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# COMPOSITE LINER DESIGN TO MAXIMIZE THE SHOCK PRESSURE BEYOND MEGABARS

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*Among the solid liners made of a single material which are imploded onto a target under the same driving condition, the aluminum liner produces the highest shock pressure. We propose the composite liner design which can increase the shock pressure several times over the the best performance obtainable from an aluminum liner. We have also developed a general formulation to optimize the composite liner design for any driving current, and derived a set of very useful scaling relations. Finally, we present some 1-D simulations of the optimal composite liners to be fielded at Pegasus and Procyon in the upcoming megabar experiments.*

## I. Introduction

Using pulsed power to implode the liner onto a target is a convenient way to produce high shock pressure. Two years ago a solid aluminum liner which could produce shock pressures in the hundreds of kbar regime was designed [1] and tested [2] at the LANL Pegasus facility. This liner design has since been used successfully for a variety of application experiments. Recently, there have been several viable experimental schemes to produce shock pressures in the megabar regime and more importantly, to ascertain what is the practical pressure limit attainable for a given pulsed power. It will be made clear later that, among the liners made of a single material (for convenience called pure liners hereafter), the aluminum one is generally the best to produce the highest shock pressure. But if we scale up the solid aluminum liner design to the same driving current as Pegasus, the highest pressure we can get is just around 2 Mbar.

In this paper we propose a composite liner design which can increase the shock pressure several times over the best performance of the aluminum liner. The composite liner is made of aluminum on the inside and high density metal on the outside. We will use 1-dimensional simulation through a Lagrangian code to study the shock pressure behavior in the Hugoniot plane and to find out the best working liner design for a given pulse. We have also developed a general formulation to optimize the composite liner design for any driving current. Using the thin liner approximation we derive the driving current dependent scaling relations for the optimal liner parameters and performance. These relations provide us a quick benchmark estimate on the maximum pressure attainable from any available driving current. For example, we can scale our results obtained for Pegasus to the Atlas parameter regime, since the driving currents for both are approximately sinusoidal.

In the next section we will present the liner implosion equations to lay the groundwork for liner design. We next discuss the general behavior of the shock pressure through the Hugoniots in Sect. III. We establish a shortcut for matching the best matching materials which maximize the shock pressure. In Sect. IV we give a detailed discussion on the Jack strategy which maximizes the liner wall velocity. The physical mechanism leading to the composite liner and general procedure to optimize the liner parameters are given in Sect. V, followed by the derivation of the scaling relations in Sect. VI. Finally in Sect. VII we discuss the optimal composite liners to be fielded in the upcoming megabar experiments at both Pegasus and Procyon, and we present some 1-D simulation results.

## II. Implosion Equations for Thin Liners

The liner implosion problem is rather complicated if the following two features, the shocking effect and the liner pressure. This means that the equation of motion must be coupled to the shock equations. XXX in a more physical treatment. Since the liner thickness is much smaller than the radius, we will [illegible] Since we are interested in the shock pressure, we optimize the liner

Rather, we will take advantage of any good approximation which helps to simplify the implosion equation and render the scaling possible. The thin-liner approximation will be assumed in this paper. It is justified if the thickness of the liner is much smaller than the radius.

Next we note that the liner radius affects the driving current only through a logarithmic term in the inductance, so the effect is negligible until the liner radius $r$ becomes much smaller than its initial value $r_0$. In the region where $r \ll r_0$, the duration is so short that the liner velocity is affected only slightly by the error in current. The above reasoning justifies that we can decouple the driving current from the liner motion. This excellent approximation not only simplifies greatly the implosion equation but also makes the scaling of the optimal liner parameters possible. Using the above approximations, the liner implosion equation is given by

$$m(t)\ddot{r} = -\left(\frac{\mu_0}{4\pi}\right)\frac{I^2(t)}{r\ell(t)} \qquad (1)$$

with the initial conditions $r(0) = r_0$ and $\dot{r}(0) = 0$, where $\ell$ is the length, $I(t)$ the driving current, $r(t)$ the radius, and $m$, the mass of the liner.

