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Computational Simulations of Plasma Flow Switches and Imploding Loads

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ABSTRACT

The Procyon system in the Los Alamos Trailmaster foil implosion project is intended to produce soft x-ray radiation by delivering about 1 MJ of kinetic energy to an imploding plasma liner. The final switching stage of this system will be a Plasma Flow Switch (PFS) which delivers current to the cylindrical foil load. 1-D and 2-D simulations are now being conducted to examine: the initiation of the PFS plasma; the dynamics of the PFS and its switching efficiency; the load implosion and resulting radiation output. Considered here, for the PFS and imploding load, are the effects of electrode walls, perturbations, and radiation. Comparisons with experiments (using the 1.5 MJ Pegasus capacitor bank) are also described.

I. Introduction

The final stage of power conditioning in the Los Alamos Procyon system[1] consists of a Plasma Flow Switch (PFS) which switches a current of approximately 15 MA to a thin cylindrical foil load. The foil plasma then implodes and is expected to produce soft x-ray radiation with a total energy of about 1 MJ. Such switches have performed satisfactorily in experiments on the SHIVA Star capacitor bank at the Air Force Weapons Laboratory (AFWL, now Phillips Laboratory).[2] In this study we have used a 1-D radiation-magnetohydrodynamic (RMHD) Lagrangian code and a 2-D multi-material Eulerian RMHD code to simulate the behavior of the PFS beginning with initiation and ending with the interaction of the switch plasma with the imploding load and the transfer of current to the load and the implosion. We will consider here primarily parameters appropriate to experiments conducted on the 1.5 MJ Pegasus capacitor bank[3] which delivers about 6.5 MA to the PFS at peak current. The experiments have been used to develop understanding of the switch behavior and for benchmarking the codes' results. We will also briefly describe some simulations applicable at the Procyon levels.

II. Perturbations

We have used the 1-D Lagrangian code RAVEN to simulate the inititiation phase of the PFS. We begin the 2-D simulations with an expanded plasma using an average density and temperature and a $1/r^2$ variation in density. Although the temperature, density, and magnetic field profiles are available from the 1-D simulations, we have found that the results of the 2-D simulations are relatively insensitive to the details of the initial conditions. This density variation is created in the experiments by using a chordal array of wires, which when combined with the downstream barrier film, produce a plasma with an approximate $1/r^2$ distribution. The density is thus matched appropriately to the distribution of the magnetic force driving the PFS. If the radial boundaries of the plasma are ideal (no electrodes present, no losses across them and no axial boundary currents), then this configuration will retain planarity as it propagates axially. Further details regarding 1-D simulations of the initiation may be found in a companion paper.[1]

In practice the PFS will not retain this density distribution and act in a planar manner during the run down the PFS barrel. First, it must be expected that some degree of initial perturbation will be present due to the fact that the wires will not spread uniformly to form the ideal distribution. There is strong evidence that this is so from previous experiments.[1] Even supposing these perturbations were alleviated (by using say, very fine wires, or a graded foil rather than a wire array), some regions will heat, fuse, and become a plasma sooner than others if only due to microscopic material defects. Radiation pulses from imploding plasmas have been successfully simulated using the assumption of random density perturbations in the plasma after initiation[5], and we have applied this same technique to the PFS simulations. Lastly, the plasma will be in contact at the inner and outer radius with a cold, conducting wall for the time of the run down the PFS barrel. It can be expected that this continuous perturbation may give rise to features which will affect switching, and, indeed, we have found this to be the most important effect. In this section we consider instabilities associated with three classes of perturbation: wall instabilities; large wavelength, small amplitude instabilities caused by random density variations; and large amplitude, small wavelength instabilities arising at initiation time. In all of the calculations shown here the PFS barrel has an inner electrode radius of 7.62 cm and an outer electrode radius of 10.16 cm. The length of the barrel has been varied according to optimizations from 0-D and 1-D simulations. The plasma mass is distributed in a 50/50 ratio between the wire array and a downstream barrier film. In the Pegasus experiments the total switch plasma mass is about 45 mg. For the Procyon system the total mass will be approximately 150 mg.

