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# COMPUTATIONAL SIMULATIONS OF THE LAGUNA FOIL IMPLOSION EXPERIMENTS*

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## ABSTRACT

The Los Alamos foil implosion project is intended to produce a source of intense laboratory x-radiation for physics and fusion studies. Following the Pioneer shot series, the project is now embarking on the Laguna foil implosion experiments. In this series a Mark-IX helical generator will be coupled to an explosively-formed-fuse opening switch, a surface discharge closing switch, and a vacuum power flow and load chamber. The system design will be discussed and an overview of zero-, one-, and two-dimensional MHD preshot simulations will be presented. The generator should provide more than 11 MA of which ~5.5 MA will be switched to the 5-cm-radius, 2-cm-high, 250-nm-thick aluminum foil load. This should give rise to a 1.1 $\mu s$ implosion with tens of kilojoules of kinetic energy.

Zero-dimensional calculations serve to optimize the pulse-power system. One-dimensional, Lagrangian, MHD calculations are made to estimate temperature, densities and radiation output. The temperature and density profiles predicted by the 1-D code are used as initial conditions for our 2-D Eulerian code.

The 2-D calculations predict a small amount of radiated energy from a decoupled plasma associated with Rayleigh-Taylor bubbles. This matter is predicted to have electron and ion temperatures in the keV regime as the bubble material thermalizes ahead of the bulk of the plasma.

## INTRODUCTION

The goal of the Los Alamos Trailmaster project is the development of an intense source of soft x-rays for fusion and materials studies. The x-ray source in Trailmaster is a foil intiated z-pinch. The Trailmaster project is unique in that the prime power source is an explosive-driven magnetic flux compression generator.

Building on the results achieved in the Pioneer shot series (Ref. 1-3), the Trailmaster project is now embarked on the Laguna shot series. The Laguna series will be performed at significantly higher energies and will be prototypic of a megajoule system.

The Laguna pulse power system consists of a Mark IX helical generator, a 100-nH storage inductor which includes a post-hole convolute design, an explosively-formed fuse opening switch, a surface discharge closing switch, and a vacuum powerflow channel. The imploding plasma z-pinch is initiated from a 2-cm high, 5-cm radius, 250-nm thick, unbacked aluminum foil. Figure 1 shows a photograph of the Laguna system on the firing pad at Los Alamos during an early sub-system test. Figure 2 is a blue print of the tower portion of this system. The tower contains the storage inductor, the switches and the load.

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Fig. 1. The Laguna system being constructed at Firing Point 88, Los Alamos National Laboratory.