A class of currents is said to be scalable to one another if we can represent them by a single function as $I_0 F(\omega t)$ using two parameters $I_0$ and $\omega$. The current wave forms we usually see in many pulsed powers are approximately sinusoidal or like a step function; each type forms a scalable class. Later when we look for possible scaling relations of the optimal liner parameters and performance for scalable driving currents, it is useful to express the implosion equations for the whole class in terms of the scaled distance traveled by the liner, $x \equiv 1 - r/r_0$, and scaled time $\tau \equiv \omega t$. The resulting implosion equation

$$\ddot{x} = \frac{\alpha I^2(\tau)}{\ell(1-x)} \qquad (2)$$

now has an invariant set of initial conditions $x(0) = \dot{x}(0) = 0$, where the dimensionless factor $\alpha = I^2(t)/\dot{I}^2$ and

$$\omega = \left(\frac{\mu_0}{4\pi}\right)\frac{\dot{I}^2}{m\omega^2} \qquad (3)$$

[illegible] the scaled equation, time $\tau$ in the [illegible] is given by

$$\tau = \omega_0 \int_0^t I(t)\,dt \qquad (4)$$

## III. Behavior of Shock Pressures Deduced from Hugoniots

When the liner collides with the target, a [illegible] the shock pressure can be read from the Hugoniots for the liner (labeled by $l$)

$$P_l(v) = \rho_l(c_l + s_l v) \qquad (5)$$

and target (labeled by $t$)

$$P_t(v_c - v) = \rho_t(v_c - v)[c_t + s_t(v_c - v)] \qquad (6)$$

by eliminating the particle velocity $v$, where $\rho$ is the density and $c$ and $s$ are material constants that relate the shock velocity to the particle velocity. From the above equations we see that higher collision velocity $v_c$ and material densities will give rise to higher shock pressure, but the material with higher values of $c$ and $s$ also helps. While the above equations provide us a precise guideline to find the best liner and target materials that will achieve the highest collision shock under a given imploding condition, the process to examine all material pairs will be extremely time consuming. Fortunately we can take a shortcut by proving the following theorem: For any collision velocity, let $P_{AB}$ be the shock pressure generated from a collision between two materials A and B; its value is bounded in between $P_{AA}$ and $P_{BB}$. We can prove this statement as follows. First, notice that the Hugoniots are parabolic functions of $v$. In the physical region $0 \le v \le v_c$, the liner Hugoniot increases while the target Hugoniot decreases with increasing $v$. Second, for the collision between identical material, the two Hugoniots always intersect at $v = v_c/2$ due to their reflective symmetry at the point, as we have the exact solution

$$P = \frac{1}{4}\rho_0 v_c^2(c + s v_c) \qquad (7)$$

Without loss of generality, we assume $P_{AA} \ge P_{BB}$ and solve for $P_{AB}$ at the intersection of the liner Hugoniot A and target Hugoniot B. Now $P_{AA}$ and $P_{AB}$ lie on the liner Hugoniot A which increases with $v$, and $P_{BB}$ and $P_{AB}$ lie on the target Hugoniot B which decreases with $v$. It follows that $P_{AB}$ can only occur in the region $v_c/2 \le v \le v_c$, and therefore

$$P_{AA} \ge P_{AB} \ge P_{BB} \qquad (8)$$

Using the above rigorous result, we can simply and [illegible] in searching for the right material to maximize the shock pressure. Instead of searching for the maximum of all $P_{AB}$, we can just look for the maximum of $P_{AA}$, provided that the highest attainable $v$ is independent of the liner material. We will show later that the [illegible] is the case. Let the two [illegible]

