COMPUTATIONAL MODELING OF THE TRAILMASTER PROCYON SYSTEM*

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I. Introduction

The goal of the Los Alamos Foil Implosion project (Trailmaster) is the development of an intense source of soft x-rays for materials and fusion studies. The x-ray source in the Trailmaster project is a foil initiated z-pinch. The next system in the Trailmaster project is designed to deliver 15 MA of current to the imploding liner creating approximately 1 MJ of soft x-ray radiation in a submicrosecond pulse. This system, designated Procyon, will consist of a Mark IX helical explosive generator, an explosively formed fuse (EFF) opening switch, detonator closing switches, a vacuum powerflow channel, a plasma flow switch (PFS), and the imploding foil load.

Companion papers at this conference will discuss the status of subsystem experiments leading up to the Procyon system,[1,2] Procyon diagnostics,[3] and details of MHD simulations of the plasma flow switch.[4] In the present paper we will focus on the computational modeling of the overall Procyon system. This effort includes circuit and zero-dimensional point mass (slug) modeling, 1-D and 2-D radiation MHD calculations, and 3-D radiation transport and view factor modeling of the vacuum powerflow channel.

II. Circuit and 0-D Calculations

A conceptual diagram of the Procyon system is shown in Figure 1. The equivalent electrical circuit for this system is shown in Figure 2. The Los Alamos firing point 88 capacitor bank and the Mark IX generator have both been documented in previous publications.[5,6] The EFF in the Procyon system is being fielded in a flux conserving geometry[1] in which the inductance of the switch remains in the circuit after the switch opens. This is the 57 nH storage inductor in Figure 2. Based on projections from small scale experiments and early Procyon subsystem experiments[1], we are modeling the resistance as a function of time for this switch with the curve shown in Figure 3.

With a seed current of 450 kA from the capacitor bank we calculate that the Mark IX generator will deliver some 23 MA into this system as shown in Figure 4. Note, however, that between the capacitor bank discharge and the generator run the build up of the current requires some 340 μs. Hence the need for pulse shaping prior to driving the plasma flow switch and imploding load.

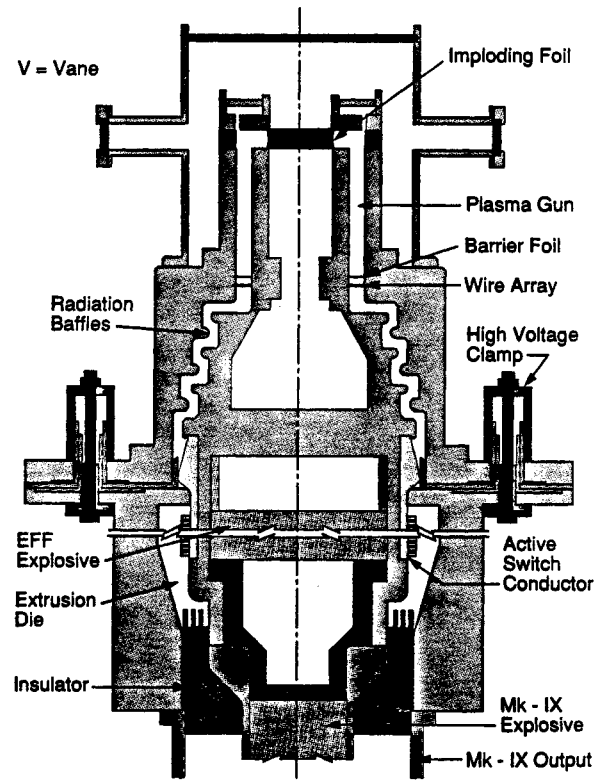

Fig. 1 Diagram of the Procyon system.

