp the fuse. Between the polyethylene and the outer insulator was an air space void 0.5-in. high. The fuse was supported on a 3/8-in.-thick Teflon tube insulating the fuse from the inner conductor. A thinner support would be desirable from the standpoint of reducing the inductance increase in the power-flow channel after switching but we were concerned that the fuse might breach a thinner insulator during vaporization.

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After this fuse design was implemented the PFS wire array mass was decreased and the gun length shortened relative to the initial design specifications. These changes resulted in a faster plasma run down and earlier pinch and hence higher impedance. To accommodate these changes the fuse should have been lengthened to increase the resistance but the changes could not be implemented resulting in some loss of transferred current.

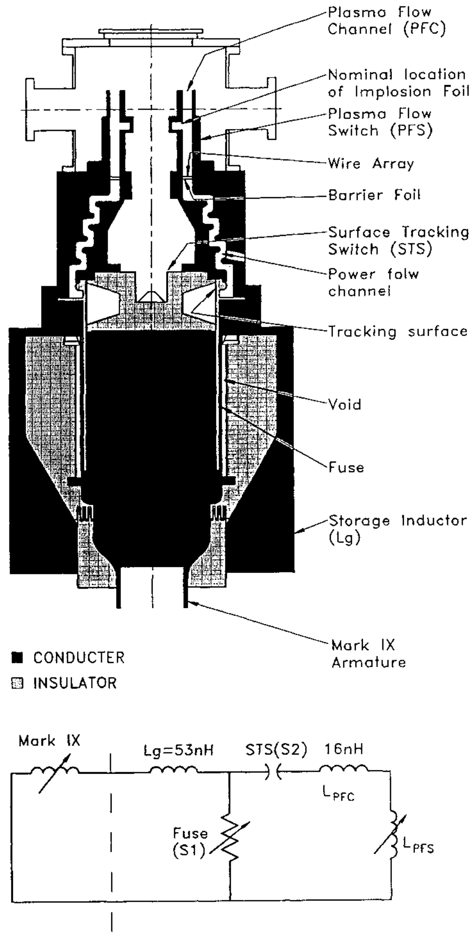

Fig. 1. The top of the figure is a scaled drawing of the complete PSS3 power-conditioning system used for the Procyon fuse test. The solid black portions are conductors, the cross-hatched portions are insulators for voltage standoff, and the unmarked portions are either vacuum or air. Power is supplied to the system from the bottom by the Mark IX FCG. The bottom of the figure is the circuit equivalent.

Closing Switch

Shunting the current from the inductive store into the PFS is the function of the STS. The time of current switching significantly effects the performance of the system components and is optimized by "CONFUSE" to deliver maximum energy to the PFS load when the plasma switches into the load region. With the predictive capabilities of the "CONFUSE" code, the voltage across the fuse at this time can be computed. A surface-tracking switch of unconventional design was installed as the closing switch and adjusted to have surface flashover when the voltage across the fuse opening reached 20 kV. The voltage at flashover time is determined by the voltage waveform and the

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14. ABSTRACT
The Los Alamos National Laboratory has applied the explosive magnetic flux compression generator (FCG) technology to the high-energy foil-implosion project, Trailmaster,1 to reach energy levels unattainable by other methods under current budget constraints. A required component for FCG systems is a power-conditioning stage that matches the slow risetime of the energy source with the fast-risetime requirements of the foilimplosion load. Currently, the Trailmaster concept is based on a two-step process of combining an intermediate power compression stage with a plasma flow switch2 (PFS) that will deliver energy to an imploding foil on the order of 100 ns.

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STS capacitance.[6] The STS design is shown in Fig. 4. Tracking is along the interior insulating surface of the cylindrical switch and the return current is along the cylindrical conductor surrounding the tracking surface insulator.

