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Author(s): R. L. Bowers, J. H. Brownell, H. Lee, A. J. Scannapieco, M. P. HOckaday, R. E. Chrien, R. Bartsch, J. C. Cochran, J. S. Ladish, H. Oona, J. V. Parker, D. Platts, J. L. Stokes, L. R. Veeser, D. S. Sorenson, R. Walton, W. E. Anderson, W. Broste, R. M. Malone, B. J. Warthen

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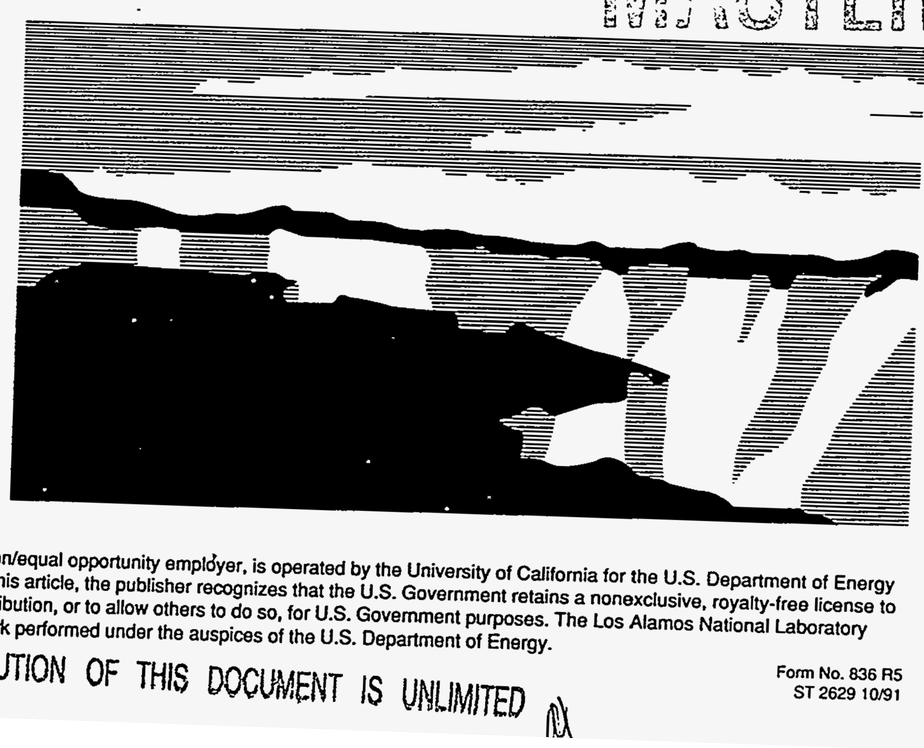

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PRECISION SOLID LINER EXPERIMENTS ON PEGASUS II

R.L. Bowers, J.H. Brownell, H. Lee, A.J. Scannapieco, M.P. Hockoday, R.E. Chrien, R. Bartsch, J. Cochrane, J. Ladish, H. Oona, J.V. Parker, D. Platts, J. Stokes, L. Veeser, D. Sorenson, R. Walton, W. Anderson
Los Alamos National Laboratory

W. Broste, R. Malone, B. Warthen
EG&G/EM, USA

I. INTRODUCTION - SOLID LINER DRIVERS

Pulsed power systems have been used in the past to drive solid liner implosions for a variety of applications.[1] In combination with a variety of target configurations, solid liner drivers can be used to compress working fluids, produce shock waves, and study material properties in convergent geometry. The utility of such a driver depends in part on how well-characterized the drive conditions are. This, in part, requires a pulsed power system with a well-characterized current wave form and well understood electrical parameters. At Los Alamos, we have developed a capacitively driven, inductive store pulsed power machine, Pegasus, which meets these needs. We have also developed an extensive suite of diagnostics which are capable of characterizing the performance of the system and of the imploding liners. Pegasus consists of a 4.3 MJ capacitor bank, with a capacitance of 850 μf fired with a typical initial bank voltage of 90 kV or less. The bank resistance is about 0.5 mΩ, and bank plus power flow channel has a total inductance of about 24 nH. The details of the machine and of the diagnostics are described in a companion paper.[2] In this paper we consider the theory and modeling of the first precision solid liner driver fielded on the LANL Pegasus pulsed power facility.