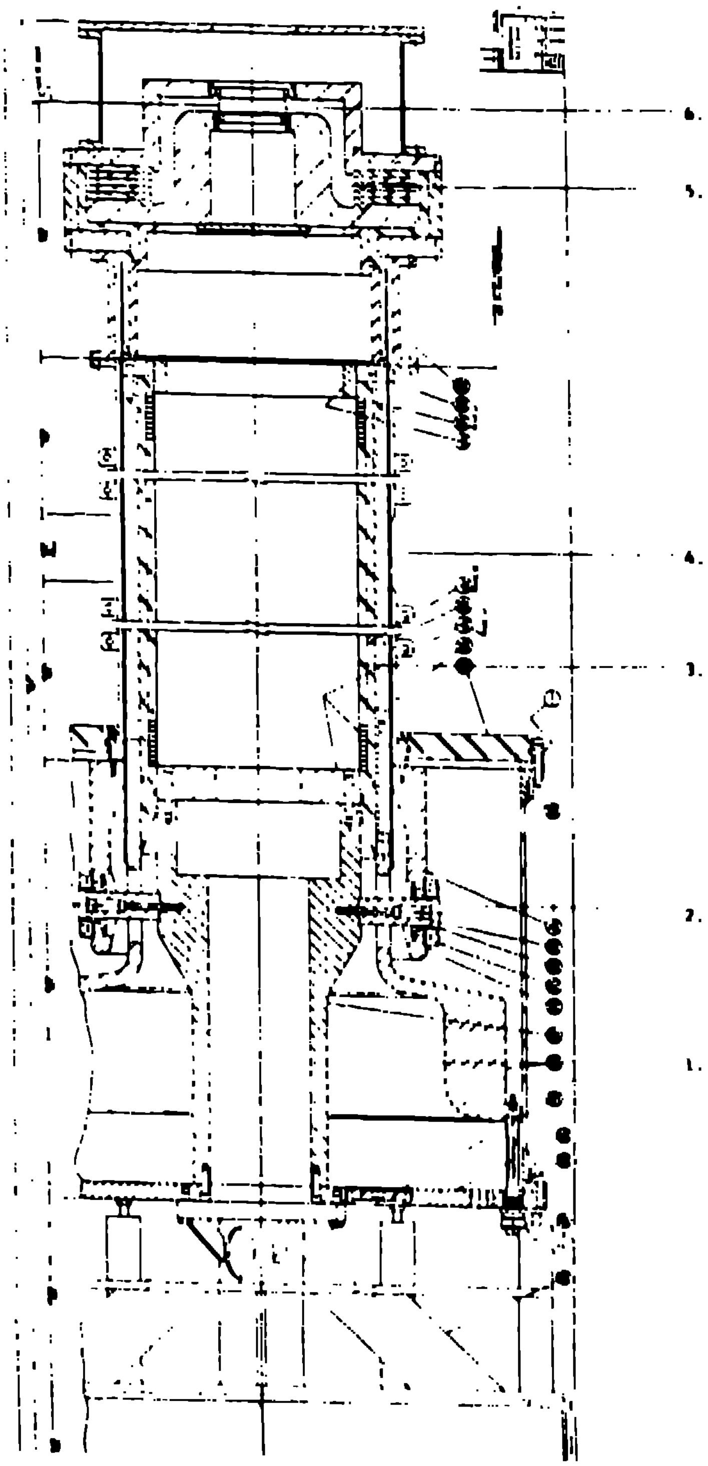

Fig. 2. Blueprint of the tower (upright) portion of the Laguna system: (1) storage inductance; (2) posthole convolute region; (3) explosively formed fuse; (4) surface discharge closing switch; (5) vacuum powerflow chamber; and (6) foil load.

The purpose of the opening/closing switch combination is, of course, pulse shaping. The capacitor bank at firing point 88 at Los Alamos requires some 135 $\mu$s to put a 450 kA seed current into the 7.2 $\mu$H initial inductance of the Mark IX generator. The generator is a sweeping wave helix which has a run time of 210 $\mu$s. We wish to switch the current to the imploding load in about 1 $\mu$s.

We have carried out pre-shot computer simulations of this system with 0-D-slug, 1-D Lagrangian, and 2-D Eulerian MHD codes. The results of these calculations are the subject of this paper.

## ZERO-DIMENSIONAL. SLUG MODEL, PREDICTIONS

The 1-D Lagrangian code RAVEN contains an extensive circuit modeling capability and a 0-D slug option. The purpose of making the 0-D calculations is really two-fold. First, these very quick and simple calculations provide implosion kinetic energies that are the same as the 1-D results Therefore, the load can be optimized, at least to a first approximation, using the 0-D calculations. Secondly, the 0-D implosion provides a dL/dt voltage pulse for the rest of the circuit model. This has allowed us to make hundreds of quick, inexpensive, calculations to optimize timings within the circuit and examine the sensitivity of the system to timing errors and other possible system problems. In the present work, however, we will discuss only the behavior of the z-pinch rather than the circuit.

The 0-D model is just

$$m\dot{v} = \frac{\mu_0}{4\pi}\frac{hI^2(t)}{r(t)}$$

where $m$ is the mass of the imploding load, $h$ is the height of the cylinder, $r(t)$ is the time-dependent radius and $I(t)$ is the time dependent current. The time dependence of the inductance is determined from $r(t)$ using the coaxial formula. The slug implosion is arbitrarily terminated when the ratio of the initial radius to the imploding radius reaches 10:1. We assume that instabilities will dominate the dynamics of the implosion beyond this point.

The 0-D calculations predict that this 10:1 implosion point will be reached in 1.1 $\mu$s from the time that the current first reaches the foil load. Figure 3 shows the circuit/0-D prediction of the load current as a function of time. Note that current first reaches the load at 340.2 $\mu$s; this is from the beginning of the capacitor bank discharge.

