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TITLE: THE LASL FAST LINER EXPERIMENT

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THE LASL FAST LINER EXPERIMENT*

ABSTRACT

The LASL Fast Liner Experiment explores a fusion concept in which a prepared plasma is adiabatically compressed to thermonuclear temperatures and densities by a rapidly imploding solid metal liner. A prepared plasma having $\beta > 1$ is in contact with the liner and end plugs, and contains an embedded magnetic field to inhibit thermal conduction. Cylindrical liners are magnetically imploded by a large axial current carried in the liner shell. Theoretical estimates indicate an implosion velocity of at least 10^6 cm/s is necessary for this geometry if the plasma heating rate is to be greater than the cross-field thermal conduction loss rate. Our experimental work to develop this concept involves attempts to provide a suitable preplasma for liner implosions as well as studies of magnetically driven liner implosions. In the plasma preparation experiments a coaxial plasma gun was used to inject plasma into a simulated liner geometry. About 2 μs after plasma injection a density of 3×10^{16} cm^{-3}, a temperature of 40 eV, and an embedded azimuthal field of 10 kG were measured. In the implosion studies cylindrical aluminum liners were imploded by Z-pinch currents of 10-15 MA produced by the Scyllac capacitor bank. Symmetrical

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implosions having velocities in the range 4-6 x 10^5 cm/s have been obtained for liners having typical initial dimensions 10-cm long, 5-cm diameter, and 1-mm thick using a 1.75 MJ section of the bank. Implosion velocities of 9-10 x 105 cm/s were observed for 6-cm-long, 5.6-cm-diameter, 1-mm-thick liners driven by a 2.4 MJ section of the bank. The observed velocities and trajectories agree well with the predictions of a one-dimensional code, CHAMISA,

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1. INTRODUCTION

The concept of compressing a plasma to thermonuclear conditions by means of imploding metal liners has been discussed by various authors for many years. The idea apparently grew from early experiments in which explosively driven liners were used to produce magnetic fields having pressure in the Mbar range. In the LASL Fast Liner Experiment we have been exploring one area of this general concept that combines aspects of both inertial and magnetic confinement. A thin solid metal liner carries a large electrical current and is magnetically imploded by the pinch effect upon a previously prepared plasma. The prepared plasma is wall-supported by the liner and contains an embedded magnetic field to inhibit thermal conduction. The metal liner acts to inertially confine the compressed plasma during the burn and energy losses are slowed by the embedded magnetic field, hence the combination of inertial and magnetic confinement. This particular area of the imploding liner approach to fusion has previously been investigated by S. G. Alikhanov and coworkers at the Kurchatov Institute [1] and has also recently been discussed by J. G. Linhart. [2]

We have concentrated on a cylindrical geometry, illustrated in Fig. 1, in which the driving magnetic field and the magnetic field embedded in the plasma are both in the azimuthal direction and solid end plugs are employed. An analytical model of the heating of a plasma by such an imploding liner [3] and a conceptual design for a fast-liner reactor [4] have been presented elsewhere. Estimates based on the analytical model for plasma heating and on heat losses by one-dimensional cross-field thermal conduction indicate a liner implosion velocity of at least 10^6 cm/s is required if the plasma heating rate is to be greater than the thermal loss rate. These calculations also indicate that initial plasma parameters of a density of several times 10^{17} cm^{-3}, a temperature of a few hundred eV, and an embedded magnetic field of around 8 T would be required for reactor conditions. However, parameters of 10^{17} cm^{-3}, 100 eV, and 20 kG would be adequate to test the concept if liner velocities of 10^6 cm/s could be achieved.

2. PLASMA PREPARATION EXPERIMENTS

The purpose of these experiments was to produce a warm magnetized plasma in a geometry suitable for use in a liner implosion experiment to aid understanding the physics of the heating of a wall-supported plasma. A large coaxial plasma gun (150-cm long, 30-cm diameter outer electrode, and 10-cm diameter inner electrode) was modified by the addition of a copper cone to its outer electrode. The cone tapered the 30-cm electrode diameter to a 10-cm diameter in a distance of 20 cm. A 10-cm diameter 10-cm long liner volume was attached to the small end of the cone. The cylinder wall was thicker than a liner and had holes in it for diagnostics. Several modifications to the inner electrode geometry were tried in combination with the modifications just described. The geometry for the results reported here is shown in Fig. 2. Note that plasma is injected through a 1.2 cm annulus which in an implosion experiment would become sealed off by the motion of the liner. Copper, titanium, tungsten, and tantalum were used as materials for the walls in the simulated liner region. Tantalum and tungsten appeared to give better plasma parameters than the other materials, and the results for tantalum are given.

