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Title: Application of Liner Implosions to High Precision EOS Measurements (u)

Author(s): Bob Reinovsky, for the ALT-3 Team

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LANL VNIEEF
Los Alamos, NM 87545

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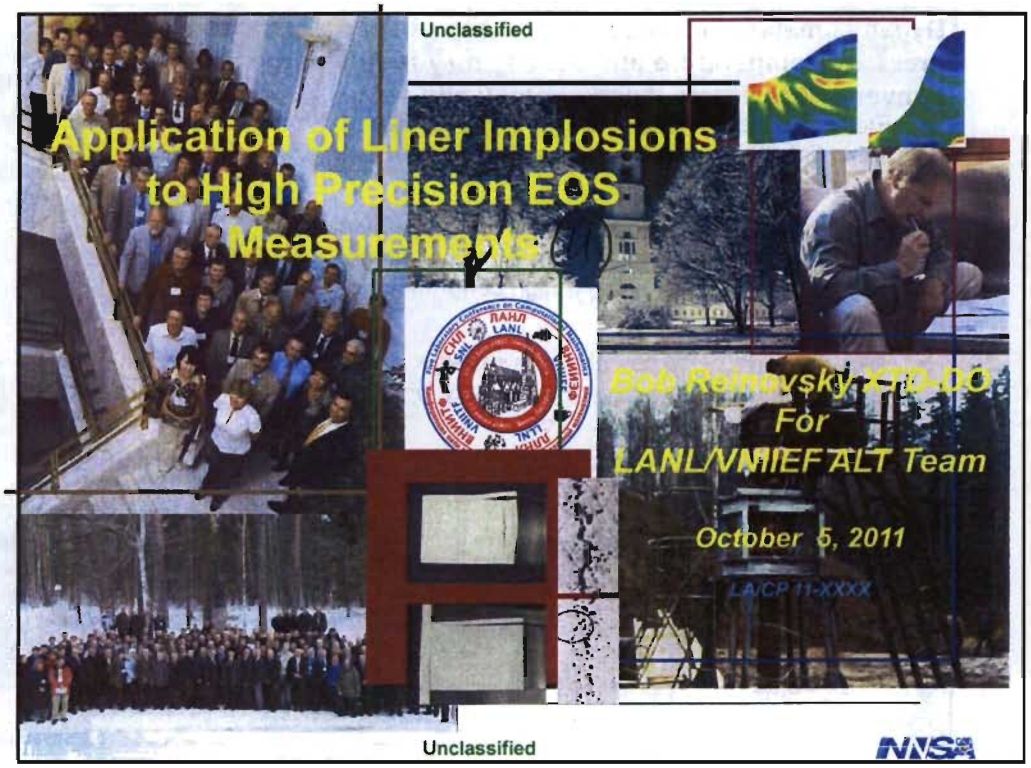
Abstract

Application of Liner Implosions to High Precision EOS Measurments (u)

The All-Russia Research Institute of Experimental Physics [VNIIEF], and Los Alamos National Laboratory [LANL] have mutual interests in studies of the study of instabilities, liner compression and behavior of materials as extreme conditions using pulsed-power hydrodynamic approaches. Los Alamos has a long-term interest in performing such experiments where more flexibility in experimental configuration, venue, and energy level are needed than is afforded by fixed laboratory pulse power systems like Atlas and Sandia Z. For such applications, explosive pulse power systems in general and the VNIIEF DEMG systems in particular offer unique advantages and VNIIEF is currently the world leader in this technology.

Los Alamos has conducted such experiments using the VNIIEF DEMG system in Sarov (DEMG-1, X-Ray-1, ALT-1 and ALT-2) with very encouraging results. LANL would like to embark on a process that will, over a period of 3-10 years make it possible to conduct such experiments, using the VNIIEF DEMG system, in the US at facilities in Los Alamos or perhaps at the NTS. A project with VNIIEF has been initiated outlining the general steps in such a process and authorizes the first of those steps. Those steps include the definition of a representative experiment for which the DEMG provides special capability; the detailed design of the physics experiment followed by the detailed design of the DEMG based pulse power system need to perform the experiment; a demonstration test of the new pulsed power system in VNIIEF with an experiment of mutual interest; the planning of the logistics of conducting the experiment in the US; the fabrication, assembly and check-out of appropriate pulse power, experimental load, and diagnostic equipment; the conduct of the experiment and the analysis of the results including evaluation of the feasibility of future DEMG based experiments.