This 5.5 MA of current will drive the imploding plasma to a velocity of 24 cm/$\mu$s, which is a kinetic energy of 120 kJ. Past experience indicates that even stopping these calculations at the 10:1 implosion ratio will overestimate, by as much as a factor of two, the energy that is given off as radiation when the imploding plasma thermalizes.

## ONE-DIMENSIONAL MODELING RESULTS

One dimensional calculations are made in order to get estimates of the plasma temperature, the radiation output, and the extent to which the plasma and radiation are in thermodynamic equilibrium. In addition, the 1-D results provide the starting conditions for the 2-D calculations discussed below. The radiation transport package presently available in RAVEN is a flux limited diffusion package. We can estimate whether the plasma is optically thick or thin using the calculated densities and temperatures.

RAVEN is a fully implicit Lagrangian code. We are modeling the 250-nm thick Laguna foil with 30 zones of equal radial spacing. The positions of the zone radii as a function of time are shown in Fig. 4. This implosion time is identical to the zero dimensional result. We should emphasize that we do not trust the 1-D results beyond the 10:1 implosion ratio that we set as the limit for the 0-D calculations. In the 1-D simulation this 10:1 point is reached at 341.33 μs, which is 1.15 μs after current first reaches the load. There is nothing magical about the 10:1 implosion ratio. The 2-D calculations indicate that instabilities may be important well before the 10:1 point is reached.

Figure 5 shows the calculated temperatures as functions of time. The code calculates that the zones of aluminum will vaporize and then ionize during the 340.2 to 340.8 μs period. After this time 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 to very high values as the plasma pinches. A more detailed examination of this temperature spike on the graph 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. 5 at 100 eV because we doubt that the actual temperatures in the experiment will exceed this value. The effect of the instabilities will be to spread out the time over which the kinetic energy is released as radiation. This will, in turn, lower the effective temperature of the radiation.

Figure 6 shows the optical mean-free path calculated by RAVEN using the Rosseland mean opacity values for aluminum from the Los Alamos SESAME tables. The behavior of the plasma temperature is clearly 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.

## TWO-DIMENSIONAL RESULTS

The quality of the x-ray pulse obtained in these experiments will depend in part on the degree to which the imploding plasma is disrupted by magnetically driven Rayleigh-Taylor instabilities. We have examined the growth of these instabilities by 2-D simulations of the implosions beginning with random density or velocity perturbations imposed on the profiles of density, velocity, temperature, and magnetic field provided from 1-D simulations at the point of maximum plasma expansion. These 2-D calculations are discussed in detail in Ref. 4. In this paper we will attempt to summarize the important results and conclusions.

The initial setup for the 2-D calculations is illustrated in Fig. 7. We should note that the baseline 1-D simulation for all of these 2-D results was made some time ago, and involved an earlier model of the Mark IX generator. For this reason, $t = 0.0$ μs for the 2-D simulations corresponds to the point $t = 319.72$ μs in this, earlier, 1-D simulation. We felt that the time histories of the current into the load and the implosion were sufficiently similar to the more recent results that we could not justify the computer time that would be involved in redoing the calculations for the present system.

A key unknown at this time is the level of perturbation that can reasonably be expected in the implosion. The calculations predict that a level of

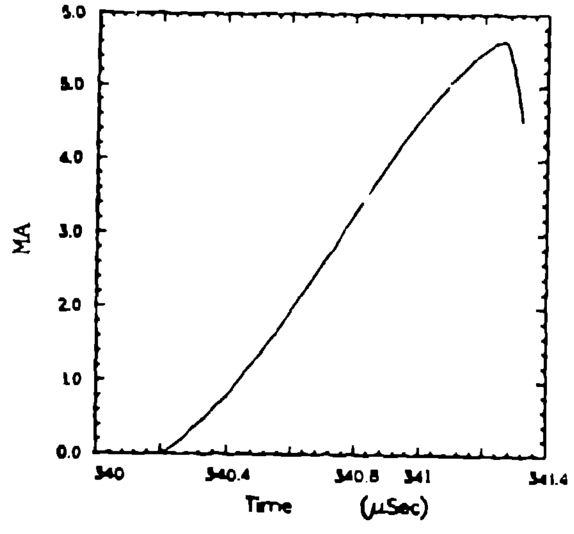

Fig. 3. Predicted time history of the current through the load in the 0-D, slug model simulations.

