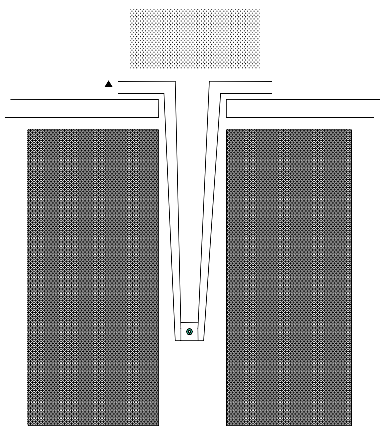
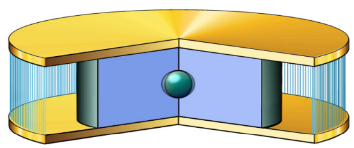
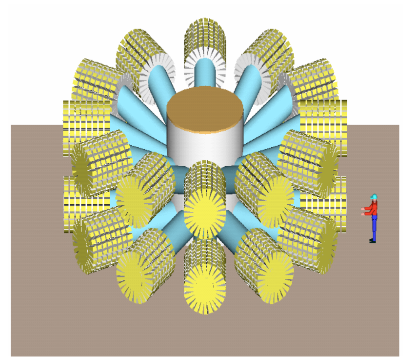
Progress on Z-Pinch Inertial Fusion Energy



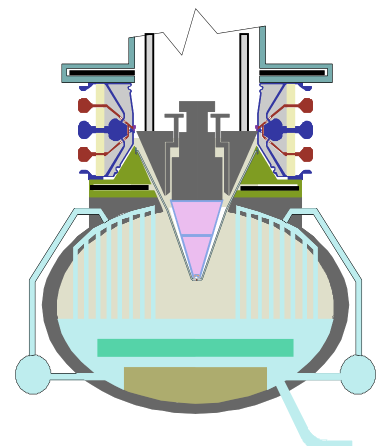
RTL



DH target



LTD driver



Chamber

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20th IAEA Fusion Energy Conference
Vilamoura, Portugal
1-6 November 2004

The Z-Pinch IFE Team

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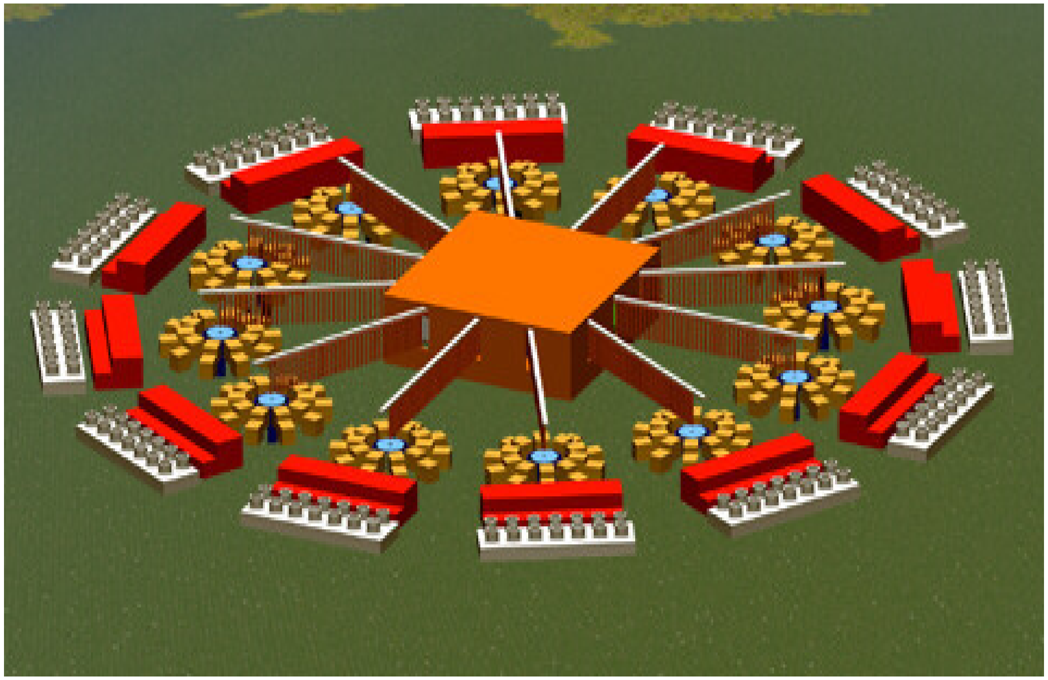
18) Institute of High Current Electronics, Tomsk, Russia
19) Kurchatov Institute, Moscow, Russia

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

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)

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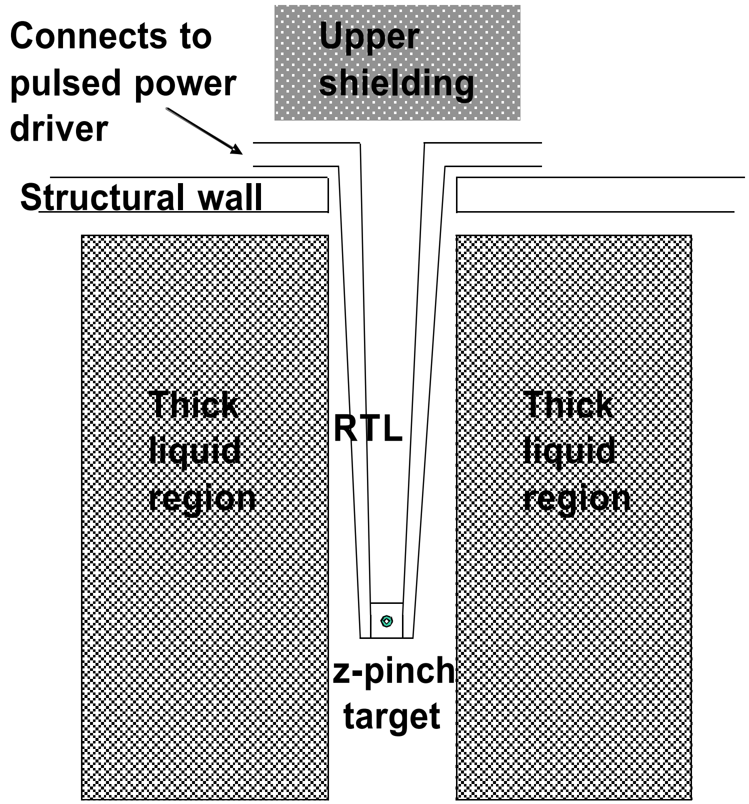
The Recyclable Transmission Line (RTL) Concept



