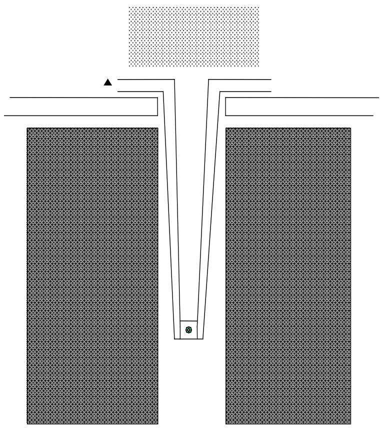
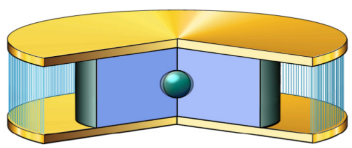
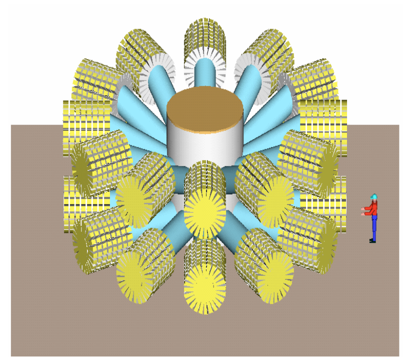
Status of Z-Pinch IFE Program



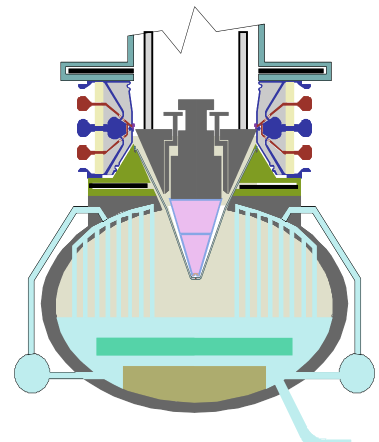
RTL



DH target



LTD driver



Chamber

Craig L. Olson
Sandia National Laboratories
Albuquerque, NM 87185

FPA 25th Anniversary Meeting and Symposium
Washington, DC
December 13, 2004

The Z-Pinch IFE Team

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4) Naval Research Laboratory, Washington, DC, USA
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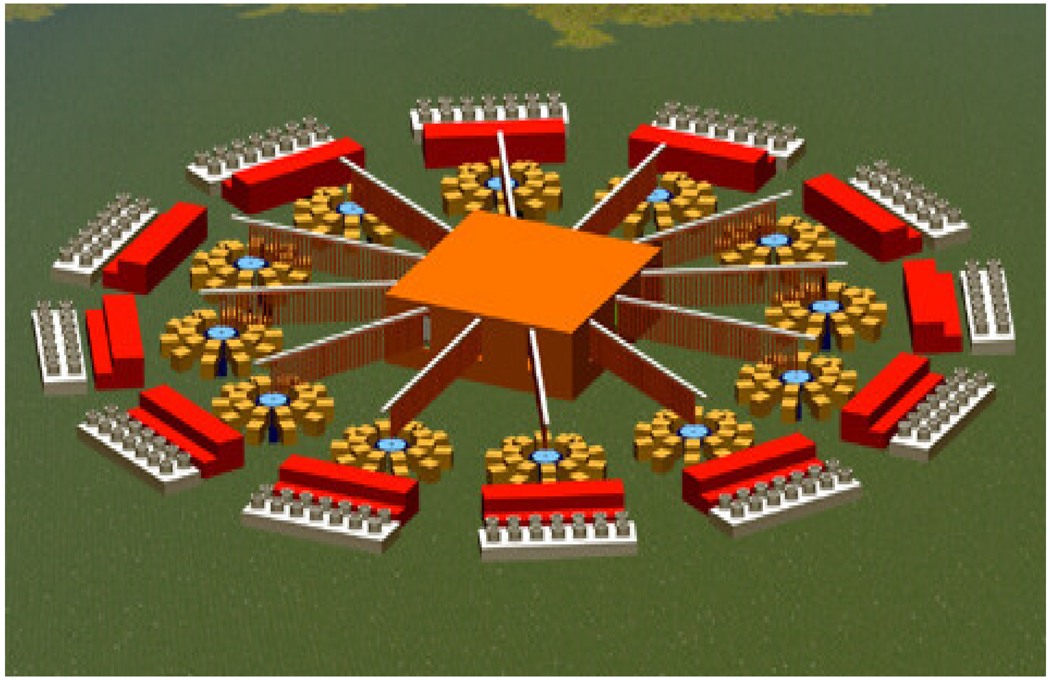
9) Georgia Institute of Technology, Atlanta, Georgia, USA
10) University of Missouri-Columbia, Columbia, MO, USA
11) University of Alabama, Tuscaloosa, AL, USA
12) University of New Mexico, Albuquerque, NM, USA
13) General Atomics, San Diego, CA, USA
14) Mission Research Corporation, Albuquerque, NM, USA
15) EG&G, Albuquerque, NM, USA
16) Omicron, Albuquerque, NM, USA
17) Fusion Power Associates, Gaithersburg, MD, USA
18) Institute of High Current Electronics, Tomsk, Russia
19) Kurchatov Institute, Moscow, Russia