Figure 1 shows contours of density for a PFS which has completed about 4 cm of its 5 cm run (initial center-of-mass position was at $z = 7.5$ cm). This model, driven by an external circuit connected across the upper and lower electrodes at the right, was initially unperturbed. Of primary importance in this case is the continuous perturbation from the electrode walls, as can be seen by the presence of a thick layer of plasma coated on the lower electode (and, to a lesser extent, on the upper electrode) trailing the main body of the plasma. The mechanism for creating the trailing material consists of preferential cooling in the plasma next to the wall, and more importantly, the transition from axial current flowing in the cold, conducting wall to radial current flowing in the hot plasma. As the current makes this bend, the magnetic pressure presses material against the wall (as well as giving it a forward velocity). Simulations which model the wall as open to energy flow but reflecting to magnetic field show this effect to a much lesser extent. In cases with greater acceleration (such as for the Procyon system) two instability "bubbles" form near the walls and a "spike" of plasma in the center of the PFS trails behind (an example of this may be seen in Fig. 8 of Ref. 1). The key effect of this trailing material is to create a bridge of material behind the PFS which may impede switching by increasing the switching time and decreasing the current delivered to the load. Moreover, a potentially large amount material is deposited onto the load (perhaps larger in mass than the load itself) and current does not arrive with axial symmetry. We note that simulations carried out without the electrodes and with reflecting boundary conditions do not show significant deviations from planarity.

The effect of random density pertubations within the initiated plasma can be seen in Fig. 2. Although the plasma develops large scale instabilities and a thicker sheath, it can be seen that the dominant effect is due to the wall-induced layer of material left on the lower electrode. A still greater thickening of the plasma sheath occurs for periodic perturbations arising at initiation time. As the chordal array of wires initiates there will be regions of enhanced density where wires cross and regions of decreased density between crossings. Although this pattern is inherently 3-D, instabilities in the azimuthal direction will grow much more slowly than those in the r-z plane because azimuthal instabilities would require bending of the field lines. Shortly after initiation the array plasma and the current flow tend toward a quasi symmetric state. We have used the length scales between wire crossings and voids in the initial array to seed periodic variations of density in the radial direction (at a level of 50% of the nominal density). An example of this is shown in Fig. 3 after the plasma has traveled about 4 cm. In this case we found that longer wavelength perturbations created a thicker sheath than short wavelength ones. Using this information, a recommendation that smaller diameter wires be used in the chordal array (which would lead to more frequent wire crossings and shorter wavelengths) was implemented. An array of 160 wires (of smaller diameter) was substituted for the original 72 wire array. Experimental measurements then indicated a reduction in sheath thickness.

III. Switching Efficiency

Ideally, as the back edge of the PFS plasma passes over the edge of the load slot, magnetic pressure on the very low density trailing edge material will cause magnetic flux to be rapidly delivered throughout the load slot transferring current to the load foil. The current should arrive in a nearly simultaneous manner across the load and with a reduction in peak current dictated by the necessity of filling this volume with magnetic flux. This type of behavior has been reported for PFS performance in experiments at AFWL.[2] It should be noted that our experiments are in a range of current and energy both below (Pegasus) and above (Procyon) that of the AFWL experiments. Our simulations have reproduced the AFWL results, and we seek now to extrapolate both above and below this regime. Computationally, we see different scenarios emerge in the Pegasus and Procyon regimes. This is illustrated in Fig. 4, which shows four $I(t)$ curves for the positions marked in Fig. 1. As the trailing switch material follows the main plasma sheath, it's considerable mass impedes the delivery of current to the load region. Basically, this material implodes onto the load, in a potentially unstable manner, with current arriving at the downstream side of the load ahead of current on the upstream side. The material remaining behind provides enough conductivity to shunt current away from the load. Thus the switching is inefficient and assymetric. Further, switch plasma carrying the magnetic field, when pushed against the electrode walls will compress the flux, raising the current value locally and causing "ringing" in the measured current. These effects have been observed in Pegasus PFS experiments.

