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RESULTS FROM THE LOS ALAMOS FAST LINER EXPERIMENT*

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ABSTRACT. We present experimental results for aluminum liners imploded magnetically using a 1.75 MJ portion of the Scyllac capacitor bank at Los Alamos. Typical liner dimensions are 10-cm length, 5-cm diameter, and 1-mm initial thickness; because they are thick, these liners remain near solid density throughout the implosion. Implosion velocities of 4-6 x 10^5 cm/s have been consistently attained. These results agree well with theoretical calculations, which will also be presented. Results obtained with various diagnostics will be presented including voltage and current measurements, pin probes, magnetic field compression probes, and flash x-ray shadowgraphs.

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1. INTRODUCTION

The use of imploding liners to support the pressure of dense thermonuclear plasmas has been discussed by scientific groups at various laboratories for many years. The general concept of the LASL Fast Liner Experiment [1] is to explore the liner approach to fusion in the 10^6 cm/s liner velocity regime, where wall-confined plasma configurations are a possibility. This regime has previously been investigated by the Alikhanov group at Kurchatov. [2] It is faster than the LINUS [3] regime and that of the Kurtmullaev group at Kurchatov [2,4] but slower than laser or e-beam driven pellet implosions. The present concept is illustrated by Fig. 1. A thin, nonrotating, cylindrical, metallic liner is driven by a magnetic field in the theta direction. The liner carries its own implosion current, and end plugs are employed. In order to inhibit thermal conduction to the walls, it is necessary that there be an embedded magnetic field in the plasma. The approach thus involves inertial confinement of the particles and magnetic confinement of the energy. An analytical model of the heating of a plasma by such an imploding liner [5] and a conceptual design for a fast-liner reactor [6,7] have been discussed previously.

This paper presents results of some liner implosion experiments conducted on a portion of the Scyllac bank [8] at Los Alamos. These implosions were done with a vacuum within the liner; there was no attempt made to provide a plasma load. Separate investigations, not reported here, aimed at producing a suitable plasma load for fast liner implosions were also conducted. Implosion velocities of about 5×10^5 cm/s have been obtained, in agreement with theoretical estimates.

2. IMPLOSION EXPERIMENTS

These liner implosion experiments were done without plasma on a portion of the Scyllac bank[8] at Los Alamos. The Scyllac bank is configured in fifteen racks. Each rack has a capacity of 388.5 μF, a source inductance of 1.5 nH, and a source resistance of about 92 μΩ. These source figures are for the bank into a radius of 4.27 m, which corresponds to the position of the theta pinch coils of the Scyllac experiment. New collector plates were added to three racks of the Scyllac bank for the liner experiments. With these collector plates, the three-rack source inductance and resistance into the liner are about 6 nH and 550 μΩ respectively. The three-rack bank energies for 55, 50, and 45 kV charge voltages are 1.75, 1.45, and 1.18 MJ respectively.

The region from the liner out to a radius of 60 cm is enclosed within a blast-containment steel chamber. Optical and electrical diagnostics enter this chamber through ports, a few of which are left open on each shot.

The first three shots were taken with a charging voltage of 55 kV. Various bank malfunctions (including a major collector-plate failure on shot 2) occurred on these shots, and the charging voltage was subsequently dropped to 50 kV for shots 4-7. A second major collector plate failure occurred on shot 7. Four more racks of the

Scyllac bank were added to the experiment during the repairs required by this second failure.

All the liners imploded in this experiment were annealed aluminum. Typical liner dimensions are 10-cm length, 5-cm diameter and 1-1.5-mm thickness. Two types of driving-current contacts to the imploding liner are employed. They are shown in Fig. 2. In the sliding contact method, suggested to us by S. G. Alikhanov, the liner slides across flat end electrodes for 1/2 to 1 cm then continues on inward across Lexan end windows drawing an arc. An advantage of this system is the access for optical and x ray diagnostics. In the deformable contact method, the liner is attached to the return conductor by thin, tapered, deformable sections, as is shown in Fig. 2. The increasing mass density towards the ends causes them to implode more slowly than the liner proper, and hard current contact is maintained during at least most of the driving current pulse. A disadvantage of this system is that such implosions are not easy to compare with our one-dimensional computer model. The lack of axial uniformity also affects some of the diagnostics.

3. DIAGNOSTICS AND THEORY

The goals of the diagnostics are to determine the velocity, radius, and mass of the liner as a function of time and to determine the azimuthal symmetry and axial uniformity of the implosion. The diagnostics used are measurements of the current and voltage at the liner, flux compression of a 1-kG axial field, contact probes, and flash x rays. All of these diagnostics give information about the velocity and radius and the last two give azimuthal symmetry and axial uniformity information as well. The mass of the liner can be measured by the attenuation of the x rays.

On the first couple of shots the current was measured by 12 small magnetic probes evenly spaced azimuthally and placed between the feed plates at a radius of 70 cm from the liner. However, we soon determined that because of large bolts which hold the feed plates together there are considerable small-scale nonuniformities in the current flow at this radius. Subsequent shots have used a Rogowski loop so that the total current can be accurately determined. It is segmented into six parts so that azimuthal current symmetry can be checked. The voltage is measured near this radius through the use of a hollow bolt which is one of the many bolts that hold the feed plates together. The voltage is also measured near the liner by using resistive wire which is placed on the brim of the hat which insulates the liner. The wire is connected to the upper and lower liner feeds. The current in this wire is then measured to determine the voltage near the liner. The current and voltage can be used to measure an average radial position of the current as a function of time. It is assumed that ohmic losses are small and that all of the $\dot{L}$ is due to radial motion of the inner conductor. Now

$$V = L\dot{I} + I\dot{L} \quad (1)$$

where V is the voltage and L is the inductance inside the position at which the voltage is measured. This gives the differential equation

$$\dot{L} = \frac{V}{I} - \frac{L}{I}\dot{I} \qquad (2)$$

which can be integrated in time for L(t) since we measure V, I, and $\dot{I}$ as a function of time. Once L(t) is known, the radius as a function of time is given by

$$r(t) = r_o e^{-\left(\frac{L(t) - L_o}{\ell \cdot 2}\right)} \qquad (3)$$

where ℓ is the length of the liner in cm, r_o is the initial radius of the current and L_o is the initial inductance in nH. L_o is found from the fact that $V = L_o\dot{I}$ at $t = 0$ and V and $\dot{I}$ are measured at $t = 0$. If all of the current flows in the liner then r(t) is the radius of the liner. It was found, as expected, that L_o is different for the two methods of voltage measurement. However, r(t) is nearly the same for both methods.

