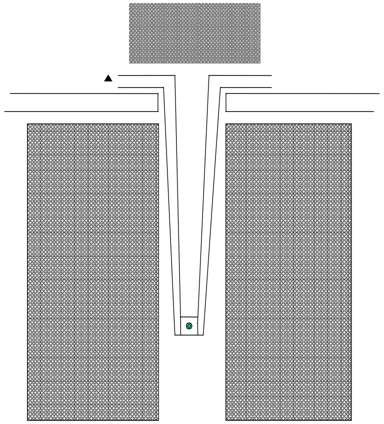
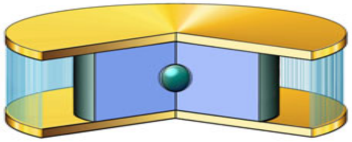
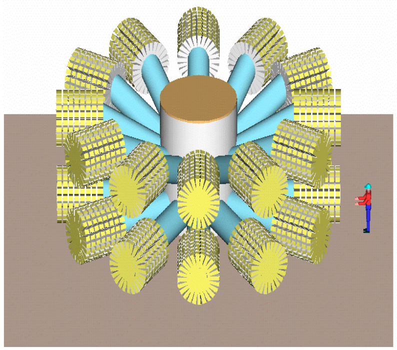
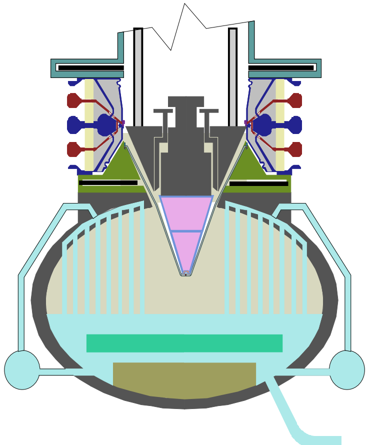
Development Path for Z-Pinch IFE


RTL


DH target


LTD driver


Chamber

Craig L. Olson + Z-IFE Team
Sandia National Laboratories
Albuquerque, NM 87185

16th ANS Topical Meeting on
Technology of Fusion Energy
Madison, WI
September 14-16, 2004

The Z-Pinch IFE Team

G. Rochau, S. Slutz, C. Morrow, R. Olson, A. Parker, M. Cuneo, D. Hanson, G. Bennett, T. Sanford, J. Bailey, W. Stygar, R. Vesey, T. Mehlhorn, K. Struve, M. Mazarakis, M. Savage, A. Owen, T. Pointon, M. Kiefer, S. Rosenthal, L. Schneider, S. Glover, K. Reed, G. Benevides, D. Schroen, W. Krych, C. Farnum, M. Modesto, D. Oscar, L. Chhabildas, J. Boyes, V. Vigil, R. Keith, M. Turgeon, B. Smith, B. Cipiti, E. Lindgren, D. Smith, K. Peterson, V. Dandini, D. McDaniel, J. Quintenz, M. Matzen, J. P. VanDevender, W. Gauster, L. Shephard, M. Walck, T. Renk, T. Tanaka, M. Ulrickson, P. Peterson, J. De Groot, N. Jensen, R. Peterson, G. Pollock, P. Ottinger, J. Schumer, D. Kammer, I. Golovkin, G. Kulcinski, L. El-Guebaly, G. Moses, E. Mogahed, I. Sviatoslavsky, M. Sawan, M. Anderson, R. Gallix, N. Alexander, W. Rickman, H. Tran, P. Panchuk, W. Meier, J. Latkowski, R. Moir, R. Schmitt, R. Abbot, M. Abdou, A. Ying, P. Calderoni, N. Morley, S. Abdel-Khalik, D. Welch, D. Rose, W. Szaroletta, H. Tran, R. Curry, K. McDonald, D. Louie, S. Dean, A. Kim, S. Nedoseev, E. Grabovsky, A. Kingsep, V. Smirnov

Lead National Laboratory

SNL

Collaborating National Laboratories:

LLNL, LANL, NRL, LBNL

Collaborating Universities:

UCB, U. Wisconsin, UCD, UCLA, Georgia-Tech,
U. Missouri, U. Alabama, UNM

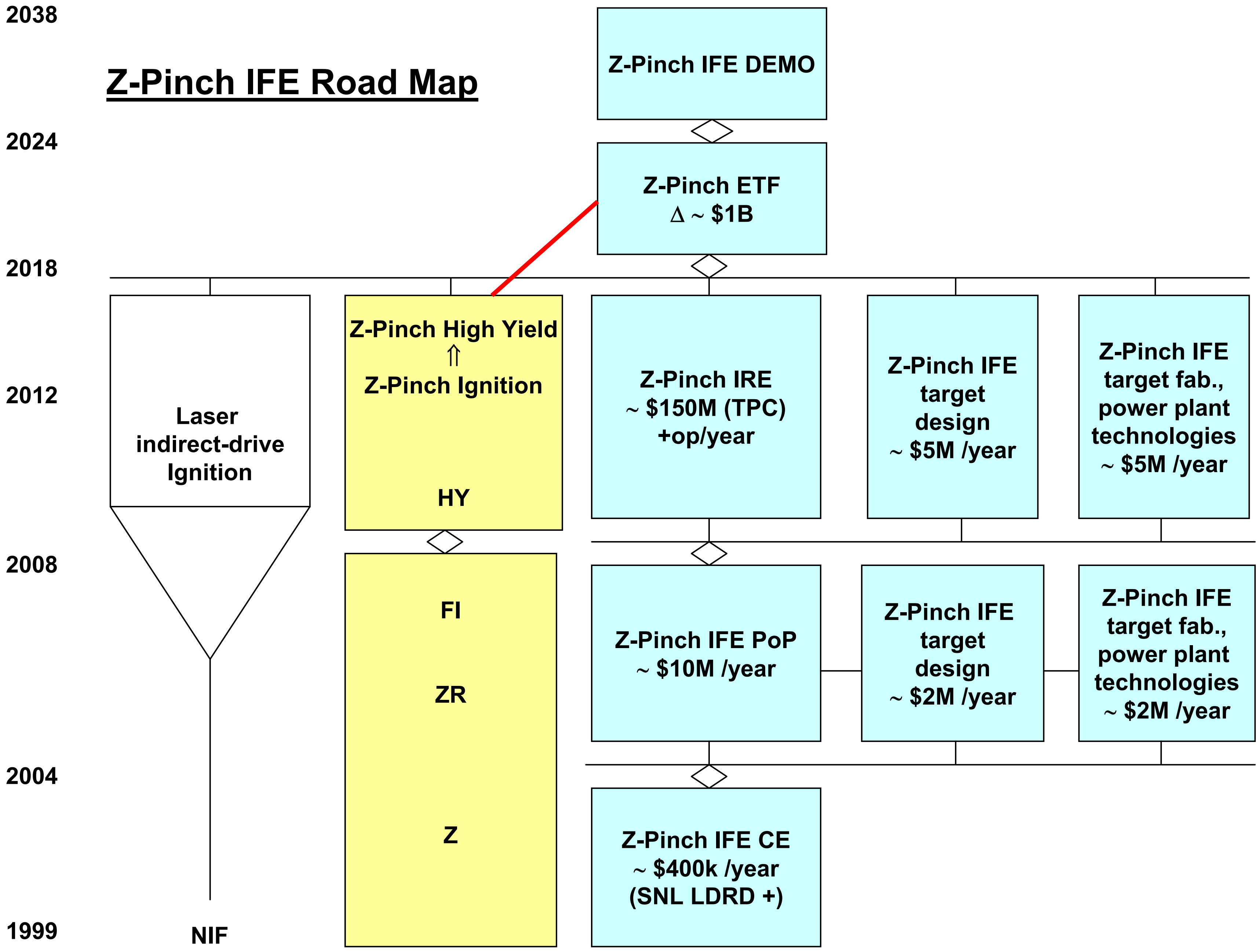
Collaborating Industry:

GA, MRC, FPA, Omicron, Luxel

Collaborating Institutions in Russia:

Kurchatov (Moscow)
Institute for High Current Electronics (Tomsk)

Z-Pinch IFE Road Map



2038

Z-Pinch IFE DEMO

2024

Z-Pinch ETF
Δ ~ $1B

2018

Laser indirect-drive Ignition

Z-Pinch High Yield
⇑
Z-Pinch Ignition

HY

Z-Pinch IRE
~ $150M (TPC)
+op/year

Z-Pinch IFE target design
~ $5M /year

Z-Pinch IFE target fab., power plant technologies
~ $5M /year

2012

2008

FI

ZR

Z

Z-Pinch IFE PoP
~ $10M /year

Z-Pinch IFE target design
~ $2M /year

Z-Pinch IFE target fab., power plant technologies
~ $2M /year

2004

Z-Pinch IFE CE
~ $400k /year
(SNL LDRD +)

