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TITLE: COMPUTATIONAL SIMULATIONS OF THE LAGUNA FOIL IMPLOSION EXPERIMENTS

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COMPUTATIONAL SIMULATIONS OF THE LAGUNA FOIL IMPLOSION EXPERIMENTS

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ABSTRACT

Building on the results achieved in the Pioneer shot series, the Los Alamos foil implosion project is embarking on the Laguna foil implosion experiments. In this paper the system design is discussed and results from zero-, one-, and two-dimensional MHD preshot simulations are presented. The system will provide 5.5 MA to the 5-cm-radius, 2-cm-high, 250-nm-thick aluminum foil load. This should give rise to a 1.1 μs implosion with nearly 100 kJ of kinetic energy.

INTRODUCTION

The Pioneer shot series in the Los Alamos foil implosion project demonstrated the proof-of-principle of using a high-explosive flux-compression generator to drive plasma implosions. Details of the Pioneer results are provided in Ref. 1. The Laguna shot series will be performed at significantly higher energies and will be prototypic of a megajoule system.

In the present paper we describe the system that has been designed for the Laguna series and discuss computer simulations that we have carried out in support of these experiments. In performing these calculations we have relied heavily on the fully implicit, one-dimensional, Lagrangian MHD code, RAVEN. This code provides us with a sophisticated electrical circuit modeling capability. This circuit can then be connected to either a 0-D slug model or a 1-D MHD model which includes a radiation diffusion package. We have used the results of the 1-D calculations together with a 3-D view factor code, GOPHER, to estimate the effects of radiation on the Laguna vacuum powerflow channel.

To examine the effects of magnetically driven Rayleigh-Taylor instabilities on the imploding load, we have used the 0- and 1-D results to set up calculations in a 2-D Eulerian MHD code. We then imposed a variety of perturbations on the load plasma and tracked the resultant instability growth.

THE LAGUNA SYSTEM

The Laguna foil/plasma implosion system will consist of a Mark IX helical generator, a storage inductor, an explosively formed fuse opening switch, a surface discharge closing switch, a vacuum powerflow channel, and a 5-cm initial radius, 2-cm high, 250-nm thick, unbacked aluminum foil load. Of the 100 nH of storage inductance in the system, 75 nH should stay in the system even if the cables between the [illegible] the current path to be the same around the 75 nH inductive store regardless of whether the current is running through the opening switch or the load.

An artist concept of the Laguna system is shown in Fig. 1. The circuit used for the 0-D and 1-D calculations is shown in Fig. 2. The capacitor bank in the first loop of this circuit is charged to 36 kV and will input a seed current of 450 kA into the 7.2 μH initial inductance of the Mark IX generator.

The time dependent inductance and resistance in the second horizontal branch together constitute a model of the Mark IX generator which has been benchmarked against experiment over the range of load inductances that are of interest in the Laguna series. The 25 nH of inductance in the third horizontal branch represents the cable connection on the generator side. The inductor labeled SI in horizontal branch four is the storage inductor. We expect the initial test in the Laguna series to be conducted with a 75 nH storage inductor. Therefore, barring cable failure, the total storage inductance will be 100 nH.

The inductance and resistance in vertical leg four represent the explosively formed fuse (EFF). The resistance curve used in these calculations is empirical. Our work on explosively formed fuses has been documented in Ref. 2.

The voltage dependent switch in the fifth horizontal branch represents the surface discharge closing switch (SDS). In the code the switch is modeled by an encoding of the results presented in Ref. 3. We are presently planning to use an SDS with a 20-cm gap and 0.076-cm thickness of mylar outside of the switch foil (see Ref. 3).

Our calculations indicate that the Mark IX generator can put a little more than 12 MA of current into this system. However, this will require 340 μs, hence, the need for an opening and closing switch combination. With this combination of switches, our calculations indicate that we should switch 5.5 of the 12 MA to the load foil in just over 1 μs. The amount of current that is switched is limited by the implosion of the load.