IV. Load Interactions

Transfer of switch plasma to the load during current switching may seriously degrade the implosion and subsequent radiation output. Even when switching is efficient, and is not accompanied by a significant amount of switch plasma, the integrity of the implosion may be affected. Z-pinches are highly susceptible to Rayleigh-Taylor instabilites and even a low level of perturbations may lead to nonlinear development and breakup of the imploding plasma shell before arrival on axis. Figure 5 illustrates the development of instabilities in an imploding shell due to the effect of a PFS. In this case, the simulation is at the higher current Procyon level (15.5 MA, with about 1 MJ of kinetic energy transferred to the load). This simulation begins with an unperturbed, $1/r^2$ density distribution PFS at the edge of the load slot moving at about 7 $cm/\mu s$. When switching occurs very little mass is transferred to the load, and about 91% of the current is delivered. Nonetheless, current is delivered to some portions of the load sooner than others. The resulting instabilities and a sketch of the expected radiation pulse from such an implosion are shown in Fig. 6. The radiation pulsewidth is increased to many times that of a 1-D implosion, and consists of two parts, a portion of the energy being delivered by the rapidly imploding Rayleigh-Taylor bubble regions and the rest associated with the main shell of material, now greatly thickened. Such behavior has been observed in experimental measurements of the radiation pulse from an imploding load.[5]

V. Future Directions

We have examined many other factors in PFS operation (energy, I, $\dot{I}$, PFS mass, electrode ablation, etc) to determine which of them affect switching and have found that the trailing material effect consistently important. There is some evidence that switching should improve at higher energies which would be advantageous. We have also determined that it may be possible to "trap" a large fraction of the trailing material in an annular groove cut into the lower electrode just prior to the load slot. Simulations using this change show a much improved switching, and experiments are currently being fielded on the Pegasus bank to test this idea.

The interaction of the PFS and the load foil are still under investigation, and there will be further calculational efforts is this area as experimental results become available.

Figures

1. Density contours of an unperturbed PFS plasma (which began with an initial $1/r^2$ density distribution) as the switch plasma nears the load slot.

2. Initial density distribution (a) and intermediate time density distributions (b and c), and contours of rB_θ (d) at the same time as (c) for a PFS with an imposed random density perturbation at the 30% level.

3. Density (a) and rB_θ (b) contours as the PFS approaches the load slot for a simulation begun with periodic perturbations at the 50% level in density with a wavelength determined by chordal array spacings.

4. $I(t)$ for the four positions labeled in Fig. 1: (1), solid, downstream near load; (2), dotted, upstream near load; (3), dot-dash, above load slot; and (4), dashed, at far right, upstream current.

5. Initial development of perturbations in the expanded load plasma due to the action of PFS switching. Density contours are shown in (a) and rB_θ contours in (b)

6. Density (a) and rB_θ (b) contours near the end of the perturbed implosion from Fig. 5. A sketch of the expected radiation pulse from this simulation is shown in (c).

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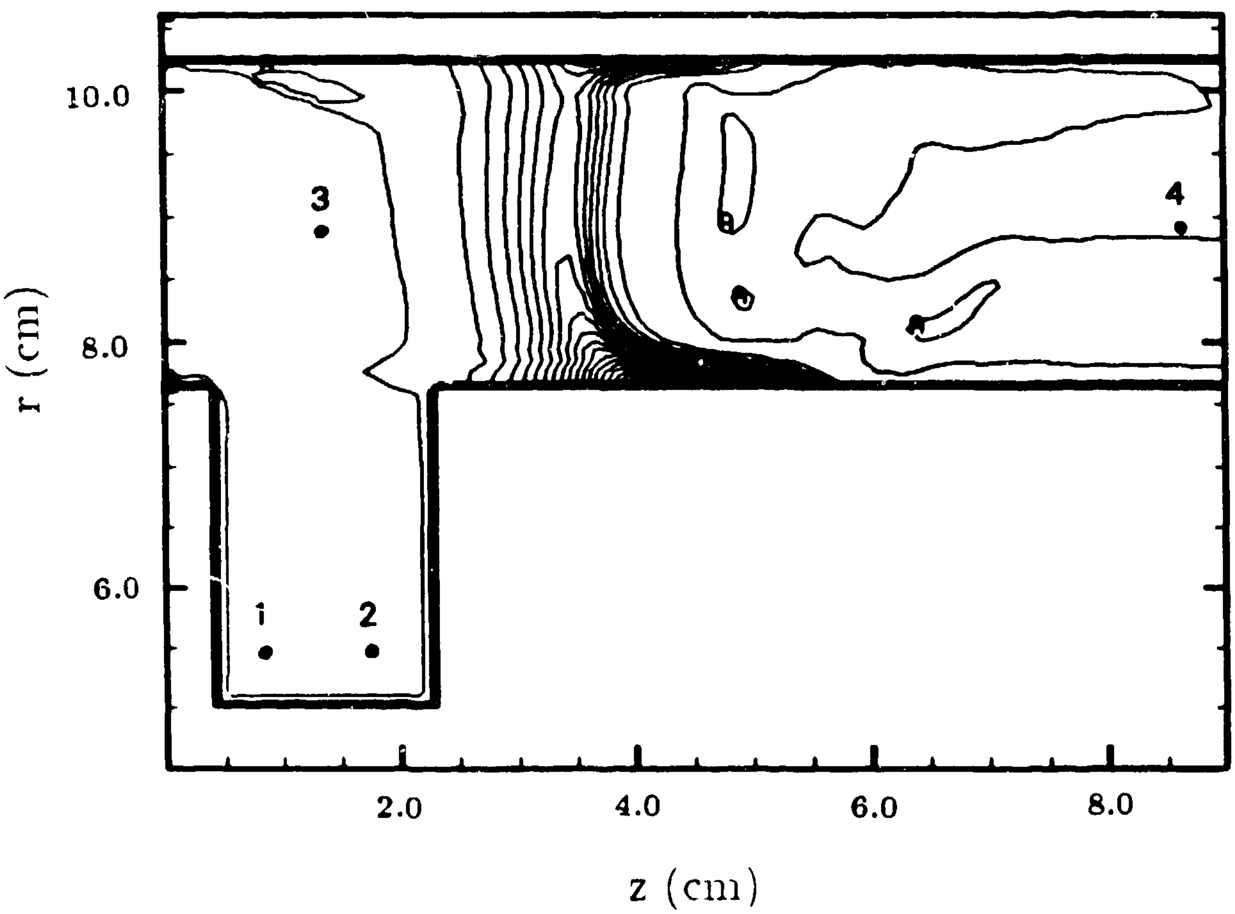