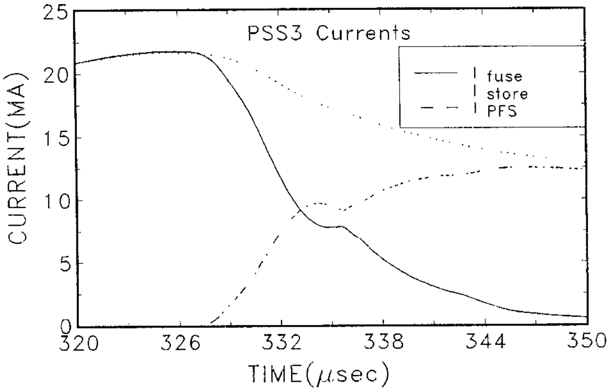

Fig. 2. Currents measured by Rogowski loops and Faraday rotation. Current is switched into the PFS at 326.8 μs. Times are relative to the time when the capacitor bank is switched into the Mark IX FCG.

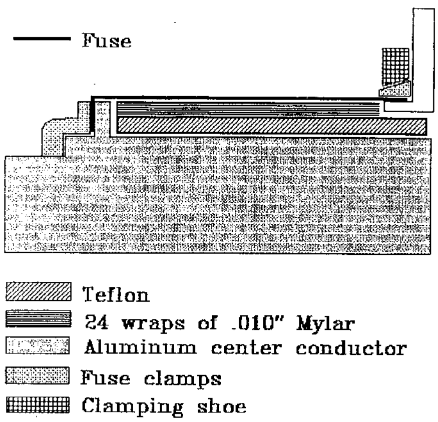

Fig. 3. Drawing of the fuse construction. This is a cross-sectional cut through the axis of revolution. Missing from the drawing is the 0.01-in. polyethylene fuse over-wrap and detail of the multiturn fuse.

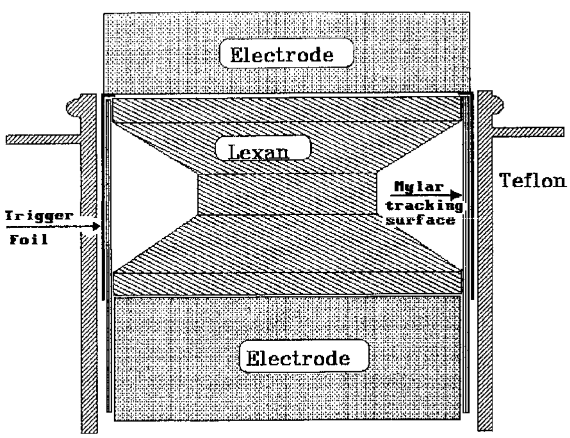

Fig. 4. Surface tracking switch (STS) with the tracking surfaces interior to the tracking film. Missing is the detail of the machined grooves in the top and bottom lands of the lexan insulator.

This switch was empirically designed through testing with a large capacitor bank. We found that unless the material in the interior volume of the STS supporting insulator was relieved around the tracking surface, the switch displayed anomalously high resistance. We also determined that machining grooves in the top and bottom portions of the insulator sections still supporting the tracking surface caused the breakdown tracks to occur at these groove positions. This gave us a method of insuring a uniform track distribution around the tracking surface. The PSS3 switch had 48 machined grooves evenly spaced around the periphery of the supporting insulator. Recovery of the switch section after the experiment revealed that the switch had indeed tracked very uniformly. Switched current into the PFS for the PSS3 experiment is shown in Fig. 2.

Analysis

Before proceeding, it is important to realize that the PFS is a dynamical load consisting of an annular plasma washer formed by vaporizing a wire array immediately after switching. This plasma is propelled down the coaxial power-flow channel and collapses into a radial notch at the end of the channel. Simulation of the plasma behavior immediately prior to compression of an implosion foil is provided by this notch. The time-dependent inductance of the PFS resulting from this motion is measured across the power-flow channel and the power-flow current waveform. The measured inductance is shown in Fig. 5 along with the predicted inductance for a thin slug of plasma moving down the power-flow channel.