1999

NIF

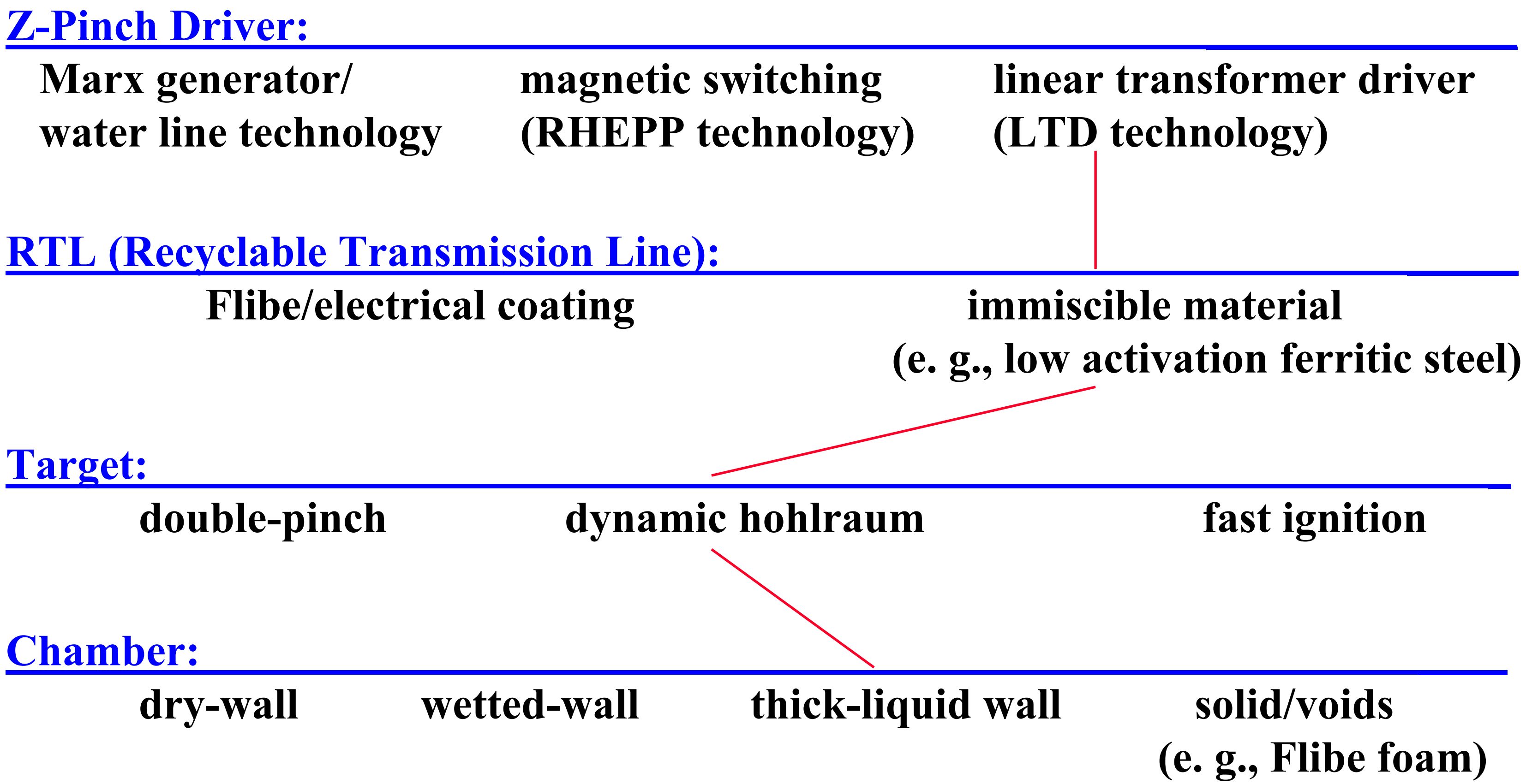
Year

Single-shot, NNSA/DP

Repetitive for IFE, OFES/VOIFE

Z-Pinch IFE Matrix of Possibilities

(choose one from each category)



Z-Pinch Driver:

- Marx generator/ water line technology
- magnetic switching (RHEPP technology)
- linear transformer driver (LTD technology)

RTL (Recyclable Transmission Line):

- Flibe/electrical coating
- immiscible material (e. g., low activation ferritic steel)

Target:

- double-pinch
- dynamic hohlraum
- fast ignition

Chamber:

- dry-wall
- wetted-wall
- thick-liquid wall
- solid/voids (e. g., Flibe foam)

Mainly science: z-pinch target physics

Mainly engineering/technology: z-pinch driver, RTL, chamber

Research is addressing the following primary issues for z-pinch IFE *for FY04*

1. How feasible is the RTL concept?

2. What repetitive pulsed power drive technology could be used for z-pinch IFE?

3. Can the shock from the high-yield target (~3 GJ) be effectively mitigated to protect the chamber structural wall?

4. Can the full RTL cycle (fire RTL/z-pinch, remove RTL remnant, insert new RTL/z-pinch) be demonstrated on a small scale?
   Z-PoP (Proof-of-Principle) is 1 MA, 1 MV, 100 ns, 0.1 Hz

5. What is the optimum high-yield target for 3 GJ?

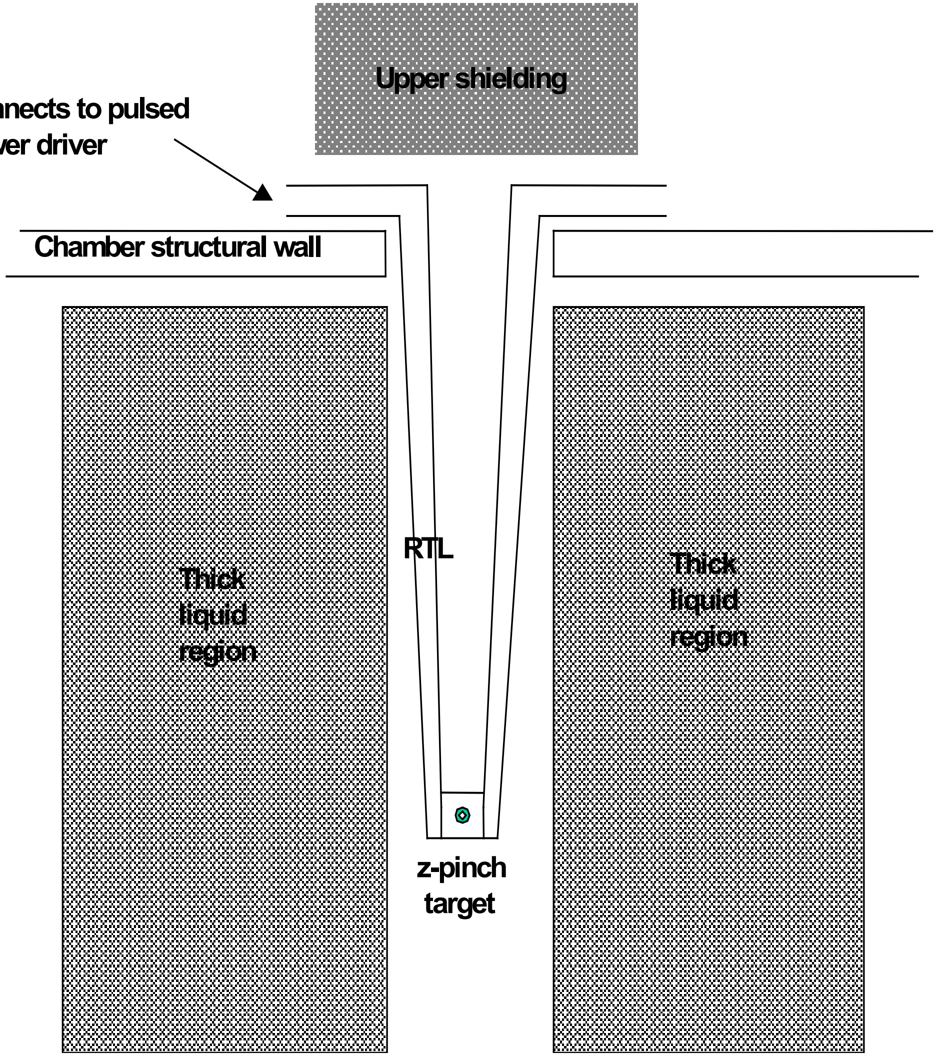
6. What is the optimum power plant scenario for z-pinch IFE?

Z-Pinch IFE Workshop held at SNL on August 10-11, 2004
64 Participants
Outstanding initial results in all areas

Recyclable Transmission Line (RTL)