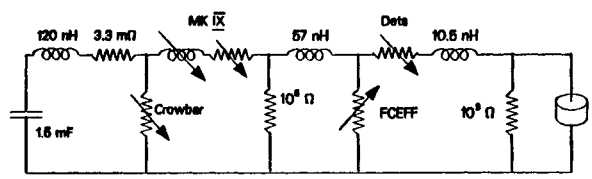

Fig. 2 Equivalent circuit for the Procyon system. (The 10^3 Ω resistor in vertical branch 4 is for computational purposes and is large enough to prevent current flow but small enough to permit accurate voltage calculations at the vacuum interface.)

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14. ABSTRACT

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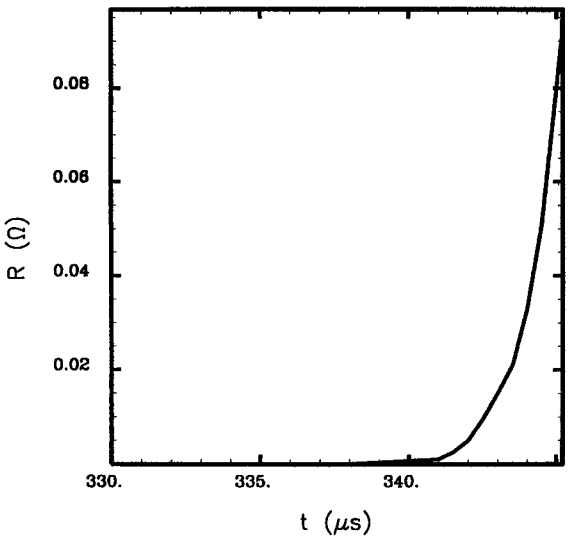

Fig. 3 Time dependent resistance of the explosively formed fuse during opening.

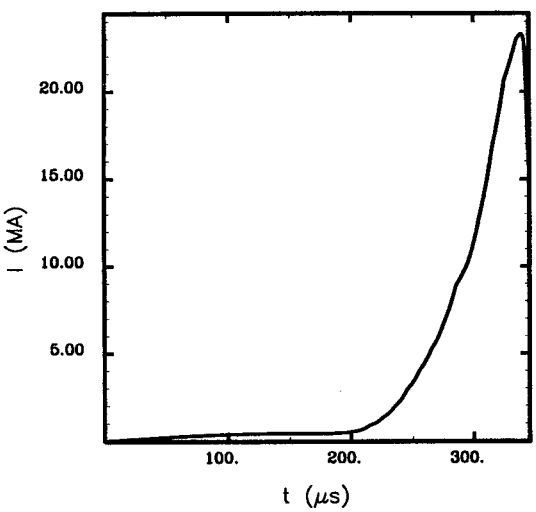

Fig. 4 Calculated current from the Mark IX generator into the storage inductor.

The time dependent resistance in horizontal branch 4 of the circuit represents the detonator closing switches. The total resistance of the six switches in parallel drops to 0.3 mΩ in about 1 μs.

Current transferred to the plasma flow switch depends to some extent on the design of the switch itself and details of the Procyon design are not yet finalized. The switch used for the calculations presented here has an inner electrode radius of 7.6 cm, outer electrode radius of 10.2 cm and a total switch mass of 150 mg. The distance from the center of mass of the wire array plus barrier foil (which merge to form the switch plasma) to the upstream side of the 2 cm long load slot is 6.5 cm. Our calculations indicate that the system described above will deliver 15 MA of current to this plasma flow switch by the time it reaches the load slot (see Figure 5).

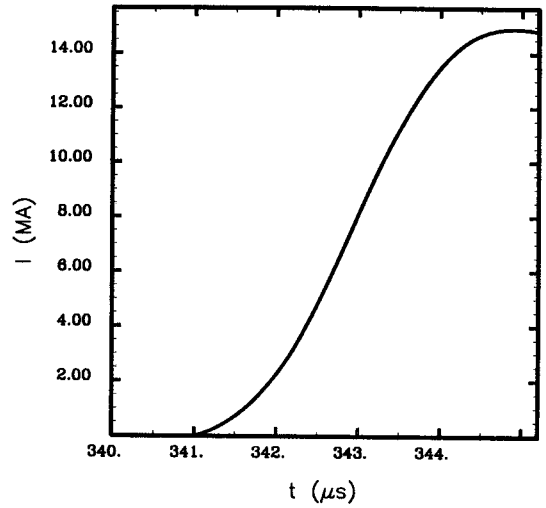

Fig. 5 Calculated current transferred to the plasma flow switch.