In this paper we review the result of the first half of the project including the design of a high pressure EOS Experiment as the first demonstration of the new system. The first demonstration is to be conducted in VNIIEF in 2012. Pulsed power design is reviewed, briefly and liner design calculations by both LANL and VNIIEF are included.



Outline

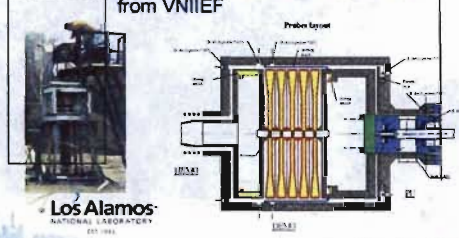
- Background
- Development of "new" driver
- Diagnostics
- Precision Liner predictions

Dynamic material science experiments, especially those at extreme pressure, temperature and density may require large amounts of energy, converted to particle kinetic energy and delivered with high precision.

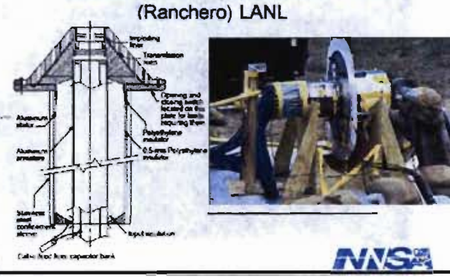
- Electromagnetic energy sources offer significant advantages in precision, controllability, reproducibility, and sometimes even energy over other drivers for some experiments
- Both magnetically imploded, cylindrical liners and magnetically driven planar impactors have met the requirements for precision on high performance laboratory sources.

- Two explosive pulse compression systems, capable of even larger energies have emerged as attractive drivers, especially for liner driven shock physics, materials EOS, and constitutive properties

Disk Explosive Magnetic Generator (DEMG) from VNIIEF

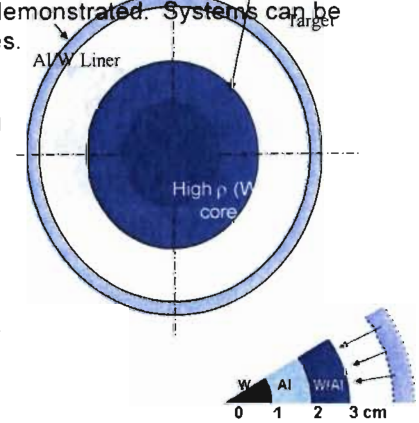


Coaxial Flux Compression Generators (Ranchero) LANL



The cylindrical, imploding liner is perhaps the most thoroughly studied mechanism for converting electrical energy into the particle kinetic energy needed for shock physics, and high energy density applications.

- Techniques producing 20-30 MJ of liner kinetic energy (at 5-8 MJ/cm) with velocities approaching 10 km/sec have been demonstrated. Systems can be designed to achieve even higher liner velocities.
  - Liner implosion techniques, compressing an initially solid, target, can convert many megajoules of liner kinetic energy into internal energy.....producing WDM with only modest requirements on liner precision
  - In hydrodynamic design calculations, an aluminum liner at 10 km/sec (2 MJ/cm) compresses a (matched) Al target to 8 gr/cc (~3X normal density) and energy densities approaching 140 kJ/gr (>1MJ/cc), at few eV, maintaining the conditions for several 100 ns.
  - Compressing the Al sample between a Tungsten liner (10 km/sec) and the tungsten core could reach densities of 10 gr/cc (>4X normal) and 150 kJ/gr (1.5MJ/cc).