- 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., 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)

red line shows preferred approach

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:

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Recyclable Transmission Line (RTL) status/issues

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

…

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

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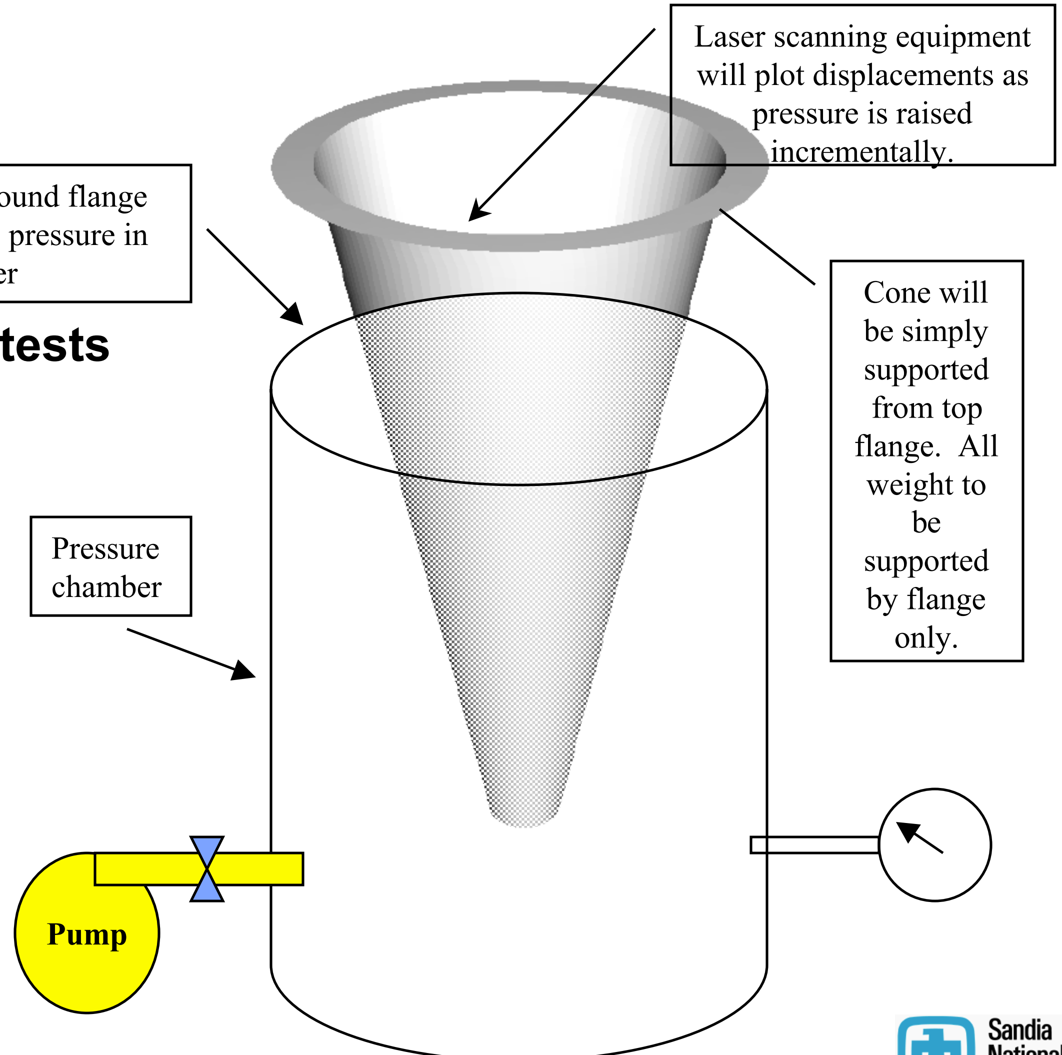
RTL Structural Testing is Starting

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



THE UNIVERSITY OF ALABAMA FOUNDED 1831

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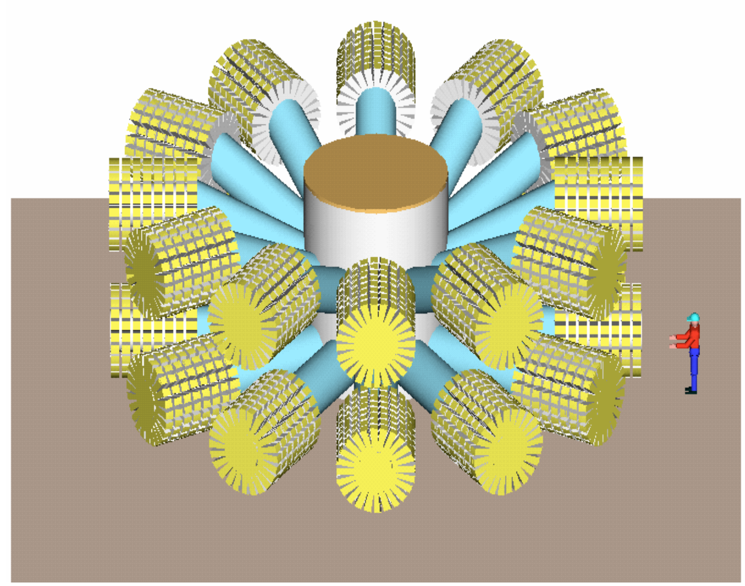
Linear Transformer Driver (LTD) technology is compact and easily rep-rateable