Fig 1

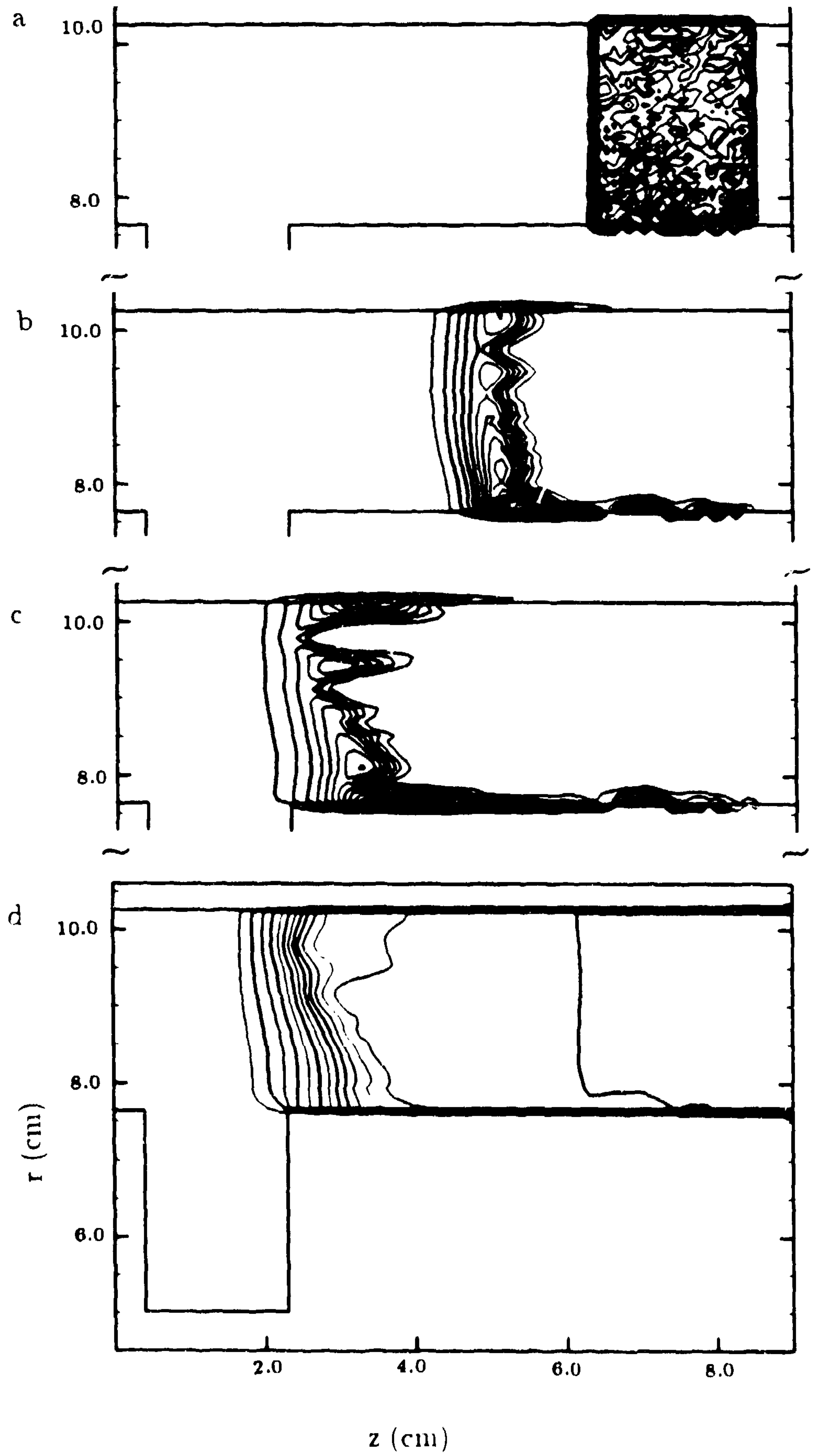