Plasma temperature, density, and magnetic field were measured within the simulated liner region. Plasma temperature was measured on the midplane of the region 2.5 cm off the symmetry axis using Thomson scattering. The density was measured using a single-pass interferometer, along a cord intersecting the Thomson scattering volume. The magnetic field was measured using a loop in a metal-walled jacket. The loop was located 2.5 cm off the symmetry axis and 2.5 cm from the rear end wall. The measured plasma parameters are shown as a function of time in Fig. 3. At 2 μs after injection $B \approx 9$ kG, $T_e \approx 38$ eV, and $n \approx 2.5 \times 10^{16}$ cm^{-3}. These parameters are close to the desired conditions for a liner shot, but $\omega_{ci} \tau_{ii} \approx 0.8$ so the ions are not magnetized. The expected thermal decay rate for unmagnetized ion conduction is about 20 μs, whereas the observed decay rate from the data of Fig. 3 is about 12 μs. In a liner implosion the ions would become magnetized during compression.

3. LINER IMPLOSION EXPERIMENTS

Liner implosion experiments were conducted without plasma on a section of the Syllac capacitor bank [5] at Los Alamos. The bank is configured in fifteen racks, each having a capacity of 389 μF. A series of implosion experiments was done at bank energies of 1.75 and 1.45 MJ using three racks; seven racks were used for a shot at 2.75 MJ, after which six racks were used for shots at 2.36 MJ.

The diagnostics employed were measurements of the driving current and voltage, flux compression of a 1-kG axial seed field, contact probes, and flash x rays. All of these diagnostics give information about the liner trajectory, and the last three can yield information about azimuthal symmetry and/or axial uniformity as well. The driving current was measured by a Rogowski loop between the collector plates at a radius of about 70 cm. The driving voltage across the collector plate was measured near the 70-cm radius and also at the liner. If all the current flows in the liner, r(t) is an average radius of the liner. The driving current and voltage is used to determine an average radial position of the driving current as a function of time. Assuming that the resistive losses are small and that all the change of inductance is due to liner motion, the relationship $V = L\dot{I} + I\dot{L}$ can be integrated for L(t) and hence r(t) since V, I, and $\dot{I}$ are measured as a function of time.

In the flux compression measurement an initial axial field B_0 is established inside the liner and a magnetic probe is placed on axis. To a first approximation the flux within the liner is conserved on the time scale of the implosion allowing the trajectory to be determined from the field values. The voltage from the probe is proportional to $v/r3$, where v is the velocity of the liner, so the measurement is insensitive at early times when v is low and r is maximum. By the end of the implosion the liner has become resistive because of ohmic heating from the large driving current (10-15 MA), and again the measurement becomes subject to error. It was found, however, that in the approximate range 1.5 cm > r > 0.5 cm the trajectory deduced from the flux compression measurement agreed well with the other diagnostics. Axial uniformity of the implosions was checked by ~~having~~ measuring r(t) in this manner at several axial positions on a given shot.

Contact probes were made from very small metal coaxial conductors. These were used to determine the time of arrival of the liner at a given point. If used, the number of contact probes employed on a given shot ranged from three to six. When we attempted to use contact probes to check azimuthal symmetry no significant information was obtained because of electrical noise problems. However, on other shots when contact probes were used to check the trajectory of the liner results were obtained which agreed with the other diagnostics.

Flash x rays were attempted on a number of liner implosion shots--180 kV and 300 kV x-ray sources were used. The best results were obtained with the 300-kV source. The x-ray head was located two meters from the liner on the axis of symmetry. There was a 2.5 cm hole in the blast containment vessel for the x rays 88 cm from the liner. The film was located 41 cm on the other side of the liner. We had considerable difficulty protecting the film from the shrapnel of a liner shot, but x-ray shadowgraphs were obtained on some shots.

The results of our experimental measurements on the liner implosion were compared with a numerical model for the expected implosion dynamics. Our liner implosion code, CHAMISA, has been described in Ref. 3. CHAMISA is a one-dimensional, Lagrangian, hydrodynamic code with a detailed treatment of the equation of state of the liner material. [6] It contains a model for the electrical resistivity at high temperature and pressure, allowing treatment of the problem of the nonlinear diffusion of the driving current through the liner material. The electrical circuit is included, so that a liner trajectory can be calculated if the capacitor bank and feedplate electrical parameters are given.