Z-Pinch IFE

The Recyclable Transmission Line (RTL) Concept



MITL/RTL Issues for 20 MA ⇒ 60 MA ⇒ 90 MA

Surface heating, melting, ablation, plasma formation

Electron flow, magnetic insulation

Conductivity changes

Magnetic field diffusion changes

Low mass RTL material moves more easily

Possible ion flow

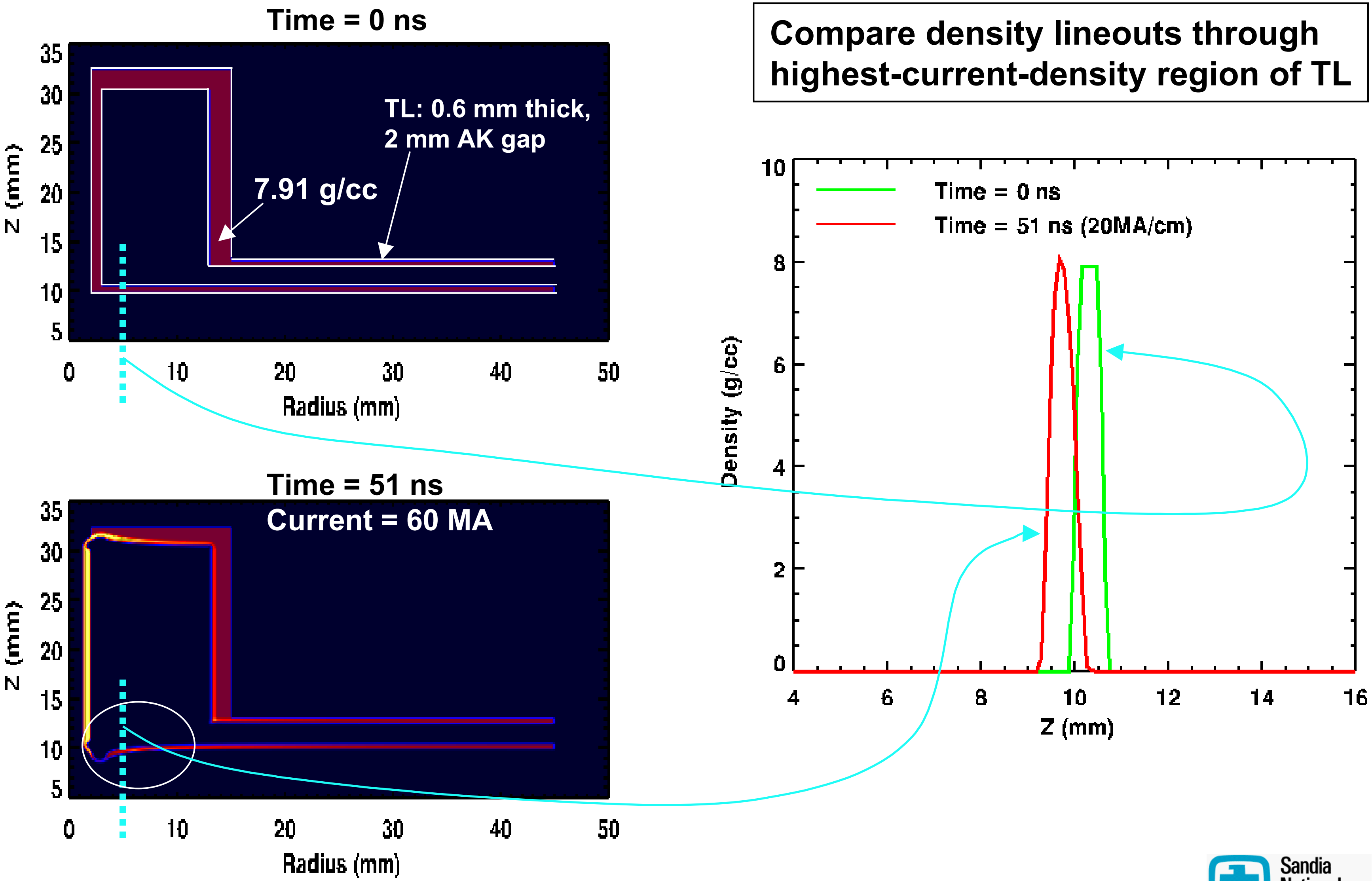
these issues become most critical right near the target

I	20 MA	60 MA	90 MA
R_{array}	~ 2 cm	~ 2 cm	~ 5 cm
$I / (2\pi R_{array})$	~ 1.6 MA/cm	~ 4.8 MA/cm	~ 2.9 MA/cm
MITL	Works on Z	?	?
RTL	?	?	?

Sandia National Laboratories

Preliminary 2-D ALEGRA MHD simulations of thin-walled disc feed show *no* disruption at *20 MA/cm*

Compare density lineouts through highest-current-density region of TL



LSP, a fully electromagnetic hybrid code, is being used to examine field penetration and plasma heating/expansion in RTLs (*for* $R_{array} = 5$ *cm*)

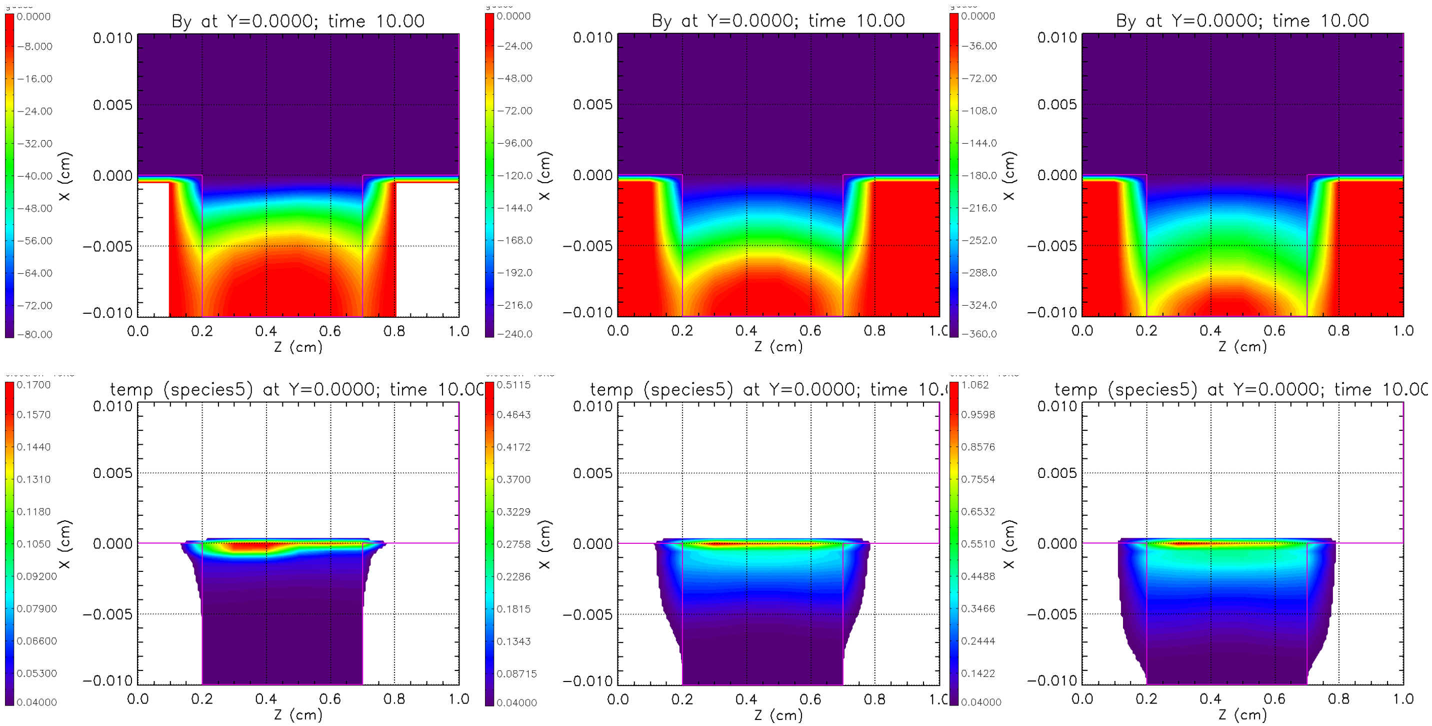
(0.6 MA/cm) 20 MA

(1.9 MA/cm) 60 MA

(2.9 MA/cm) 90 MA

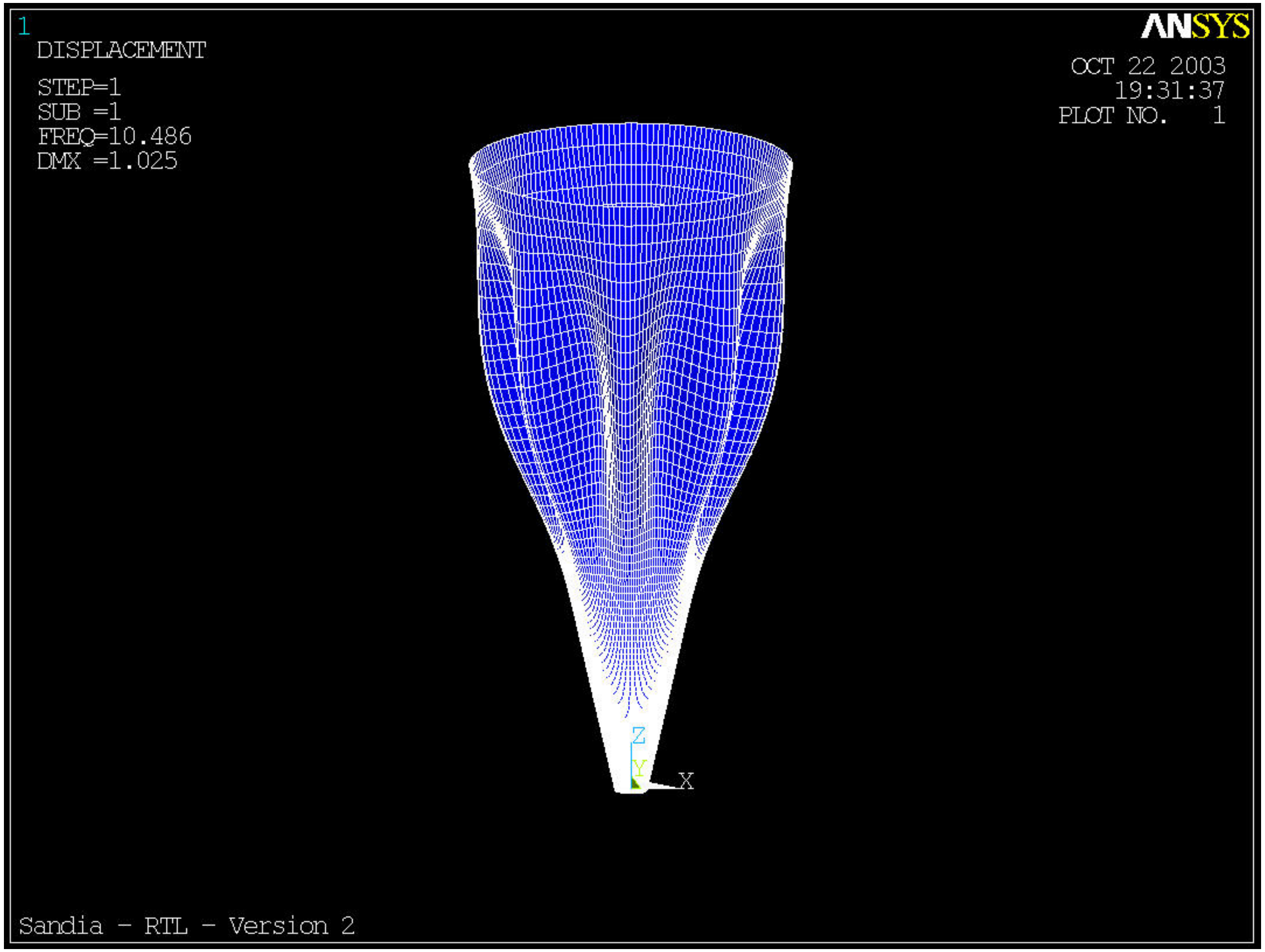
B field (T)