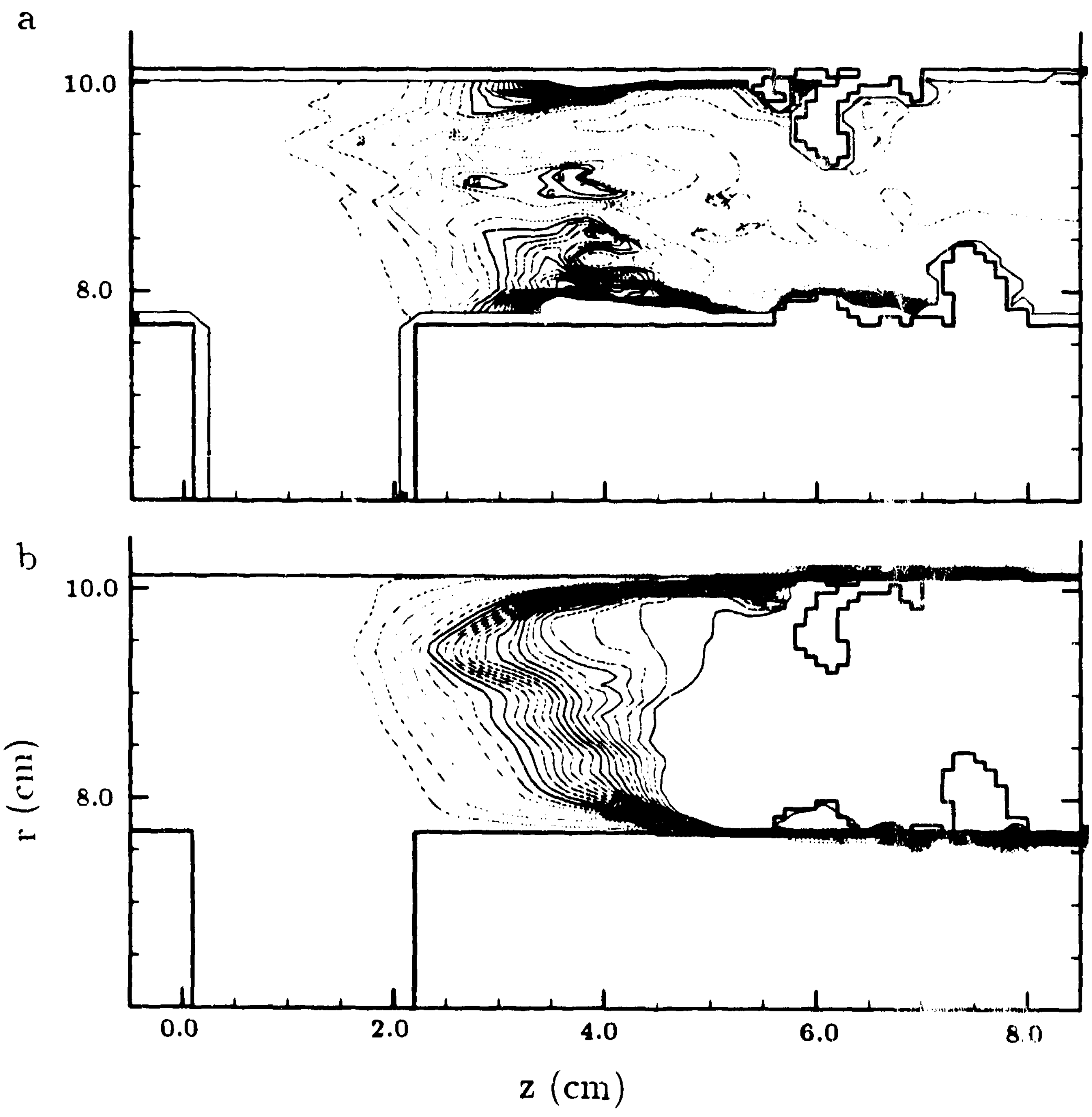