- 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

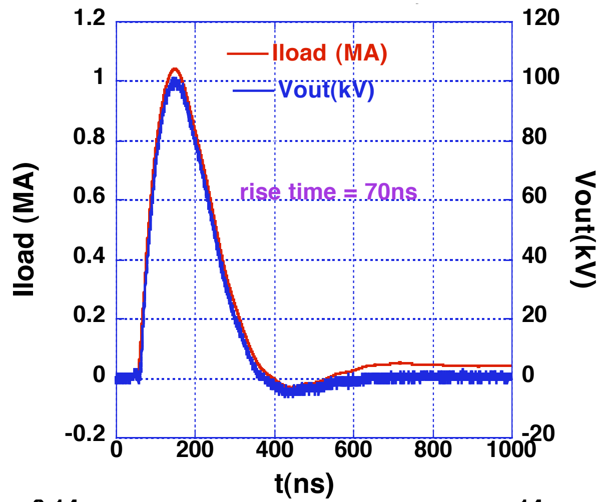
High Efficiency (~ 90% for driver)

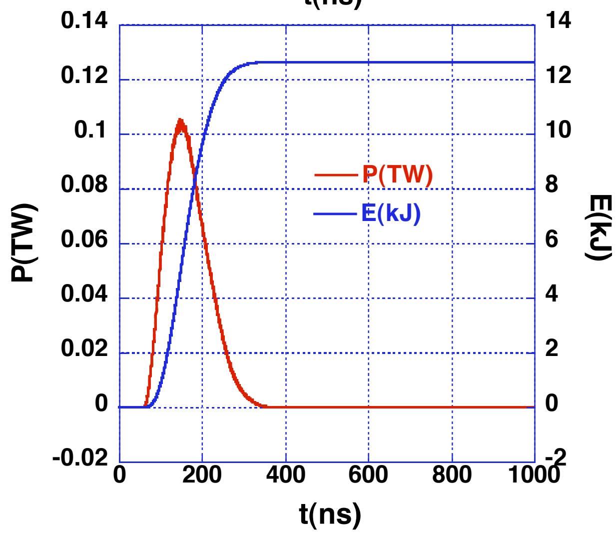
Low Cost (estimates are ~1/2 that for Marx/water line technology)

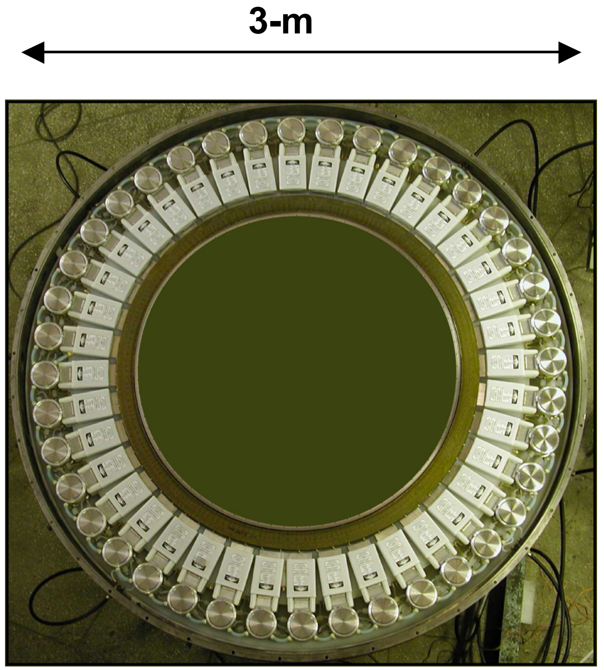
Easily made repetitive for 0.1 Hz

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







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

80 Maxwell 31165 caps,

40 switches, ±100 kV

0.1 Ohm load 0.1TW

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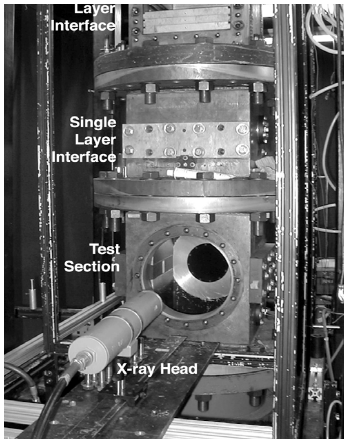
3. Shock mitigation

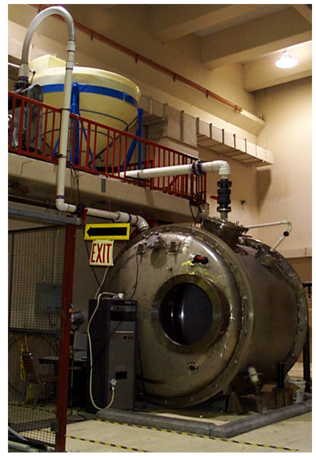
Shock mitigation experiments/code calculations in progress

Shock tube + water layers



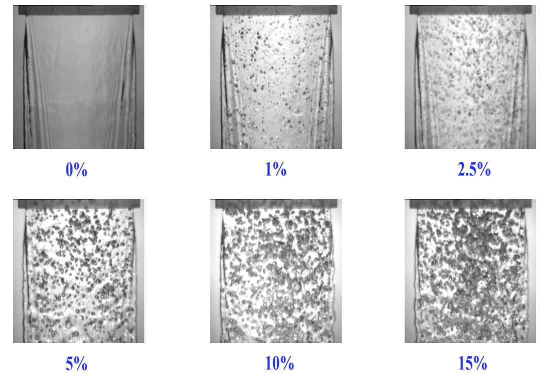
Shock tube facility at the University of Wisconsin