The load is housed in a vacuum powerflow channel, and there is 19 nH of inductance between the EFF and the vacuum interface, including 8 nH for the SDS. At the vacuum interface there is a stack of five, donut shaped, centimeter thick, teflon insulators. These insulators are separated by thin aluminum rings. Outside of the vacuum these rings extend into a moat containing a dilute solution of $CuSO_4$. This solution, combined with the rings, serves to grade the voltage uniformly between the anode (upper electrode) and cathode. Inside the vacuum the aluminum rings have been stamped into a sine-wave valley and peak to serve as radiation baffles to protect the insulators.

The $CuSO_4$ moat is represented in Fig. 2 by the voltage dependent resistor in the sixth vertical leg of the circuit. This resistance starts at 10 Ω but drops rapidly to zero as the voltage across it exceeds 250 kV. We have chosen the 250 kV value to be representative of

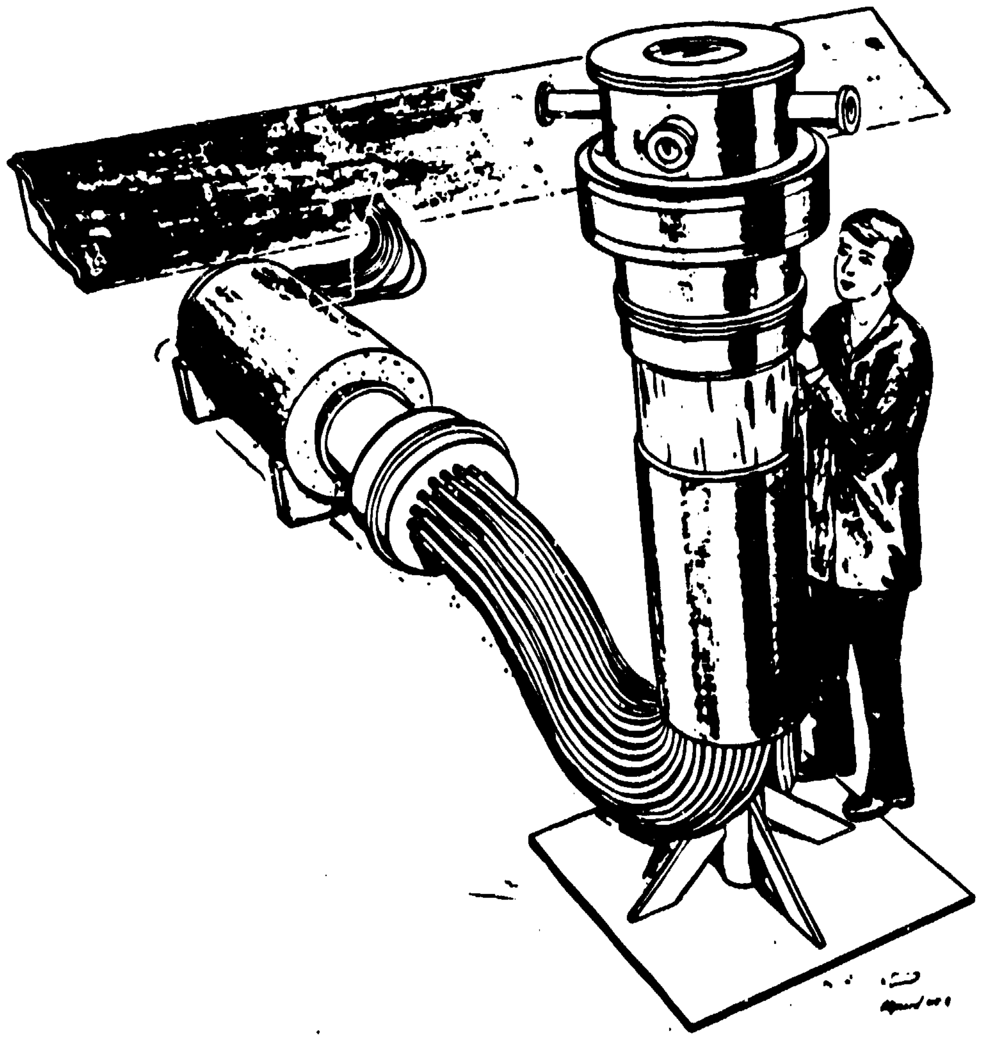

Fig. 1. Artist concept of the Laguna experimental apparatus.