Fig 2



(Fig 3)

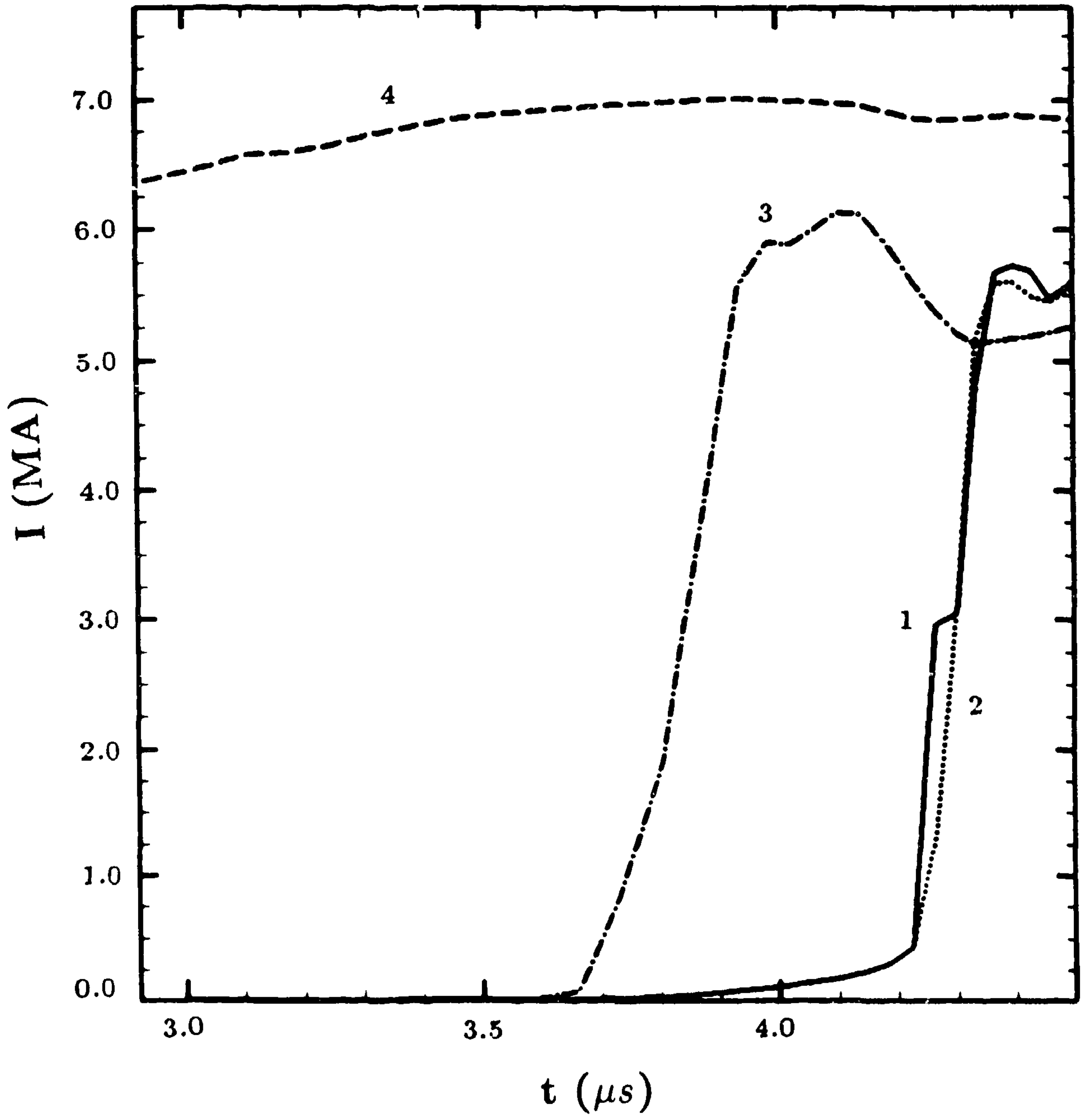


Fig 4

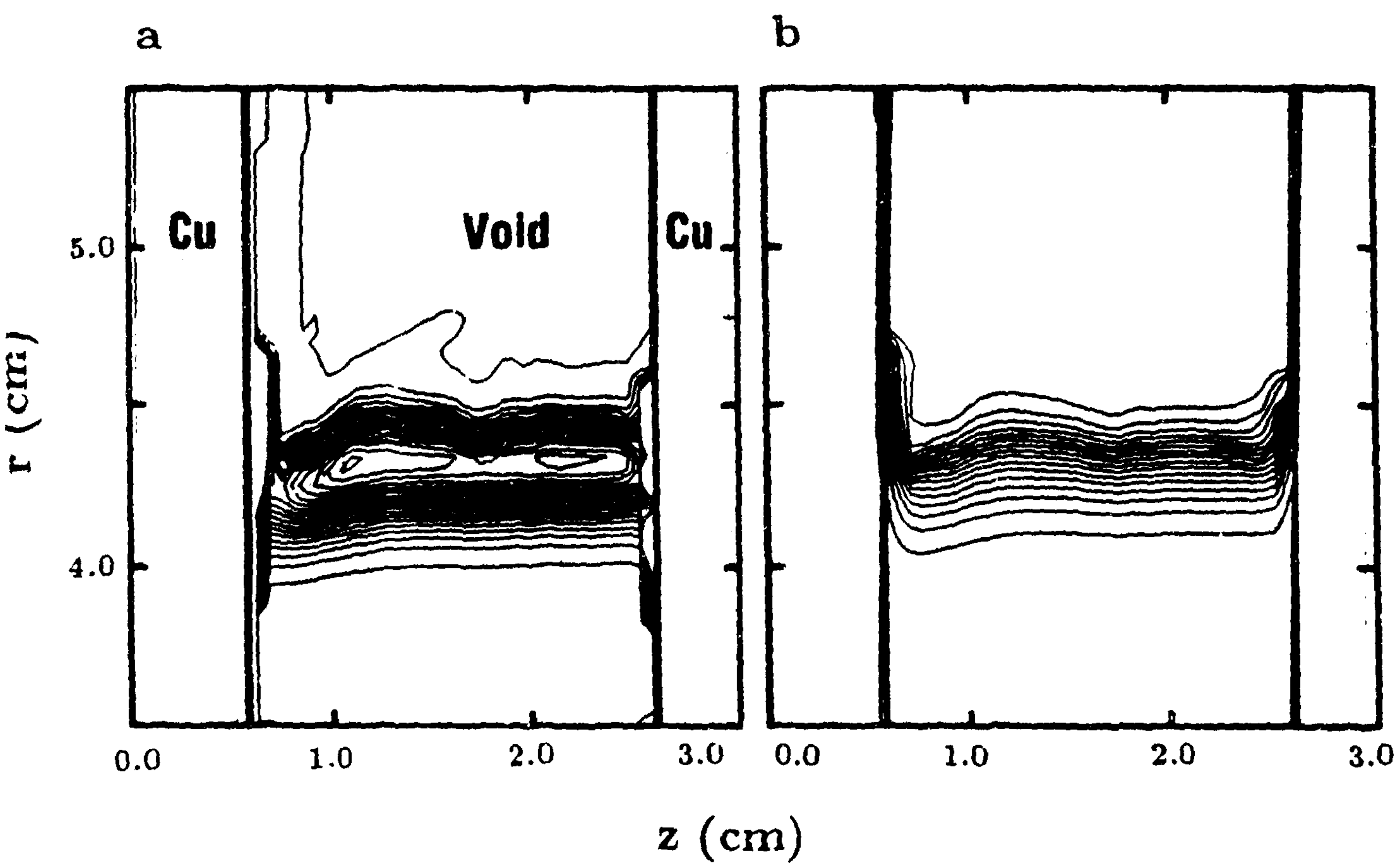