Temperature (eV)



- **Scaling of initial 2D LSP calculations with Au cathode and 10-ns current rise show acceptable cathode field penetration and heating for Z-IFE (1-1.6 μm/ns for 100 ns rise)**
- **Higher currents require thicker electrodes for efficient conduction**

PRELIMINARY BUCKLING ANALYSIS of steel RTL



78 Torr

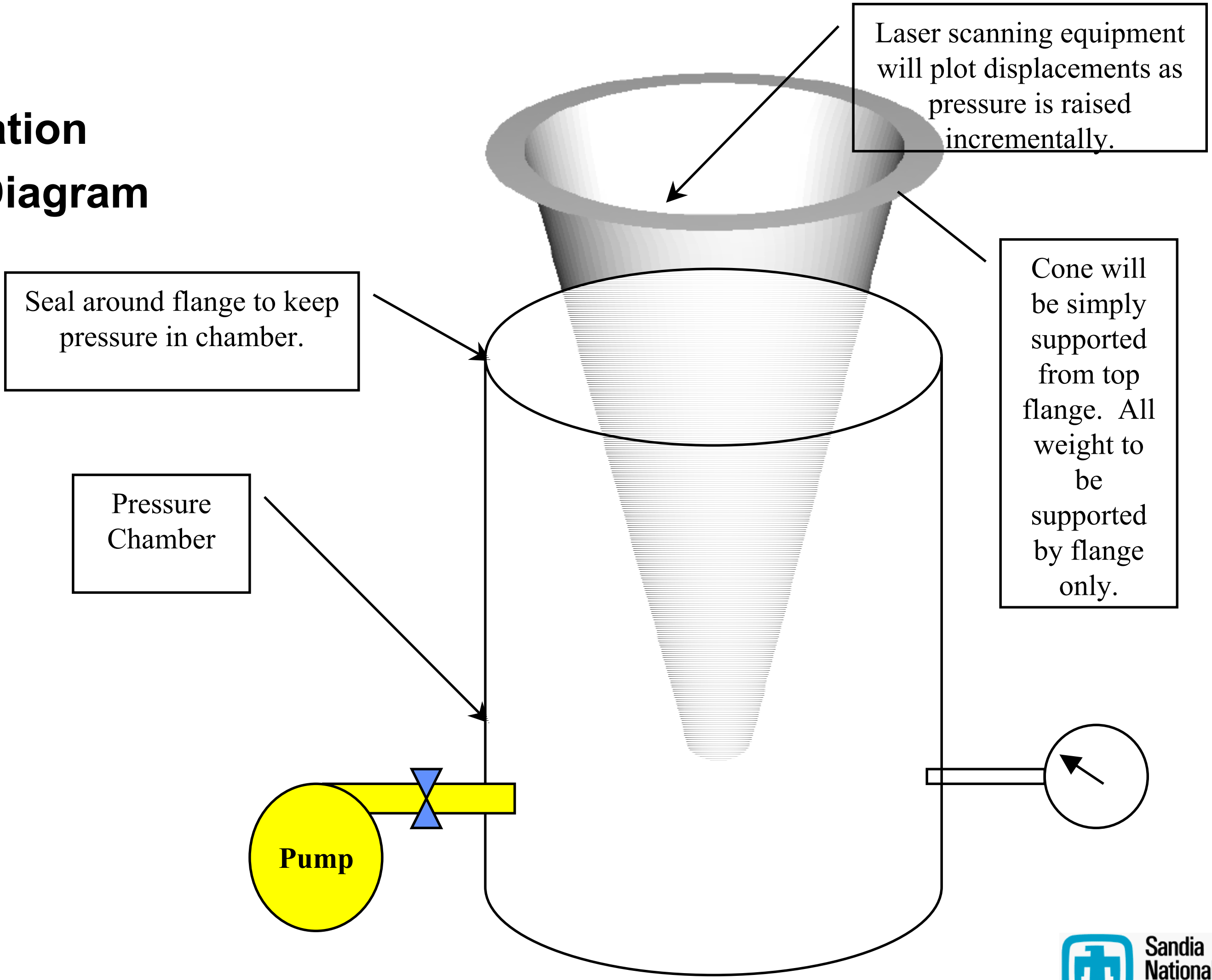
RTL buckles at
1.52 psi = 78 Torr
as shown

20 Torr

no effect
(safe operating point)

RTL Structural Testing

- **Model Validation**
  - **Testing Diagram**



Laser scanning equipment will plot displacements as pressure is raised incrementally.

Seal around flange to keep pressure in chamber.

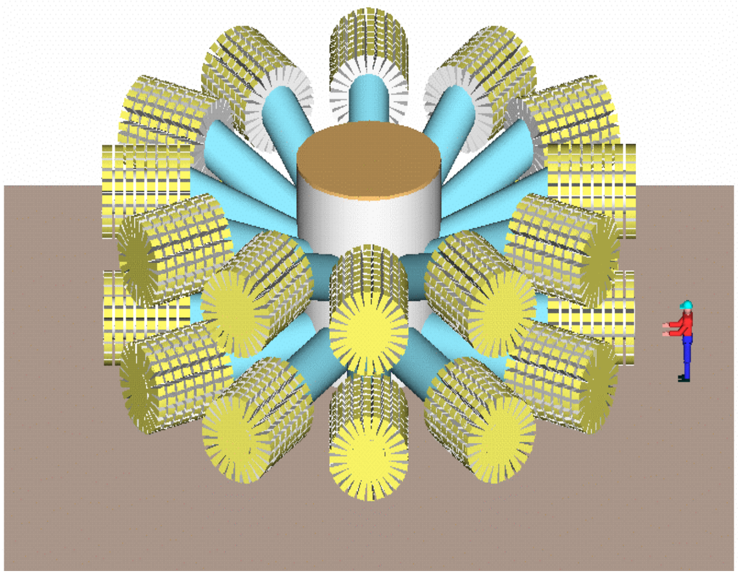
Cone will be simply supported from top flange. All weight to be supported by flange only.

Pressure Chamber

Repetitive Pulsed Power Driver

Linear Transformer Driver (LTD) technology is compact and easily rep-rateable

- •LTD uses parallel-charged capacitors in a cylindrical geometry, with close multiple triggered switches, to directly drive inductive gaps for an inductive voltage adder driver (Hermes III is a 20 MV inductive voltage adder accelerator at SNL)
- •LTD requires no oil tanks or water tanks
- •LTD study (as shown) would produce 10 MA in about 1/4 the volume of Saturn
- •LTD pioneered at Institute of High Current Electronics in Tomsk, Russia



Modular

High Efficiency (~ 90% for driver)

Low Cost

Easily rep-rateable for 0.1 Hz

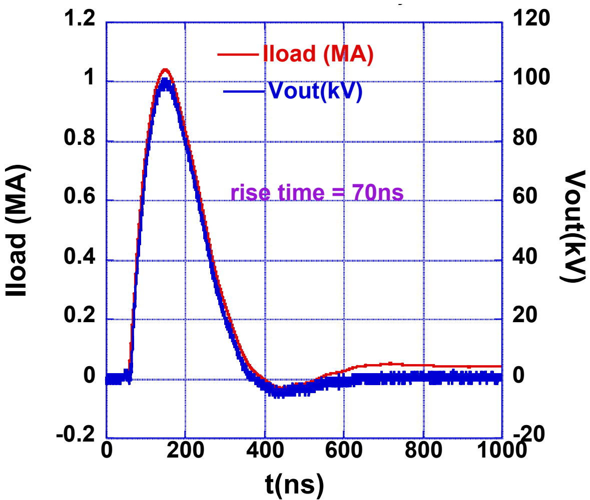
Switch Options for LTD are being assessed

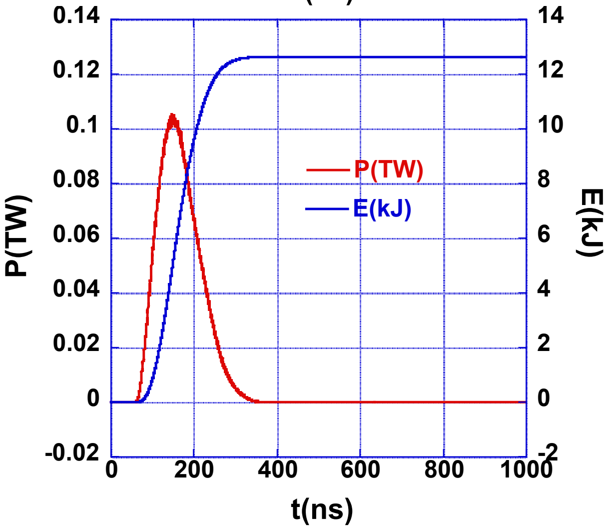
- Magnetic switch
  - Requires pulse charging, and core reset
  - May require multiple stages
- Photo-triggered semiconductor switches
  - May have current density/voltage problems
  - Requires laser development
- Electrically-triggered gas switches
  - Gas blown designs may work
    - ATA switch was 20 kA, 1 to 1 kHz, 2 x 10^6 shots
  - Electrode wear must be compensated
  - Techniques for reducing current density will help
- High-pressure fluid switches
  - Bubble formation/water damage minimized with high pressures
  - Will likely require purging/fluid flow
- Laser-triggered water switches
  - Preliminary work at SNL
  - Water-switching work at UNM and Old Dominion Univ.