Some experimental results for 1.4 MJ shots are shown in Figs. 4 and 5. The liner dimensions for these shots were 10-cm length, 5-cm diameter, and 1 mm thick. Figure 4 shows a comparison of the trajectory deduced from the driving current and voltage with three points in the useable range of the trajectory deduced from flux compression. Also shown is the position of the liner at a particular time given by the flash x-ray photograph. Although the x-ray photo was not as clear as we would have liked due to plate damage, it shows good azimuthal symmetry. The point labeled on Fig. 4 as "abrupt current change" denotes the time when the liner implosion hit axis. This point is characterized by a discontinuity in the slope of the current trace caused by the sudden ending of the $I\dot{L}$ contribution to the voltage. The external circuit inductance is not known exactly; therefore it was used as a fitting parameter in CHAMISA. A value of 6.5 nH (which is quite reasonable) gave excellent agreement both in shape and magnitude between the measured and calculated driving currents. The liner trajectory is then calculated with no further free parameters. Figure 5 shows the results of the calculation for the inner and outer radius of the liner along with the position of the current deduced from the voltage and current measurements. Also shown is the position of the inner surface of the liner at three times as determined by the contact probes and the arrival of the liner on axis and the arrival of the liner on axis as determined from the current trace. The agreement between the measurements and the calculations exhibited in Fig. 5 is considered by us to be evidence that the implosion dynamics indeed follow close to the predictions of the code. The final implosion velocities determined from the experimental data for these 1.4 MJ shots ranged from 3-6 km/s except when there was a capacitor bank malfunction.

Figure 6 shows the trajectory predicted by CHAMISA and the experimental data obtained for a 2.4 MJ shot. On this particular shot flux compression data was not obtained, but the contact of the liner with the magnetic probe on axis was detected. The liner dimensions for the 2.4 MJ shots were 6-cm length, 2.8-cm radius, and 1-mm thickness. The trajectories deduced from the driving current and voltage traces were not reasonable. They showed a finite velocity at $t=0$ and a higher acceleration for the first couple microseconds than was possible. The velocity inferred from the discrete experimental points in Fig. 6 is 10 km/s, in agreement with the prediction of CHAMISA.

An x-ray shadowgraph of the imploding liner in a 2.4 MJ shot is shown in Fig. 7. This reproduction is negative so white color indicates mass. The outer edge of the dark disc is at $r=2$ cm and is the boundary between the sliding contact (opaque) and the end windows. The white spots on axis and the white radial streaks are magnetic probes, pin probes, and signal wires. This exposure was taken on the shot presented in Fig. 6. The liner has nearly completed its implosion. Its inner radius is at about 7 mm, and at the time of this exposure its velocity was 10^6 cm/s. The liner implosion is seen to be azimuthally symmetric. The fuzzy appearance of the outer edge of the liner in Fig. 10 is caused by the fact that the material there has been vaporized by the ohmic heating associated with the penetration of the driving current into the liner. The inner edge of the liner is still solid, and a slight fuzziness of the image there is due to resolution effects and to x ray scattering in the plates protecting the film.

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FIGURE CAPTIONS

FIG. 1. Geometry of the LASL Fast Liner concept.

FIG. 2. Plasma preparation experimental configuration.

FIG. 3. Gun-injected plasma parameters as a function of time.