The other diagnostic which gives, in principle, continuous r vs t information is the flux compression. In this diagnostic an initial known field B_o of about 1 kG is put inside the liner and a magnetic probe is placed on the axis. Since the liner is a good conductor, the flux inside the liner is conserved and

$$r(t) = r_o \sqrt{\frac{1}{1 + \int_o^t \dot{B}(t)/B_o \, dt}} \qquad (4)$$

where $\dot{B}(t)$ is measured by the probe.

Contact or pin probes are made from solid metal coaxial conductors where a metal cap is placed on the outside of the coax. The cap is driven by the liner into the inner conductor. This action completes a series circuit of a capacitor and a light-emitting diode. The light from the LED is then sent to the screen room by fiber optics where it is detected. This method eliminates ground currents in these probes and helps to eliminate noise problems. Despite these efforts there are occasionally noise signals from these probes which confuse their interpretation. This was not the case for the data presented in this paper.

In the earliest shots, it appeared that various capacitor bank components failed causing erratic bank operation. The exact nature of such problems is difficult to ascertain, making modeling of such misbehavior completely out of the question. Therefore, the results from shot #4 provided the first test of our numerical liner implosion code CHAMISA. CHAMISA [1] is a one-dimensional, hydrodynamic code with a very detailed treatment of the equation of state of the liner material.[9] It contains a model for the electrical resistivity at high temperature and pressures, allowing treatment of the problem of the nonlinear magnetic diffusion of the driving magnetic field into the liner. The electrical circuit dynamics are included, so that a liner trajectory can be calculated if the electrical parameters of the capacitor and feedplate system are given. Comparison of the results of CHAMISA with one of our shots is shown in Figs. 3 and 4.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The driving capacitor bank was enlarged from three racks to seven after shot #7 and was reduced to six during shot #8. Only the low energy data are reported here. The results of measurements on 1.4 MJ shots are shown in Figs. 3, 4, and 5. A usable x-ray plate almost survived shot #5. Although the photo was not as clear as we would have liked, it shows good azimuthal symmetry. Figure 3 shows the measured and calculated current for shot #4. The external circuit inductance is not known exactly; therefore it is used as a fitting parameter to make the experimental and theoretical currents agree. The liner trajectory is then calculated with no further free parameters. The value obtained for the external inductance is believed from geometrical considerations to be quite reasonable. Figure 4 shows the results of the calculation for the inner and outer radius of the liner along with the measured position of the current. The apparent current radius drops to a smaller radius early in time partly because at the early times ohmic losses are greater than $\dot{I}I$ and should not be ignored. The resistance in the return conductors and the feed plates can cause the apparent current radius to move in further than the actual current. From simple estimates one would expect these ohmic loss errors to be 0.5 mm which is on the order of that observed. The fact that the current radius stays within the expected position of the metal at all times and that the probes agree with the inside wall position is good evidence that the implosion dynamics indeed follow close to that predicted. The x ray and flux compression agree fairly well with the calculations and show that the liner is coming in only slightly later than predicted. See Fig. 5.

5. CONCLUSIONS

Naturally, the measurements are not sufficiently precise to check the details of the liner physics such as exact position of phase transitions. Although the current radius as a function of time as determined by V(t), I(t) is an indirect measurement, other diagnostics such as x ray, flux compression, and pin probes provide confirmation that the implosion velocity is about 5 x 10^5 cm/sec. The data shows that within experimental error the liner dynamics are predicted quite well by the physics in the CHAMISA code. We are confident, from further calculations, that the whole Scyllac bank is capable of driving larger sized aluminum liners to velocities of 10^6 cm/sec.

FIGURE CAPTIONS

Fig. 1. Schematic of the liner fusion concept.

Fig. 2. Drawings of the two types of contacts used with the liner experiments. Sliding contacts are on the left. The windows are Lexan and the liners are aluminum. In the shots reported here sliding contacts were used.

Fig. 3. Experiment and theoretical currents. The exact value of the external circuit inductance is found by using it as the only fitting parameter to achieve agreement between theory and experiment for the current.

Fig. 4. Inner and outer radius of the liner from the theory compared to the current radius calculated from the data. Contact or pin probe data is also shown. This is from Shot 4.

Fig. 5. The current radius of the liner vs time calculated from the data and is shown with the liner radius as measured by x-rays and flux compression.