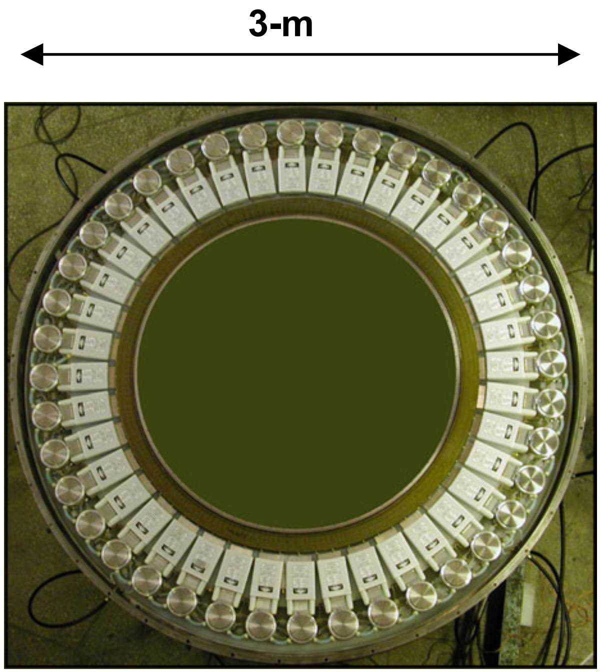
Switch requirements:

~ 25 kA
~ 200 kV
0.1 Hz
50-100 ns risetime
low cost
~ 3x10^6 shots/year

1-MA LTD Cavity Performs as Expected during the first 100 Shots







1-MA, 100kV, 70ns LTD cavity (top flange removed)

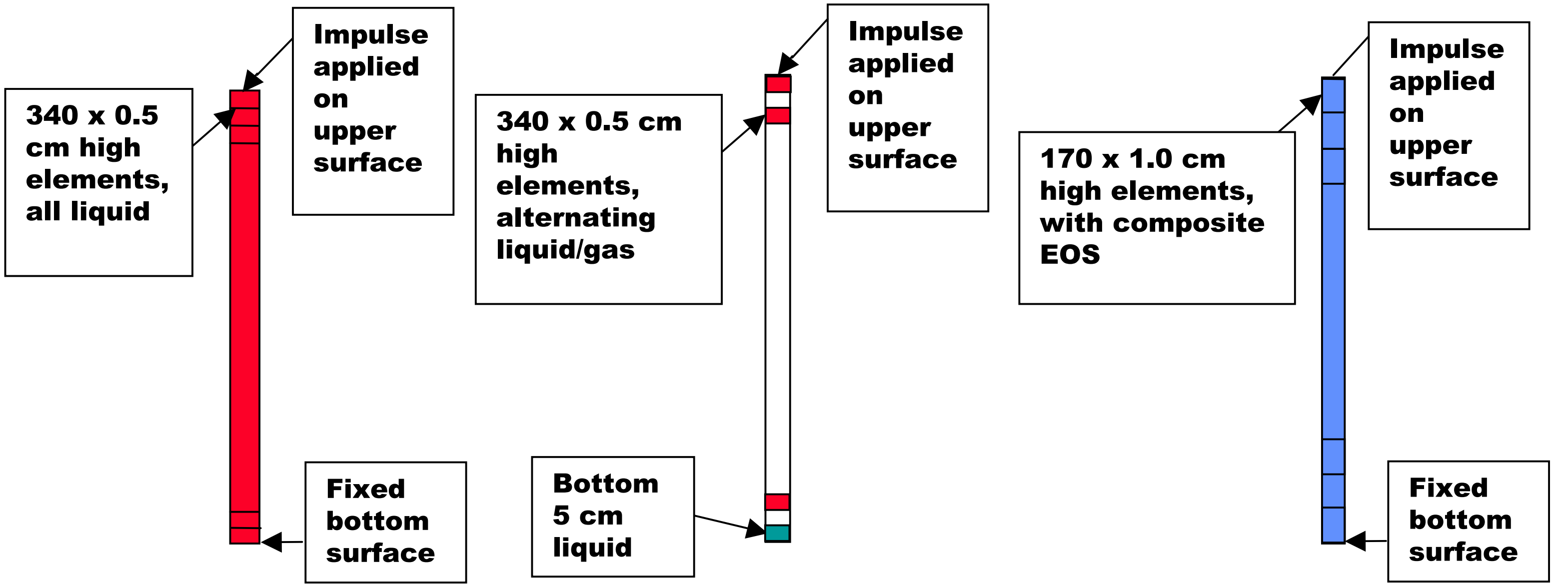
80 Maxwell 31165 caps,

40 switches, ±100 kV

0.1 Ohm load 0.1TW

Shock Mitigation

Models used for Studying Shock Mitigation with Foamed Flibe



340 x 0.5 cm high elements, all liquid

Impulse applied on upper surface

Fixed bottom surface

340 x 0.5 cm high elements, alternating liquid/gas

Impulse applied on upper surface

Bottom 5 cm liquid

170 x 1.0 cm high elements, with composite EOS

Impulse applied on upper surface

Fixed bottom surface

Case 1

100% Solid Flibe

Gruneisen EOS

Case 2

Discrete Flibe/Gas Cells

Gruneisen eos for flibe

Perfect Gas eos for gas

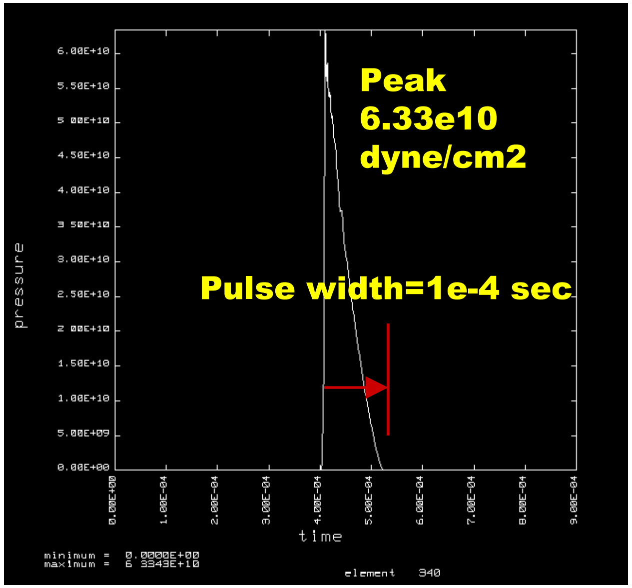
50% void ratio

Case 3

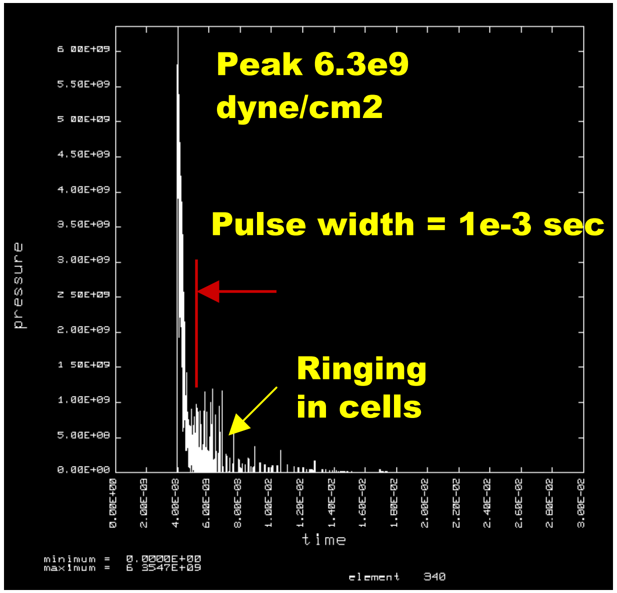
Modified Gruneisen EOS

With 50% void ratio

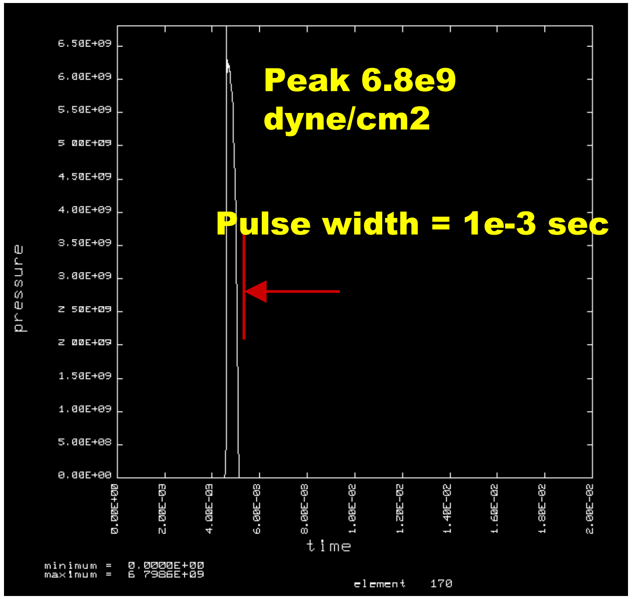
Dyna2d Calculation Showing Order of Magnitude Reduction in Peak Wall Pressure with 50% void Flibe