- However, shock physics, and materials experiments, while sometimes relaxing the need for total energy, place MUCH more stringent requirements on precision

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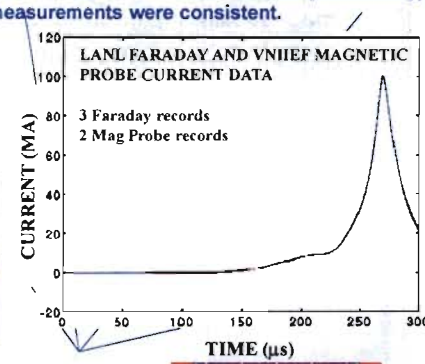
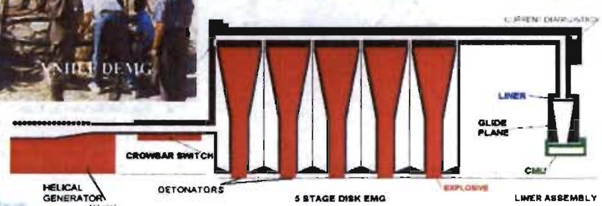
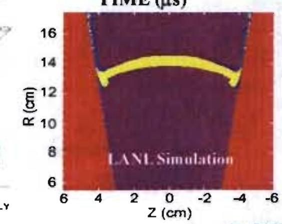
To demonstrate very large energies, LANL teamed with VNIIEF in 1996 to conduct the High Energy Liner (HEL-1) experiment, producing world record liner implosion kinetic energy with a 100-MA current drive.

- With more than 50% of the 1-kg liner mass unmelted, 2D effects were manifested (computationally) primarily in "glide plane run-ahead." Experimental measurements were consistent.
- Liner velocity at CMU was 6.7 km/sec - 8.4 km/sec
- Liner kinetic energy at CMU (4:1 radial convergence) was between 22 MJ and 35 MJ







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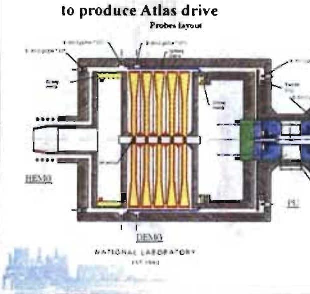
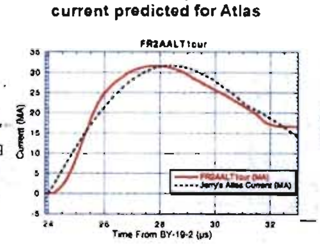
In November 2000, as Atlas neared completion, the ALT-1 experiment provided the first full-scale demonstration of Atlas-level technology by imploding an Atlas liner with 32 MA to a velocity exceeding 12 km/sec.

- VNIIEF DEMG and fuse pulse shaping produce current wave form virtually identical to Atlas.
- ALT-1 liner fabricated in VNIIEF to Atlas specifications reached velocities, measured by US VISAR team, required for initial Atlas experiments on hydro, spall, strength.
- Initial VNIIEF attempt at radiography were unsuccessful because of damage to film, leaving the question of liner stability unanswered -- for the moment.

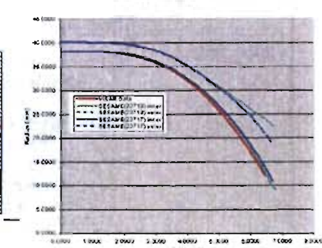
ALT-1 used VNIIEF DEMG to produce Atlas drive



ALT-1 current duplicates current predicted for Atlas



Liner Motion compared with 1D model using experimental current confirms power flow



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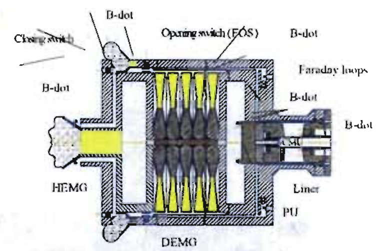
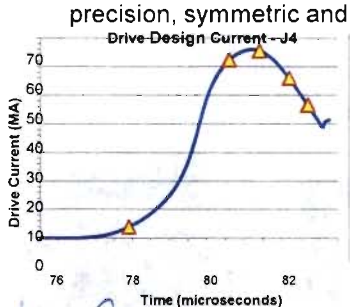
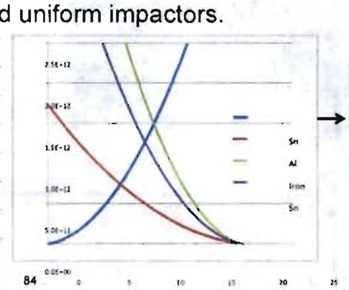
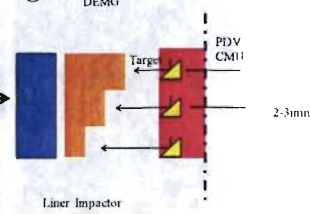
Since 2004, LANL and VNIIEF have collaborated in the design of a TPa EOS experiment based on a 60 MA, 20 km/sec, imploding liner powered by a Disk Explosive Magnetic generator.