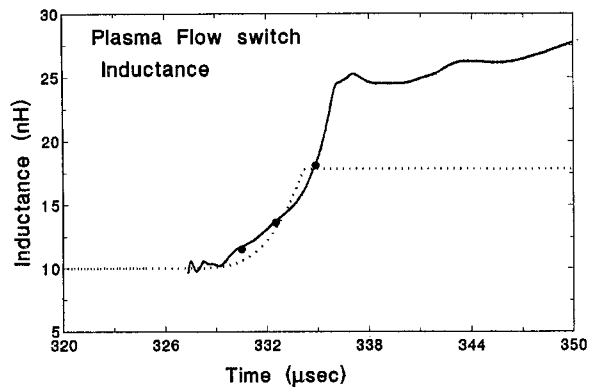

Fig. 5. Measured and computed inductance of the plasma flow switch (PFS). The calculated inductance assumes the plasma stops at the end of the PFS gun notch location, whereas, the plasma actually pinches into the notch and continues to flow out of the gun assembly, thus, accounting for the continued rise in inductance of the measured curve. The dots indicate the down-stream inductance of the PFS at the plasma arrival time for three small current loops spaced along the plasma flow channel.

Our method of evaluating system performance is to look at system flux losses since we know the system inductance, and determine how these compare with the ideal system. We also compare the amount of current available to the PFS at the time of plasma implosion relative to the current available in the inductive store. In Fig. 6 we present the flux that is resident in the generator and the inductive store with curve 1 and the flux transferred to the PFS and its associated power-flow channel with curve 2. Included in curve 2 is the extra inductance picked up in the storage inductor because of the differing current path for the current shunted to the PFS. Not included is the flux in the closing switch inductance since at present this is unknown. A third curve gives the sum of curves 1 and 2 and is the total system flux.

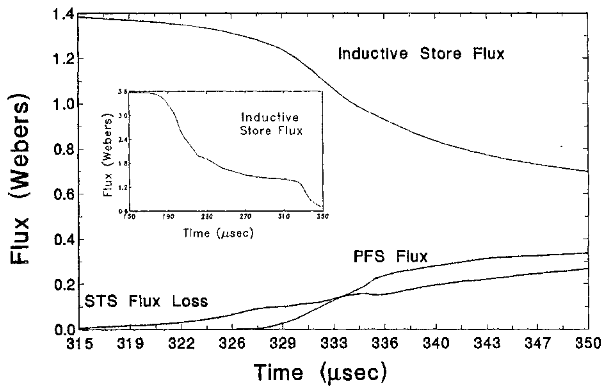

Fig. 6. Magnetic flux present in the storage inductor and the PFS. These curves were inferred from the measured and time derivatives and the system inductances. The flux loss from the surface tracking switch (STS) is the integral w.r.t. time of the STS voltage.

The initial system flux resulting from the capacitor bank loading of the Mark IX generator is 3.3 Wb, which drops to 1.25 Wb at the end of the generator run. This loss is typical of the Mark-IX generator and is mostly due to flux diffusion into the stator conductors and is unrecoverable. From 320 μs to 328 μs, 0.08 Wb is lost as the fuse resistance increases creating a substantial voltage across the fuse and, hence, flux transfer into the PFS region. Since the closing switch has not yet closed this flux escapes the system altogether. After the closing switch starts conducting, the flux loss continues due to resistive drop across the STS and inductance changes in the STS. Indeed, if all the flux loss is attributable to the STS, then we can infer the voltage drop across this switch (shown in Fig. 7) from the power-flow measurements. The actual resistive contribution to this voltage cannot be distinguished from the inductive component. About 0.18 Wb of flux was lost out of 1.18 Wb remaining at time of current transfer. This is a 15% loss of flux or a 28% loss in system energy. The best STS performance, corresponding to a 5-kV drop across the switch, would net a 16% energy loss. Whether the PSS3 switch can be modified to reduce these excessive inductive and resistive losses remains to be investigated. Looking back at Fig. 2 we see that the current transferred into the PFS is slightly more than half of the current available at the time of plasma pinch (335 μs). This unswitched current remains in the fuse circuit and is proportional to the fuse resistance. Figure 8 shows the fuse resistance inferred from several of the system current waveforms. At the time of plasma pinch the fuse resistance was 180 times the initial resistance. This value is rather typical of high energy fuses but there is reason to expect that varying tamping, fuse length, and thickness may improve this resistive multiplication to 300 or greater. Under this circumstance we would expect to see 14 MA transferred.