Case 1



Case 2



Case 3

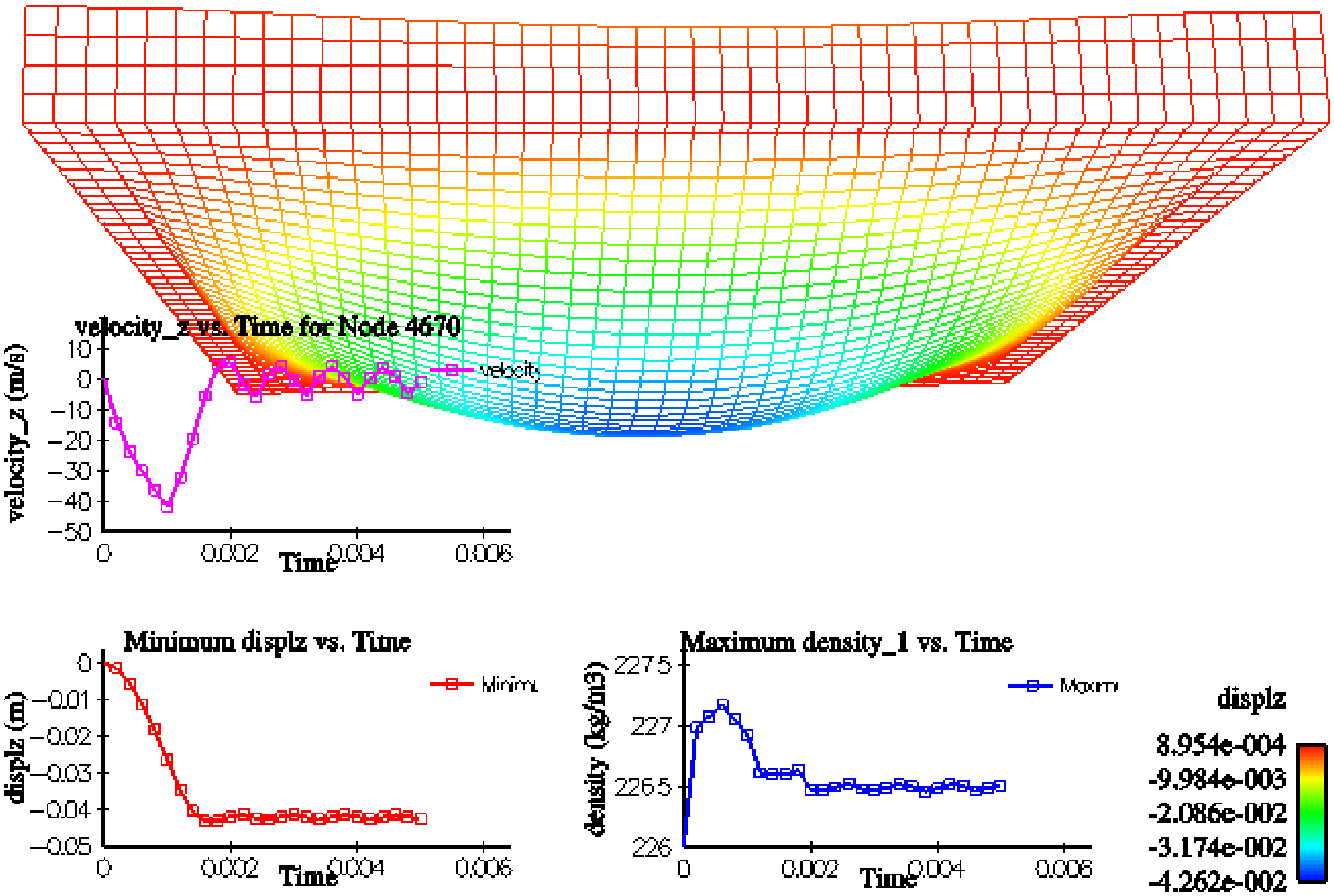
Note: factor of 10 larger pressures for this case

with no mitigation.

These two cases are about the same and show order of magnitude reduction in peak wall stress and order of magnitude stretch in time.

GENERAL ATOMICS

Preliminary ALEGRA Shock Tube Metal Foam Experiment Simulation

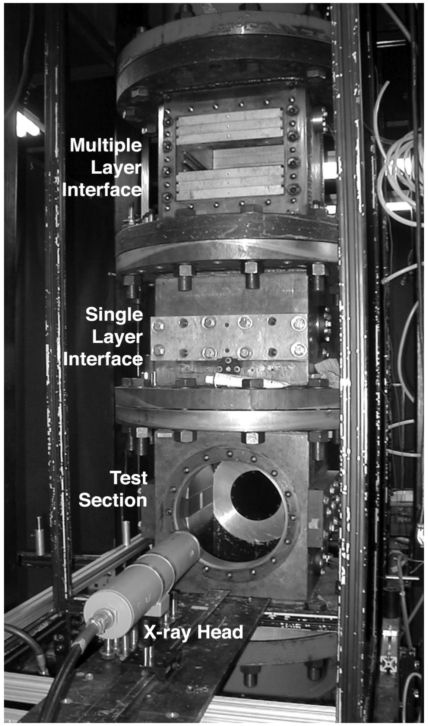


Shock tube + water layer experiments

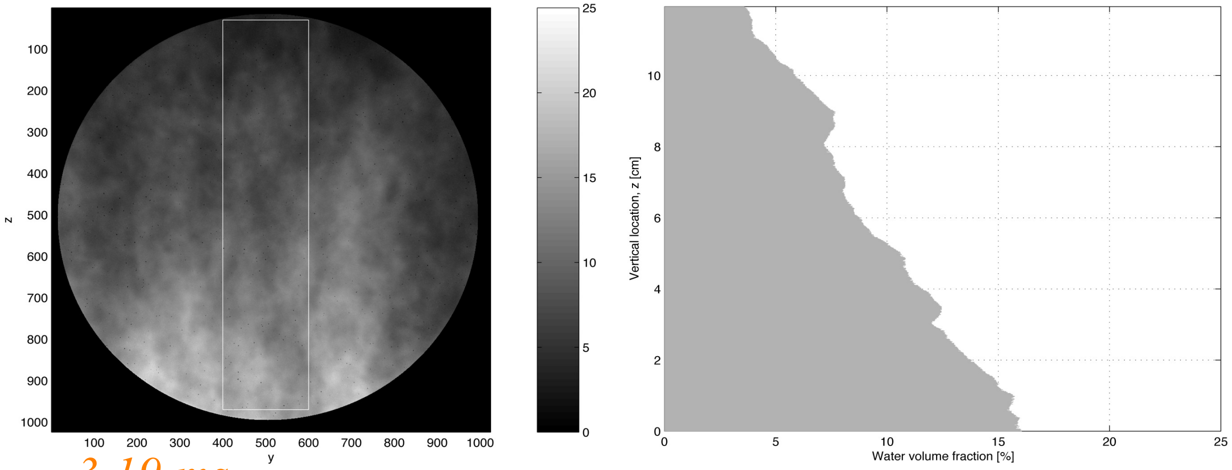
Mass fraction of water layer from x-ray measurements

- M = 2.12
- 12.8 mm

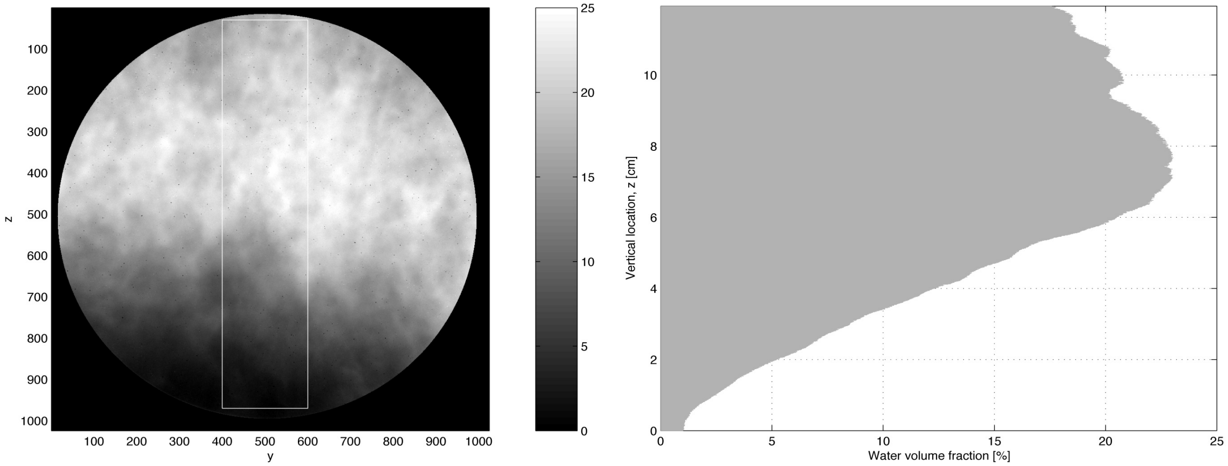
Water layer



3.40 ms



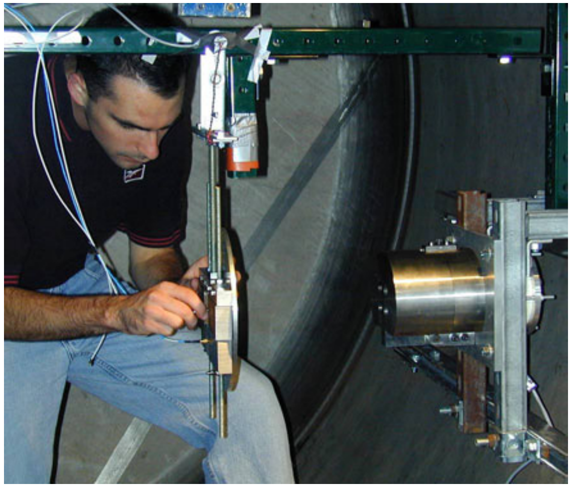
3.19 ms



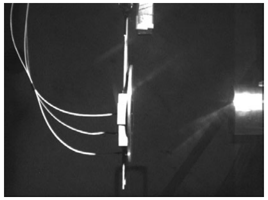
U. Wisconsin

Vacuum Hydraulics Experiment (VHEX) studies blast response of liquid jet assemblies

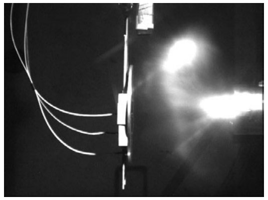
- Create hydrodynamically similar single jets and several jet arrays
- Transient flow into large vacuum vessel—water simulates flibe