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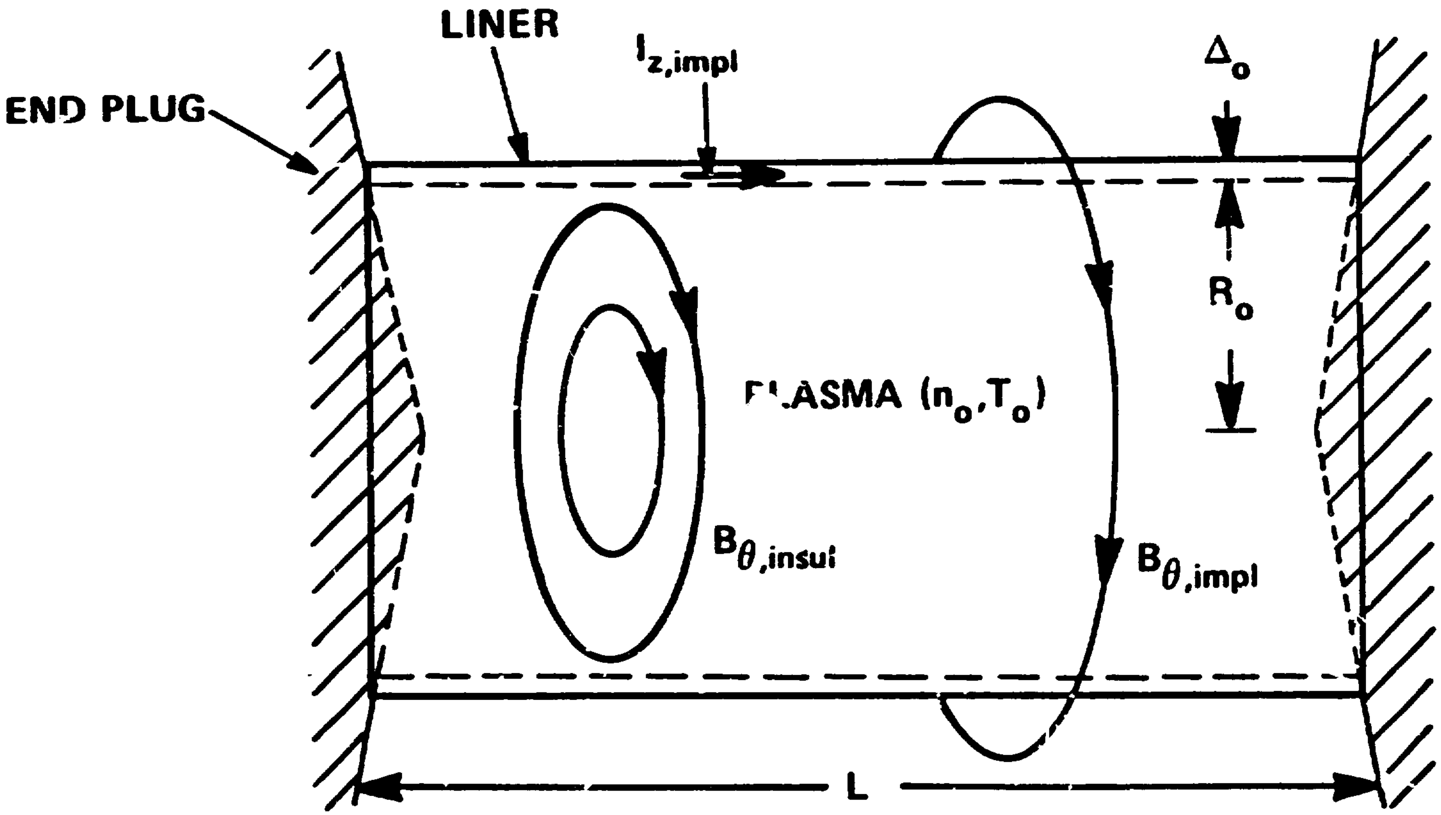
LINER SCHEMATIC