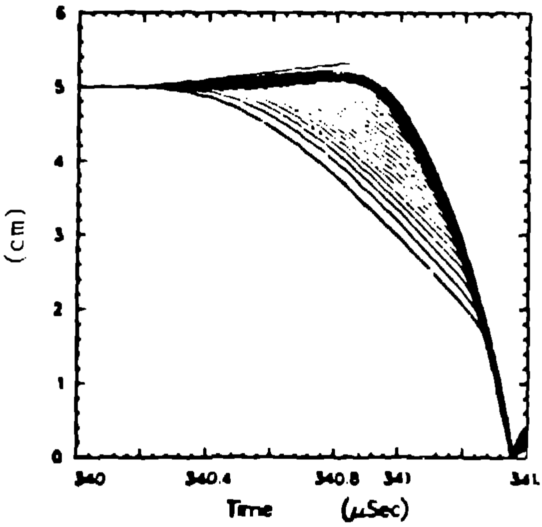

Fig. 4. Implosion history predicted by a 1-D Lagrangian, MHD, code.

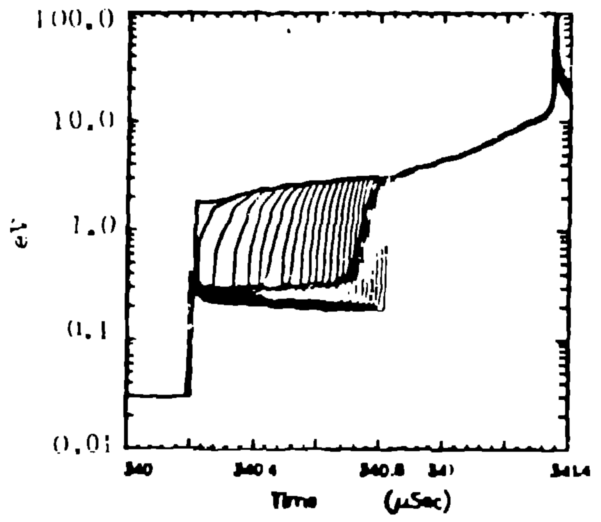

Fig. 5. Time history of the temperatures of the Lagrangian zones from the 1-D, MHD, calculation. This graph is arbitrarily capped at 100 eV; a value that is higher than we expect to be reached during the experiment.

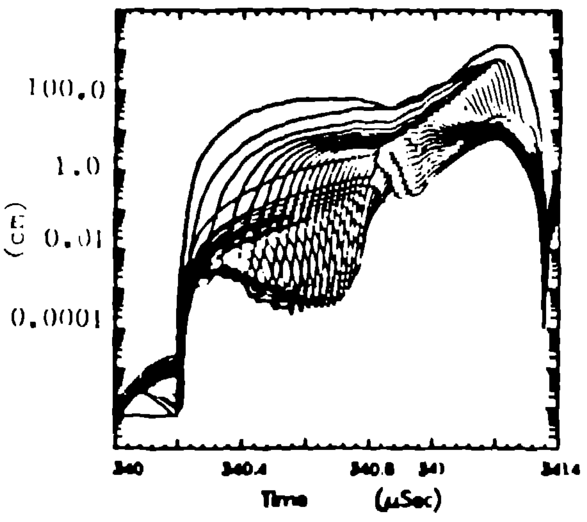

Fig. 6. Radiation mean-free path values for the Lagrangian zones as a function of time. These values are calculated using the Rosseland mean opacities for aluminum from the SESAME tables.