Explosives with water curtain



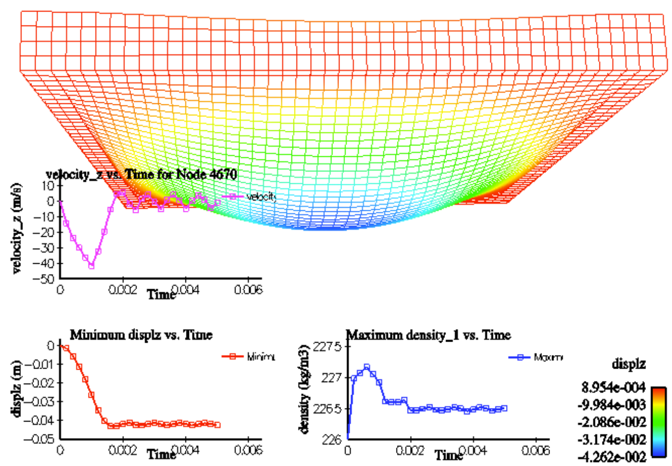
Vacuum Hydraulics Experiment (VHEX) at UCB

Foamed liquid sheets



Georgia-Tech

ALEGRA simulation of shocked metal foam sheet (SNL)



4. PoP planning

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

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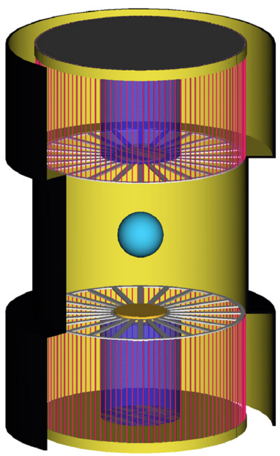
5. Z-IFE targets

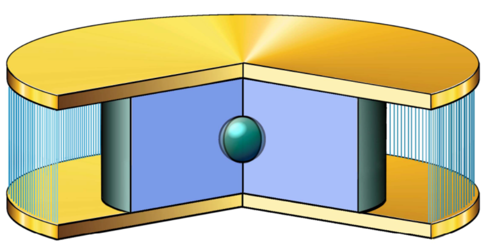
Dynamic hohlraum and double-ended hohlraum targets scale to Z-IFE with gains ~ 100

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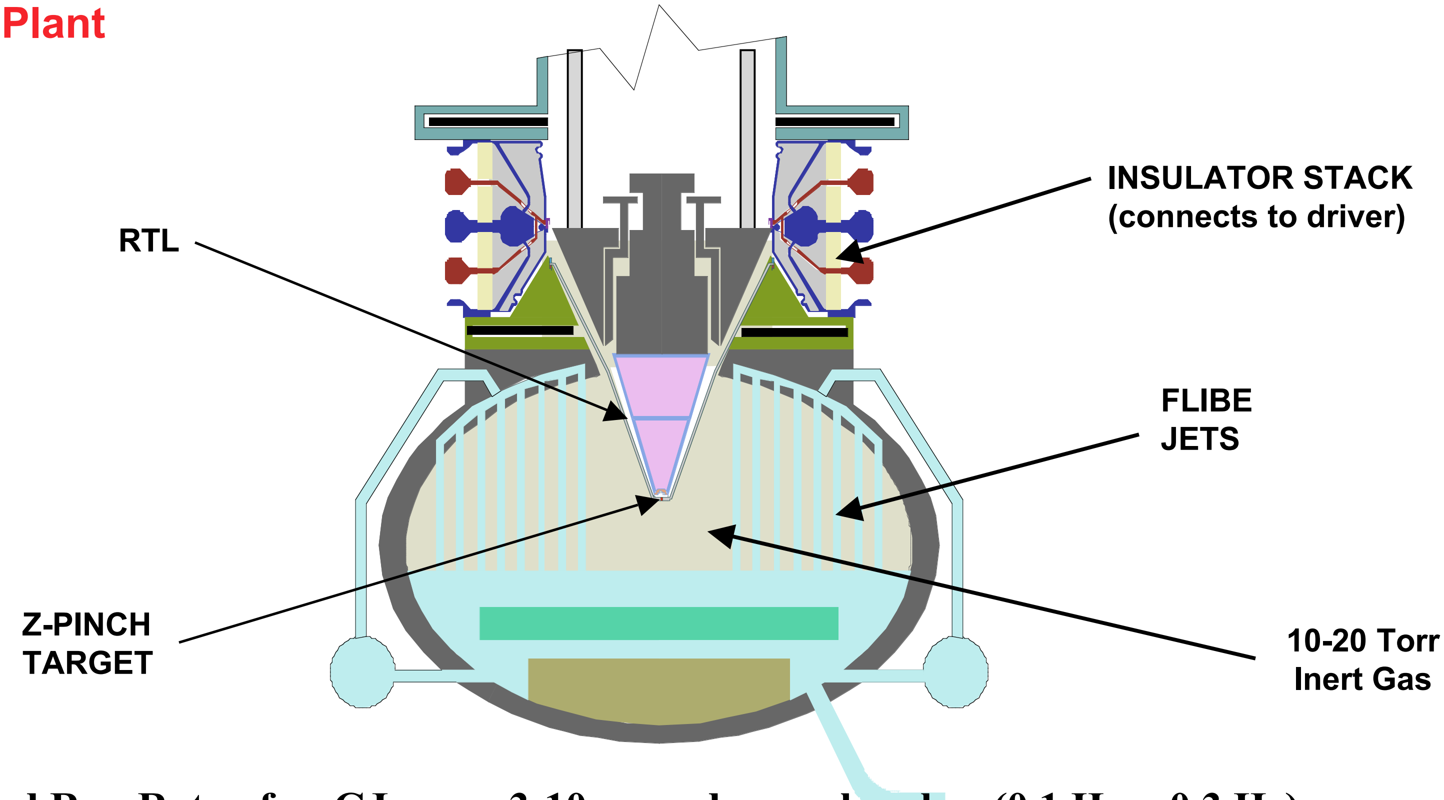
The first Z-Pinch Power Plant study (ZP3) provides a complete, but non-optimized, concept for an IFE Power Plant