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

Fig 7

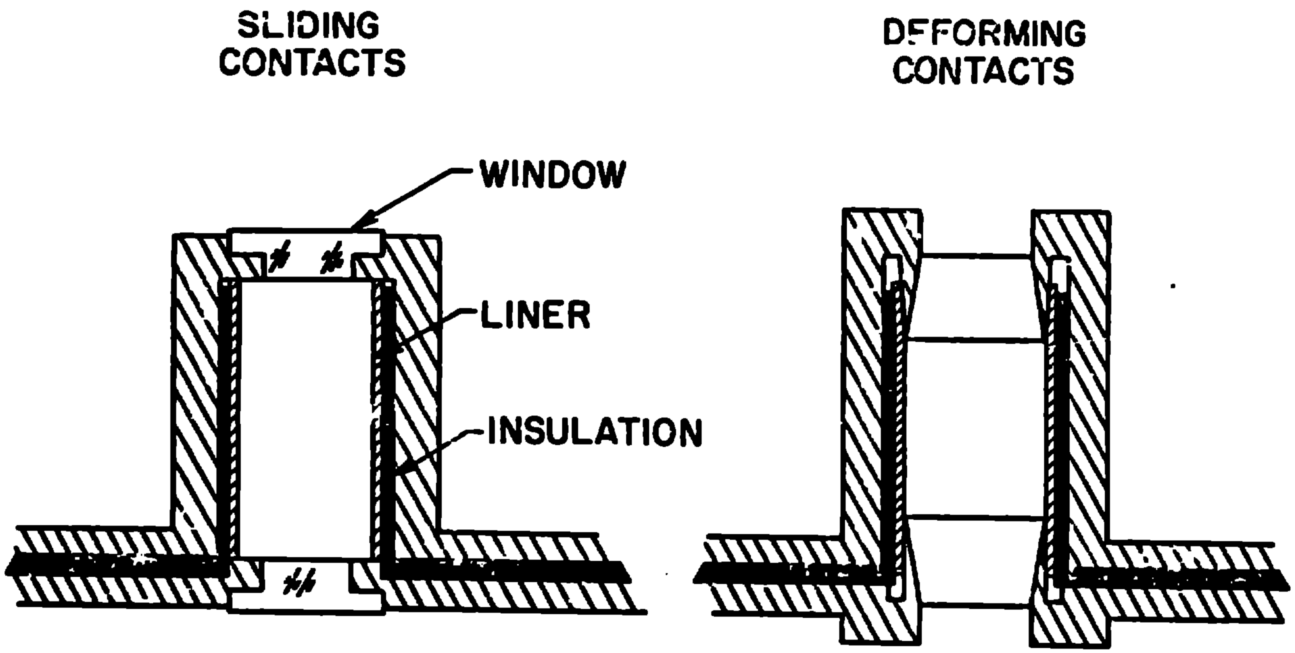

SLIDING CONTACTS
DEFORMING CONTACTS
WINDOW
LINER
INSULATION

Fig 2

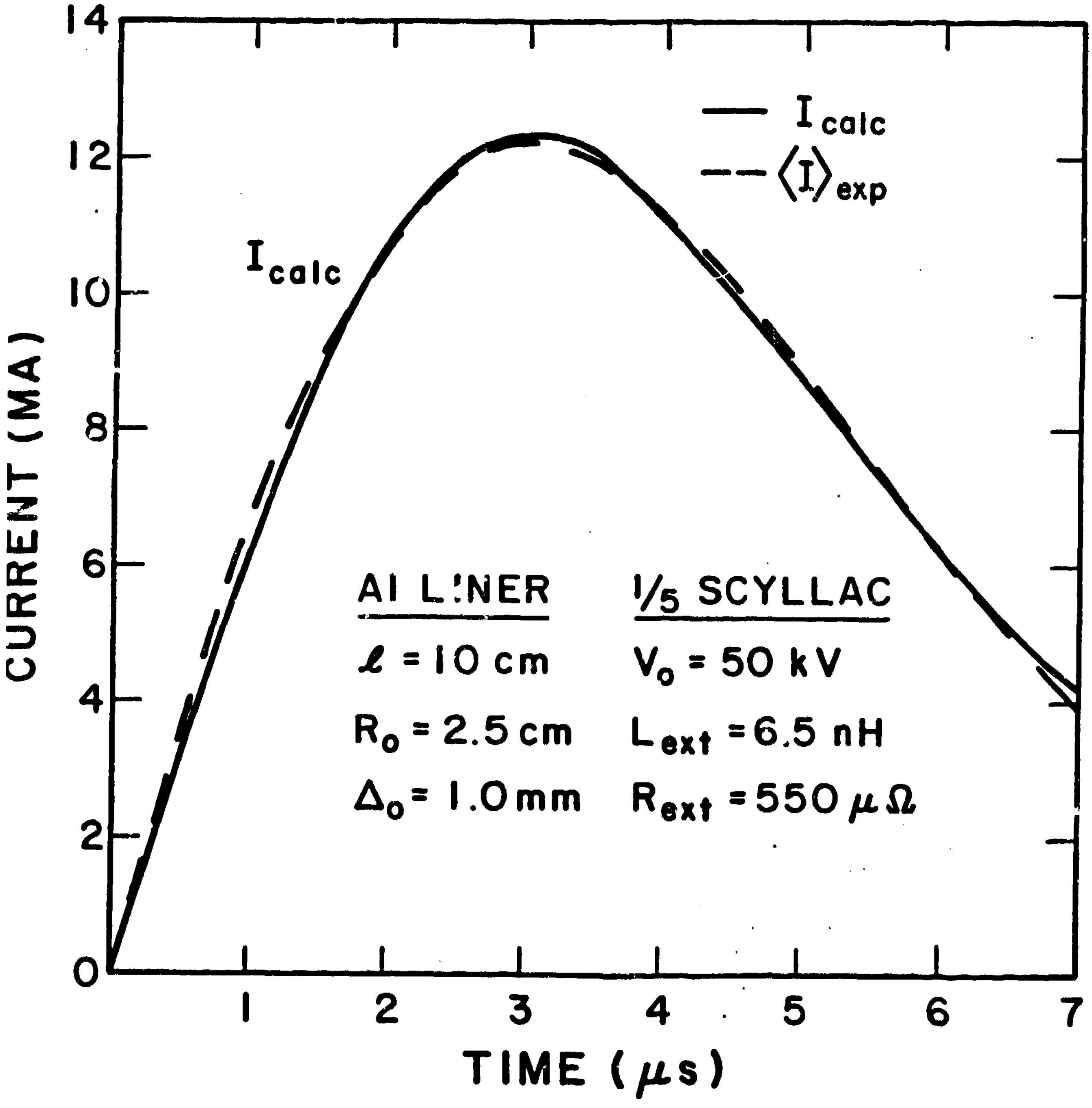

CURRENT (MA)
TIME (μs)
I calc
⟨I⟩ exp
Al LINER
ℓ = 10 cm
R₀ = 2.5 cm
Δ₀ = 1.0 mm
1/5 SCYLLAC
V₀ = 50 kV
L ext = 6.5 nH
R ext = 550 μΩ