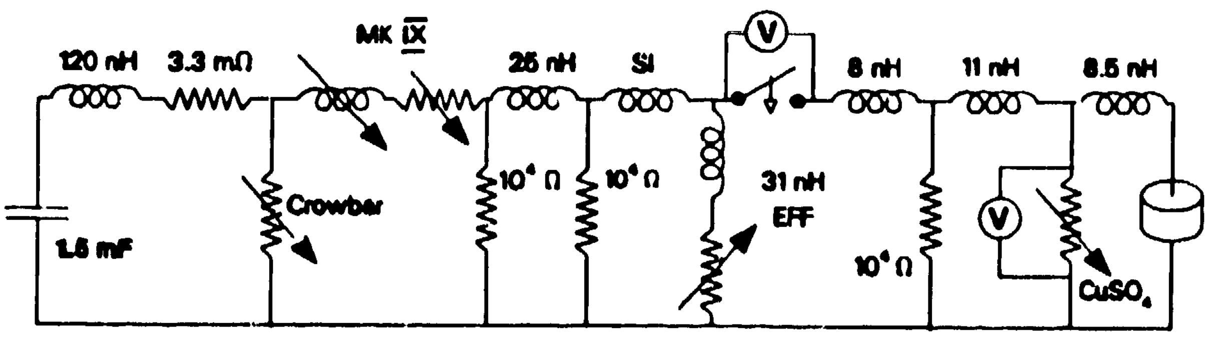

Fig. 2. Equivalent circuit used to simulate the Laguna system in the 0-D and 1-D RAVEN calculations.

ZERO AND ONE DIMENSIONAL MODELING RESULTS

Our 0-D calculations indicate that the imploding plasma will reach a kinetic energy of 120 kJ by the time that the implosion ratio has reached 10:1. This ratio is arbitrary but agrees with the kinetic energy calculated by our 2-D code in the presence of instabilities. From the time that current first reaches the load foil the implosion will require 1.13 μs.

One-dimensional calculations are made in order to get estimates of the plasma temperatures and densities, and the radiation output. In addition, the 1-D results provide the starting conditions for the 2-D calculations discussed below. We are modeling the 250-nm thick Laguna foil with 30 zones of equal radial spacing. The positions of the zone radii and the zone temperatures as functions of time are shown in Fig. 3. We do not trust the 1-D results beyond the 10:1 implosion ratio after which we expect instabilities to dominate. After 340.8 μs the plasma is basically isothermal with its temperature increasing from 4 eV up to about 12 eV by 341.3 μs. The temperatures of the zones then jump rapidly as the plasma pinches. A more detailed examination of this temperature spike makes it clear that the plasma is no longer isothermal. The rapid increases occur almost entirely after the implosion has passed the 10:1 point and the peak values predicted are certainly overestimates. We have arbitrarily capped the temperature rise in Fig. 3 at 100 eV because we doubt that the actual temperatures in the experiment will exceed this value. The behavior of the plasma temperature is explained by its radiation properties. When the plasma is isothermal and its temperature is relatively low, it is optically thin (the radiation mean free path is much larger than the plasma thickness). During this time period the energy deposited through Joule heating is quickly radiated away. When the density increases during the pinch to the point that the plasma becomes optically thick, this energy is trapped in the plasma and rapidly drives up the temperature.

Results from the RAVEN calculations have been coupled with 3-D simulations of the powerflow channel made with the view factor code GOPHER. We have used this combination to estimate the radiated fluence on the vacuum interface insulation and the radiation induced ablation of the powerflow channel walls. We find that the design of the powerflow channel is sufficient to keep the fluence on the vacuum interface below 50 $\mu J/cm^2$, a value that has been shown to induce flashover in Teflon.[4] For radiation induced ablation, we use RAVEN to predict the flux from the load, GOPHER to transport and deposit the radiation in the channel, and RAVEN again to calculate the ablation. Here we find that a clean, bare aluminum channel will not close during the experiment. However, if the electrode surfaces are covered with a hydrocarbon, blowoff may well close the channel before the end of the experiment.