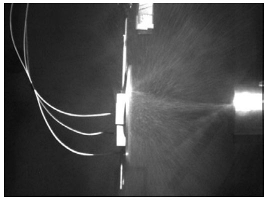
Impulse load calibration underway



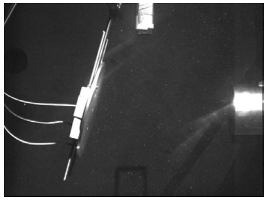
t = 0



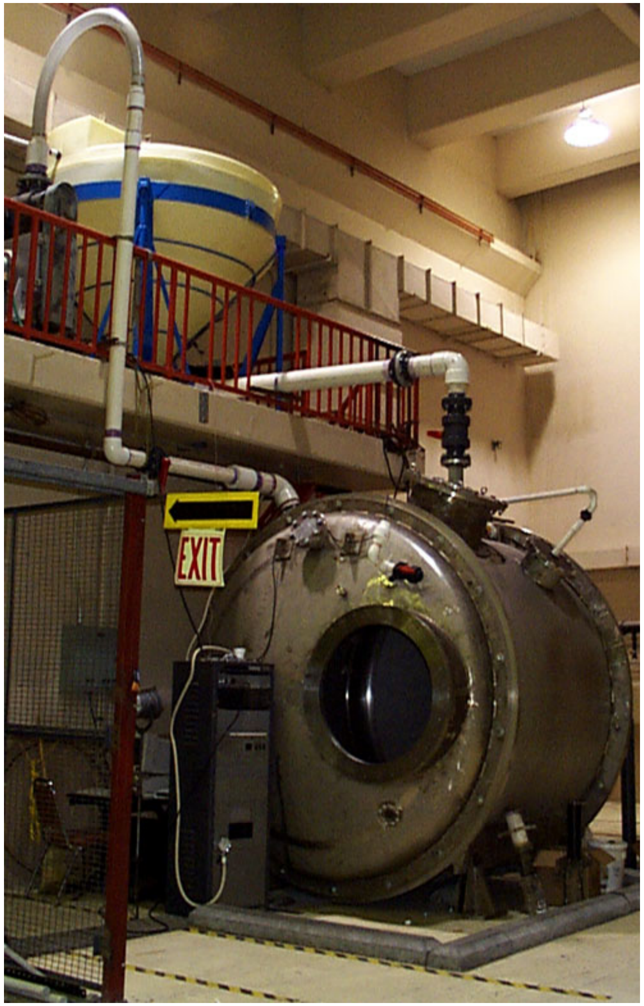
t = 0.8 ms
(muzzle flash)



t = 1.6 ms
(plume has hit)



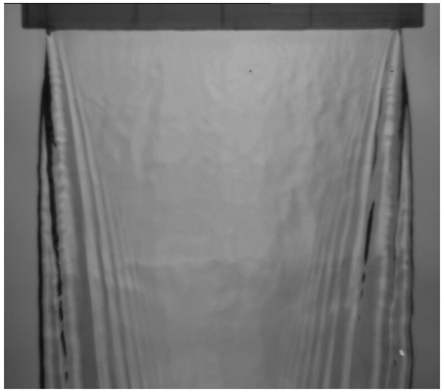
t = 32 ms
(peak deflection)



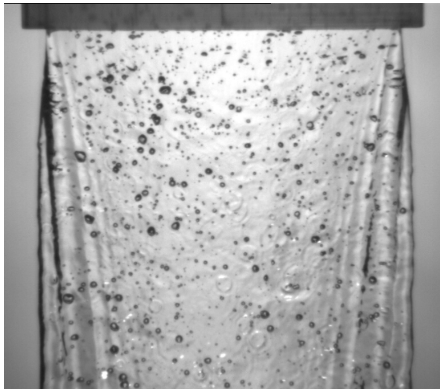
UCB

Effect of Void Fraction

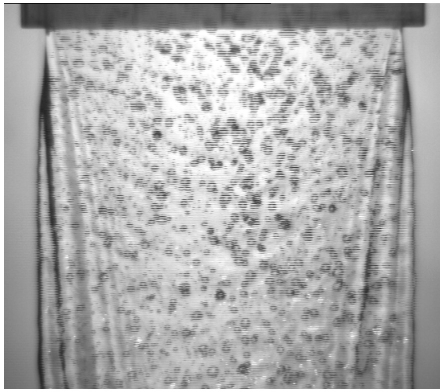
(Average Liquid Velocity = 2.5 m/s)



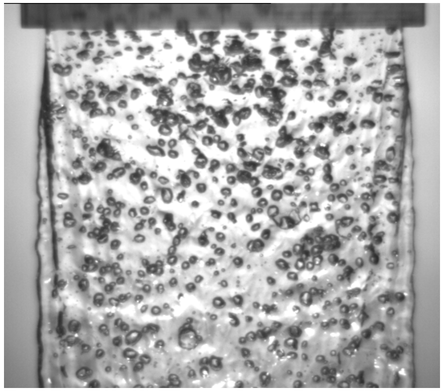
0%



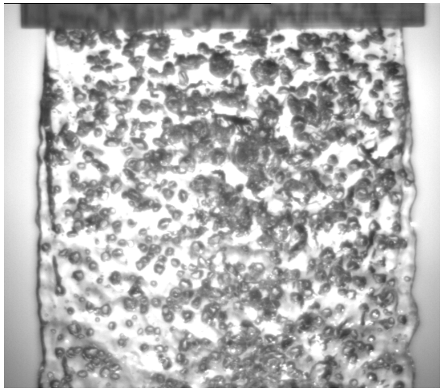
1%



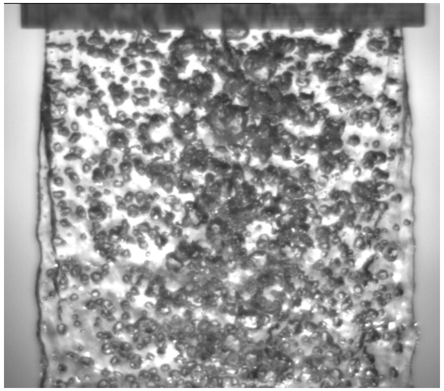
2.5%



5%



10%



15%

Z-PoP experiment planning

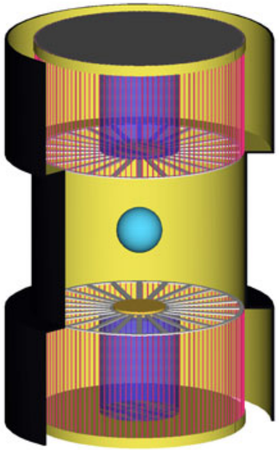
COTS Automation

- Commercial off-the-shelf (COTS) robotics:
  - Improvements in typical specs:
    - Payloads up to 60 kg
    - Placement accuracy to 0.04 mm
    - Workspace: ~1.5×1.5×1 m
    - Velocity: 1.5m in < 2 s
  - Multiple vendor options

Targets

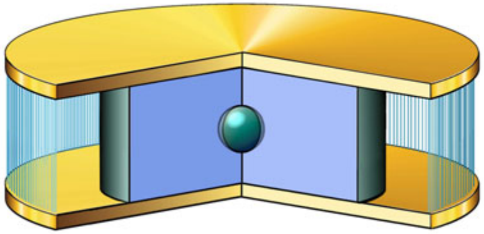
We are exploring 2 complementary Z-pinch indirect-drive targets for high-yield ICF and Z-IFE

Double-Ended Hohlraum



	ICF IFE
Peak current	2 x (62 – 82) MA
Energy delivered to pinches	2 x (19 – 33) MJ
Z-pinch x-ray energy output	2 x (9 – 16) MJ
Capsule absorbed energy	1.2 – 7.6 MJ
Capsule yield	400 – 4700 MJ

Dynamic Hohlraum



Peak current	56 – 95 MA
Energy delivered to pinch	14 – 42 MJ
Capsule absorbed energy	2.4 – 7.2 MJ
Capsule yield	530 – 4600 MJ

J. Hammer, M. Tabak *J. Lash, S. Slutz, R. Vesey*

The idealized 3 GJ indirect-drive target with CR ~ 20 is close to satisfying the Gain ~ 100 IFE requirement.*

For DT Yield ~ 3,000 MJ:

X-ray energy into hohlraum wall:
3800 TW x 6 ns ~ 22.8 MJ
170 TW x 10 ns ~ 1.7 MJ
34 TW x 50 ns ~ 1.7 MJ

X-ray energy into capsule ~ 6 MJ

Total energy into target ~ 32 MJ*

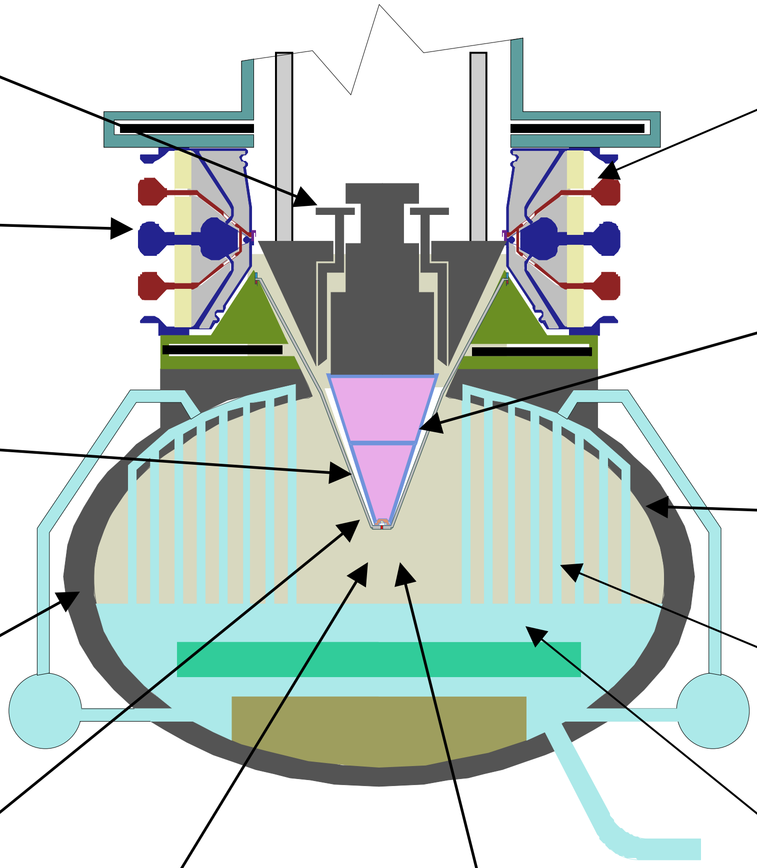
Overall target gain ~ 94

*Inefficiencies such as untrapped or leaking X-rays, non-spherical hohlraum walls, absorption by symmetry shields, etc. have not been considered and will reduce the target gain. On the other hand future developments, such as cocktail hohlraums might substantially reduce E_{wall}.