From the above implosion equation [illegible] that [illegible] the same

material always maximizes the pressure for all values of $v_c$. But for multi-megabar pressures or higher, this is indeed the case. This follows from the fact that, for a wide variety of materials [4], c is around a few mm/$\mu$s and $1.2 < s < 2$. At high megabar pressures, $v_c$ is large enough so that the term $sv_c$ dominates over 2c in Eq.(7) and consequently we have

$$P \approx \frac{1}{4}\rho s v_c^2. \tag{9}$$

This ensures that $P$ is the maximum for the material with the highest value in $\rho s$ at any $v_c$. In the same approximation, the shock pressure between two different materials behaves like

$$P_{AB} \approx \frac{v_c^2}{[(s_A\rho_A)^{-1/2} + (s_B\rho_B)^{-1/2}]^2} \tag{10}$$

## IV. Joule Heating Limitation on Liner

The current passing through the liner has to diffuse into its interior from the outer surface, so calculating the resistive heating of the liner is quite complicated unless the diffusion time is faster than the implosion time. In general we do not expect the temperature distribution across the liner to be uniform, but rather to increase monotonically toward outside. To simplify the formulation, let us consider a pure liner and assume that the temperature is uniformly distributed. Since radiation loss is negligible, the time dependence of the liner temperature is given by the energy balance equation

$$R(t)I^2(t)dt = mc(T)dT, \tag{11}$$

where c is the specific heat of the liner material and $R$ the resistance. In term of the resistivity $\eta$ and density $\rho$, we can integrate the above as

$$\frac{\ell^2}{m^2}\int_0^t I^2(t)dt = \int_{T_0}^{T(t)} \frac{\rho^2(T)c(T)}{\eta(T)}dT, \tag{12}$$

where $T_0$ is the initial temperature. Notice that the right hand side is only a state function of the liner material. The left hand side is proportional to the electrical action integral defined as

$$Q(T(t)) = \frac{1}{A^2}\int_0^t I^2(t)dt. \tag{13}$$

where A is the liner cross section. The electrical action for any conductor can be measured by passing a current through a thin sample wire. Setting a limit on the action by requiring $T(t_c) = T_c$, we constrain the liner mass to be a function of the collision time $t_c$ as

$$\frac{\ell^2}{m^2}\int_0^{t_c} I^2(t)dt = \frac{Q(T_c)}{\rho^2}. \tag{14}$$

For pure liners, a reasonable limit on $T_c$ is the melting point $T_m$, since the solid phase maintains a sharp shock front. The relation derived in Eq.(14) is still useful even when we deal with the realistic situations in which the temperature distribution is not uniform. In this case we should set the limit on the temperature of the inside liner surface, denoted by $T(t)$, which is the coolest at any time since the current has to diffuse radially inward. It is easy to see that we can still write

$$\frac{1}{m^2}\int_0^t I^2(t)dt = \beta(T(t), m), \tag{15}$$

except that $\beta$ now has a weak dependence on m. Once we set $T$ to a limit $T_c$ at $t = t_c$, $\beta(T_c, m)$ can be determined by using the 1-D MHD code to compute the left hand side of Eq.(15). Later when we apply the above relation to optimize the liner mass, we only need to vary $m$ in a narrow range around the optimal solution. We can therefore represent $\beta(T_c, m)$ as a constant plus a small linear term in $m$ and determine it by just two code simulations.

Among all metals, empirically aluminum has the highest value (only copper is a close second) in the ratio $Q(T_m)/\rho$, where $Q(T_m)$ is the action to the melting point. In terms of $Q(T_m)/\rho^2$, the aluminum is ahead of other heavier metals even more by an extra density factor. Using Eq (14) the same can be said about the current integral on the left hand side. We therefore conclude that the aluminum liner can be driven with a longer $t_c$, before reaching the melting point, than any other pure liner (of higher density) having the same mass m and length $\ell$. But longer imploding time before melt implies higher attainable velocity since all these liners are governed by the same implosion equation ****** Using Eq (10), we see that this $1/\rho$ advantage in attainable velocity for aluminum over materials of higher density is sufficient to ensure that the aluminum liner will also generate the highest shock pressure on any chosen target.