Fig 3

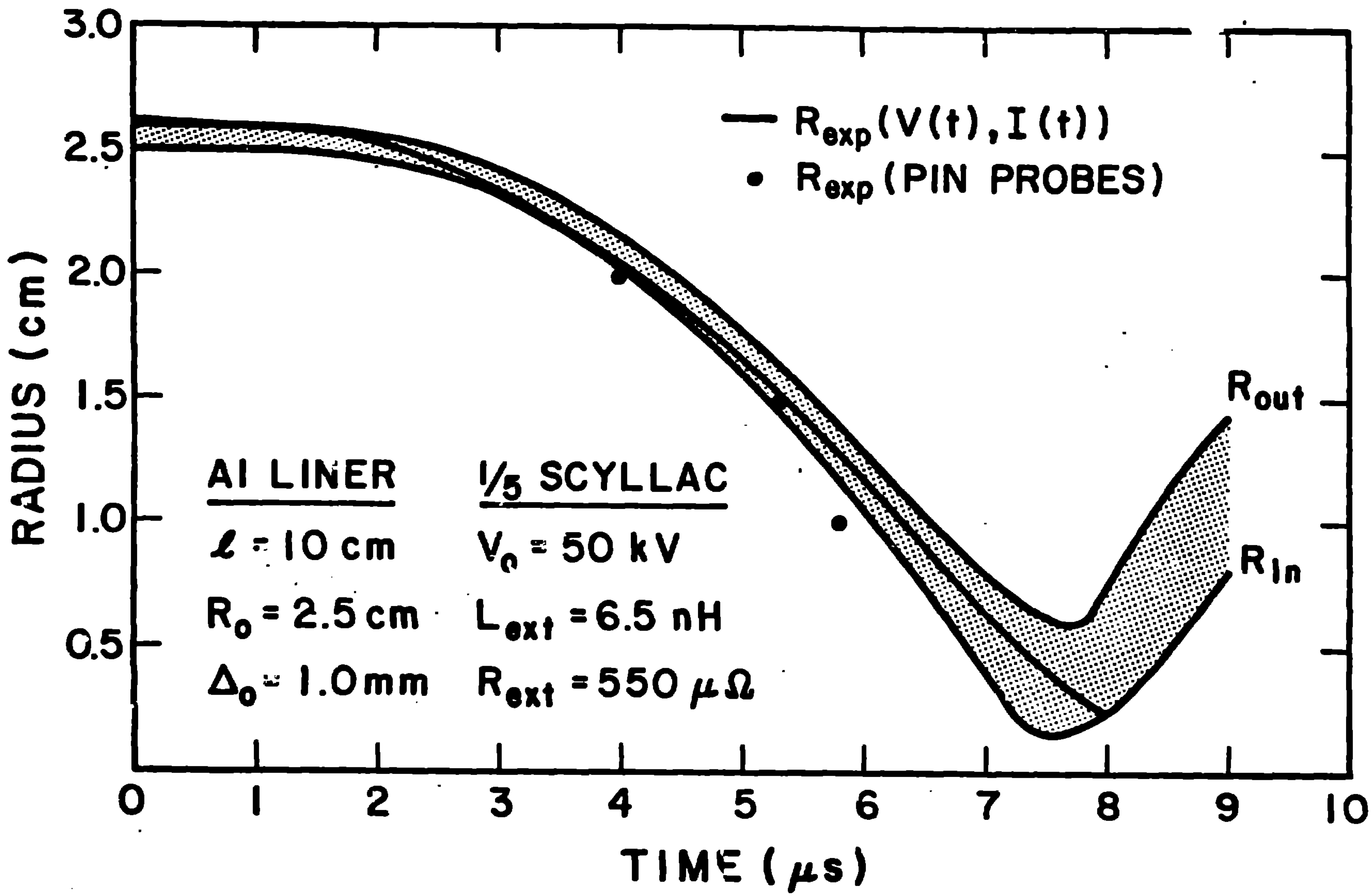