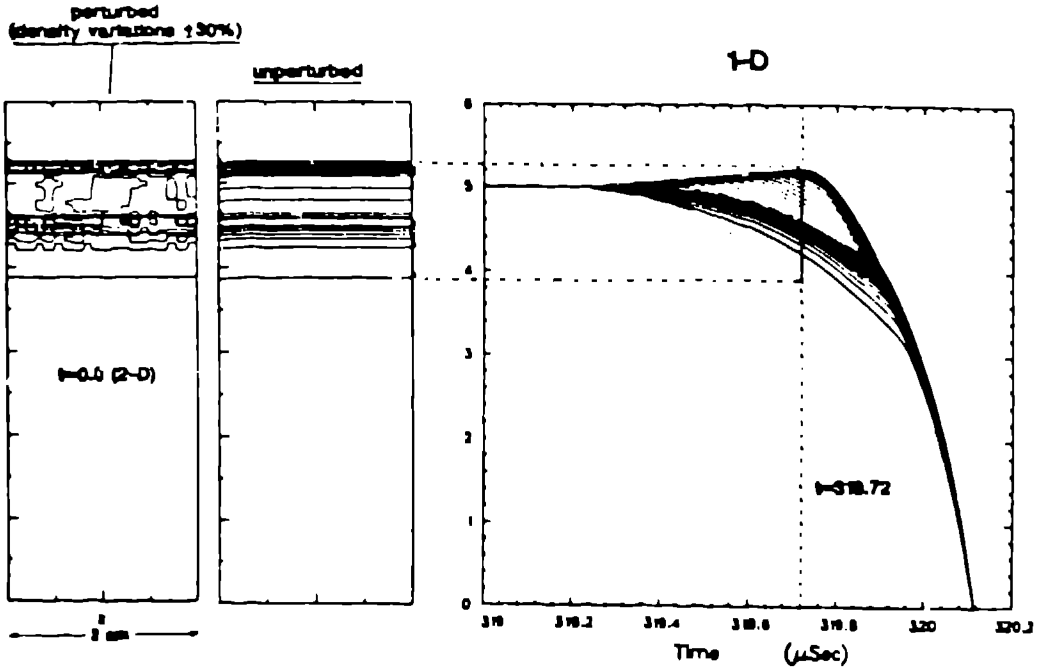

Fig. 7. Initialization of 2-D simulations from a 1-D simulation. The plot on the right shows 1-D Lagrangian cell boundaries as a function of time. The center plot shows density contours for a 2-D unperturbed implosion and the left plot shows density contours where the density has been varied randomly between -30% and +30%.

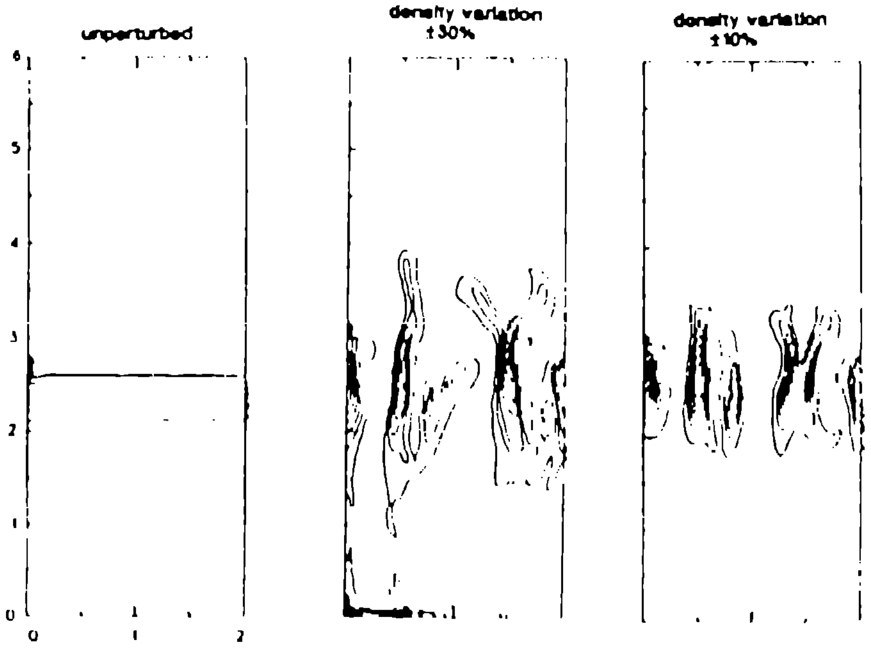

Fig. 8. Contours of constant density for three 2-D simulations at $t$ 0.3 μs: unperturbed (left); 30% density variation (center); 10% density variation (right).