## V. Composite Liner and Optimization

With the physical insights gained from our discussions on shock Hugoniots and Joule heating, the composite liner seems to be an excellent idea to improve the attainable shock pressure substantially over the pure liners. Clearly we still want to use

aluminum on the outside for carrying most of the driving current to retain its highest attainable velocity. For the inner layer we look for a material with high value in $\rho\sigma$ to enhance the shock pressure, subject to some other criteria discussed below.

We find that platinum is the best impacting material for the composite liner, not just for its high density but also for its high melting point and electrical resistivity. Based on these criteria, other materials such as tungsten are equally satisfactory, but the fact that platinum can be electroplated is a big plus for fabrication. The Joule heating in the platinum layer is reduced dramatically since the current has to diffuse in through the aluminum. The skin resistance of the platinum layer is two orders of magnitude higher than that of the aluminum, owing to a much higher resistivity and smaller cross section. This factor also helps to reduce the Joule heating in Pt after the current is diffused in.

The high melting point is an extra advantage since we can now drive the Al layer beyond its melting point while still keeping the Pt layer solid. Consequently, the composite liner can take considerably more Joule heating than a pure aluminum one with the same mass and thereby achieving a corresponding higher velocity. How much we can push this advantage depends on the ability of the solid Pt layer to withstand the magnetically driven Rayleigh-Taylor instabilities in the melted Al layer. No definitive answer has been known so far from the 2-D MHD simulations. Hopefully, we will get some valuable clue from the upcoming composite liner experiment at Pegasus.

For the composite liner, clearly the Joule heating constraint should be applied to the aluminum layer. In applying Eq. (15), therefore, $m$ is replaced by the aluminum mass per unit length, and $T_c$ is the melting temperature of Al. On the inner surface, the platinum mass per unit length should be kept as low as practical so that it will not reduce the liner velocity significantly. In the following, typical numbers are used.

To optimize the liner design, we need to find the liner mass per unit length which maximizes the shock pressure at a given target radius $r_f$, which is usually determined by the experimental requirement of diagnostic limitations. For a step function current, $I(t) = I_0$ for $t > 0$, the liner implosion trajectory can be approximated by $r(t) = r_0 - \frac{1}{2}at^2$, where $a = \frac{\mu_0 I_0^2}{4\pi m r_0}$. Therefore, the peak shock pressure is proportional to $a^2$. For a general current waveform, we optimize the liner parameters numerically as follows. Taking the liner mass $m$ as the free parameter, we use Mathematica to solve Eq. (1) iteratively to find the correct initial radius $r_0(m)$ such that the solution for $r(t)$ satisfies $r(t_s) = r_f$, where $t_s(m)$ is given by the Joule heating constraint Eq. (15). The optimal mass is then the one which maximizes the collision velocity $v_0(m)$. The result is then used in the 1-D MHD code to compute the more accurate liner motion and detailed shock pressure history. In spite of the thin-liner approximation and using a current-independent current in our formulation, the code simulations (with coupled circuit model) have demonstrated that we hardly need to refine the optimal liner parameters.

## VI. Scaling Relations for Optimal Liners

We now proceed to derive a set of very useful scaling relations for the optimal liner parameters and performance. While these relations are derived under some idealized scaling conditions, they nevertheless provide us a valuable benchmark to make a good estimate on the maximum pressure achievable by an unexploded pulsed power facility that is usually approximately available in a given ....

It is important to realize that the liners optimized by the procedure described in Sect. V do not scale in a simple way even though the driving currents are exactly scalable. For one thing, in a realistic design the target radius $r_f$ is usually determined by experimental requirements and the liner mass will not stay the same from one driving condition to the other. Furthermore, the optimization requirement also complicates the scaling. Therefore, some idealized conditions are necessary for us to deduce a set of simple (but adequate) scaling relations. In this and the next section, we have to assume that the implosion distance $\Delta r = r_0 - r_f$ is not much smaller than the optimal liner radius $r_0$. In terms of the scaled distance introduced in Part II, $\Delta r = r_0 - r_f$, this means $\Delta r \gtrsim 1$. However, $\Delta r \ll 1$ is generally valid for well optimized liner designs. Therefore, our fast implosion assumption is not seriously violated.