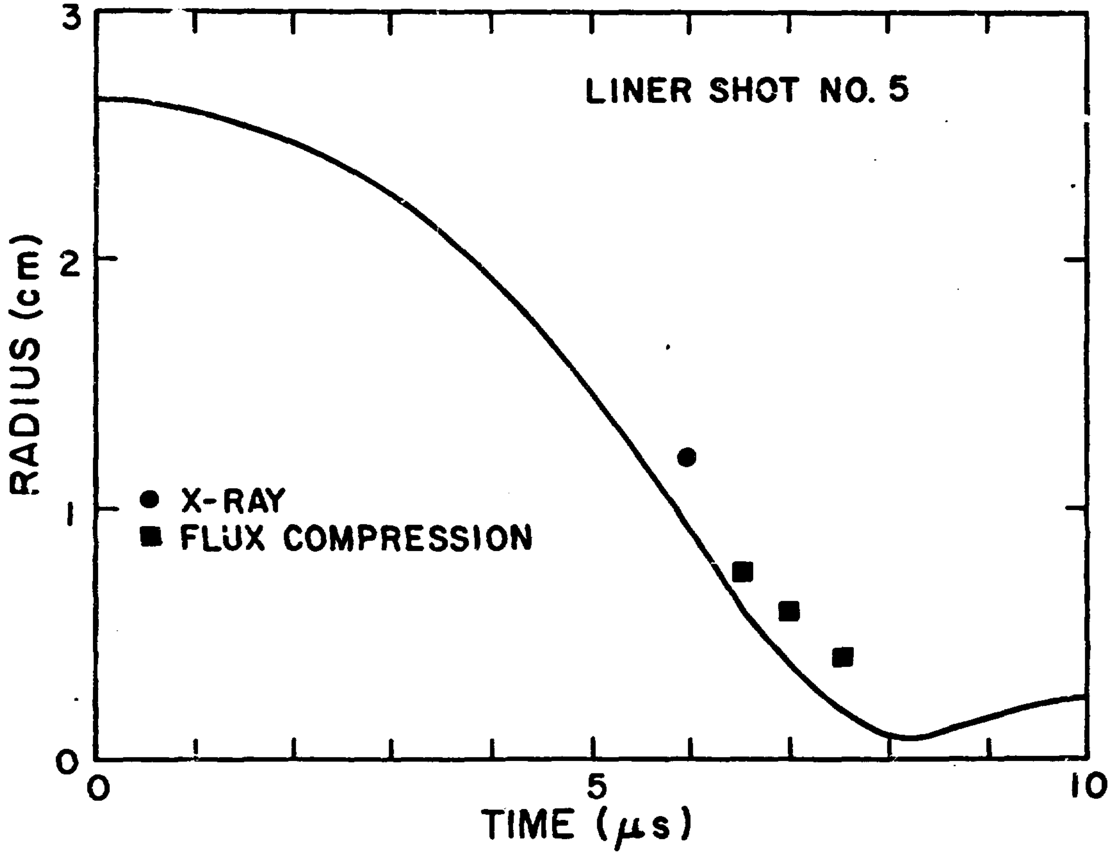
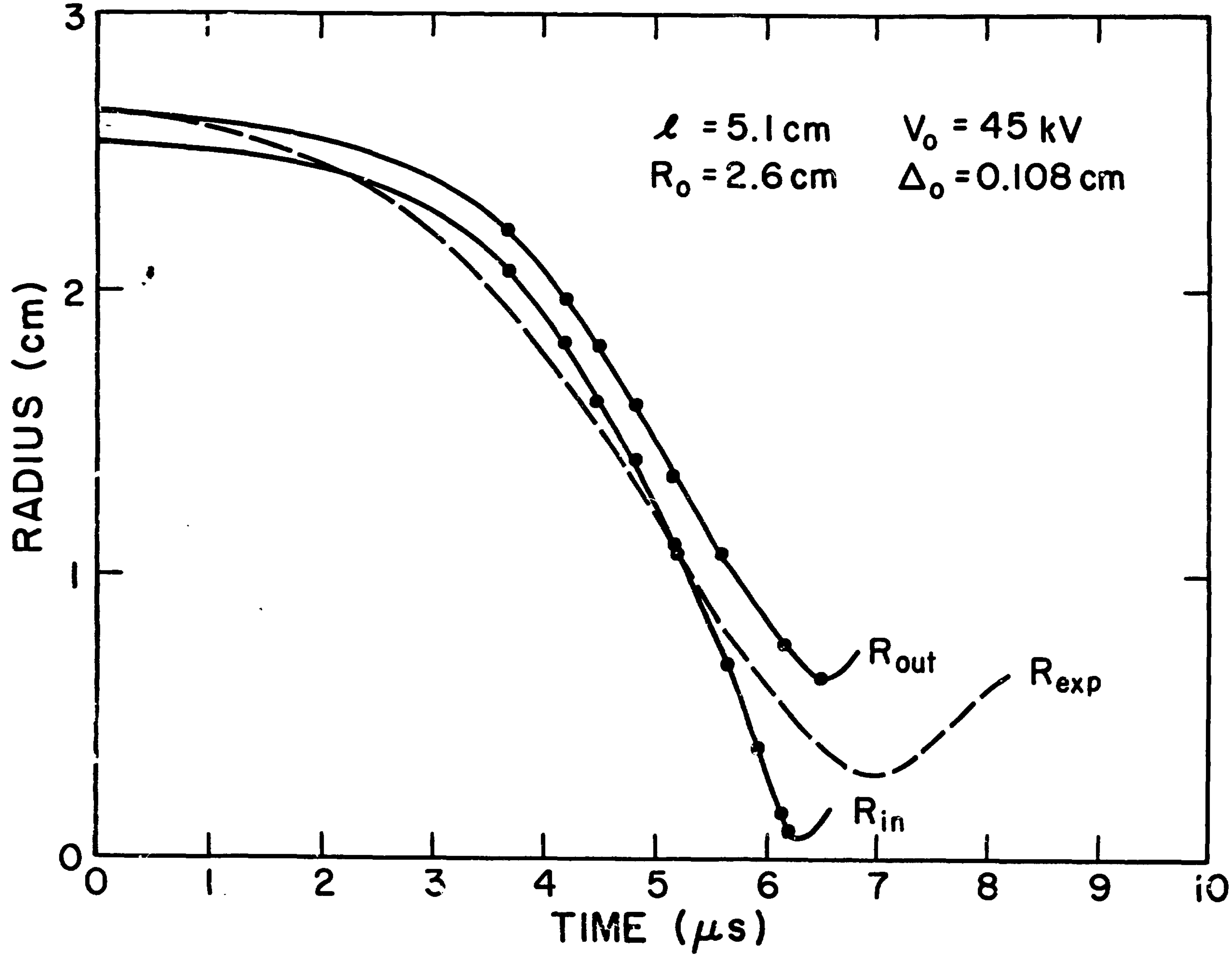