The radiation output from this system will depend on the switching efficiency of the PFS, the mass and geometry of the imploding load, and the quality of the implosion. These are all issues that are being addressed by experiments and calculations at the present time. A simple slug model calculation of the implosion of the load fielded in the previous shot series (a 250 nm thick, 2 cm long, 5 cm radius, unbacked aluminum foil) driven by this system with a final implosion ratio of 10:1 predicts a kinetic energy of 750 kJ; essentially all of which will be converted to radiation. However, with the lower inductance power flow channel shown in section V this system will deliver more than 16 MA to the plasma flow switch. With that current level it is easy to design an imploding load for which slug model calculations predict more than 1 MJ of kinetic energy.

III. 1-D Plasma Flow Switch Calculations

We are using the 1-D, radiation MHD code, RAVEN, in planar geometry to provide radiation flux estimates and initial conditions for 2-D, Eulerian, calculations. The 1-D calculations permit us to model, at least to some approximation, the initiation of the aluminum, its assembly on the barrier foil, and the total switch plasma's run down the coaxial barrel. We have used the radiated flux estimates from these calculations to estimate the extent to which the vacuum powerflow channel may close due to radiative induced ablation[7] (see also section V below).

In 1-D we simulate the wire array as a 55.86 cm wide by 2.54 cm long, solid density, aluminum foil that is 1.94 μm thick. The barrier foil is modeled as a 3.78 μm thick polyurethane foil. This gives a total mass of 150 mg. The equations-of-state for these calculations are taken from the Los Alamos SESAME tables.

The calculated positions of the Lagrangian zones as functions of time are shown in Figure 6. Note that this calculation predicts that the plasma will reach a maximum expansion of 1.5 cm before the expansion due to the explosion of the foil is overcome by the j X B force (the slight expansion of the barrier foil is due to a small positive pressure from the EOS table at the initial conditions which is slightly above room temperature). The plasma will reach the location of the imploding load slot in almost exactly 4 μs. At that time the 1-D simulation predicts a thickness of the current carrying sheath to be 0.4 cm. After 4 μs the fastest zones are moving at 7.3 cm/μs and the slowest at 6.5 cm/μs.

The calculated temperatures as functions of time are shown in Figure 7. The temperature peaks are each associated with internal compressions within the plasma. These compressions start when the back of the aluminum plasma overtakes the front which has been slowed by the collision between the aluminum and the polyurethane. The 1-D calculations indicate that the maximum temperatures occur on the back (upstream) side of the aluminum plasma rather than at the boundary between the aluminum and the barrier foil.

IV. 2-D Plasma Flow Switch Calculations

More details concerning the PFS calculations are available in the companion paper by Peterson et al. Figure 8 shows a 2-D, Eulerian, Procyon, PFS calculation near the point at which material and field begin to enter the load slot. In this calculation the load is a 5 cm radius copper rod. We are, therefore, just calculating the efficiency with which this switch will deliver current to the position of the load, r=5 cm. This calculation was driven by the I(t) curve shown in Figure 5 above. The calculation was started 2 μs after the current reaches the wire array which is approximately the point of maximum expansion shown in Figure 6. In this calculation the 150 mg plasma was treated as all Al. It was given an expansion of 1.5 cm in the z direction, a uniform temperature of 1 eV, and a $1/r^2$ density distribution.