- The experiment employs a very high precision magnetically imploded condensed matter liner imploding at velocities well above those achievable by gas guns or direct HE.
- … and depends upon successful application of new insights in the design and simulations of high performance liners to produce high precision, symmetric and uniform impactors.









- Approximately 32 probes
- 8 probes for liner at 2 axial stations
- 24 probes => 8 targets using 3/tgt
- 2 materials, 4 measurements per

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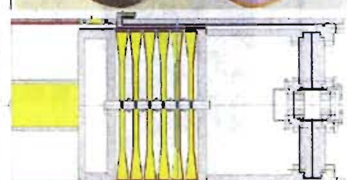
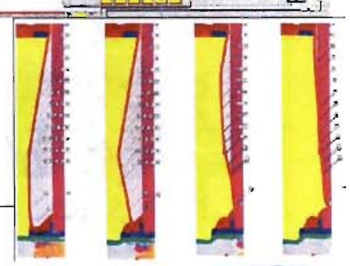
Since 2004 LANL and VNIIEF have collaborated in the development of … ed on VNIIEF DEMG.

Simulated performance of systems with N-module Ø0.4 m DEMG, FOS and ECS in the liner load

N (I_0,MA)	10(6). ALT-1,2	15(6)	15 (7)	15 (7)
$\Delta_f(L_{ol})$, mm (nH)	0.12 (8)	0.155 (10)	0.18 (4)	0.15 - 0.12 (6)
E_{gm}, MJ	10	-	33	27-21
U_{fm}, kV	200	430	250	300-230
W_{fm}, TW	3	10	17	15-14
S_{fm}, MJ	10	10	39	35-36
E_{lm}, MJ	5	6	13	20-19
I_{lm}, MA	32	36	73	71-65
j_{fm}^2, MA^2/cm^4	420	830	630	500-270
w_{fm}, GW/g	4.4	7	4.7	6.4 – 2.9

- I_0 - current supplied to the DEMG,
- $\Delta_f(L_{ol})$ – FOS Cu foil thickness (load inductance);
- E_{gm} – DEMG peak magnetic energy;
- U_{fm} – FOS peak voltage;
- W_{fm} and S_{fm} – peak power and max. EM energy to load
- E_{lm} and I_{lm} – peak magnetic energy and current in the load;
- j_{fm} and w_{fm} – peak current density and specific Joule heating power in the FOS Cu foil.





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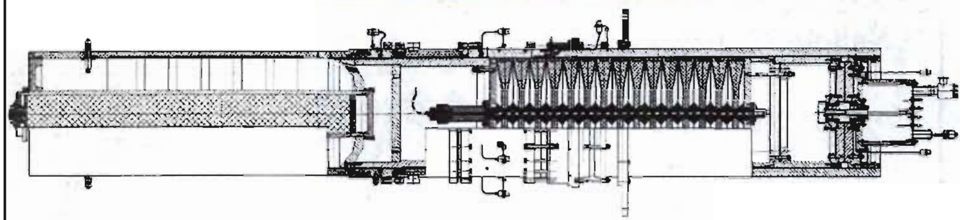
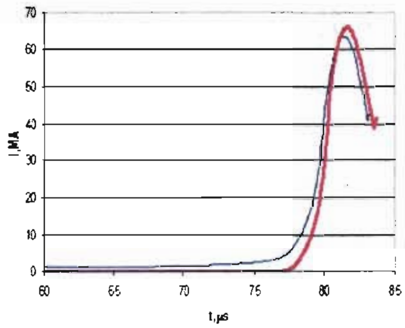
… and a system using the new components





NUMBER OF DEMG SEGMENTS	15
DEMG INITIAL CURRENT	> 7 MA
RATED (MAX) DEMG OUPUT	~70-90 MA
LOAD CURRENT WITH FOS	~60-70 MA
RISETIME (LOAD) WITH FOX	2 μsec
LINER VELOCITY	~20 KM/SEC