TWO-DIMENSIONAL INSTABILITY RESULTS

The quality of the X-ray pulse obtained in the experiment will depend in part on the degree to which the imploding plasma is disrupted by magnetically-driven Rayleigh-Taylor instabilities. This has been examined by 2-D simulations of the implosion beginning with the profiles of density, velocity, temperature, and magnetic field provided from 1-D simulations at the point of maximum plasma expansion. A random density or velocity perturbations is then imposed on the plasma configuration.

An unknown is the level of perturbation that can be expected. Sources of perturbation include wrinkles on the foil created during mounting, non-uniform ignition of the foil, the catenary, and the inducement of variations due to the cold electrode walls. Preliminary simulations of the effects of the electrode walls and the catenary of the foil do not indicate that they will be very disruptive of the implosion in the Laguna experiments.

Figure 4 shows the development of the instabilities for random density perturbations of 30%. The width of the thermalization time can be estimated from this simulation to be of the order of $0.5\,\mu s$. Similar calculations indicate that a perturbation at the 10% level will degrade the thermalization time to about $0.25\,\mu s$. Random variations in velocity in the range up to $1.0\,cm/\mu s$ produce instabilities of about the same size as those for the 10% level of density perturbation. It appears from our simulations, that the key parameter for the growth of an existing perturbation is the distance traveled by the plasma, and not the implosion time. Radiation output has also been calculated for these simulations. Fig. 5 shows the radiated power predicted for the 2-D calculation with no initial perturbation and the 30% initial perturbation case.

CONCLUSIONS

We calculate that the Laguna experimental setup should deliver 5.5 MA to the aluminum foil load in about 1.1 μs. This current should drive an implosion to nearly 100 kJ of kinetic energy. However, 2-D calculations indicate that magnetically-driven Rayleigh-Taylor instabilities may spread the radiation pulse out to as long as 0.5 μs, drastically reducing the radiated power level.

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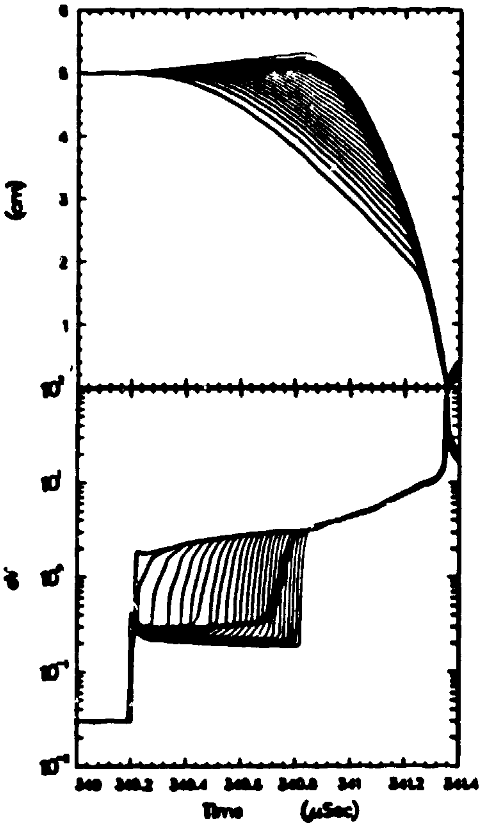

Fig. 3. Implosion history (top) and temperatures predicted by a 1-D Lagrangian, MHD, code.