The *long-term* goal of Z-Pinch IFE is to produce an economically attractive power plant using high-yield z-pinch-driven targets (~3 GJ) at low rep-rate per chamber (~0.1 Hz)



Z-Pinch IFE DEMO (ZP-3, the first study) used 12 chambers, each with 3 GJ at 0.1 Hz, to produce 1000 MWe

The *near-term* goal of Z-Pinch IFE is to address the science issues of repetitive pulsed power drivers, recyclable transmission lines, high-yield targets, and thick-liquid wall chamber power plants

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Z-Pinch is the newest of the three major drivers for IFE

1999 Snowmass Fusion Summer Study, IAEA CRP on IFE Power Plants,
2002 Snowmass Fusion Summer Study, FESAC 35-year plan Panel Report (2003),
FESAC IFE Panel Report (2003)

Major drivers:

Laser
(KrF, DPSSL)

Heavy ion
(induction linac)
GeV, kA

Z-pinch
(pulsed power)
MV, MA

Targets:

Direct-drive

Indirect-drive

Fast Igniter option
(major driver + PW laser)

Chambers:

Dry-wall **Wetted-wall** **Thick-liquid wall** **Solid/voids**

Thick liquid walls essentially alleviate the "first wall" problem, and can lead to a faster development path

What has already been accomplished that is relevant to Z-Pinch IFE

x-rays: 1.8 MJ of x-rays, up to 230 TW, on Z (demonstrated) available now

low cost: ~$30/J for ZR (demonstrated cost)

high efficiency: wall plug to x-rays: ~15% on Z (demonstrated)
can be optimized to: ~25% or more

capsule compression experiments on Z:

double-pinch hohlraum[1] (~70 eV): Cr ≈ 14-20 (demonstrated)
symmetry ~3% (demonstrated)

dynamic hohlraum[2] (~220 eV): ~ 24 kJ x-rays absorbed, Cr ≈ 10,
up to 8×10^{10} DD neutrons (demonstrated)

hemisphere compression for fast ignition[3]: Cr ≈ 3 (demonstrated)

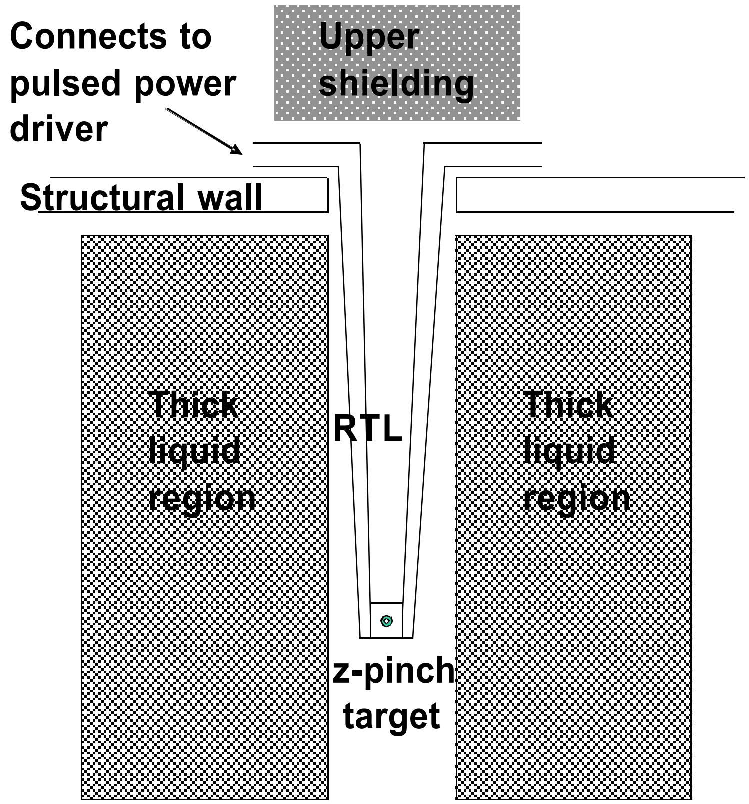
([1]Cuneo, et al.; [2]Bailey, Chandler, Vesey, et al.; [3]Slutz, et al.)

repetitive pulsed power:

RHEPP magnetic switching technology:
2.5 kJ @ 120 Hz (300 kW ave. pwr. demonstrated)

LTD (linear transformer driver) technology:
being developed (compact, direct, simple)

The Recyclable Transmission Line (RTL) Concept



•Eliminates problems of final optic, pointing and tracking N beams, and high-speed target injection

•Requires development of RTL

Z-Pinch IFE Power Plant has a Matrix of Possibilities

Z-Pinch Driver:

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

RTL (Recyclable Transmission Line):

- frozen coolant (e.g., Flibe/ electrical coating)
- immiscible material (e. g., carbon steel)

Target:

- double-pinch
- dynamic hohlraum
- fast ignition

Chamber:

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

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
•TOFE in Madison, WI on September 14-16, 2004:
  14 talks/posters on Z-pinch IFE

Selected initial results for each of the 6 research areas follow:

Recyclable Transmission Line (RTL) status/issues

	Issue	Status
	RTL movement	small acceleration – not an issue
	RTL electrical turn-on	RTL experiments at 10 MA on Saturn
	RTL low-mass limit	RTL experiments at 10 MA on Saturn
	RTL electrical conductivity	RTL experiments at 10 MA on Saturn
→	RTL structural properties	ANSYS simulations, buckling tests
	RTL mass handling	comparison with coal plant
	RTL shrapnel formation	under study
	RTL vacuum connections	commercial sliding seal system
	RTL electrical connections	under study
→	RTL activation	1-1.5 day cool down time
	RTL shock disruption to fluid walls	experiments/simulations in progress
	RTL manufacturing/ cost	~$3 budget, current estimate ~$3.95
→	RTL inductance, configuration	circuit code modeling in progress
→	RTL power flow limits	ALEGRA, LSP simulations

Effects of post-shot EMP, plasma, droplets, debris up the RTL – under study

Shielding of sensitive accelerator/power flow feed parts – under study

…

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MITL/RTL Issues for 20 MA ⇒ 60 MA ⇒ 90 MA
(now on Z) (high yield) (IFE)

1. RTLs

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} (z-pinch)	? 2 cm	? 2 cm	? 5 cm
I / (2 ? R_{array})	? 1.6 MA/cm	? 4.8 MA/cm	? 2.9 MA/cm
MITL	Works on Z	?	?
RTL	?	?	?

Initial ALEGRA and LSP simulations suggest all should work at these linear current densities, which are << 20 MA/cm

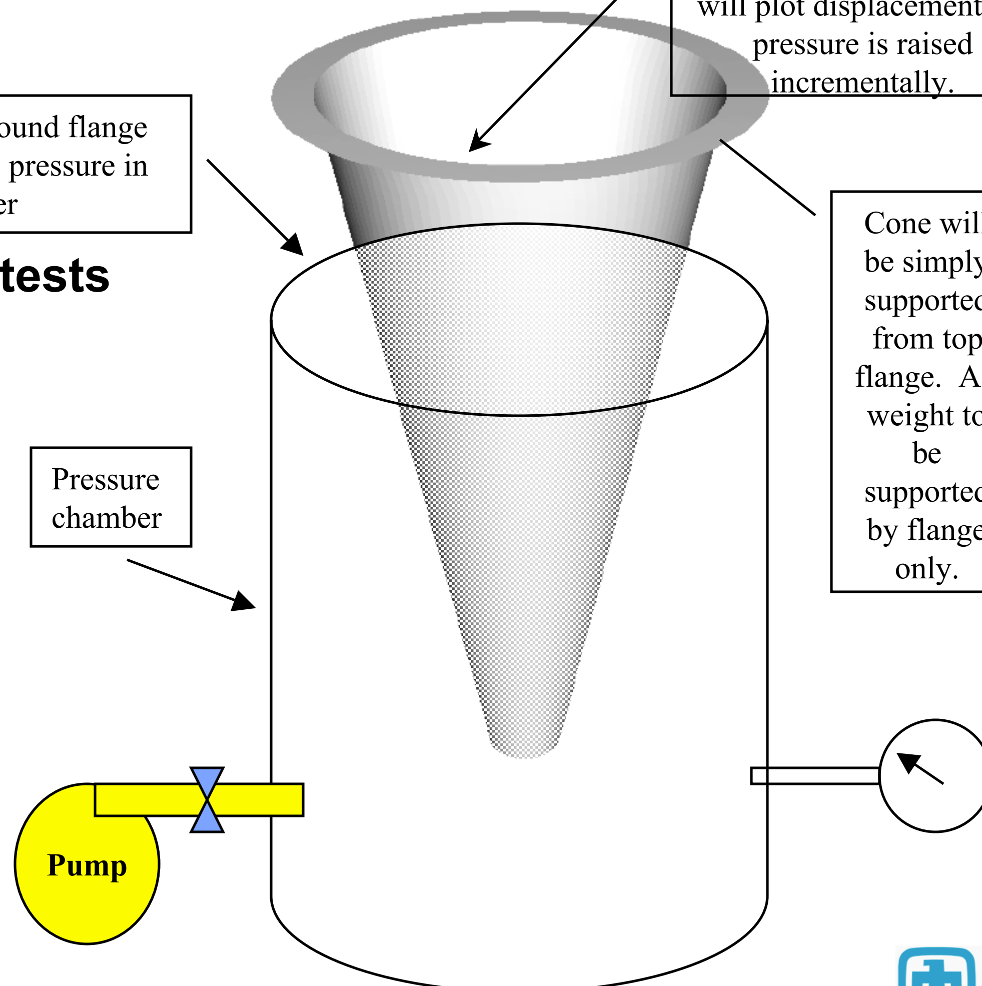
SNL, MRC, NRL, Kurchatov

Sandia National Laboratories

RTL Structural Testing is Starting

- **Model Validation**
  - **Testing Diagram**
- **RTLs manufactured for tests**
  - **2 meter RTLs**

THE UNIVERSITY OF ALABAMA FOUNDED 1831



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RTL activation

<u>Carbon steel RTL (preferred)</u> U. Wisconsin (L. ElGuebaly)

- recycle remotely in ~ 1.5 day
- after 35 years, material can be released for reuse (clearance index <1)
- RTL dose peaks at 160 Sv/hr, and drops to 1 Sv/hr in one hour
- advanced remote handling can have up to 3000 Sv/hr
  - (so should have large safety margin)

<u>Iron, or frozen Flibe</u> LLNL (W. Meier et al.)