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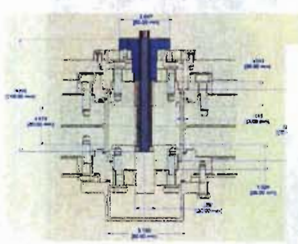
ALT-3 Target Assembly is comprised of a precision Target Cylinder, alignment components and CMU with ~32 separate PDV velocimetry measurements

- Partial grooves (200 deg) turned on ID with Fast Tool Servo on Single Point Diamond Turning Lathe (SPDTL)
- Can diamond turn Aluminum, Copper, Gold, Brass, Silver, Tin, Zinc
- No Ferrous metals for diamond turning (Steel, Iron, Beryllium, Titanium, Molybdenum)

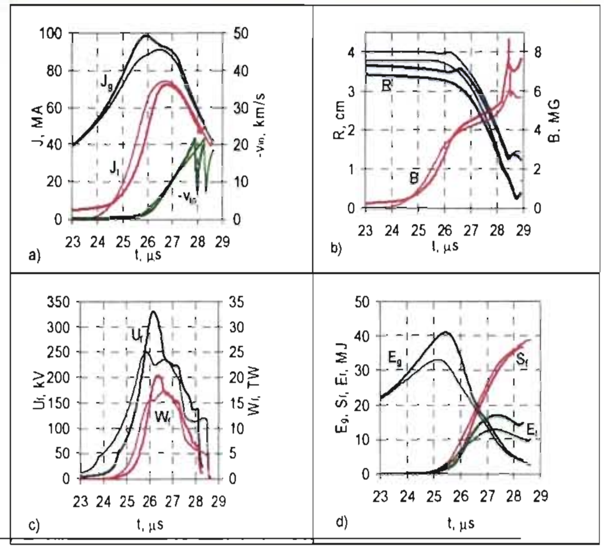
- 2 piece, "CMU inside a CMU"
- 32 Photon Doppler Velocimetry (PDV) probes
- 3D printed thermoplastic not precise enough
- 7075 Al for dimensional and thermal stability
- Epoxied together



1-D Simulated parameters of pulsed power systems and imploding, composite, Al+W liner in proposed devices with/without series (isolating) switch.

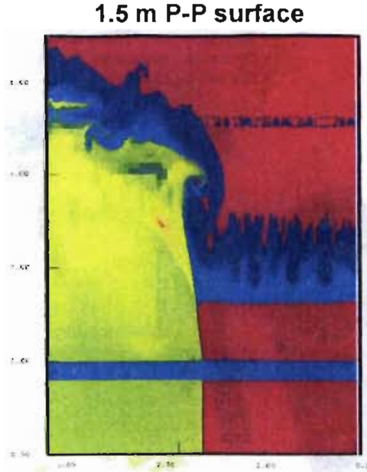
- J_g and J_l – currents in DEMG and in load
- v_{in} and R – inner boundary velocity and radius of both liner boundaries
- B - magnetic field at the outside liner boundary

- U_f – FOS voltage;
- W_f and S_f – power and electromagnetic energy transferred through the FOS to the load;
- E_g and E_l – magnetic energies in the DEMG-FOS system and in the load

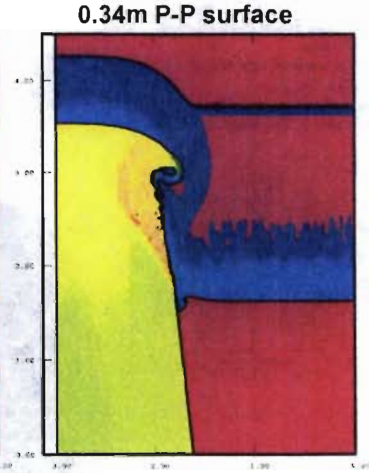


Improving (outer) surface finish, arising from conventional machining, by 5X significantly improves precision of inner surface. Best technology can improve ~10X