The dynamics of the driver can be obtained by solving a set of coupled equations that describe the pulsed power system (represented by a single loop lumped circuit containing a bank capacitance C and and inductance L)[3], and the equations of motion for the load. The full set of equations are solved numerically, and the results of these computations are discussed below. Here, we consider a simple approximation that illustrates the underlying physics. The kinetic energy of the driver (mass m) is related to stored magnetic energy and the energy delivered by the bank by

$$\frac{1}{2}mv(t)^2 = \int_{t_o}^{t} V(t')I(t')dt' - \frac{1}{2}L(t)I(t)^2 \tag{1}$$

The change in inductance of the system is described by[3]

$$L(t)I(t) - L(t_o)I(t_o) = \int_{t_o}^{t} V(t')dt' \tag{2}$$

Numerical calculations indicate that the liner motion does not begin until near peak current, and that for targets of interest liner-target impact will occur shortly after peak current. We may use these observations to obtain order of magnitude estimates of the liner's performance. First, we assume that essentially all of the electrical energy is delivered by the bank prior to the beginning of liner motion (during the first quarter cycle), and approximate the integral in (1) by $(1/2)\ C^2V_o$, where V_o is the initial bank voltage. Next, apply (2) to the first quarter cycle of the bank with zero initial current and initial inductance L_o. Representing the time scale

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[1]P.J. Turchi, A.L. Cooper, R.D. Ford,, D.J. Jenkins, and R.L. Burton, *Megagaouss Physics and Technology*, Ed. by PIJ. Turchi, (Plenum: New York; 1980), pg. 375; J.H. Degnan, et. al., "Multi-Megajoule Solid Liner Implosions", *Megagauss Technology and Pulsed Power Applications*, Ed. by C.M. Fowler, R.S. Caird, and D.J. Erickson, (Plenum Press: New York; 1987), pg. 699; J.H. Degnan, et. al., "Multi-Megajoule Shaped Solid Liner Implosions", *Megagauss Fields and Pulsed Power Systems*, Ed. by V.M. titov and G.A. Shvetsov, (Nova Science Publishers: New York; 1990), pg. 623.

[2]M. Hockaday, et. al., "Liner Target Interaction Experiments on Pegasus II", these proceedings.

[3]The system and load resistance is small, and will be omitted in the simple estimates presented here.

by $(L_oC)^{1/2}$ we approximate the integral on the right side of (2) by $V_o\ (LC)^{1/2}$ and obtain for the peak current $I_{max} \sim V_o\ (C\ /\ L_o)^{1/2}$. After peak current the voltage approaches zero, and we assume that the right hand side of (2) is small compared with $L_o I_{max}$ so that the current I_c and inductance L_c at collision are given approximately by $I_c\, L_c \sim I_{max}\, L_o$, which gives $I_c \sim I_{max}\, (l_o\ /L_c\ )$. These approximations can be used to express the velocity of the liner at impact in the form

$$v = \left[\frac{CV_o^{\ 2}}{m}\left(1 - \frac{L_o}{L}\right)\right]^{1/2} \tag{3}$$

For a modest bank charge $V_o =\ 33\ kV$, and $L_o = 33\ nH$, our simple estimates give $I_{max}= 5.3\ MA$. Assuming at impact $L_c= 35nH$, we find $I_c= 5.0\ MA$. Finally, for a 4 g liner, we estimate $v \sim 0.36\ cm/\mu s$.

At impact, the solid liner will produce a shock wave in a central target, whose magnitude can be obtained from the Hugonoit relations. For a liner and target made of the same materials, the shock pressure in the target is approximately

$$P_s \simeq \frac{1}{4}\rho v_c(2c + sv_c) \tag{4}$$

where c and s appear in the relation between the particle and shock velocities. For applications of interest here, c is a few cm/μs and s > 1. Using (3) with $v \sim 0.36\ cm/\mu s$, and approximating (4) by $P_s \sim (1/2)\rho_o v^2$, we estimate shock pressures of order *200 kbar* for aluminum and as high as *1 Mbar* for platinum. Higher voltages may, in principle, be used to produce higher velocities.