Next we require that the scaled collision time $\tau_c = t_c/t_0$ must also stay constant. This is equivalent to the condition that the kinetic energy for the liner at collision is certain constant fraction of the total driving energy. While we are unable to prove rigorously that this condition ensures the optimal liner parameters to remain optimal physically at various pulse powers, we do empirically observe that the validity of the scaling results with the numerical optimization. We now

that the solutions for Eq (2) with different values of $v$ do not intersect except at $r = 0$, so there is only one solution which passes through $z = z_s$ at $r = r_s$ as required. Using Eq (3) the unique value of $v$ implies

$$m r_0^4 \propto I_p^4 \omega^{-2} \tag{16}$$

The Joule heating constraint given by Eq (15) can be written as

$$\frac{I_p^2}{m^2 \omega} \int_0^{r_s} F^2(r) dr = A T_s \kappa_0 \tag{17}$$

when we ignore the small amount of platinum mass. Neglecting the weak $\kappa$ dependence on $T$ we get the scaling for the liner mass as

$$m \propto I_p \omega^{-3/4} \tag{18}$$

From Eqs (16) and (18) we obtain the scaling for the liner radius as

$$r_s \propto I_p^{1/2} \omega^{-1/4} \tag{19}$$

Finally, $z(r_s)$ is constant and using Eq (4) we get

$$v \propto I_p^{1/2} \omega^{1/4} \tag{20}$$

for the collision velocity and

$$P \propto I_p \omega^{1/2} \tag{21}$$

for the shock pressure. As mentioned earlier, we have $m r_0^2 \propto I_p^2$ to verify that the liner kinetic energy at collision is indeed a constant fraction of the total driving energy.

In applying these scaling relations, we can always if necessary refine the result by looking the local expansion due to the finite resistivity of Al and liner deviation from strict scaling in other respects at collision radius.

## VII. Megabar Liners for Pegasus and Procyon

Our compressible liner design has been adapted to the upcoming megabar liner experiments at LANL Pegasus and Procyon. The optimum case to be fielded at Pegasus capacitor of 8 g of Al cylinder and 1 g of platinum and it has an inner radius of 3 cm and a length of 3 cm. The liner design is based on the high Pulsed Power at LANL using the low voltage crowbar effect as shown in Fig. 1. Notice that the current is well represented by a sine curve up to the quarter cycle time at 8.8 $\mu$s. From the 1-D simulation we expect a peak shock about 8 Mbar at the platinum target. In Fig. 2 we display the liner trajectories. The platinum layer is less than 1 cm thick but the plot does not show it. We have plotted the radius of the aluminum layer as a single curve in the plot.

In Fig. 3 we show the velocity of the inner liner surface. The collision velocity is 8 mm/$\mu$s.

The temperature histories for the two liner layers are shown in Fig. 4. The dashed and solid (dotted and dot-dash) curves represent respectively the outer and inner surfaces of the platinum (aluminum) layer. We note that the inner aluminum surface begins to melt at 4 $\mu$s and we show the inner one about 7.5 $\mu$s but the platinum layer remains way below the melting point before collision.

Finally in Fig. 5 we plot the shock pressure profiles against the inner radius for different times. The platinum target assumes the zones from 1 to 21, platinum in the liner from 24 to 42 and Al from 43 to 102. The solid curve is right after the collision at $t = 8.881$ $\mu$s. Below it by the dashed and dot-dash curves at 2 ns interval and then the short and long dashed curves are considered. The peak pressure is around 8 Mbar and it gets slightly less than this. The peak shock duration is limited by the width of the Pt layer or the liner which is more or less a factor below. The calculation was carried beyond the Pt-Al interface to check the collision stability.

Procyon is an explosive driven pulsed power facility at LANL, the current wave form is approximately a sine function with a short rise time about 1 $\mu$s and peak current of 25 MA. Based on the driving current and the high explosive at hand, the optimum liner-target has a mass of 12

Figure 2 Inner and outer liner radial screen lines

Figure 3 Velocity history of the inner liner surface

of Al and 1 g of Pu and has a length of 2 cm and an inner radius of 3.3 cm. According to our 1-D simulations, the liner will generate a peak shock about 40 Mbar on a Pu target.