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

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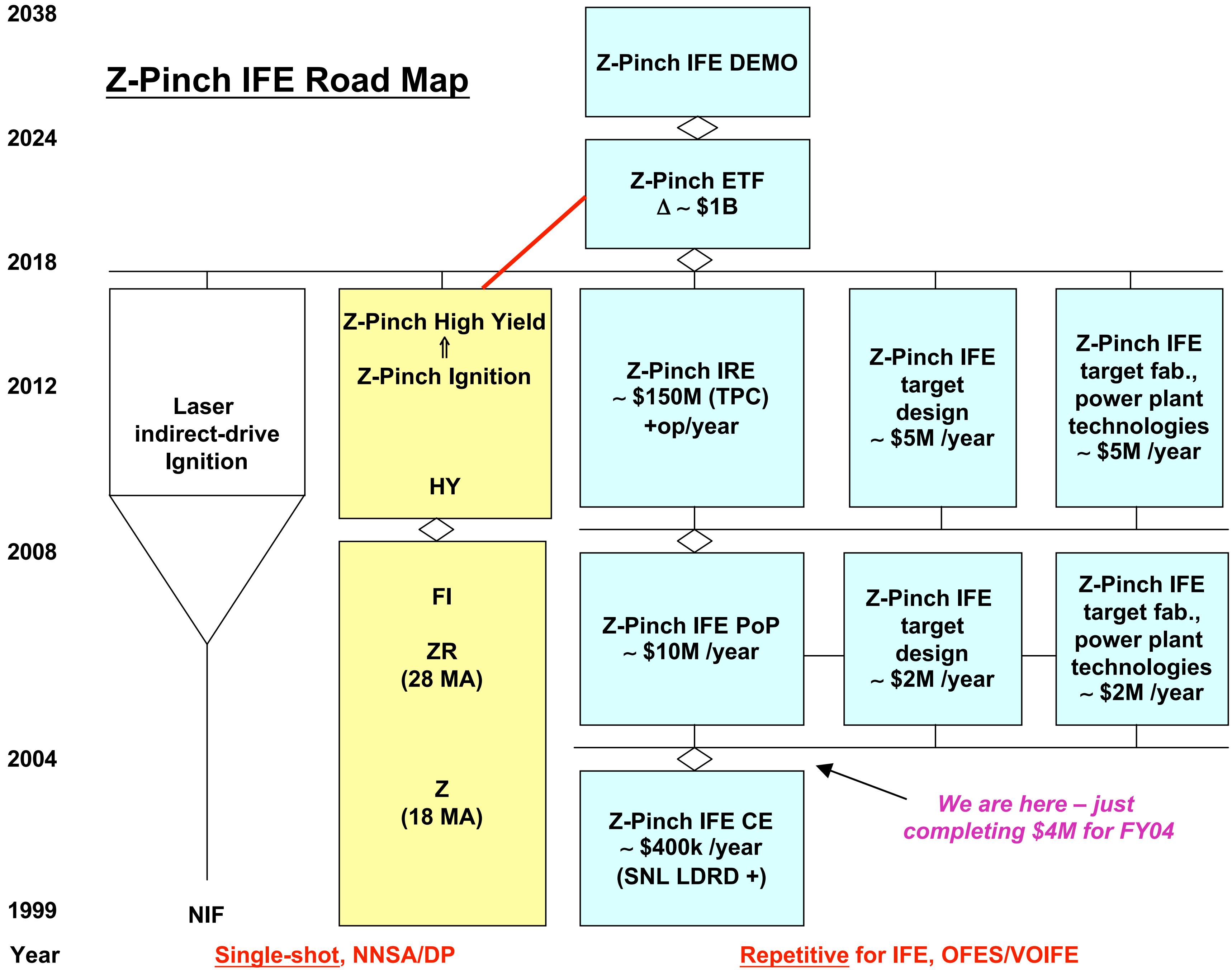
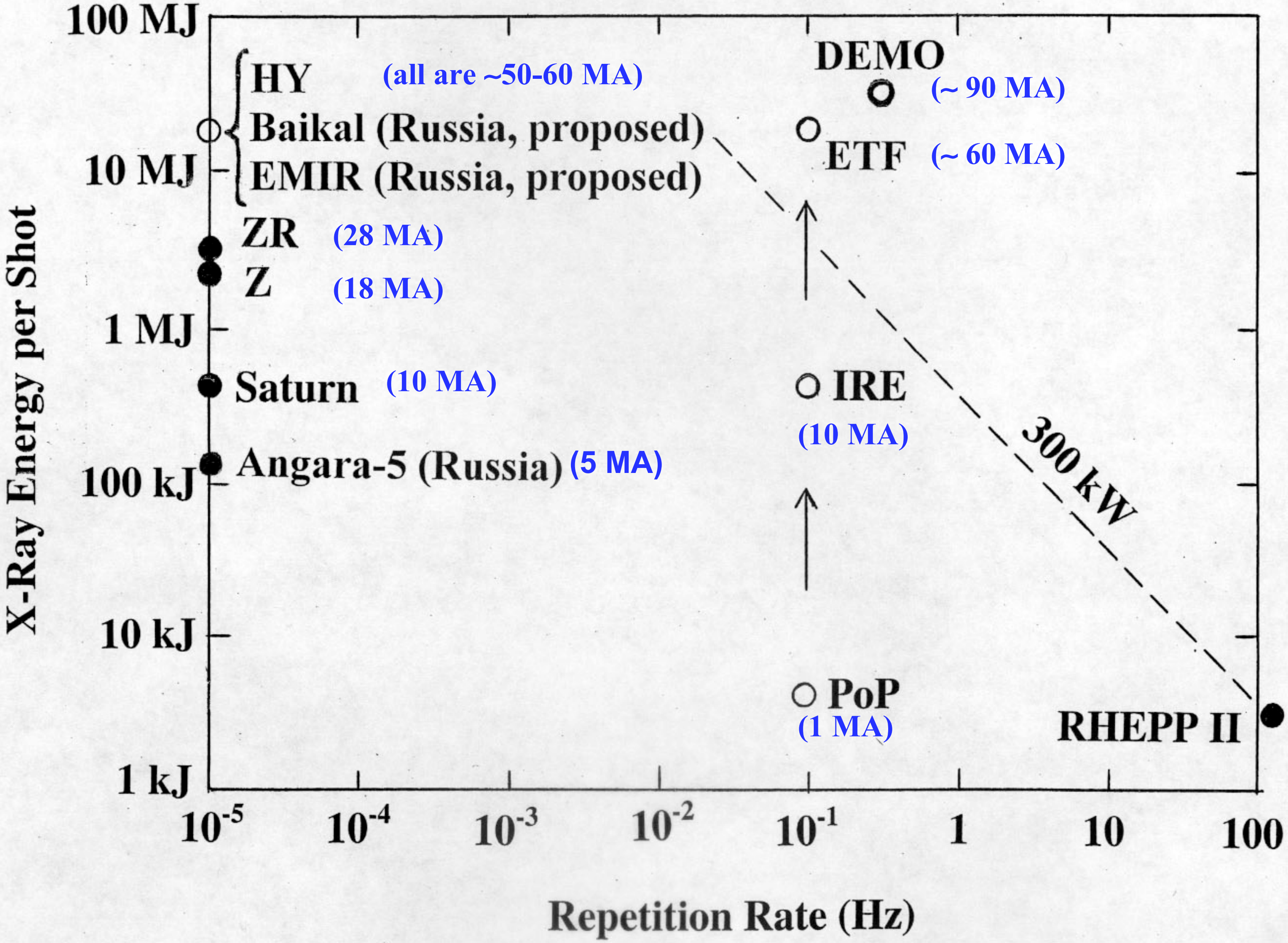