1.5 m P-P surface



0.34m P-P surface



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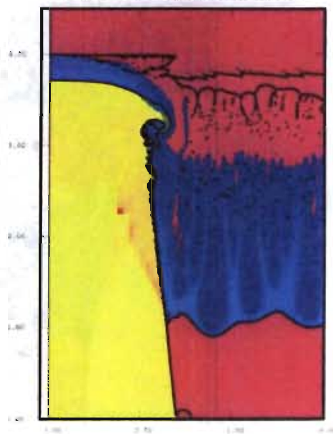
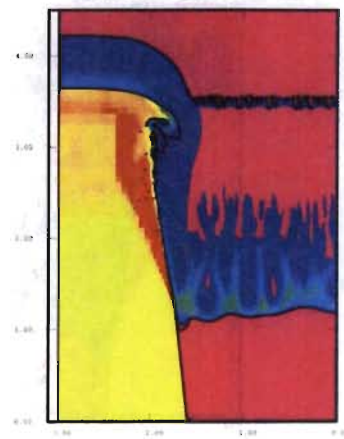
Perhaps surprisingly, increasing drive current, for otherwise fixed conditions, actually improves implosion precision (2mm thick liner)

32 MA Peak Current



68 MA Peak Current



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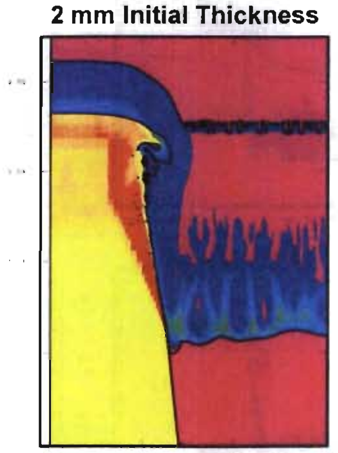
... and increasing the initial thickness results in additional improvement for 68 MA peak current.

2 mm Initial Thickness



3 mm Initial Thickness

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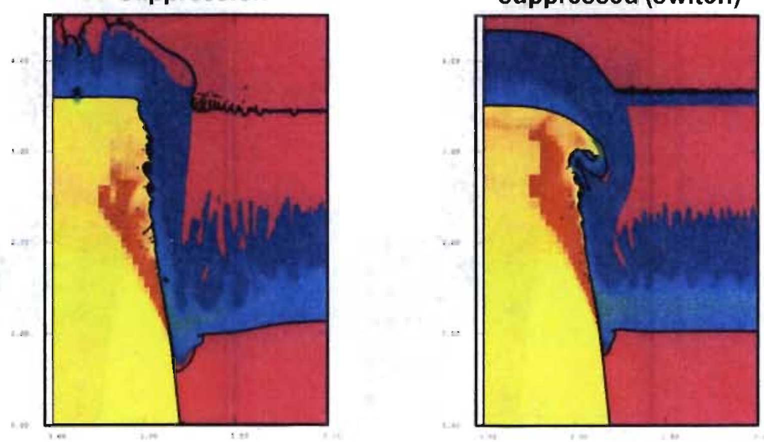
… and suppressing the long current precursor is also essential



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2-D Eulerian AMR simulations of the liner-end wall interactions were conducted to explore geometric affects

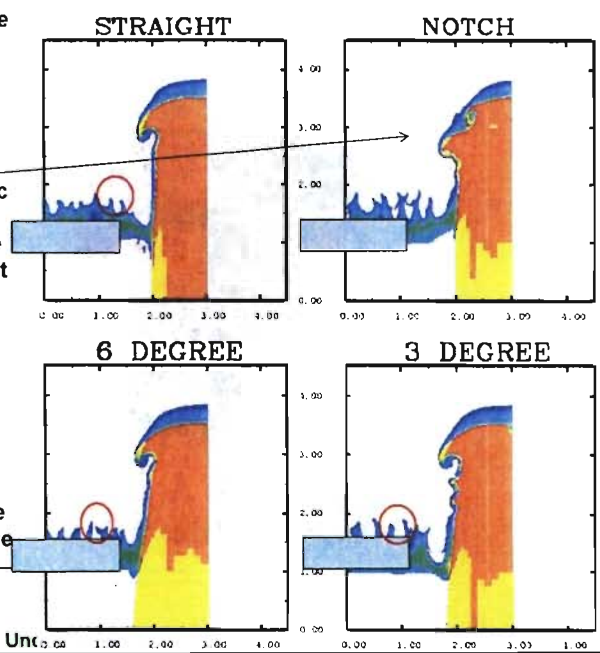
- One-half microsecond later, the inner surface of the liner has moved about 27 mm to 10 mm radius

  t= 6.2 μsec
  I(t)~ 46.6 MA
  Velocity$_{AV}$ = 20 mm/μsec

- The "notched" case shows the thinned region pressed against the glide plan. In similar calculations with other parameters (2mm thick liner) the thin section explodes.