## I Conclusions

We have proposed the aluminum-plutonium composite liner design based on the physical insights obtained from our study of the behavior of the Hugoniots and electrical conductivities of various materials. The composite liner could be used to achieve a shock pressure several times over the best performance attainable from the solid aluminum liner. The improvement in peak shock pressure results mainly from the high density of the plutonium layer and to a lesser extent from the fact that we can keep the aluminum liner in solid phase while driving the aluminum liner to yield the desired shock pressure, thereby achieving an even higher radial convergence ratio than the pure aluminum liner. We also point out a possible loading history of the pure plutonium liner. We note that the pure plutonium liner will have a much smaller critical mass than the pure aluminum liner. Hopefully the upcoming magnetic experiments at both Pegasus and Procyon will shed some light on this question. We have developed a general formulation to optimize the composite liner design so that the shock pressure in the plutonium layer can be kept at the desired value while the aluminum liner is driven to the highest possible velocity. Based on the optimal liner parameters

well performance.

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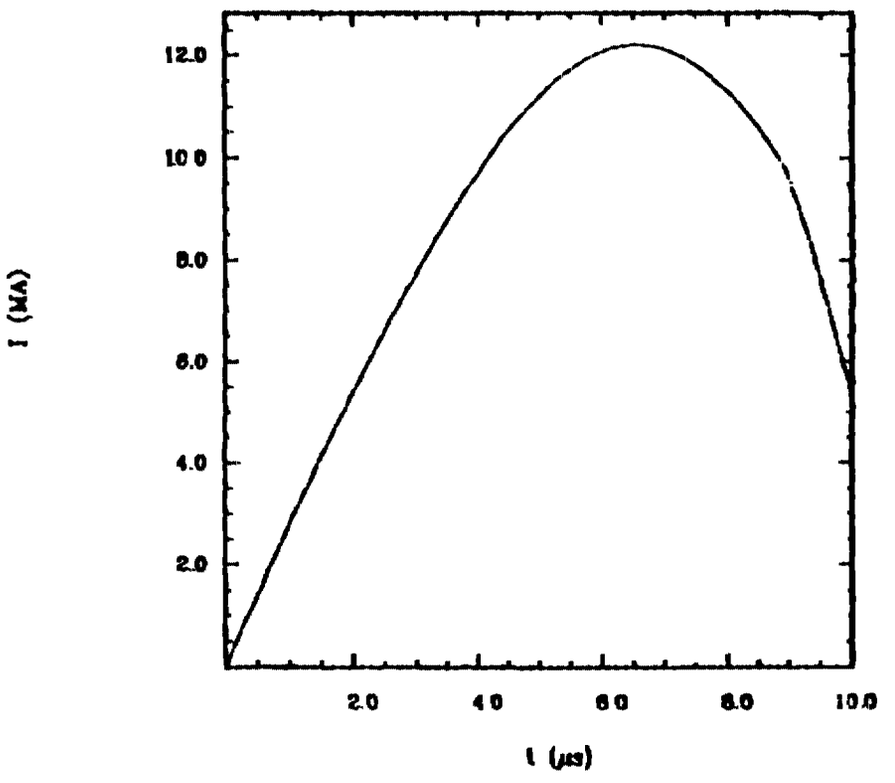
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5 [illegible]