3.0
2.5
2.0
1.5
1.0
0.5
RADIUS (cm)
0
1
2
3
4
5
6
7
8
9
10
TIME (μs)
Rexp(V(t), I(t))
Rexp (PIN PROBES)
Rout
Rin
Al LINER
ℓ = 10 cm
Ro = 2.5 cm
Δo = 1.0 mm
1/5 SCYLLAC
Vo = 50 kV
Lext = 6.5 nH
Rext = 550 μΩ

Fig 4

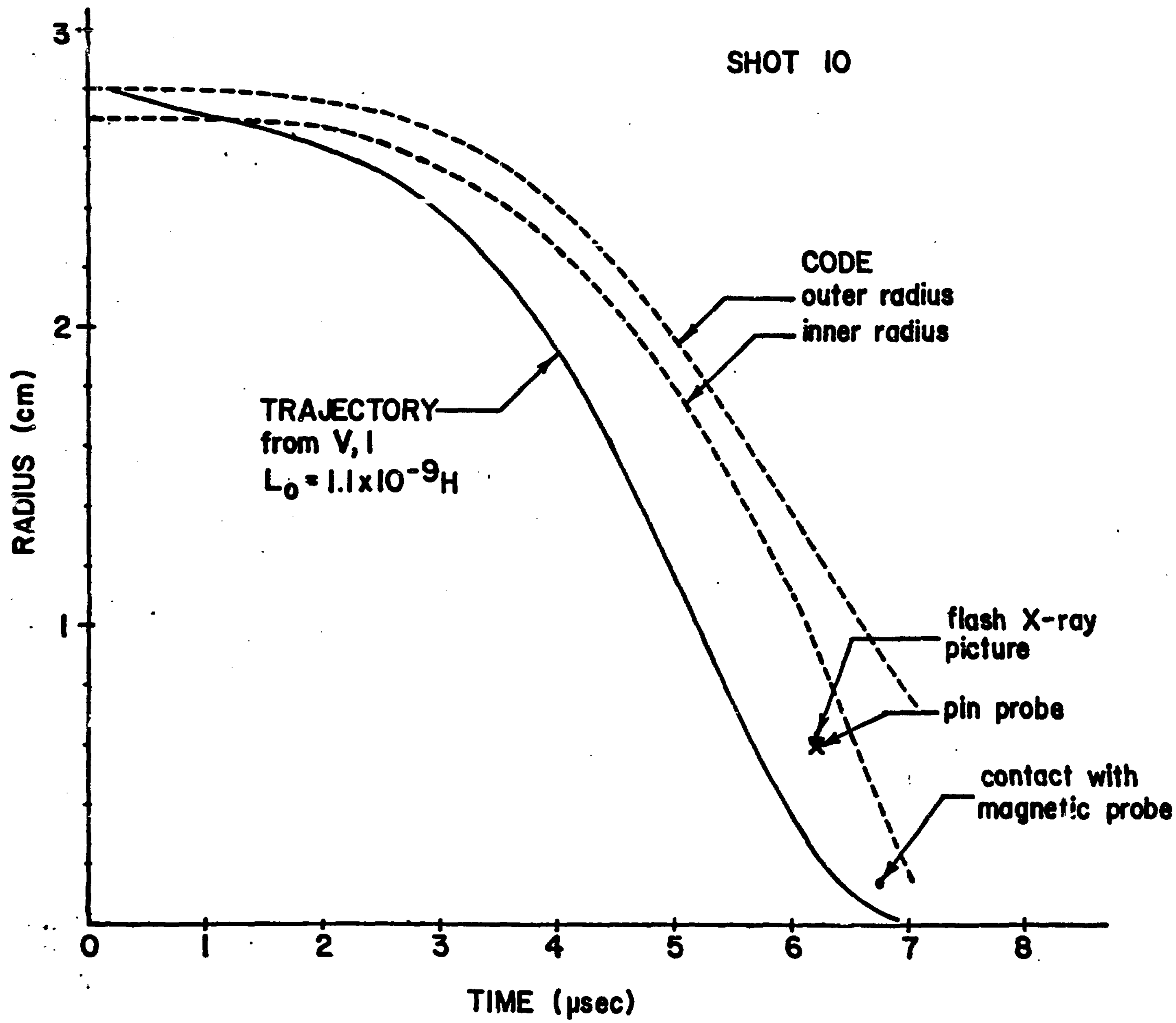


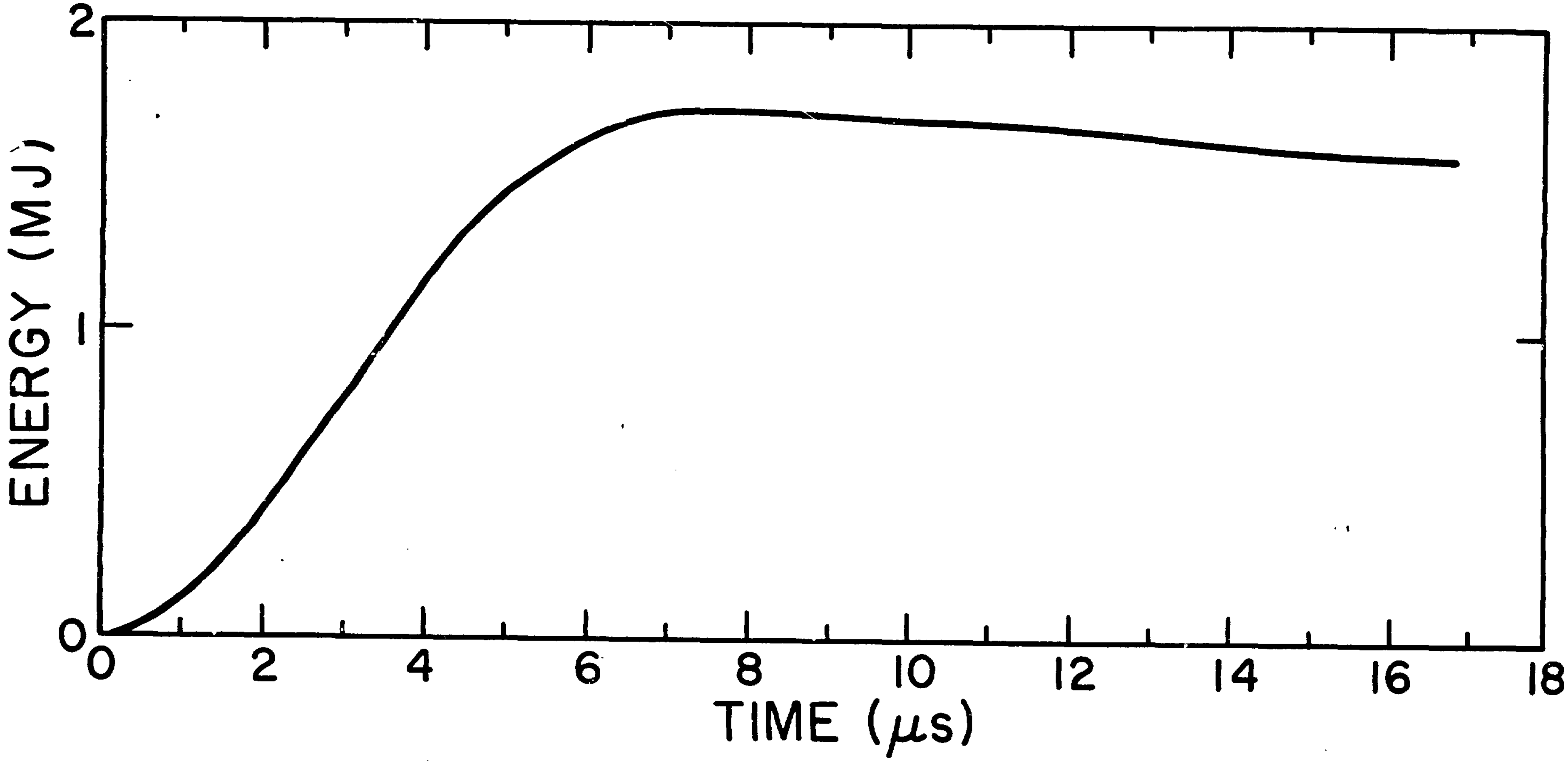
3
2
1
0
RADIUS (cm)
LINER SHOT NO. 5
X-RAY
FLUX COMPRESSION
0
5
10
TIME (μs)