- analyzed each element in periodic chart
- considered 1 day recycle with WDR < 1
- contact dose rate in range of 10-100 Gy/hr for iron
- acceptable lifetime dose to machinery for < 114 Gy/hr
  - (so should have some safety margin)

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1. RTLs

A 60 MA Z-pinch Circuit Model for Sensitivity Analysis (based on Marx/water line technology)

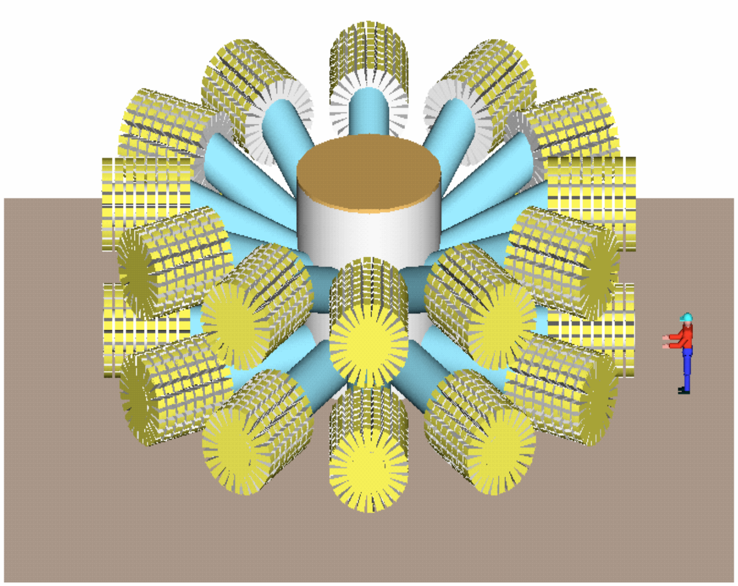
- A reasonable circuit model for IFE parameters may be scaled up from ZR Marx generator and water line circuit models, which are benchmarked against the Z machine performance.
- Model results for a 10 nH RTL and 1 + 7.6 nH (L + ΔL) load
- Example of a 10 nH conical RTL: upper radius 1 m, height 5 m, gap 5 mm
- Except for the vacuum insulator stack at near 8 MV, the pulsed power component voltages can be kept to between 5 and 6 MV.
- As the RTL inductance ranges from 10 to 30 nH, the load current reduces by nearly 40%, and the vacuum insulator stack voltage increases by about 11%.
- Over the same range the price we pay for additional inductance averages to about 1.2 MA / nH and 43.5 kV / nH.
- Up to some limit the pulsed power source can be modified to provide the additional current penalty, if necessary.
- Alternative pulsed power driver technologies may have a different sensitivity to the RTL inductance.

SNL (D. Smith)

Sandia National Laboratories

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

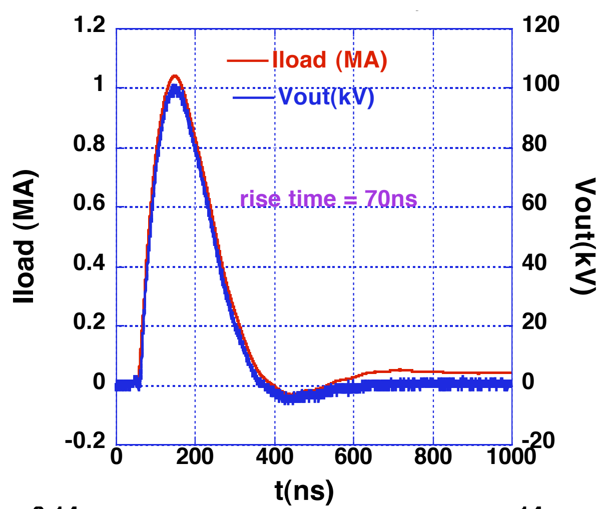
High Efficiency (~ 90% for driver)

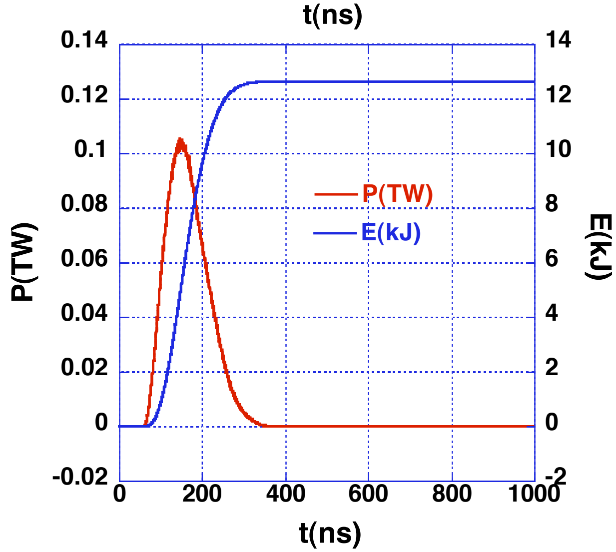
Low Cost (estimates are ~1/2 that for Marx/water line technology)