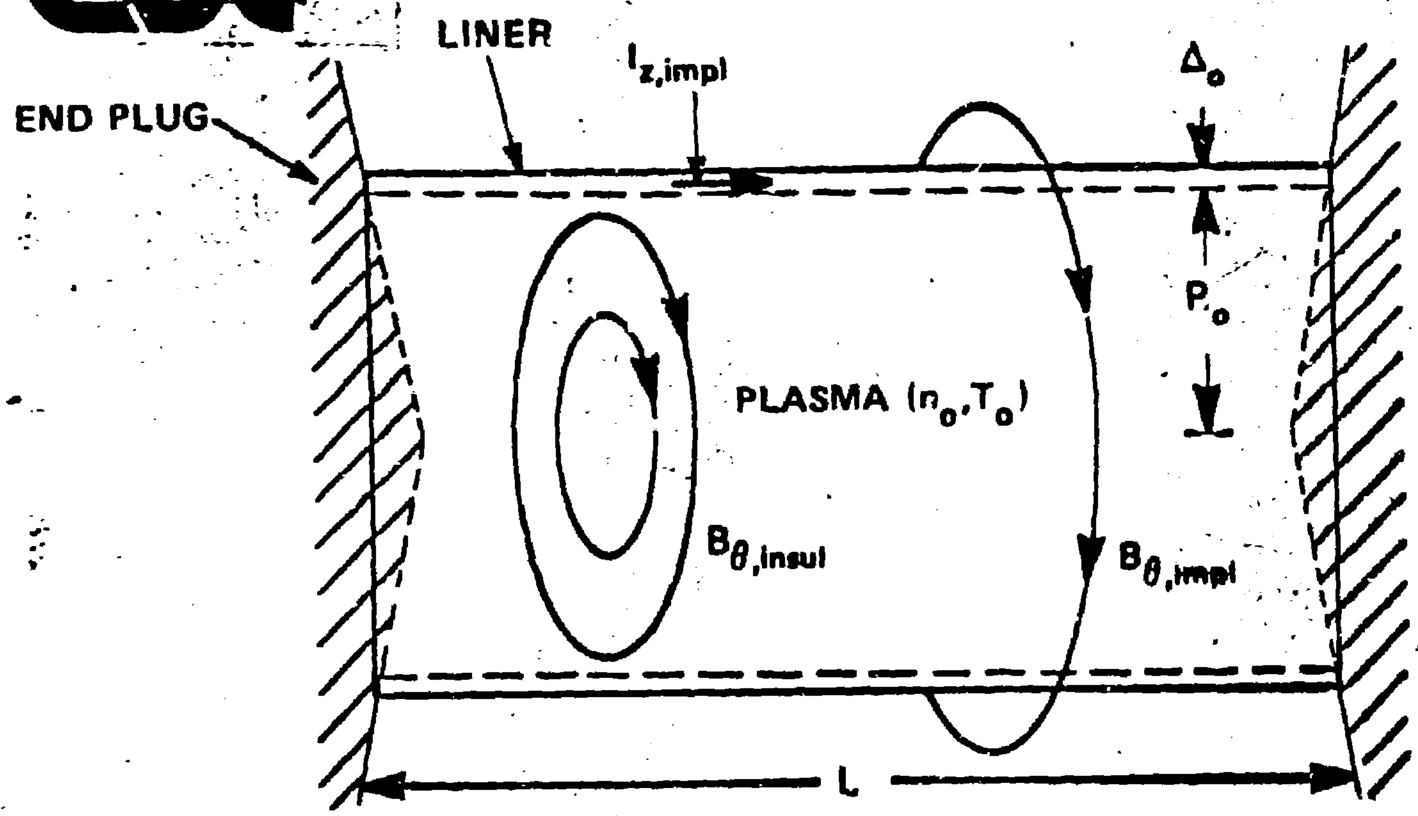
FIG. 4. Comparison of liner trajectory calculated from V(t) and I(t) with other experimentally determined positions.

FIG. 5. Comparison of theoretical and measured liner trajectories for a 1.4-MJ shot.

FIG. 6. Computed trajectory and experimentally determined positions for a 2.4-MJ shot.

FIG. 7. Flash x-ray photograph of an imploding liner.

LINER SCHEMATIC



$R_o \sim 10$ cm	$n_o \sim 10^{17}$–10^{18} cm^{-3}	$I_{z,impl} \sim 10$–60 MA	$t_{impl} \sim 10$–30 μs
$\Delta_o \gtrsim 1$ mm	$T_o \sim 100$–500 eV	$B_{\theta,impl} \sim 50$–100 T	$t_{burn} \sim 1$ μs
$L \sim 10$–30 cm	$B_{\theta,insul} \sim 50$ kG		