perturbation of 30% in the density will seriously degrade the thermalization of the plasma and the resultant x-ray pulse. We estimate from this simulation that such a perturbation will lead to a thermalization time of 0.5 $\mu$s. In Fig. 8 a comparison is made between an unperturbed implosion, one with a 30% level density variation, and one with a 10% level of density variation. These calculations indicate that a perturbation at the 10% level will also seriously degrade the thermalization (the pulse width can be estimated at 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. The effects of anomalous resistivity, which could enhance current crossover between the spike regions and reduce the growth rate of the instabilities, have not been included in these simulations. The unperturbed calculation will subsequently also be referred to as the 1-D Eulerian calculation.

Figure 9 shows time histories of the kinetic energy in the plasma, the material energy in the plasma (kinetic+internal) and the radiation energy output for the unperturbed implosion. The low level of radiation output, essentially linear in time, during the first 0.4 $\mu$s is from bulk emission from the plasma during the run-in phase of the implosion. The majority of the radiation output in this 1-D Eulerian case occurs over about 0.02 $\mu$s when the plasma assembles on axis, and, in this calculation, exceeds 135 kJ.

Radiation output has also been calculated for the simulation with an initial level of perturbation of 30%. Figure 10 shows material, kinetic and radiation energies for this 30% initial perturbation level. For $t \leq 0.26$ $\mu$s these results are essentially the same as those shown in Fig. 9. However, Fig. 8 shows that by 0.3 $\mu$s these results are essentially the same as those shown in Fig. 9. However, Fig. 8 shows that by 0.3 $\mu$s the bulk of the plasma has been disrupted at three points. As the connecting material in these regions thins its reduced density leads to an increased magnetic acceleration relative to the denser surrounding material. The velocity of this low density material that is thrown forward varies, but is in the range of 60 to 150 cm/$\mu$s. At about 0.26 $\mu$s the low density bridge at $z \simeq 0.25$ cm begins to accelerate ahead of the main body of the plasma. About $2 \times 10^{-6}$ g reaches the axis by $t = 0.28$ $\mu$s. The thermalization of this hot, low density plasma corresponds to the marked increase of radiation output seen at $t \simeq 0.28$ $\mu$s in Fig. 10. A slight decrease in the slope of the kinetic energy rise is also visible at this time, corresponding to the thermalization of this low density plasma. The low density plasma continues to accumulate on axis and by $t = 0.32$ $\mu$s the radiation energy output from this low density material has reached about 30 kJ.

Our calculations indicate that this low density, optically thin plasma is not in local thermodynamic equilibrium (LTE). Instead, the ion, electron and radiation temperatures decouple. The ions and electrons have temperatures in the range of a few keV while the radiation temperature is much lower, only a few tens of eV. The later radiation, that arising from the thermalization of the denser, optically thick, plasma is in LTE. It has physical properties that are essentially identical to those predicted by the 1-D models. The unperturbed implosion simulation achieves a final peak radiation temperature of about 200 eV. The 2-D simulations with instabilities predict final peak temperatures in the range from 60 to 80 eV.

## CONCLUSIONS

In this paper we report the results of preshot calculations made for the Laguna shot series of the Los Alamos Trailmaster project. These calculations