Fig. 5

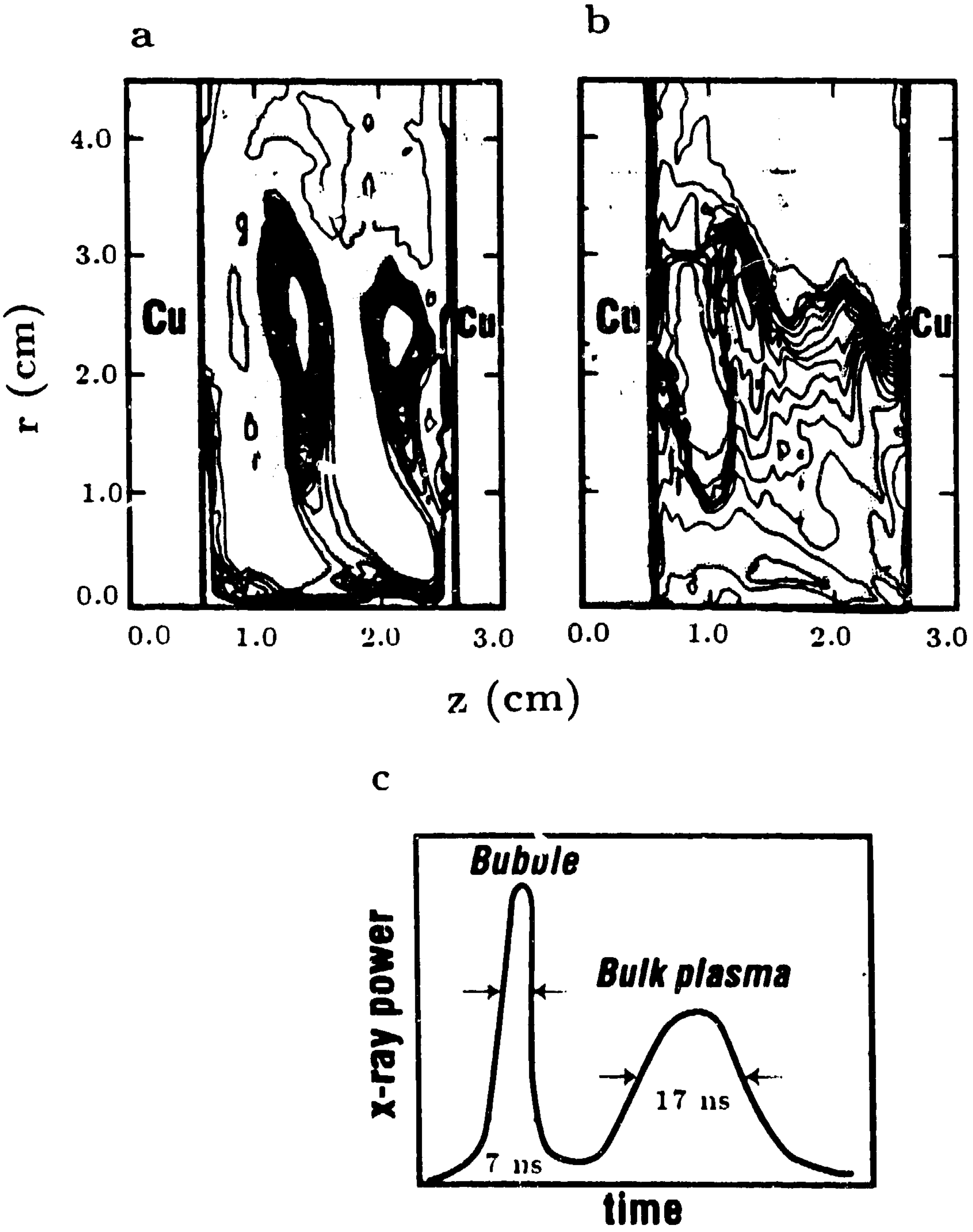

a
b
Cu
Cu
Cu
Cu
4.0
3.0
2.0
1.0
0.0
r (cm)
0.0
1.0
2.0
3.0
z (cm)
c
Bubule
Bulk plasma
x-ray power
7 ns
17 ns
time

Fig. 6