FIG 1

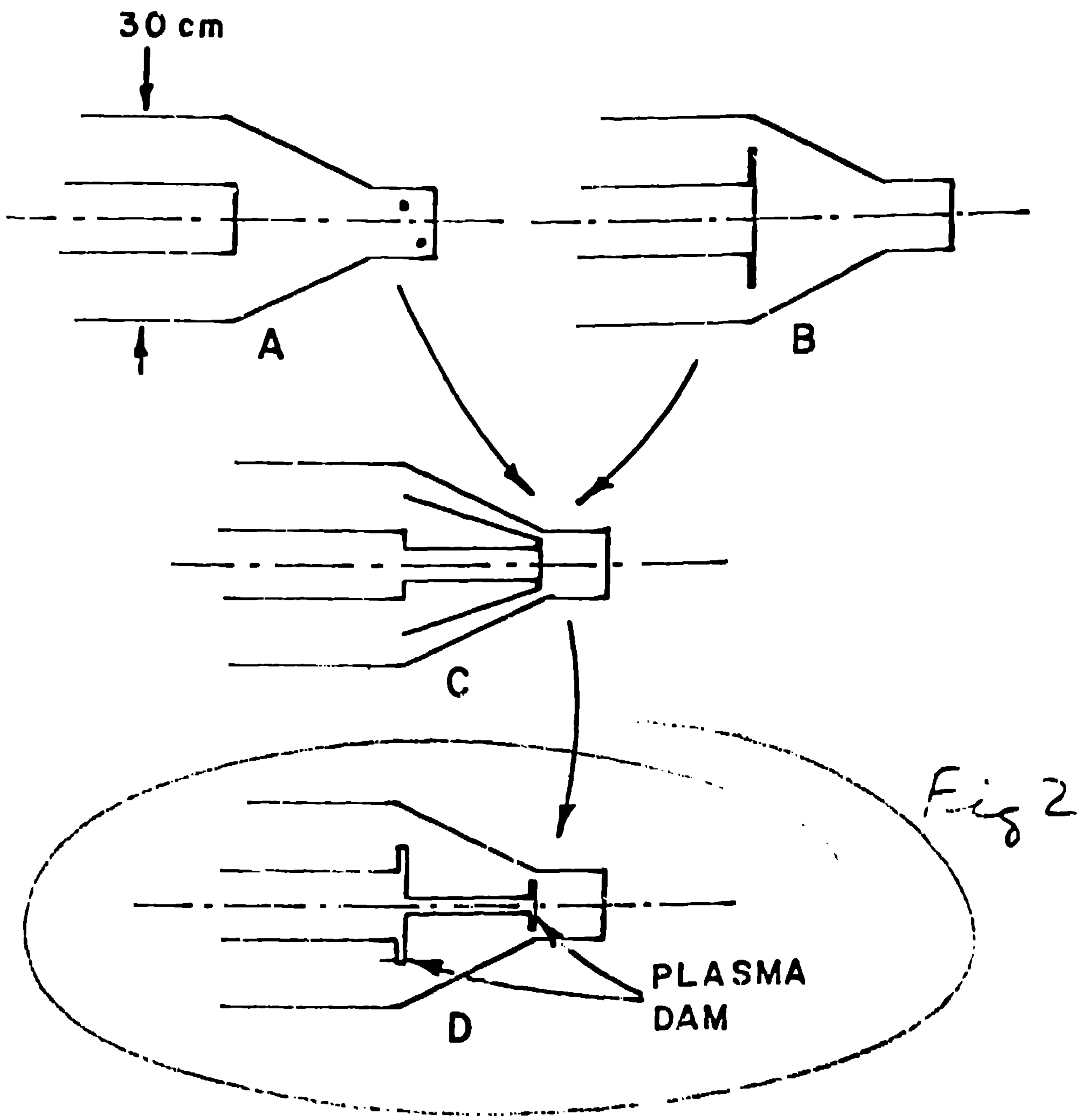


FIG. 6. EVOLUTION OF GUN INJECTED LINER CONFIGURATIONS.