Fig 1 H. Lee



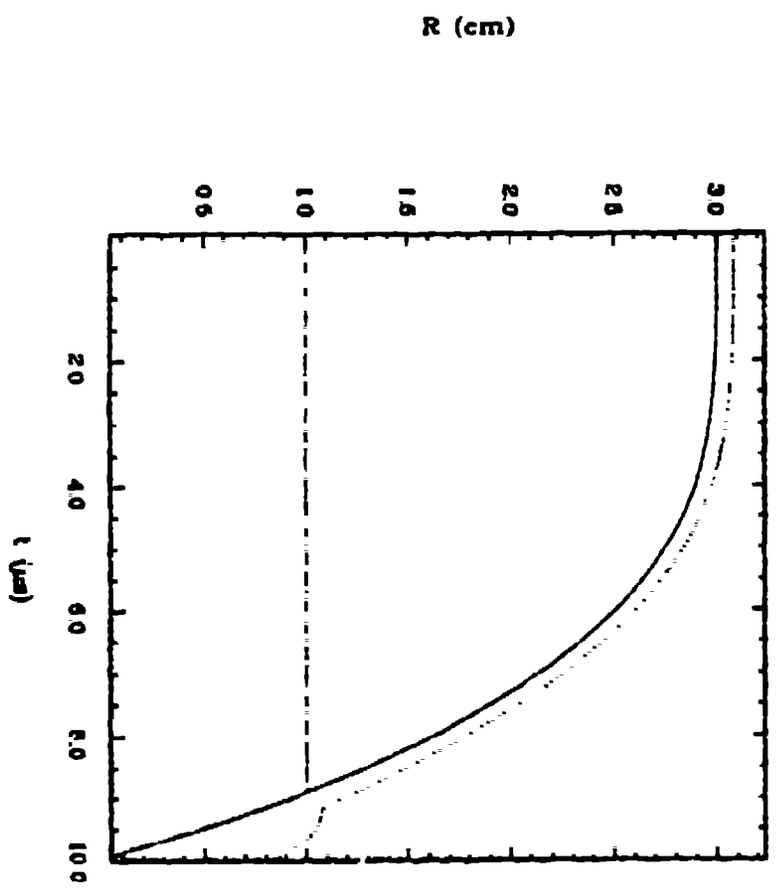
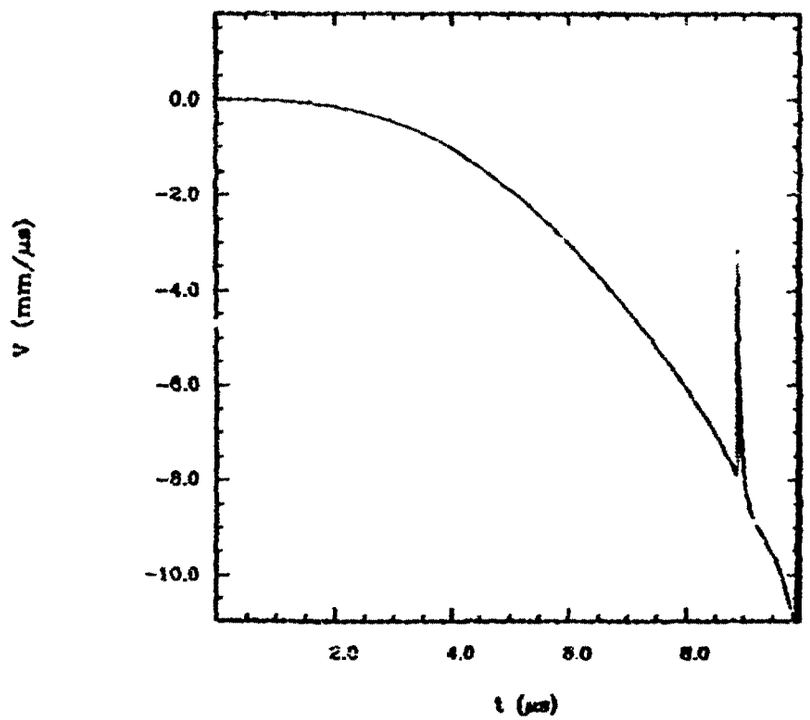

R (cm)
0.5
1.0
1.5
2.0
2.5
3.0
t (ms)
0.0
20
40
60
80
100

Fig 3



T (eV)
20-25.2
10-20.1
00+20.1
00+25.2
t (ms)
2.00
4.00
6.00
8.00
10.00

Fig 5