The pressure estimates above assumed modest initial bank voltages. Using (3) for a 4 g liner with an initial voltage of *85 kV* would predict impact velocities of order $1\ cm/\mu s$. The successful production of high pressures in a target requires that the front edge of the liner remain at, or near, solid density, ρ_o , up to impact. As the liner implodes it will be resistively heated by the drive current and may eventually reach melt conditions. If melt reaches the inner edge of the liner, thermal expansion will occur. As the density of the front edge drops, so will the value of the pressure produced at impact in the target. In the extreme case the front edge will thermally expand forming low density blow-off. In this case shockless assembly of the liner on the target will produce very little pressure in it. It is critical that the design of a solid liner driver be such that the front edge remains at or near solid densities. We have used analytic models and a one-dimensional magnetohydrodynamic code to obtain the design of an aluminum liner that remains solid to impact on a target.

Several multi-dimensional issues also arise in the design of a successful solid liner driver. The behavior of the liner as it elastically deforms and then moves through a few times its initial thickness will have an important effect on the reminder of the implosion. It is therefore necessary to design the mounting of the liner on the electrode walls with care. The subsequent implosion of a solid liner occurs by plastic deformation of the cylinder. During this time it is important that the liner maintain good electrical contact with the electrode walls. The outer surface of the liner is unstable to magnetically driven Rayleigh-Taylor modes, but the presence of material strength effectively stabilizes small scale mode growth. The interaction of the walls with the moving liner will induce larger scale perturbations. These effects are largely two-dimensional (2-D), and have been modeled with a 2-D multi-material magnetohydrodynamic code.

An accurately characterized, magnetically-driven solid liner may be used to address a wide range of physics issues. These include: material strength studies; asymmetric deformation or flow in the elastic plastic regime; modeling seams and joints, and micro-jetting; fluid instability studies; and quasi-particle ejecta and mix. A critical step in addressing these issues is the development and characterization of a precision solid liner driver. A series of experiments has been designed to characterize a solid liner driver capable of producing shock pressures of order 300 kbar in an inner target. The first series of experiments, which were completed in April 1993, had as their primary purpose the characterization of the imploding liner. Specifically, they included driver characterization, diagnostic development and validation of the 1-D and 2-D magnetohydrodynamic codes used for the design. The design of the liner for these experiments will be discussed here. A review of the experimental results is given elsewhere in these proceedings[2]

II. SHOCK INDUCED QUASI-PARTICLE EJECTA

A solid liner driver can be used to characterize shock induced quasi-particle ejecta[4] from the surface of a target liner. In particular, we are interested in obtaining experimental data on quasi-particle distribution functions *f(r, v, a, t)*, where *r* and *v* are the position and velocity of the ejected quasi-particles, *a* is their diameter or characteristic scale, and *t* is the time. Such distribution functions are important for models of quasi-particle transport (using for example mass, momentum and energy bins), or models which transport an average quasi-particle appropriate for mass, momentum and energy coupling between particles and an atomic background. Regardless of the specific assumptions underlying a given model, the distribution function *f(r, v, a, 0)* is needed to define initial conditions for theoretical or computational models. Finally, we note that experimentally measured distribution functions provide a set of data against which to compare quasi-particle transport schemes.

As the first application of our solid liner driver we are characterizing quasi-particle distributions in the few hundred kbar regime. The design issues for this series includes production of a 300 kbar shock at the inner surface of an aluminum target cylinder, and the development of laser holography to measure particle size. Figure 1 shows a schematic representation of such an experiment. Subsequent experiments will address the issue of quasi-particle ejecta from the surface of different materials. These constraints set parameters for the design of the liner, which is discussed in the next section.

III. DESIGN OF A PRECISION SOLID LINER

We now consider the design of the solid liner driver. This was done using simple analytic modeling, and Lagrangian 1-D and Eulerian 2-D magnetohydrodynamic codes coupled to a lumped circuit representation of the capacitor bank and power flow channel. The analytic models and 1-D codes were used to determine the initial bank voltage, and the mass and initial radius of the liner. A simple two loop circuit was used to represent Pegasus II. One loop contained the capacitor, the bank voltage and resistance. The other loop contained the power flow channel inductance and was connected to the computational grid. The common branch between the two loops contained the damping resistor. Magnetic energy from the bank produces a **J**x**B** force which radially implodes the cylindrical load.