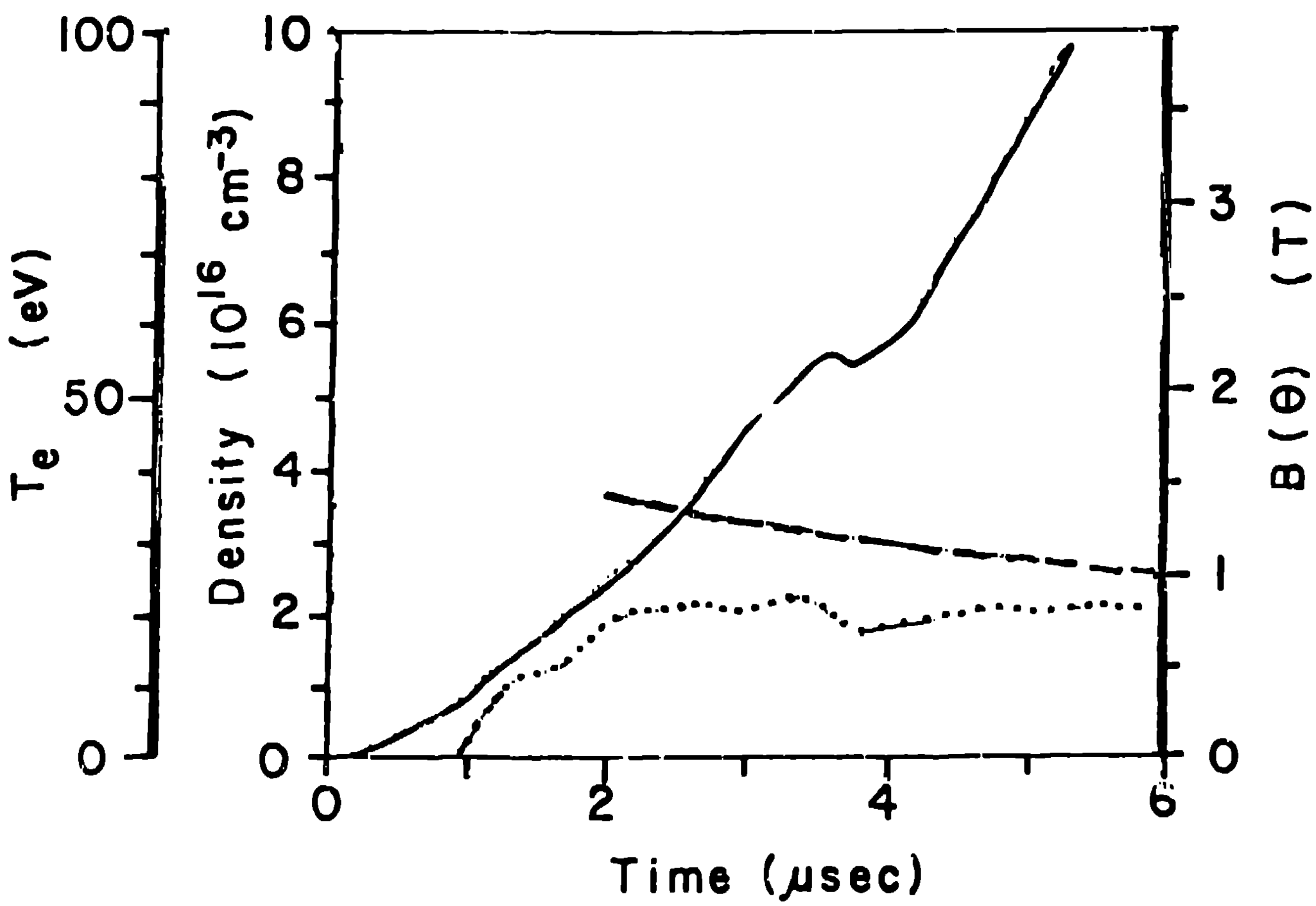
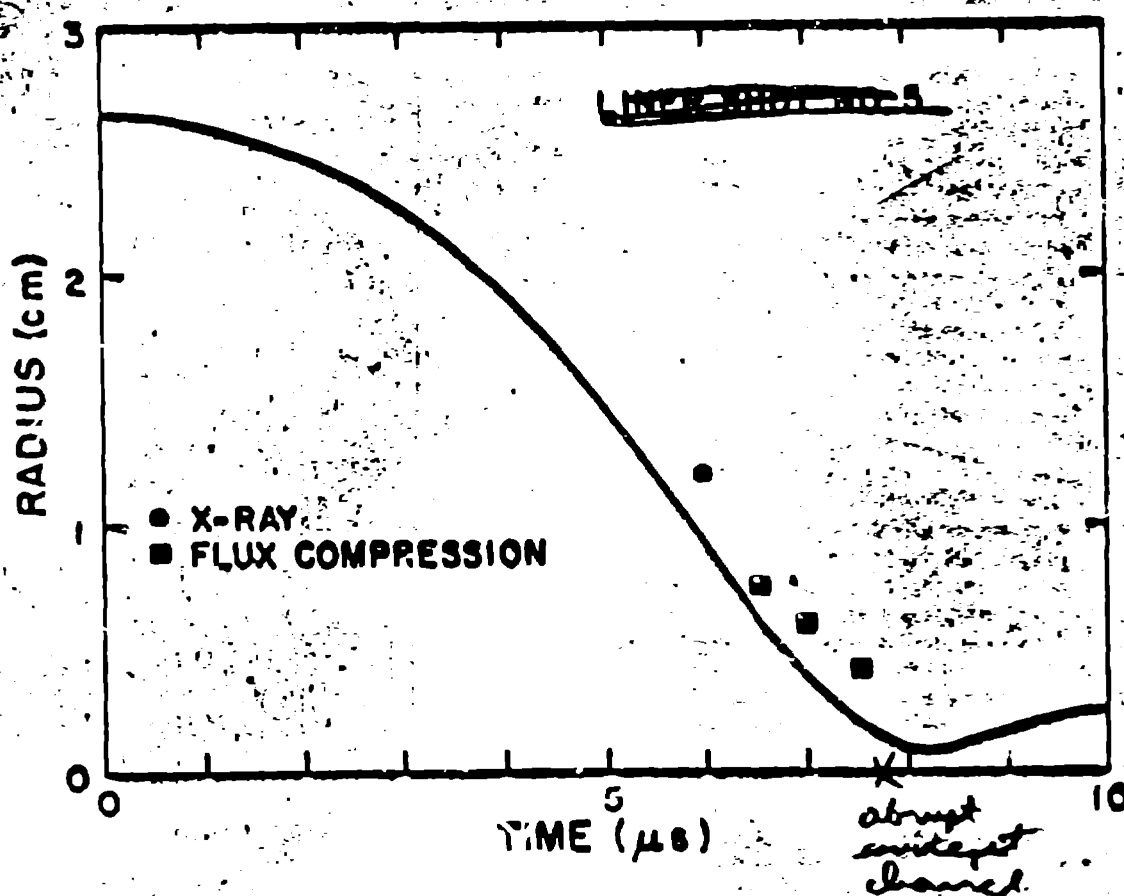