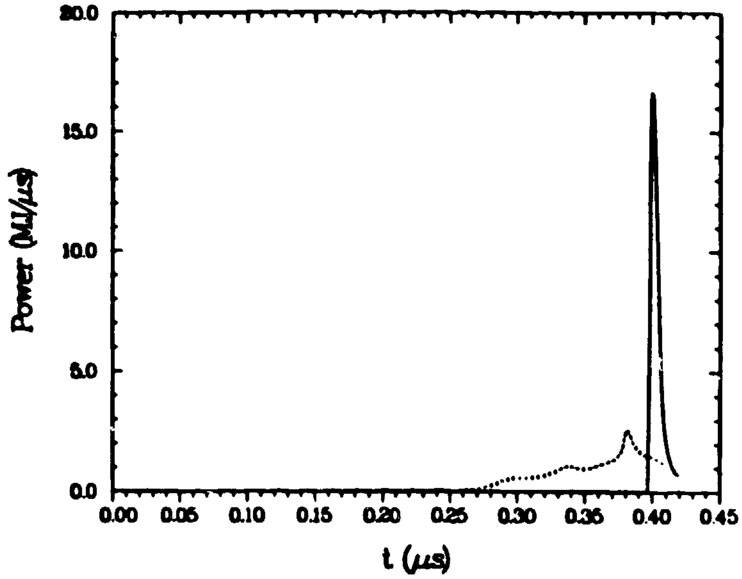

Fig. 5. Radiation power output for the unperturbed case (solid line) and for the simulation with a 30% level of perturbation (dashed line).

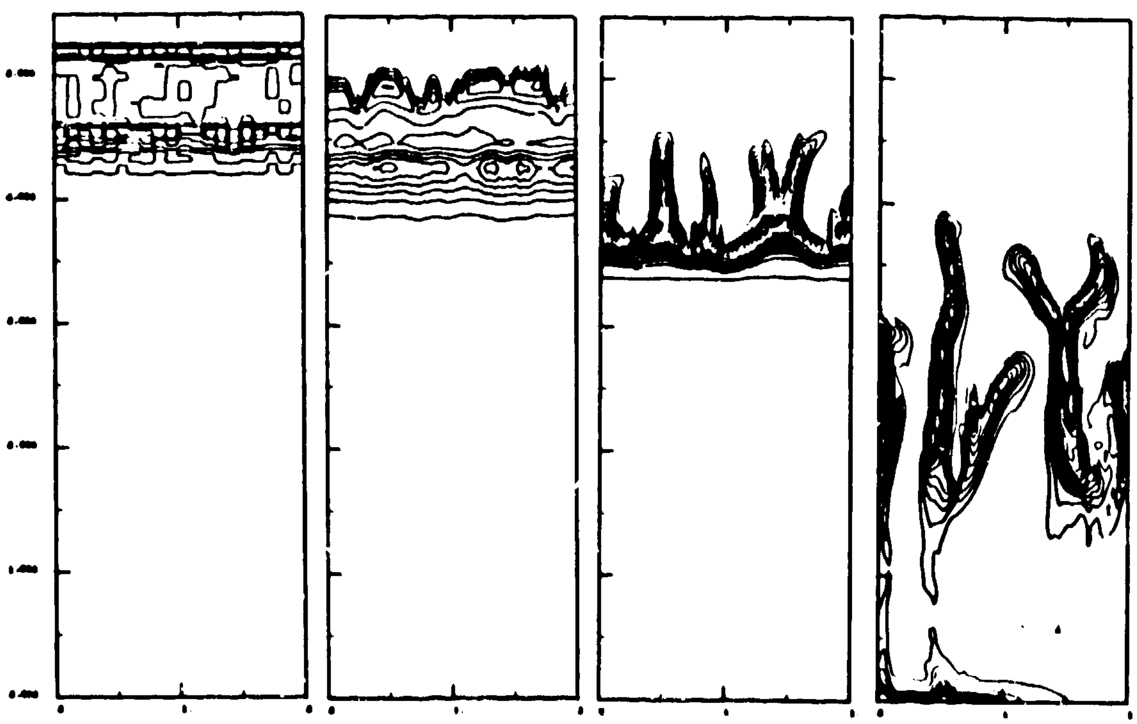

Fig. 4. Contours of constant density showing instability development at t = 0.0, 0.1, 0.2, and 0.3 μs into the 2-D simulation. The 1-D unperturbed pinch would occur at about 0.40 μs.