Key features of CR > 20, hot spot ignition, and propagating burn, with T_r ~ 250-300 eV are to be demonstrated at NIF within the next 5-10 years.
(However, the yields at NIF will be ~ 100x less than the Z-pinch IFE target.)

Power Plant Technologies

University of Wisconsin Areas of Research on the Z Chamber



n leakage up the RTL

n effects to Insulator Stack

Driver-chamber interface

Structural stability of RTL's

Waste stream & recycling

Activation and decay heat of chamber material

Spatial distribution of radiation damage around chamber

Assessment of coolant options

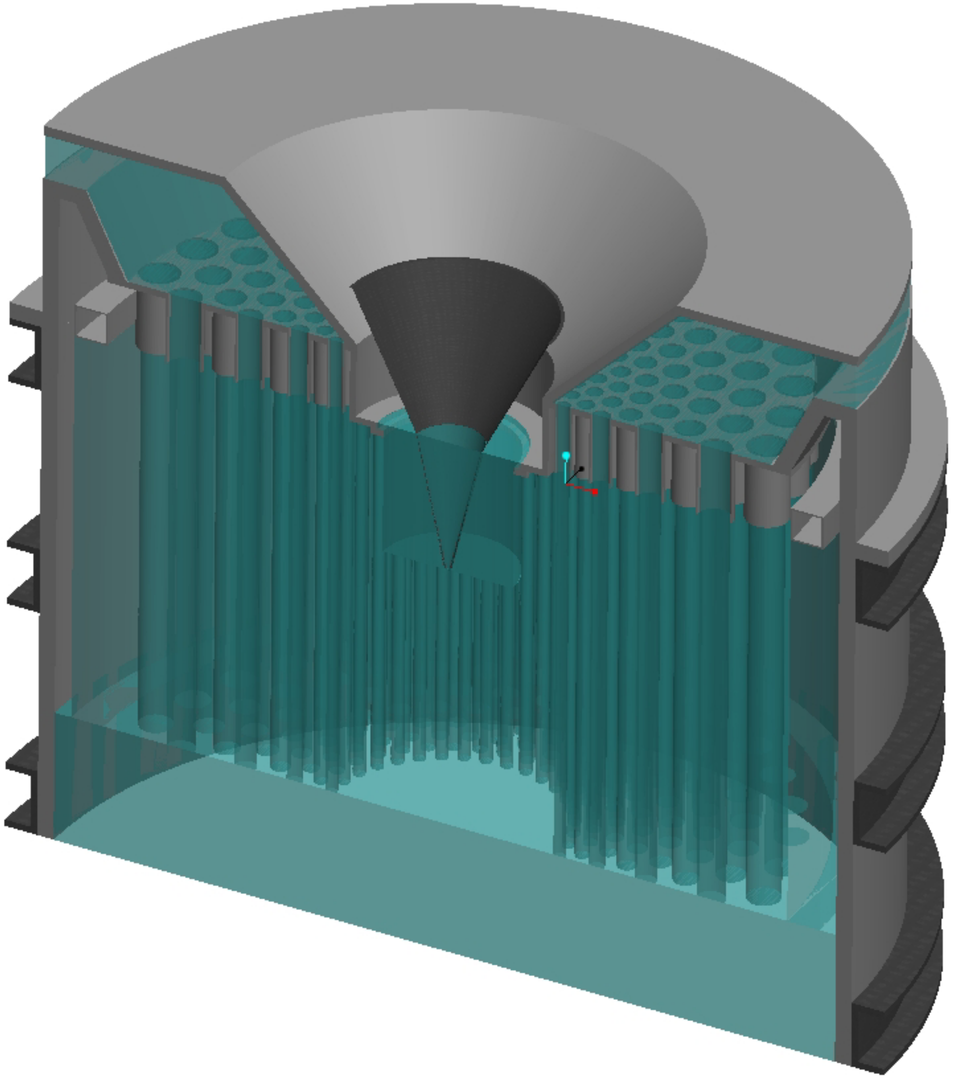
Target-neutron spectra

Mitigation of blast effects (experiments)

Mitigation of blast effects (modeling)

Activation of the coolant

A carbon composite wall might be an attractive option



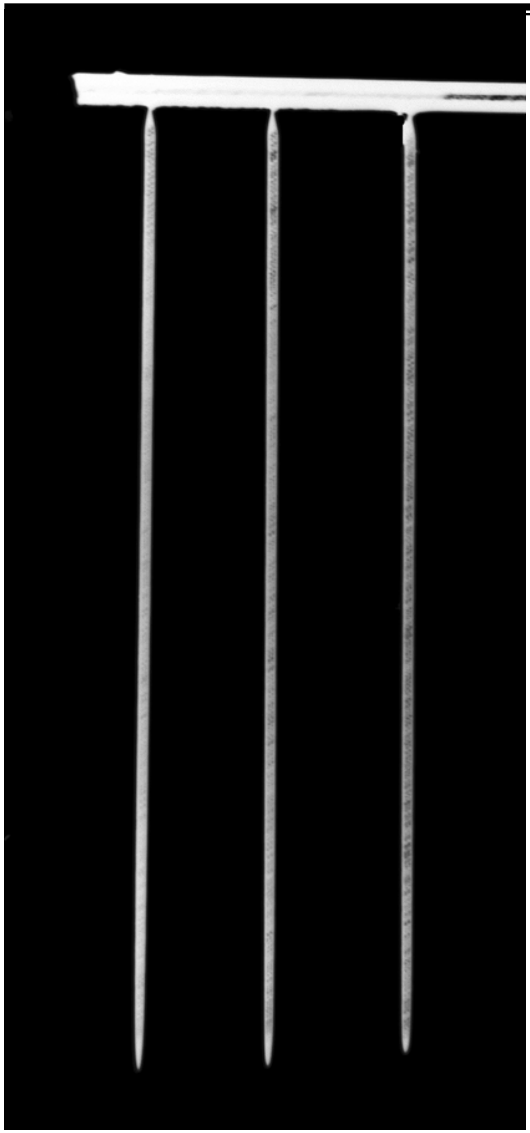
- We consider the following system:
  - Single chamber
  - 20 GJ yields @ 0.1 Hz
  - 6 m radius
  - 10 m height

- A lifetime damage limit of 10 dpa is achievable with ~1 m of flibe

- Jets are gravity driven

LLNL

Initial work in new chamber demonstrates carbon wire growth



LCVD (laser chemical vapor deposition)

- Growth of array of 3 x Ø45 μm carbon fibers, each 4 mm long, demonstrated in “long wire” deposition chamber
  - Carbon is easiest material to work with
- Continuing FY04 challenges:
  - Demonstrate growth of 4” long C wire
  - Grow 4” long W wire
  - Reduce wire diameter to ~10 μm
  - Demonstrate growth of W wire array

LANL, SNL

Research is addressing the following primary issues for z-pinch IFE *for FY04*

1. How feasible is the RTL concept?

2. What repetitive pulsed power drive technology could be used for z-pinch IFE?

3. Can the shock from the high-yield target (~3 GJ) be effectively mitigated to protect the chamber structural wall?

4. Can the full RTL cycle (fire RTL/z-pinch, remove RTL remnant, insert new RTL/z-pinch) be demonstrated on a small (PoP) scale?

5. What is the optimum high-yield target for 3 GJ, and what are the power flow requirements for this target?

6. What is the optimum power plant scenario for z-pinch IFE?

Z-Pinch IFE Workshop held at SNL on August 10-11, 2004
64 Participants
Outstanding initial results in all areas

Other Talks on Z-Pinch IFE

P-I-13	Olson - Target Physics Scaling for Z-Pinch IFE
P-I-16	Calderoni - Study of Voltage Breakdown over Flibe ...
P-I-25	El-Guebaly - Neutronics and Activation Issues ...
P-I-32	Rochau - Manufacturing concepts for Z-Pinch IFE
O-I-4.5	Rochau - Progress toward Z-Pinch IFE Power Plant
O-II-2.1	Goodin - Demonstrating target supply for IFE
O-II-2.3	Moses - High Energy Density Simulations for IFE Reactors
P-II-50	Modesto-Beato - Thermal Analysis of Z-Pinch Power Plant
O-II-6.6	Peterson - Dynamics of Liquid-Protected Fusion Chambers
O-III-3.2	Abdel-Khalik - Overview of Fluid Dynamics of Liquid Protection
O-III-3.5	Anderson - Protection of IFE first wall by multiple liquid layers
O-III-3.6	Rodriguez - Z-Pinch Power Plant Shock Mitigation