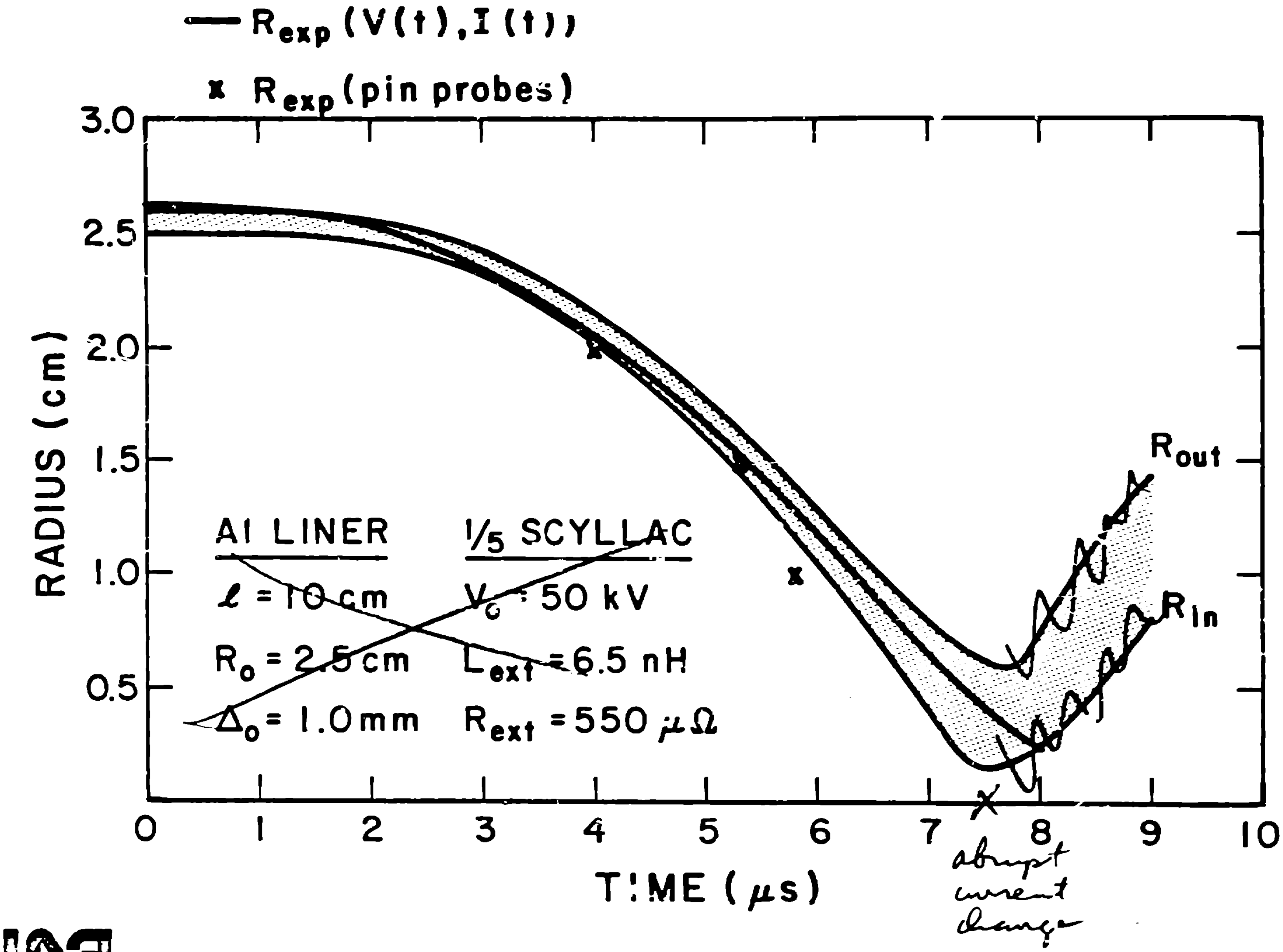