- In the sloped cases the "lag" has become a leading "foot"

- Back surface perturbations are pronounced –but not disruptive



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VNIIEF 2-D Lagrangian-Eulerian simulations of the quality of the liner implosion inform design choices as well.

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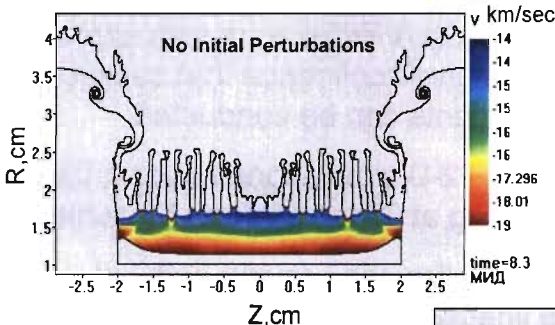
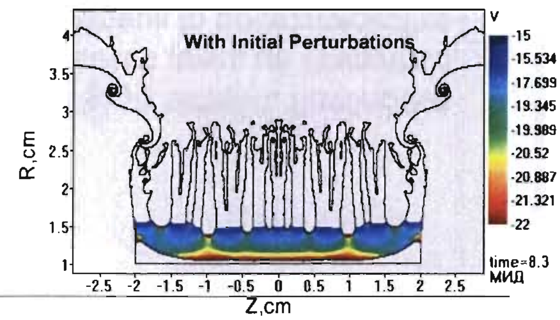


Radial component of liner velocity using h=50 μm mesh scale



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The next step in controlling the liner/end wall interaction is the formulation of a simple, phenomenological, criteria for shaping the "glide planes" to control the damaging effects of these interactions.

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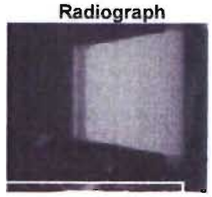
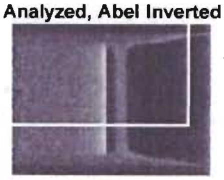
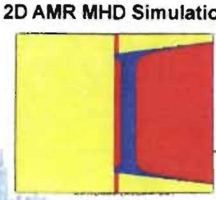
Radiograph



Analyzed, Abel Inverted



2D AMR MHD Simulation



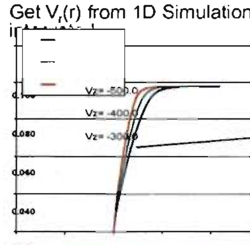
Since Axial Velocity is a Function of Radial Velocity and Slope of Glide Plane

$V_z(t)=V_r(t)*\tan(q_{gp})= V_r(t)*dz/dr$

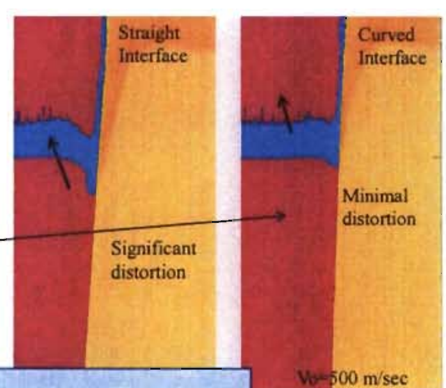
To hold V_z Constant at some low value say 500 m/sec, let

$dz \sim V_z(t)/V_r(t) * dr= Vo/V_r(r)*dr$

Get $V_r(r)$ from 1D Simulation and i...



Contouring the end wall (in r-z) to maintain a constant axial velocity at the interface significantly reduced the "run ahead"



If electrodes converge too fast material piles up…if too slowly a low P region appears through which B can penetrate.

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Summary

- Two decades of joint LANL/VNIIEF work with explosive pulsed power systems give confidence that successful liner implosion experiments can be conducted.
- Both LANL and VNIIEF 2-D simulations suggest that an adequate liner impacting at 20 km/sec can be achieved
- Multi-point PDV diagnostics can provide detailed characterization of liner/target interactions and, potentially an initial assessment of the feasibility of conducting multiple EOS measurements in a single shot