Fig 5

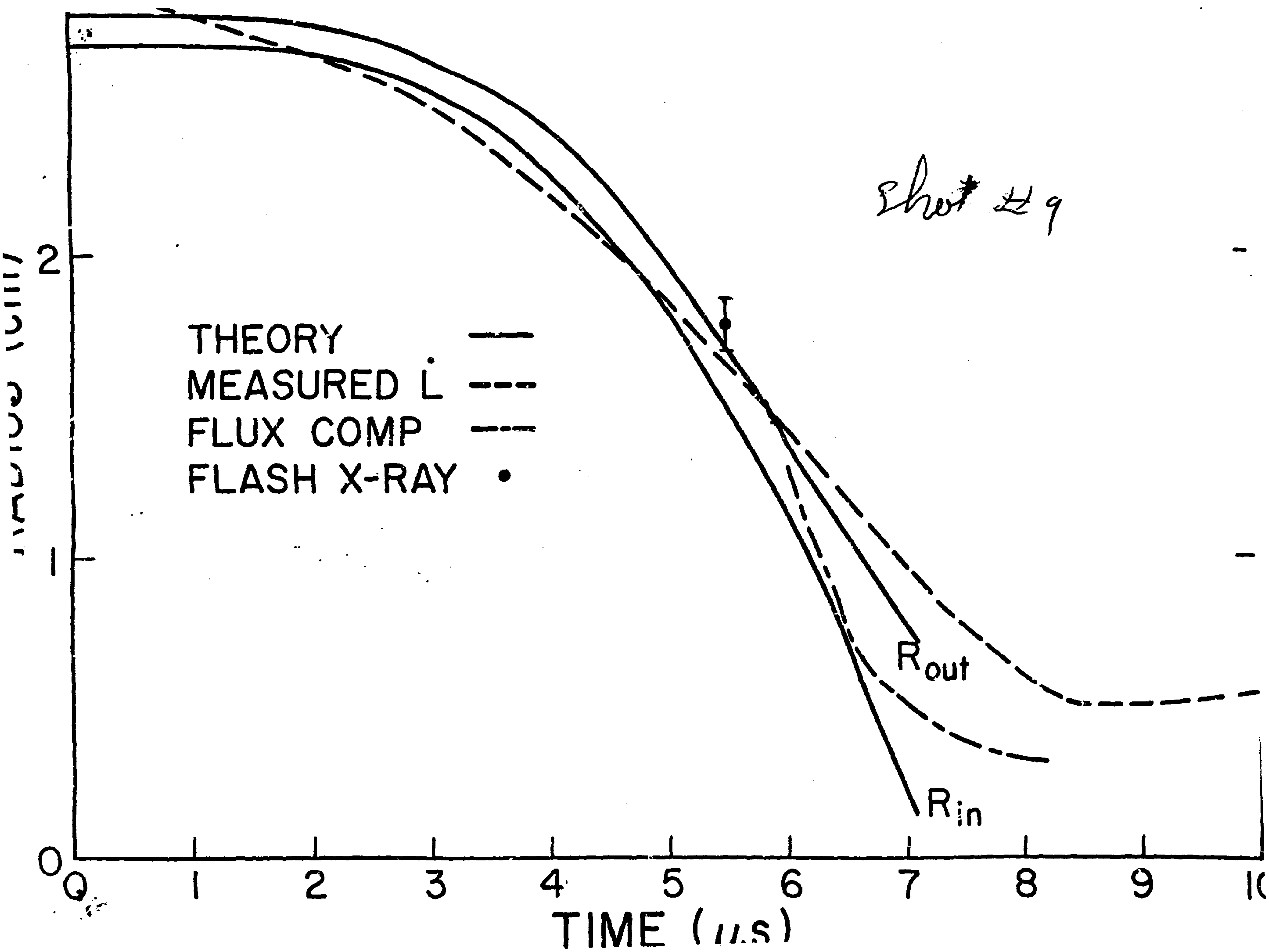


ℓ = 5.1 cm
V₀ = 45 kV
R₀ = 2.6 cm
Δ₀ = 0.108 cm
R_out
R_exp
R_in
RADIUS (cm)
TIME (μs)
0
1
2
3
4
5
6
7
8
9
10


SHOT 10
CODE
outer radius
inner radius
TRAJECTORY
from V, I
$L_0 = 1.1 \times 10^{-9}$ H
flash X-ray picture
pin probe
contact with magnetic probe
RADIUS (cm)
TIME (μsec)
0
1
2
3
4
5
6
7
8



ENERGY (MJ)
2
1
0
0
2
4
6
8
10
12
14
16
18
TIME (μs)



Shot #9
THEORY
MEASURED L̇
FLUX COMP
FLASH X-RAY
R_{out}
R_{in}
0
1
2
0 1 2 3 4 5 6 7 8 9 10
TIME (μs)