2038
Z-Pinch IFE Road Map
Z-Pinch IFE DEMO
2024
Z-Pinch ETF
Δ ~ $1B
2018
Z-Pinch High Yield
⇑
Z-Pinch Ignition
HY
Laser indirect-drive Ignition
Z-Pinch IRE
~ $150M (TPC)
+op/year
Z-Pinch IFE target design
~ $5M /year
Z-Pinch IFE target fab., power plant technologies
~ $5M /year
2012
2008
FI
ZR
(28 MA)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

Z-Pinch IFE Development Path *Facilities*



OV/3-5Rb

Wire Array Z-Pinch Precursors, Implosions and Stagnation

M.G. Haines, S.V. Lebedev, J.P. Chitenden, S.N. Bland, M. Sherlock, D.J. Ampleford, S.C. Bott, G.N. Hall, C. Jennings, J. Rapley, ***Imperial College, London***
P.D. Le Pell, C.A. Coverdale, B. Jones, C. Deeney, ***Sandia National Laboratories, Albuquerque, NM***

PURPOSE: Understand wire array plasma precursors, implosions, and stagnation at 1.5 MA on MAGPIE, considering the radiated z-pinch energy can sometimes be 3-4 times the kinetic energy

(1) Precursor plasma velocities and densities

High global B increases the ablation rate
gap size/core size: small ratio ⇒ ablation velocity constant
large ratio ⇒ ablation velocity decreases
ablation velocities affect radial density profile just prior to main implosion
precursor plasmas modeled with hybrid code model
3-D MHD simulations for MAGPIE

(2) Effects that can increase the final x-ray radiation

Late implosion of trailing mass
m=1 instabilities ⇒ increased Ohmic dissipation
m=0 instabilities ⇒ ion viscous heating (on Z at 20 MA, may explain ion temperatures of 100-300 keV)

OV/3-5Rc

Investigations of Radiating Z Pinches for ICF

E.V. Grabovski, V.V. Alexandrov, G.S. Volkov, M.V. Zurin, V.I. Zaitzev, K.N. Mitrofanov, S.L. Nedoseev, G.M. Oleinik, I.Yu. Porofeev, A.A. Samokhin, M.V. Fedulov, I.N. Frolov, E.A. Azizov, V.P. Bakhtin, A.N. Gribov, Yu.A. Khalimulin, V.F. Levashov, A.P. Lototsky, A.M. Zhitlukhin, M.K. Krylov, V.D. Pismenny, E.P. Velikhov, G.I. Dolgachev, Yu.G. Kalinin, A.S. Kingsep, V.P. Smirnov, SCR RF TRINITI
V.A. Glukhikh, V.G. Kuchinsky, O.P. Pechersky, RRC Kurchatov Insititute
I.A. Glazyrin, A.I. Kormilitsin, G.N. Rykovanov, Efremov Institute

PURPOSE: Investigations leading to creation of facility BAIKAL for thermonuclear target ignition (and yield)