Easily made repetitive for 0.1 Hz

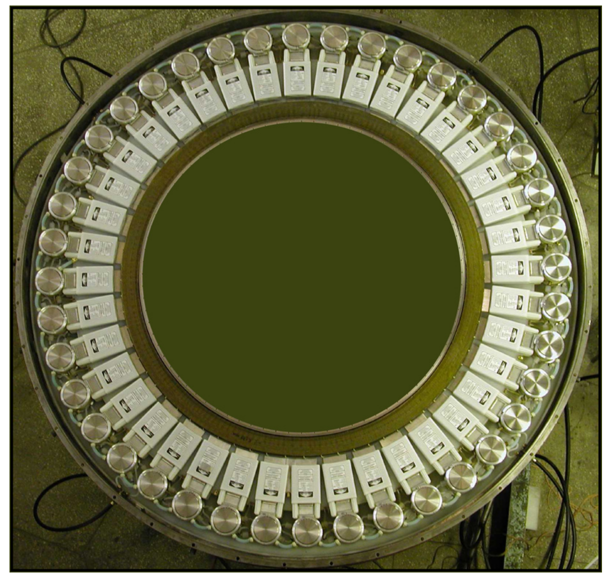
One 1-MA LTD cavity built - performs as expected during first 100 shots (two more cavities ordered – need ten for Z-PoP)

2. Repetitive driver





3-m



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

80 Maxwell 31165 caps,

40 switches, ±100 kV

0.1 Ohm load 0.1TW

SNL, Tomsk

Sandia National Laboratories

Switch Options for LTD are being assessed

2. Repetitive driver

- 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:

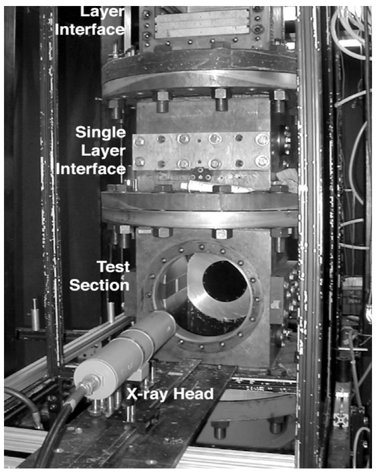
~ 25 kA
~ 200 kV
0.1 Hz
50-100 ns risetime
low cost
~ $3x10^6$ shots/year

SNL, U. Missouri-Columbia

3. Shock mitigation

Shock mitigation experiments in progress

Shock tube + water layers

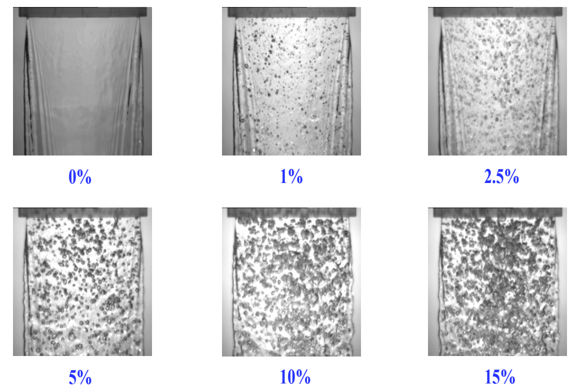


Shock tube facility at the University of Wisconsin

Explosives with water curtain

Vacuum Hydraulics Experiment (VHEX) at UCB

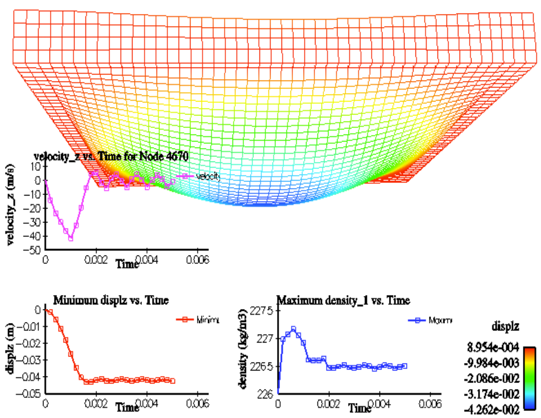
Foamed liquid sheets

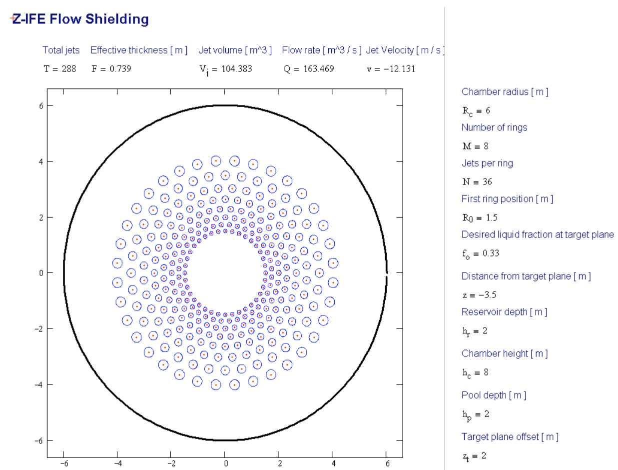


Georgia-Tech

Shock mitigation code calculations in progress

3. Shock mitigation





Liquid walls

Foamed Flibe

Liquid pool

Bubbles

ALEGRA simulation of shocked metal foam sheet (SNL)