Other Observations

A blowup of the dI/dt of the PFS reveals the event history of the exploding wire array. The event history is detailed in Fig. 9 and corresponds almost exactly with the available empirical data on exploding wires. The significance of this observation is that in order to see this detail, the wire array had to explode simultaneously over the whole area. This indicates that the current flow in the power channel was uniform as must have been the current across the STS. There were several single-turn magnetic pickup loops in the power flow channel. The plasma arrival time at these loops is plotted versus the PFS inductance for a thin plasma washer and indicated in Fig. 5 by the closed circles. The fact that these points fall so close to the measured curve can lead to the interpretation that the current is confined to a thin plasma disk. Another paper at this conference presents data on the plasma run down in the PFS.[7]

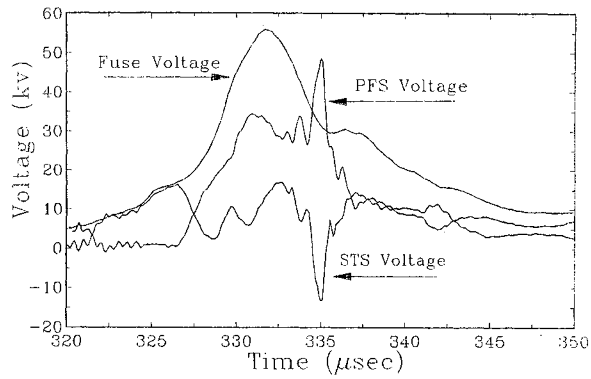

Fig. 7. Fuse voltage was inferred from the time derivative of the storage inductor current added to the $-d\Phi/dt$ of the Mark IX FCG. The PFS voltage was measured directly by an electric field probe inserted into the power flow channel. The STS voltage is the difference between the two above measurements less a correction for 5-nH additional inductance resulting from the alternate conduction path in the storage inductor. The voltage across the STS was 17 kV when the switch closed.

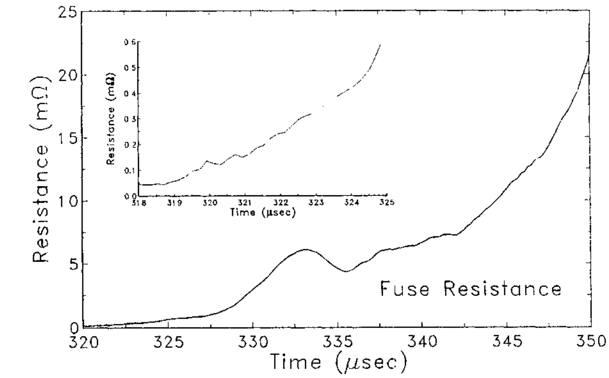

Fig. 8. Fuse resistance inferred from the fuse voltage divided by the fuse current. Calculated initial resistance of the fuse was 26 $\mu\Omega$.

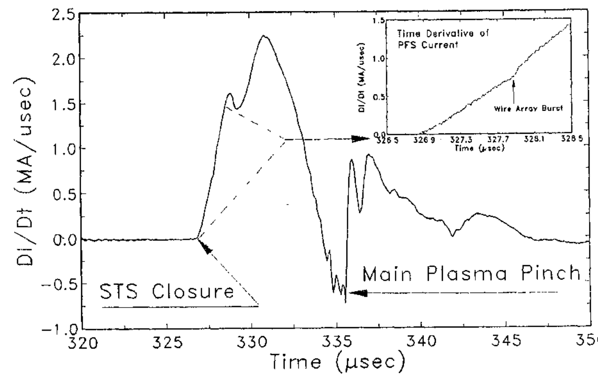

Fig. 9. Time derivative of the PFS current. Inset indicates the time when the wire array burst. Negative peak is caused by the plasma pinching into the load slot.

Conclusions

This was the first integrated test of the fuse power-conditioning concept applied to the Trailmaster problem. We achieved 70% of our design goal by providing 10 MA of current to the PFS at foil implosion time. Very possibly an improved STS design and a different fuse parameter regime could lead to a realization of the full 14 MA delivered to the PFS at pinch time.

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