The target chamber included a coax with inner radius 3" and outer radius 4". Electric current from the bank flows along the inner electrode, through a cylindrical load in a 2 cm high load slot, and then back along the outer electrode. The outer electrode contains a series of windows which allow diagnostics a clear view of the implosion volume.

The Pegasus II machine operated in a direct drive mode for these experiments. In direct drive mode, current is delivered to the load without an intervening fast opening switch. In these experiments currents of order 5 MA were produced with a quarter cycle time of about 8 μs.

The experimental chamber contained a series of diagnostic windows located in the outer electrode just above the load region. Analytic analyses of the effect of these windown on the implosion was carried out to ensure that asymmetries would not degrade the quality of the implosion. The initial configuration contained windows of varying sizes, which introduced in a slight but measurable motion of the liner relative to the axis of symmetry. Calculation verified that this effect would be removed by symmetrizing the structure. It was also shown that the growth of fluting modes associated with the windows was neglibible.[5]

The free parameters were constrained so that the liner would remain solid during the implosion, and would produce 300 kbar shocks in a suitably designed target. To achieve this we used a 2 cm high, 3.37 g aluminum liner having an initial outer radius of 2.4 cm. The initial thickness of the liner was 0.04 cm. Figure 2 shows the calculated current wave form delivered to the liner by Pegasus II charged to an initial voltage of 38 kV. The peak calculated current is 5 MA, and the quarter cycle time is about 8 μs. The liner's inner and outer radii are shown as a function of time in Figure 2. Figure 3 shows the velocity of the inner and outer surface versus time obtained from the 1-D calculations. The arrows at the right denote the velocity of the inner surface at radii of 1.6 cm, 1.5 cm and 1.4 cm respectively. We note that for a given liner mass and initial radius, the actual velocity at 1.5 cm can be tuned by adjustments in the initial voltage of the bank.

The 1-D modeling of the magnetically imploded liner used SESAME equations of state and electrical resistivities for aluminum, and an elastic-plastic material strength model with parameters fit to aluminum to

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[4]Defined as particulate matter with characteristic sizes of a few to tens of microns.

[5]H. Lee, "Perturbation Force on Pegasus Liner Due to Current Non-Uniformity", Los Alamos National Laboratory Report, LA-UR-95-2328.

verify that the liner would remain solid during the implosion. The results indicated that the liner would remain solid until it reaches the 1.5 cm radius target . The electric current was also found to be essentially uniform throughout the liner during the implosion. The 1-D calculations indicated, as expected from analytic models, that pure aluminum (1100 series) should experience less Joule heating than would Al alloys.

Having established the overall parameters for the solid liner from 1-D calculations, we addressed several 2-D design issues using a 2-D multi-material Eulerian MHD code. These issues included: (a) the mounting of the solid liner on the electrodes; (b) launching the liner in such a way as to maintain good liner-electrode contact during the implosion; (c) possible boundary (electrode) induced perturbations on the liner; (d) sensitivity of the design to material and alloy properties; and (e) the effect of sloped electrodes on the implosion.

The first issue considered was the liner mounting on the electrode glide planes. The launch and travel of the liner along the electrodes were investigated in detail. It was found in our 2-D simulations that the integrity of the liner contact with the electrode and the uniformity of the liner structure was greatly enhanced by the introduction of a step joint in the electrode wall just below the launch position of the liner.

Calculations also demonstrated that the behavior of the liner at this stage was sensitive to the aluminum alloy used. Simple joint calculations with hardened alloys produced significantly more bending of the liner at the electrode glide plane than did the calculations using pure Al. Pure Al has a lower electrical resistivity than do its alloys, and thus should experience less Joule heating during the implosion. The inside surface of the liner near the electrode wall is planar in the case with the step joint as opposed to the curved surface seen in the case of the simple step joint. Calculations with other Al alloys showed even more curvature at this stage. In addition, the liner material laid down against the electrode wall is thicker in the case with the step joint.

The 2-D calculations also indicated that to maintain both the planarity of the inside surface of the liner and the integrity of the contact with the electrode it was necessary to include in the design sloped glide planes for the electrodes. Calculations were performed to model the effect of 5°, 8° and 15° sloped electrodes on the integrity of the liner-electrode contact. The results indicated that 8° slope should maintain good contact.[2]

Finally, we note that the backside of the liner is unstable to magnetically driven Rayleigh-Taylor instability growth. Although the liner was initially unperturbed, interactions with the electrodes during the implosion could have set up disturbances that could, in principle, result in growth. An analysis of the 2-D calculations demonstrated that the liner was able to adjust to these effects without exhibiting perturbations. Part of this is due to the fact that material stresses oppose the growth of magnetically driven perturbations.