Flibe jet geometry for shock mitigation (LLNL)

Dyna2D simulations (GA)

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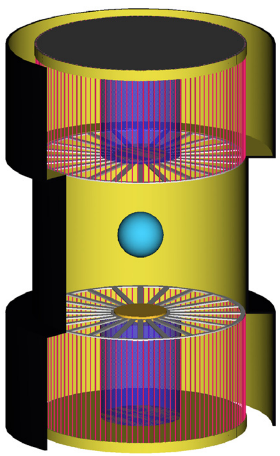
Robotic automation is very close to that needed for Z-Pinch IFE

- 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

5. Z-IFE targets

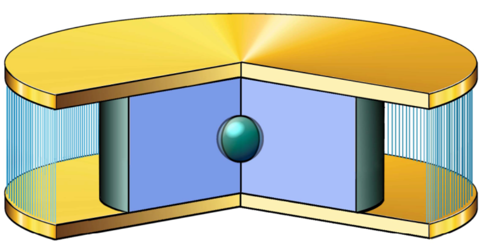
Dynamic hohlraum and double-ended hohlraum targets scale to Z-IFE with gains ~ 100

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*

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We've just scratched the surface of indirect-drive target design for IFE with either the DH or DEH

- **1D capsule designs with yields of 4 - 5 GJ have been developed for both approaches**
- **More 1D optimization is definitely desirable**
- **Much work remains in 2D design:**
  - **Hohlraum modeling for energetics & symmetry**
  - **Capsule modeling for symmetry and stability**
- **Z-IFE target design work benefits from the larger ICF effort:**
  - **Design tools (LASNEX simulation methods)**
  - **Experimental validation of energetics, pulse-shaping, and symmetry control on Z and ZR is ongoing**
    - **Dynamic hohlraum implosion symmetry control expts.**
    - **Double-ended hohlraum P4 radiation shimming expts.**

SNL R. Vesey

Further studies of Z-IFE targets with ~3 GJ yields

Z-IFE target physics scaling — SNL (R. Olson)

analytic arguments/ rad-hydro simulations/ empirical scaling from Z hohlraums
6 MJ of x-rays absorbed by capsule (26 MJ by hohlraum), adequate for 3 GJ yield
gains of 50-100 are conceptually feasible

Double-shell targets — SNL (W. Varnum)

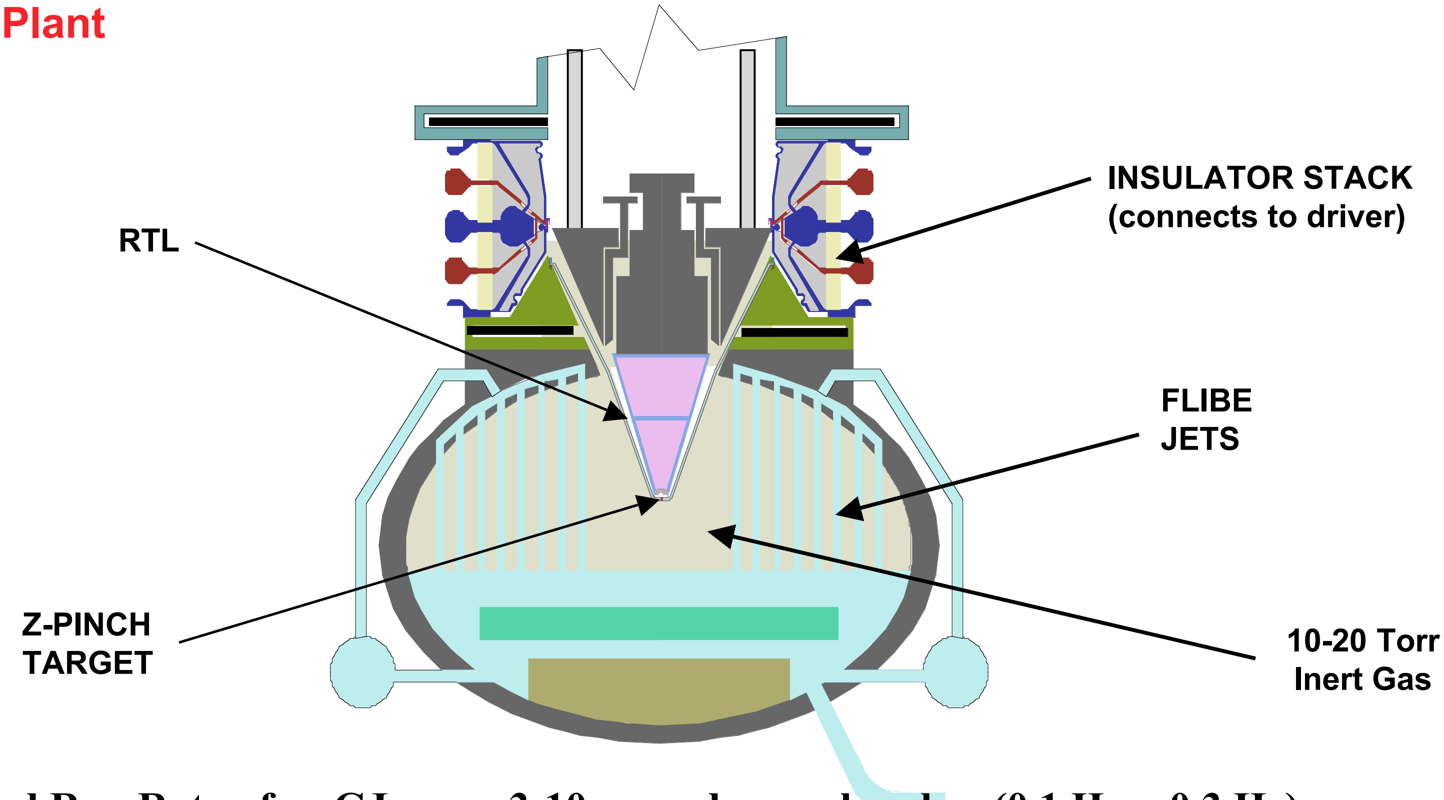
outside of inner shell typically unstable (Rayleigh-Taylor)
density gradient stabilization (Amendt, et al., LLNL)
capsule gains of 380-500 for yields of 3.5-3.8 GJ