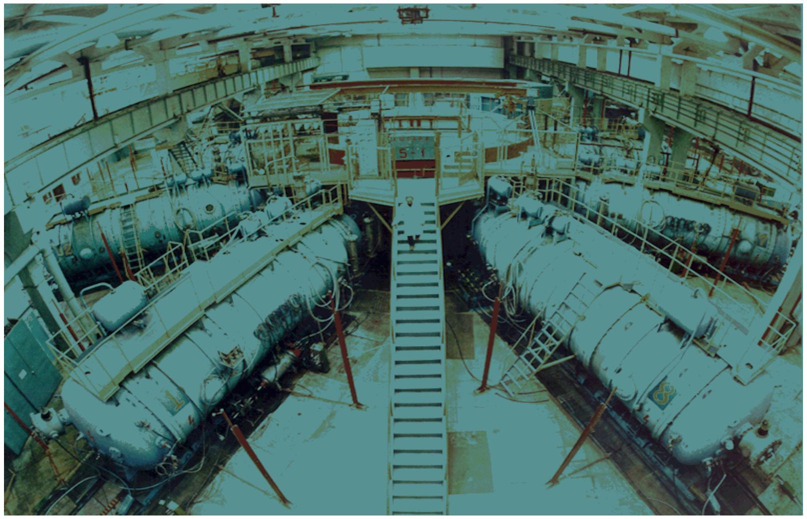
1. **Wire array implosion investigations on ANGARA-5-1 (5 MA, 100 ns)**

   X-pinch: x-ray radiography of wire array during implosion
   measure density distribution and look at precursor plasmas
   magnetic micro-probes: measure B at various radii
   (inside inner array, between arrays, outside outer array)
   1-D and 2-D simulations of wire arrays

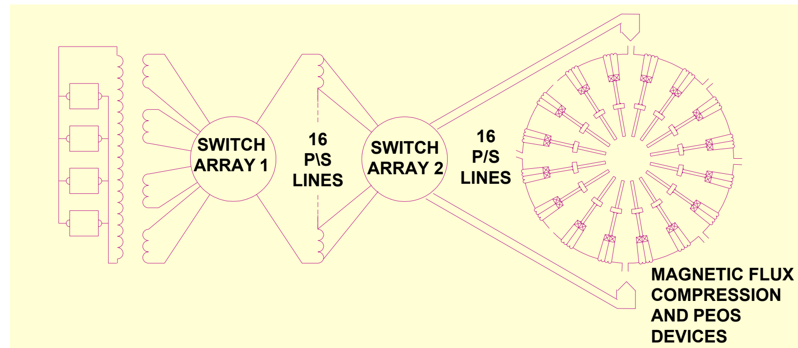
2. **For BAIKAL project, develop one prototype module (MOL): 4.5 MV, 1.5 MJ, 150 ns**

   inductive store (12 MJ)
   magnetic amplifier
   magnetic compressor (100 μs – 2 μs)
   transformer
   POS (sharpens to 150 ns)
   imitator load

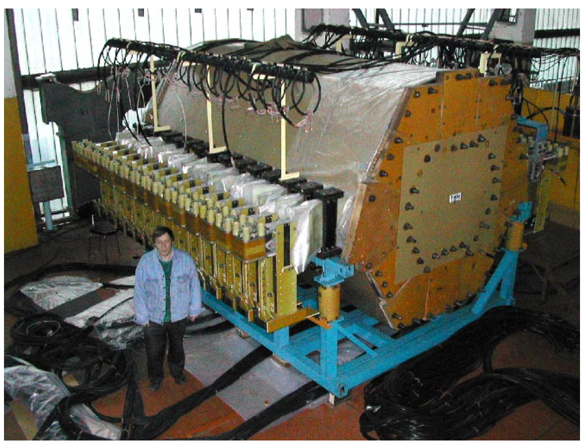
ANGARA-5-1



BAIKAL Project



MOL inductive storage



TIN 900 view in TRINITI

IF/P7-26

Investigations of Radiating Z Pinches for ICF

Yu. Kalinin, Yu. Bakshaev, A. Bartov, P. Blinov, A. Chernenko, K. Chukbar, S. Danko, G. Dolgachev, A. Fedotkin, A. Kingsep, D. Maslennikov, V. Mizhiritsky, A. Shashfov, V. Smirnov, Kurchatov Institute
I. Kovalenko, A. Lobanov, Moscow Institute for Physics and Technology

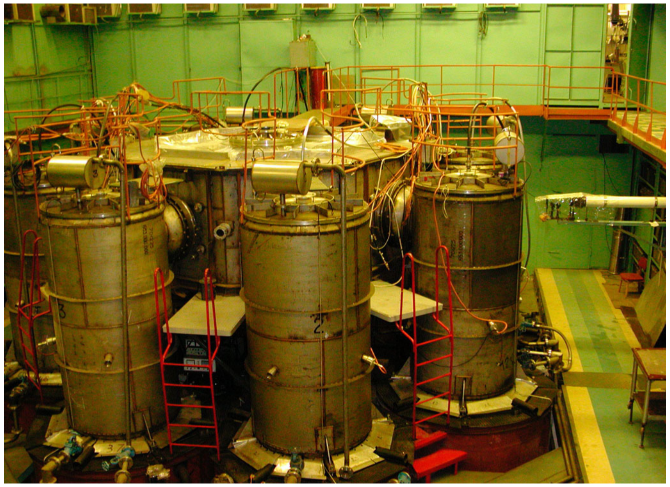
PURPOSE: Investigation of z-pinch wire array implosions on S-300