The final design consisted of a 3.37 g, 2 cm high Al liner having an initial outer radius of 2.4 cm and a thickness of 0.04 cm. It was turned out of dead soft, 1100 series aluminum with a surface finish of 1 μm. The electrodes were fabricated out of copper, and were sloped at 8°. The final design is shown in Figure 4.

IV. QUASI-PARTICLE EJECTA EXPERIMENTS

The calculations and data for the series of solid liner experiments reviewed in the previous sections demonstrates that a well characterized drive has been designed. As the next step we have designed an experiment using the precision solid liner whose ultimate purpose is to produce and diagnose shock induced quasi-particle ejecta. The driver described above will be used as designed. An aluminum alloy (6061-T6) was chosen for the target. Figure 5 shows the target design which is to be fielded on the next experimental series. The target, having an outer radius of 0.75 cm, and a thickness of 0.2 mm, produces a 320 kbar shock at the inner surface. Experimental results in planar geometry have demonstrated that shocks of this magnitude should produce about 5 $\mu g/cm^2$ of Al ejecta in the form of particles. There is no empirical data on the particle size distribution for Al. Experimentally, we will look for particles with sizes in the range 1 - 20 μm.

Laser holography is under development as a way of measuring quasi-particle ejecta. In order to be able to unambiguously resolve individual particles with this diagnostic, it is necessary to limit their number to a few thousand. For this purpose a tantalum collimator has been designed as shown in Figure 5. Its mass and radius were chosen to satisfy the following requirements. First, the most rapidly moving particle ejected from the inner surface of the target must not reach the axis before the bulk of the slower moving ones pass through the collimator gap. Second, the shock set up in the collimator when the target's inner surface impacts it must not contribute to the ejecta in the central volume. These constraints are sufficient to establish the geometry shown in Figure 5.

V. CONCLUSIONS

The first series of solid liner experiments established the following. The liner was imploded plastically, with a well-characterized front surface capable of driving shocks in a target liner. Excellent electrical contact between the liner and the electrode was preserved during the implosion. The implosion remained cylindrical and concentric to better than 100 μm. Finally, the liner appeared to be free of perturbations or magnetically driven instabilities. These observations indicate that we now have a well-characterized, precision solid liner driver for applications experiments.

Based on the solid liner driver described above, a preliminary series of applications experiments have been designed to diagnose quasi-particle ejecta from an aluminum target. The goal of this series of experiments will include measuring with laser interferometry the quasi-particle distribution function for aluminum.

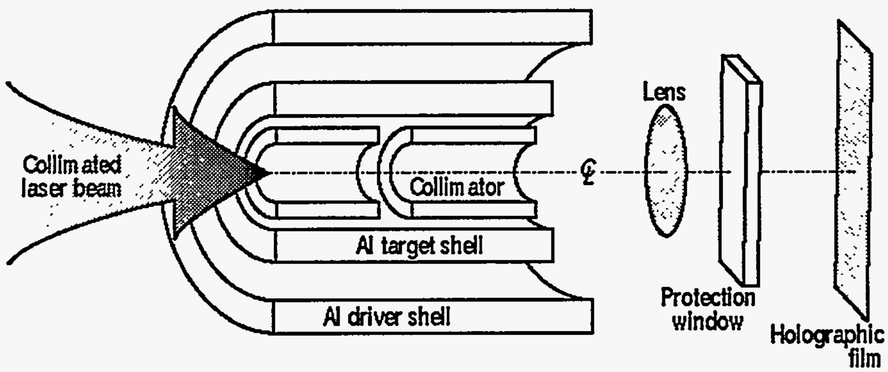

Figure 1. Schematic of Pegasus II experiments to produce quasi-particle ejecta.