Threat spectra for Z-IFE targets — LANL (R. Peterson)

initial BUCKY (1-D) results for 3 GJ yield DH targets

The first Z-Pinch Power Plant study (ZP3) provides a complete, but non-optimized, concept for an IFE Power Plant

6. Power Plant



Yield and Rep-Rate: few GJ every 3-10 seconds per chamber (0.1 Hz - 0.3 Hz)
Thick liquid wall chamber: only one opening (at top) for driver; nominal pressure (10-20 Torr)
RTL entrance hole is only 1% of the chamber surface area (for R = 5 m, r = 1 m)
Flibe absorbs neutron energy, breeds tritium, shields structural wall from neutrons
Neutronics studies indicate 30 year wall lifetimes
Activation studies indicate 1-1.5 days cool-down time for RTLs
Studies of waste steam analysis, RTL manufacturing, heat cycle, etc. in progress

Sandia National Laboratories

Z-Pinch IFE power plant studies: neutronics, chambers, target fabrication

6. Power Plant

<u>Neutronics for Z-IFE</u> — U. Wisconsin (M. Sawan)

Li, Flibe, LiPb assessed

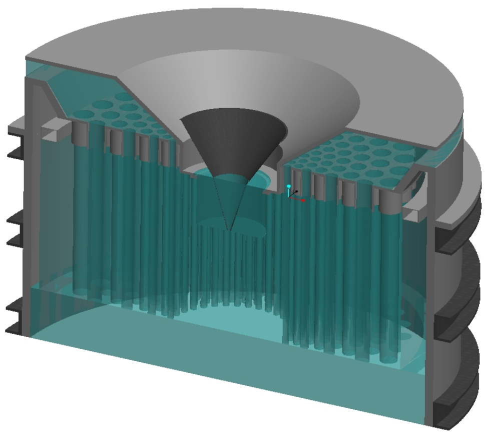
If assume a lifetime limit of 200 dpa for ferritic steel wall chamber,
It will last for the whole 40 FPY plant life for 40 cm Flibe

<u>Activation for Z-IFE</u>

Flibe and chamber wall qualify for Class C low level waste after 40 years plant life

<u>Chamber options proposed</u> — LLNL (W. Meier et al.)

Carbon-carbon composite wall



<u>Tungsten wire array + dynamic hohlraum/cryogenic target fabrication</u> — GA (R. Gallix, et al.)

Complete load: \$2.12 - \$2.86/ shot

(recall budget for target and RTL is a few \$ for 3 GJ yields)