(1) Experiments on S-300 (3 MA, 100 ns, 0.15 ohm) at Kurchatov

Pass through of outer array through inner array

Plasma flow switch

S-300



(2) POS study on RS-20 facility (1 MV, 350 kA, 2 μs) for BAIKAL project

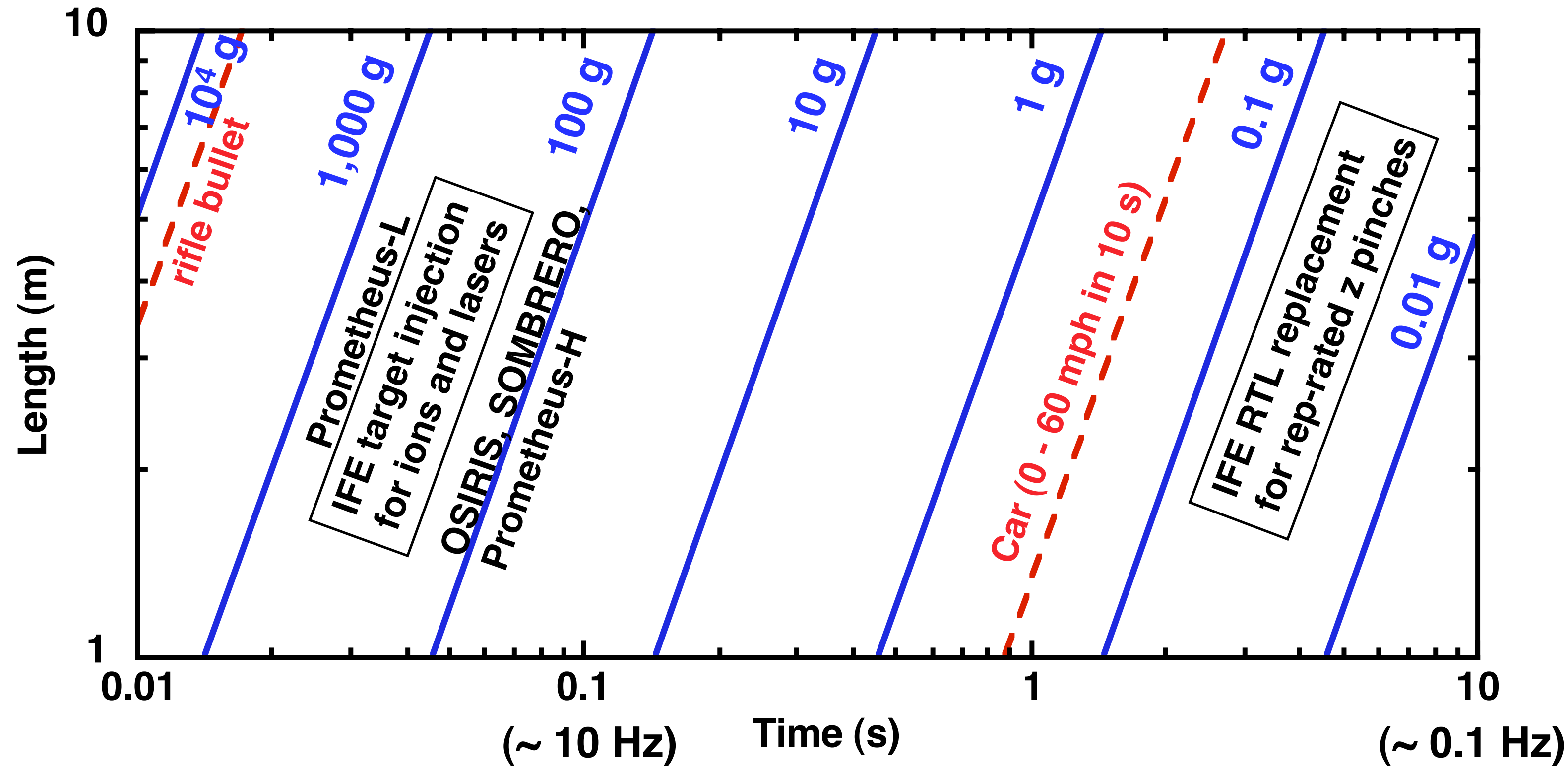
remove 40 μs prepulse leaving 100 ns main pulse

extra slides

RTL replacement requires only modest acceleration for IFE

$L = 0.5\, a\, t^2$, or $a \sim 1/t^2$

Acceleration is 10^4 less than for IFE target injection for ions or lasers



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One day storage supply of RTLs (at 50 kg each) has a mass comparable to one day's waste from a coal plant

Z-Pinch IFE
(1 GWe Power Plant)

RTLs one-day storage supply at site is 5,000 tons

RTLs are recycled with minimum waste

Coal-fired Power Plant
San Juan Generating Station (1.6 GWe)
(Four Corners area, NM)
Burns: 7 million tons coal/year
Waste: 1.5 million tons/year

Coal 30-day storage supply at site is 600,000 tons

Burns: 20,000 tons/day
Waste: 5,000 tons/day
(flyash and gypsum, that must be disposed of in the adjacent coal mine)

RTL research completed prior to 2004 (under LDRD) had encouraging results

RTL electrical turn-on	**<u>Saturn experiments at 10 MA</u> (2000)** **tin, Al, stainless-steel all show negligible losses**
RTL low-mass and electrical conductivity	**<u>Saturn experiments at 10 MA</u> (2001)** **20μ mylar; 50μ, 100μ, 250μ steel** **RTL mass could be as low as 2 kg** **RTL mass ~ 50 kg has low resistive losses**
RTL structural	**Calculations (U. Wisconsin) (2002)** **full-scale RTL (~50 kg) of 25 mill steel ok for background pressure ~ 10-20 Torr**
RTL manufacturing	**(allowed RTL budget is a few $ for 3 GJ)** **Flibe casting (~$0.70/RTL)** **ferritic steel stamping (~ $1.20-3.95/RTL)**

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