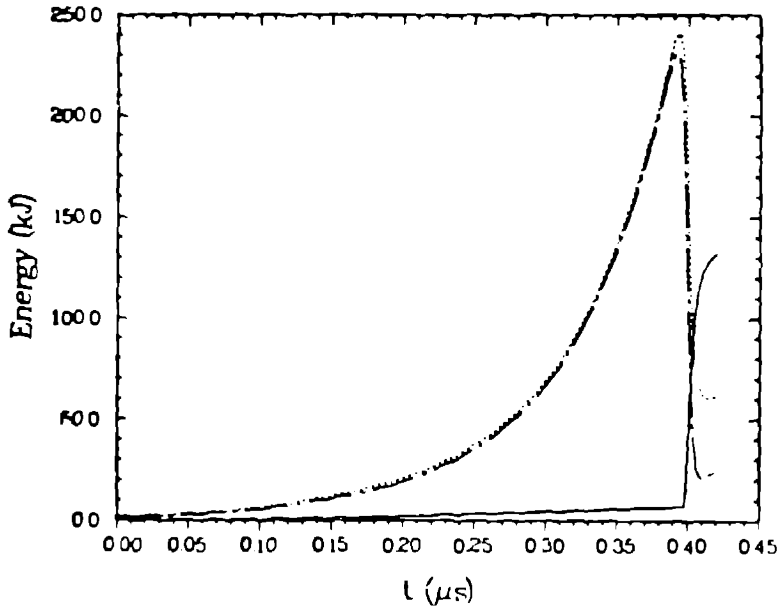

Fig. 9. Energy contained in the material (kinetic + internal, dotted line), kinetic energy (dash-dot line), and radiation energy output (solid line) for a 1-D implosion (2-D simulation with no perturbations).

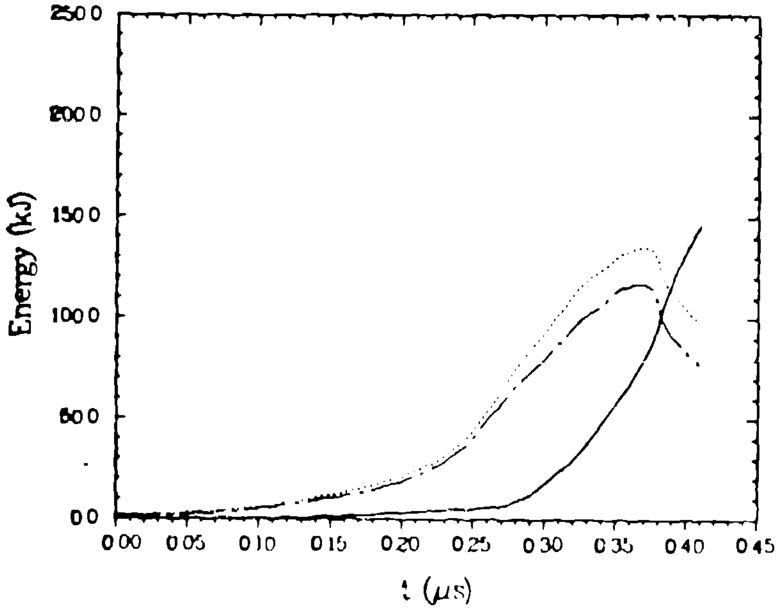

Fig. 10. Energy contained in the material (dotted line), kinetic energy (dash-dot line) and radiation energy output (solid line) for the 2-D (30% perturbation) simulation.

have been made using 0-D, 1-D Lagrangian, and 2-D Eulerian MHD codes. Our 0-D and 1-D simulations have included detailed, self-consistent circuit modeling. The 2-D calculations start from conditions predicted by the 1-D simulations and use the current history predicted by the 1-D code. The 2-D calculations allow us to predict the effects of magnetically driven Rayleigh-Taylor instabilities.

Our circuit modeling predicts that the Mark IX generator will put nearly 12 MA of current into the Laguna system. The combination of opening and closing switches will transfer about 5.5 MA of this current to the foil/plasma load while shortening the pulse from over 340 $\mu$s to 1.13 $\mu$s.

The 0-D and 1-D calculations predict that this 1.1 $\mu$s implosion will have a kinetic energy of about 120 kJ. However, past experience indicates that these estimates may be optimistic by as much as a factor of two, at least in terms of the x-ray output from the implosion.

The 2-D calculations predict that Rayleigh-Taylor instabilities, starting either from density or velocity perturbations, will seriously disrupt the imploding plasma. We show that these disruptions can lead to actual breakthroughs that drive low density plasma in well ahead of the bulk of the plasma. We predict that this low density material will not be in thermodynamic equilibrium. It will have electron and ion temperatures as high as a few keV. However, the early radiation temperature from this low density material will be only a few tens of eV. When the bulk of the plasma thermalizes on axis it may have radiation temperatures in the range of 60 to 80 eV.

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