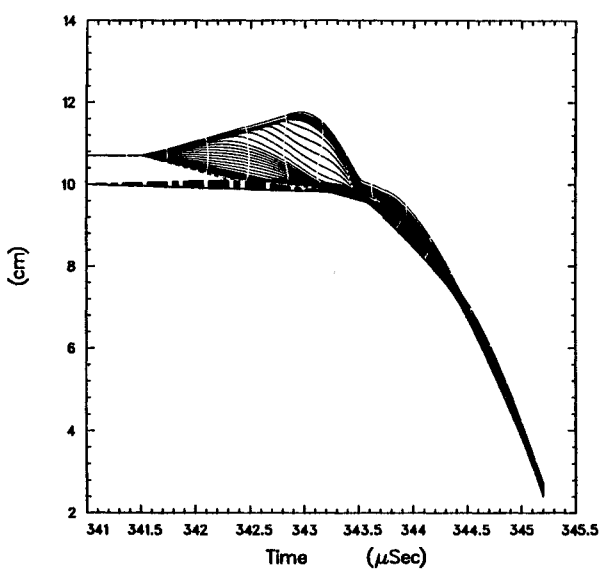

Fig. 6 Positions of the Lagrangian zones in the 1-D planar plasma flow switch calculation.

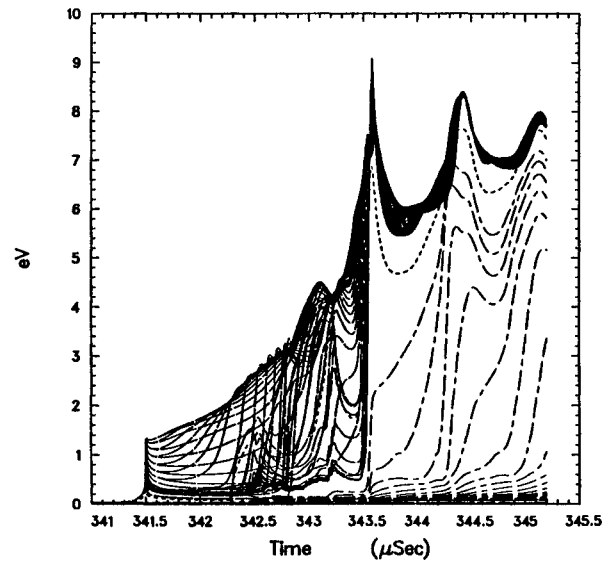

Fig. 7 Temperatures of the Lagrangian zones in the 1-D plasma flow switch calculation.

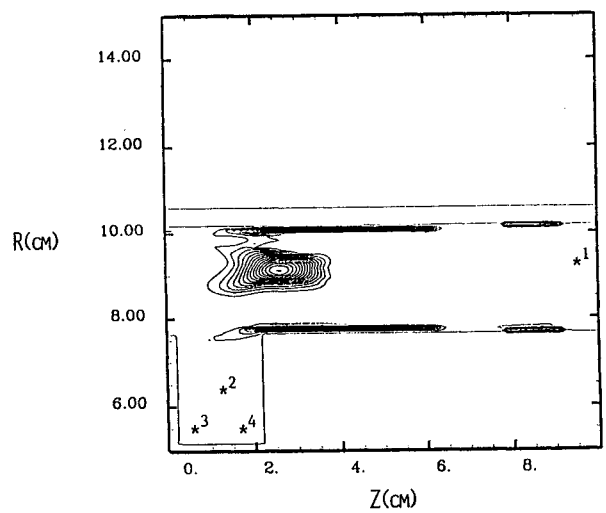

Fig. 8 Density contours in the 2-D calculation at 4 μs. Minimum density shown is 1.0 X 10^{-4} gm/cm^3. Starred points were edited to provide figure 9 values.