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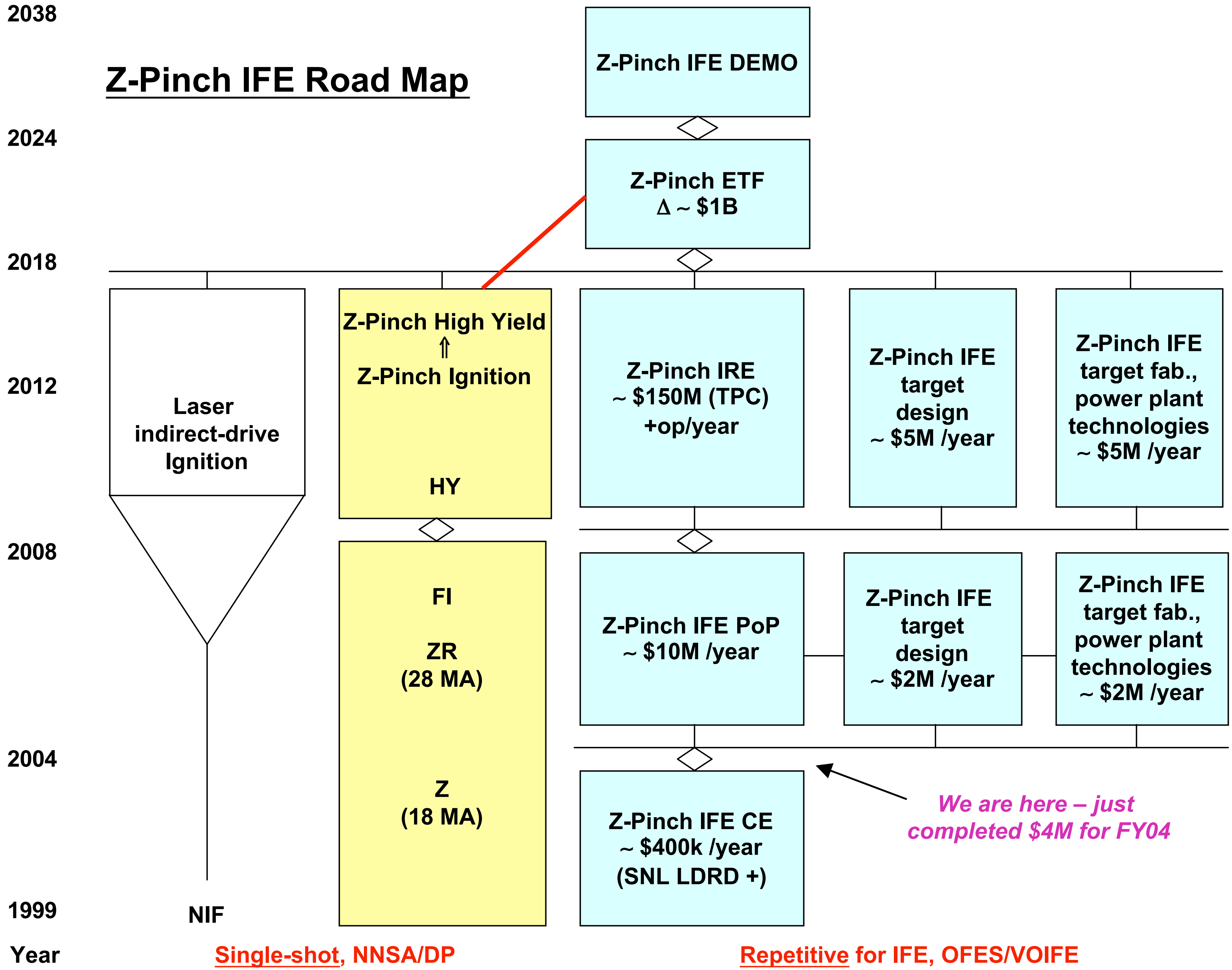
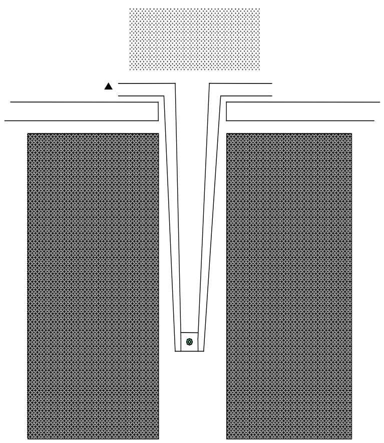
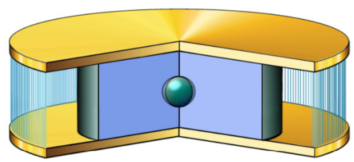


Z-Pinch IFE Road Map
2038
2024
2018
2012
2008
2004
1999
Year
Z-Pinch IFE DEMO
Z-Pinch ETF
Δ ~ $1B
Laser indirect-drive Ignition
NIF
Z-Pinch High Yield
⇑
Z-Pinch Ignition
HY
FI
ZR
(28 MA)
Z
(18 MA)
Z-Pinch IRE
~ $150M (TPC)
+op/year
Z-Pinch IFE target design
~ $5M /year
Z-Pinch IFE target fab., power plant technologies
~ $5M /year
Z-Pinch IFE PoP
~ $10M /year
Z-Pinch IFE target design
~ $2M /year
Z-Pinch IFE target fab., power plant technologies
~ $2M /year
Z-Pinch IFE CE
~ $400k /year
(SNL LDRD +)
We are here – just completed $4M for FY04
Single-shot, NNSA/DP
Repetitive for IFE, OFES/VOIFE

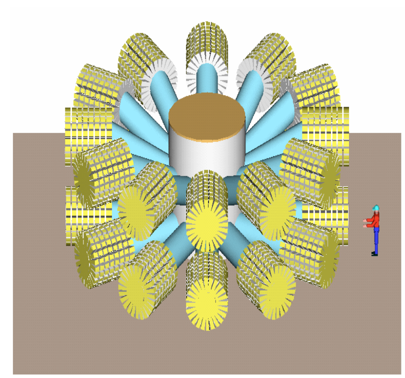
Status of Z-Pinch IFE Program



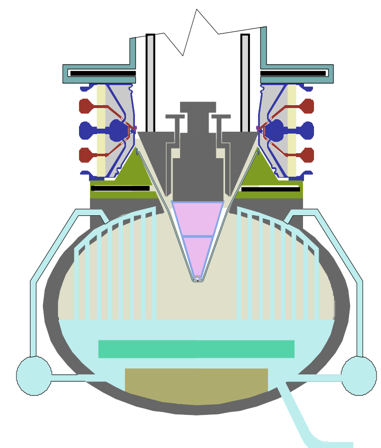
RTL



DH target



LTD driver



Chamber

- **Substantial progress has been made in all areas of Z-Pinch IFE**
- **A growing Z-Pinch IFE program is envisioned**