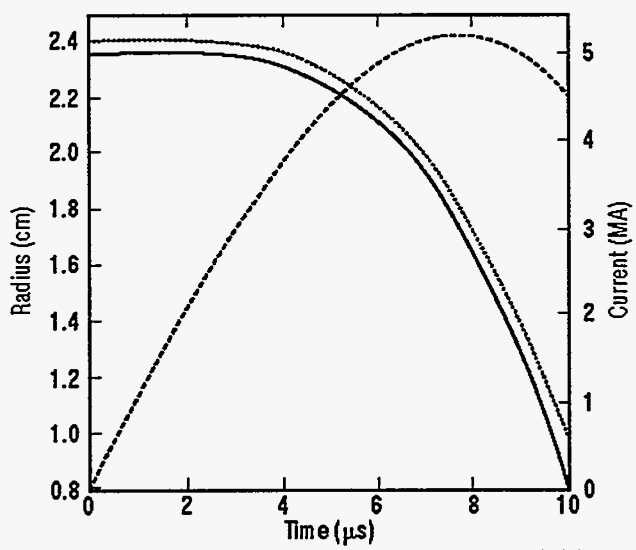

Figure 2. Calculated electric current delivered to the 3.37 g Al liner at in initial bank voltage of 38 kV (right scale). Also shown are the inner and outer radii of the liner versus time (left scale).

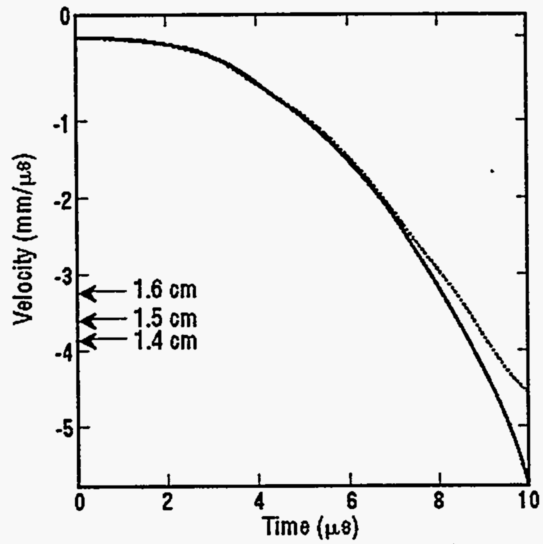

Figure 3. Velocity of the inner and outer surface versus time obtained from the 1-D calculations.

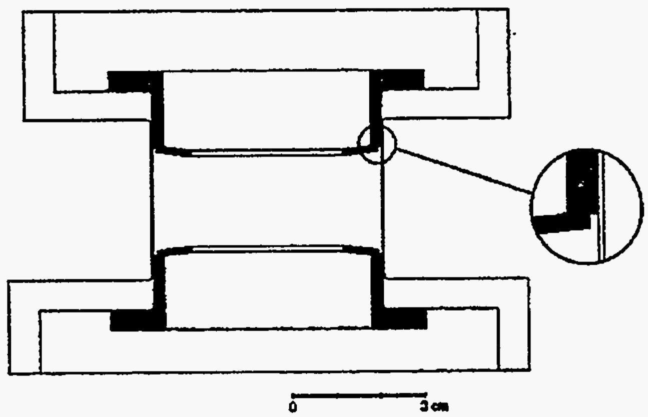

Figure 4. Final design of the precision solid liner driver for Pegasus II.

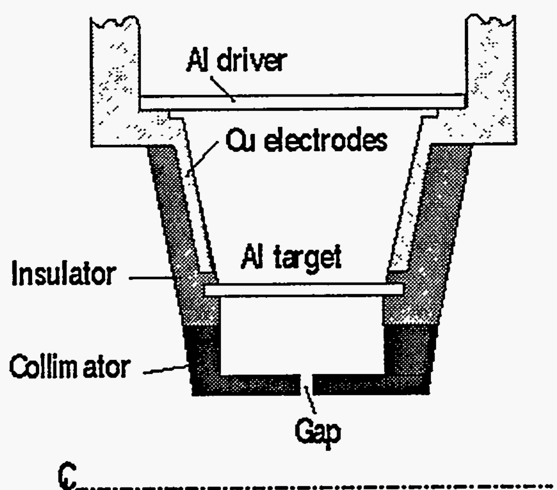

Figure 5. Solid liner driver and Al target proposed for quasi-particle ejecta experiments. The collimator design includes a gap to limit the number of ejected particles that reach the central volume.