Figure 9 shows calculated time dependent current traces for the positions indicated in Figure 8 during switching. The calculated values in the load slot oscillate above and below the feed value (curve 1) because the magnetic field is being compressed as the switch material carrying it encounters the fixed inner electrode in the load slot. The curves have settled by 4.7 μs (2.7 μs after the start of the calculation) to values quite close to the feed value. The slow, 0.2 to 0.4 μs rise times indicate that these currents are being carried into the load slot by a significant amount of switch material. Indeed, in this calculation some 4 mg of switch mass was deposited into the load slot. This is essentially the same as the mass of the load described in section II. We are presently exploring a variety of options for reducing the mass deposited while maintaining switching efficiency.

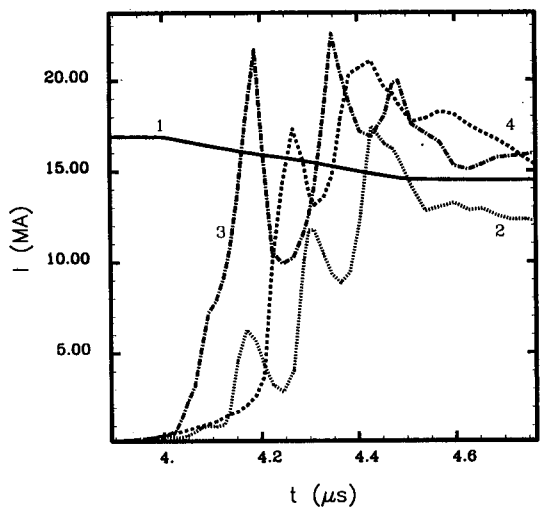

Fig. 9 Calculated time dependent current profiles at locations marked in figure 8.

V. 3-D View Factor Calculations

Our 3-D radiation transport and view factor code has been benchmarked against the measured radiation attenuation of the vacuum powerflow channel shown in Figure 1. We find that with an average surface albedo of 0.35 for the anodized surfaces, radiation emitted from the initial position of the wire array is attenuated by a factor (output/input) of 1.6 X 10^{-8}. Our 1-D calculation provides an estimate of 1.1 X 10^2 J/cm^2 radiated toward the vacuum interface. Therefore, we expect about 1.8 μJ/cm^2 to reach the interface through the present channel, almost surely a safe level.[8]

Figure 10 shows a greatly reduced powerflow channel which we calculate to have about 8.5 nH of inductance. Our view factor calculations indicate that this revised channel can provide essentially the same level of attenuation if the average surface albedo of the double lined surfaces can be reduced to 0.1. This will require the actual removal of material from these surfaces to provide radiation traps. Experiments on this approach are now in progress.

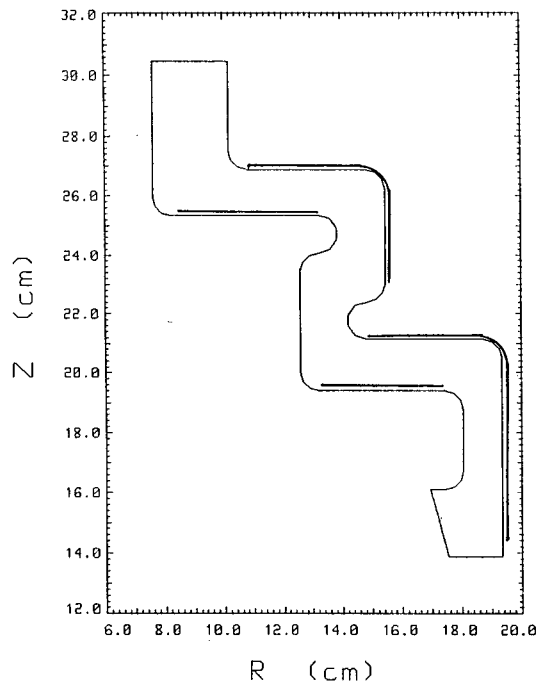

Fig. 10 Diagram of a reduced inductance vacuum powerflow channel. Double lines indicate walls which must have albedoes reduced to 0.1 by removal of material.

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