100
50
0
Te (eV)
10
8
6
4
2
0
Density (10^{16} cm^{-3})
3
2
1
0
B(θ) (T)
0
2
4
6
Time (μsec)

FIG 3



RADIUS (cm)
3
2
1
0
X-RAY
FLUX COMPRESSION
0
5
10
TIME (μs)
abrupt
change

FIG 4



$R_{exp}(V(t), I(t))$
x R_{exp}(pin probes)
RADIUS (cm)
TIME (μs)
R_{out}
R_{in}
Al LINER
ℓ = 10 cm
R_o = 2.5 cm
Δ_o = 1.0 mm
1/5 SCYLLAC
V_o = 50 kV
L_{ext} = 6.5 nH
R_{ext} = 550 μΩ
abrupt current change

FIG 5

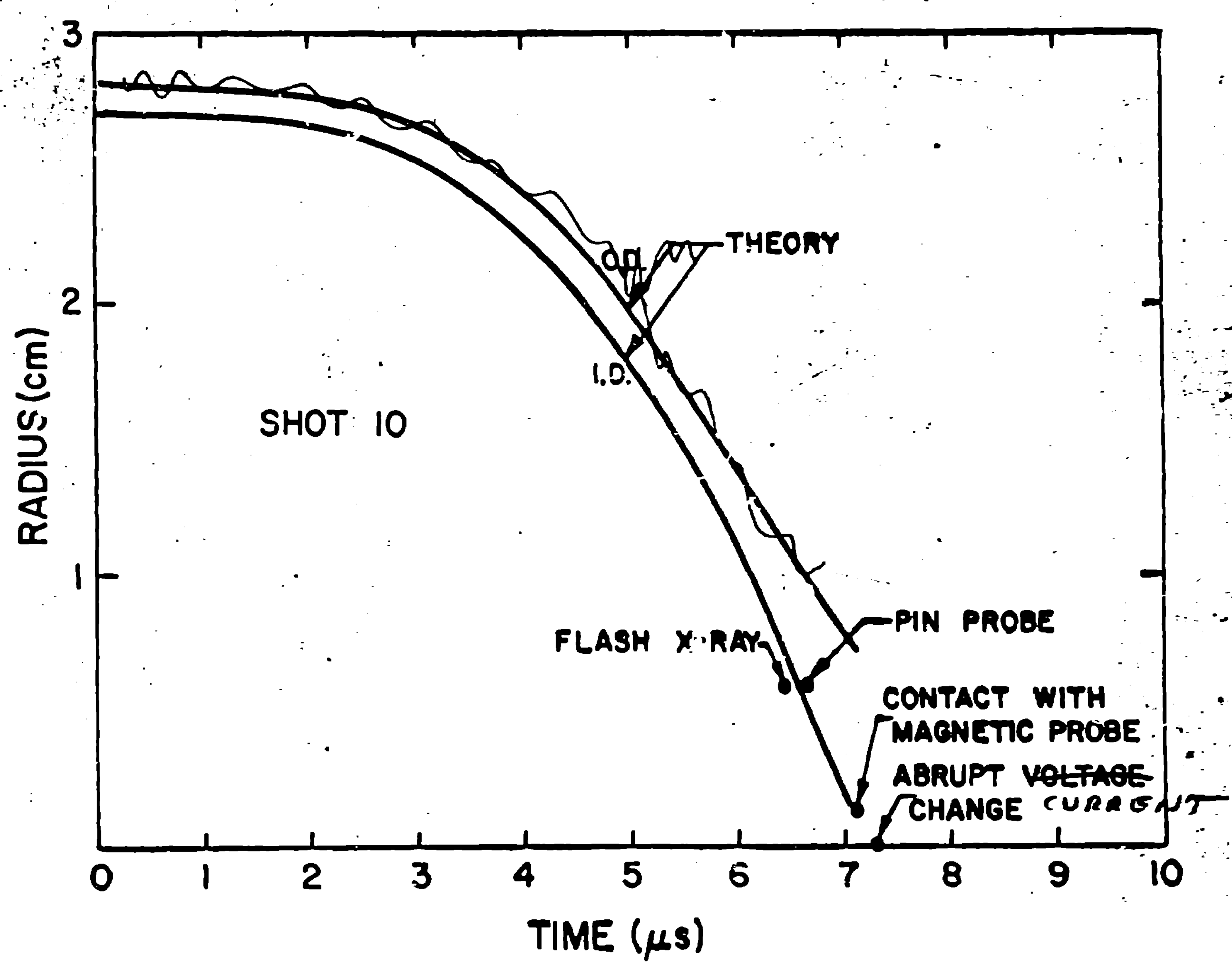

3
2
1
RADIUS (cm)
SHOT 10
O.D.
THEORY
I.D.
PIN PROBE
FLASH X-RAY
CONTACT WITH
MAGNETIC PROBE
ABRUPT ~~VOLTAGE~~ CURRENT
CHANGE
0
1
2
3
4
5
6
7
8
9
10
TIME (μs)

FIG 6