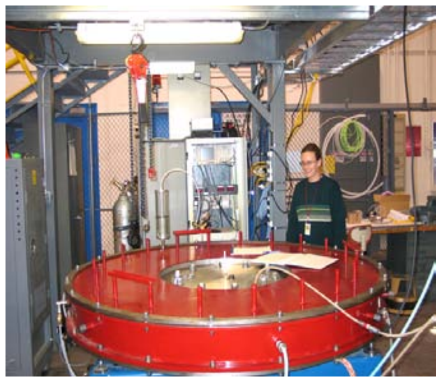
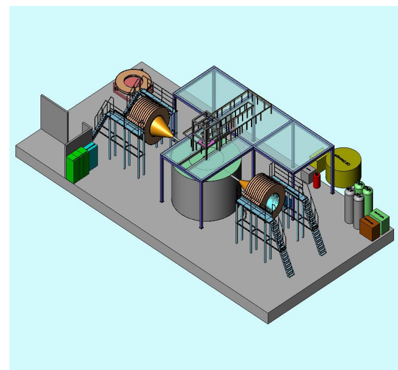
Z-Pinch Inertial Fusion Energy

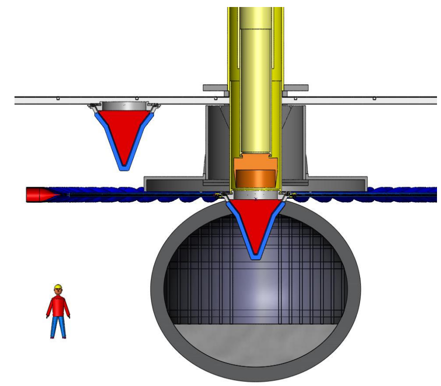
RTL



LTD driver



Z-PoP



Chamber

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

Fusion Power Associates
Annual Meeting and Symposium
Washington, DC
October 11-12, 2005

The Z-Pinch IFE Team

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Lead National Laboratory

SNL

Collaborating National Laboratories:

LLNL, LANL, NRL, LBNL

Collaborating Universities:

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

Collaborating Industry:

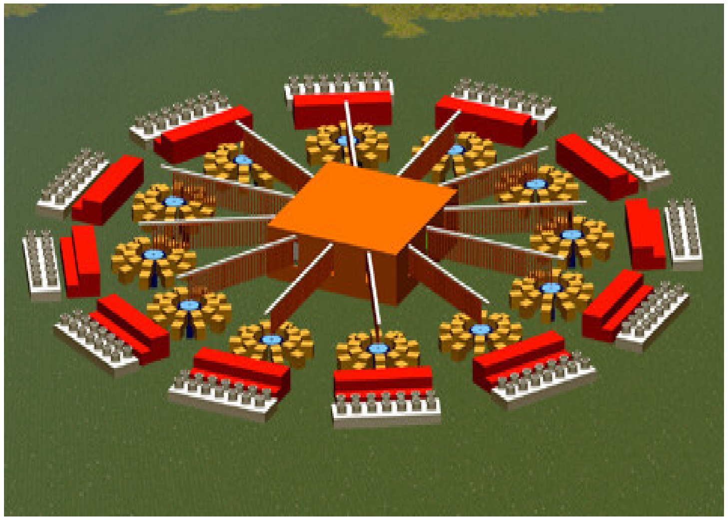
GA, ATK-MRC, SAIC, Omicron

Collaborating Institutions in Russia:

Kurchatov Institute (Moscow)

Institute for High Current Electronics (Tomsk)

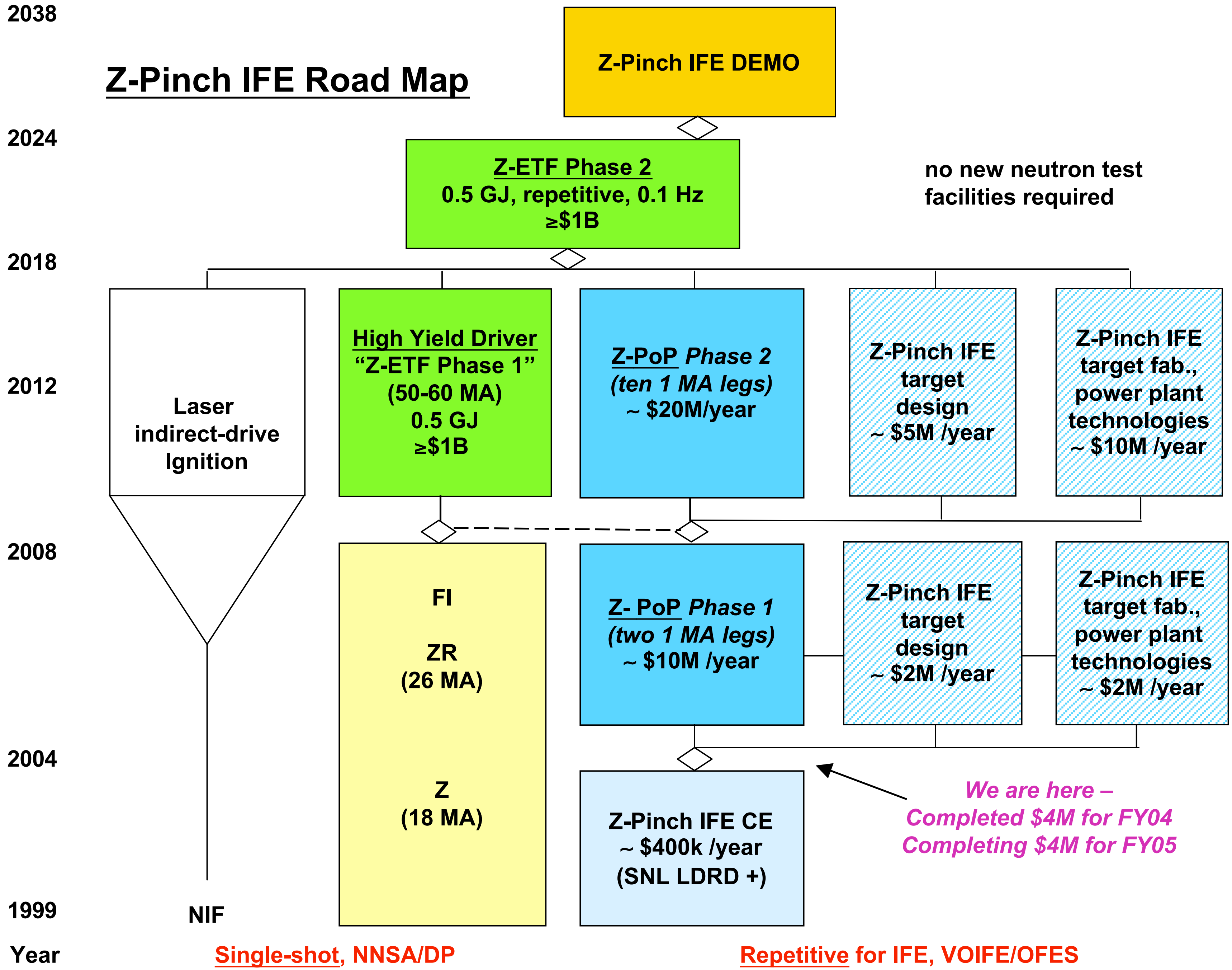
The *long-term* goal of Z-Pinch IFE is to produce an economically attractive power plant using high-yield z-pinch-driven targets (~3 GJ) at low rep-rate per chamber (~0.1 Hz).



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.

Considerable progress has been made toward these goals, as will be reported in this talk

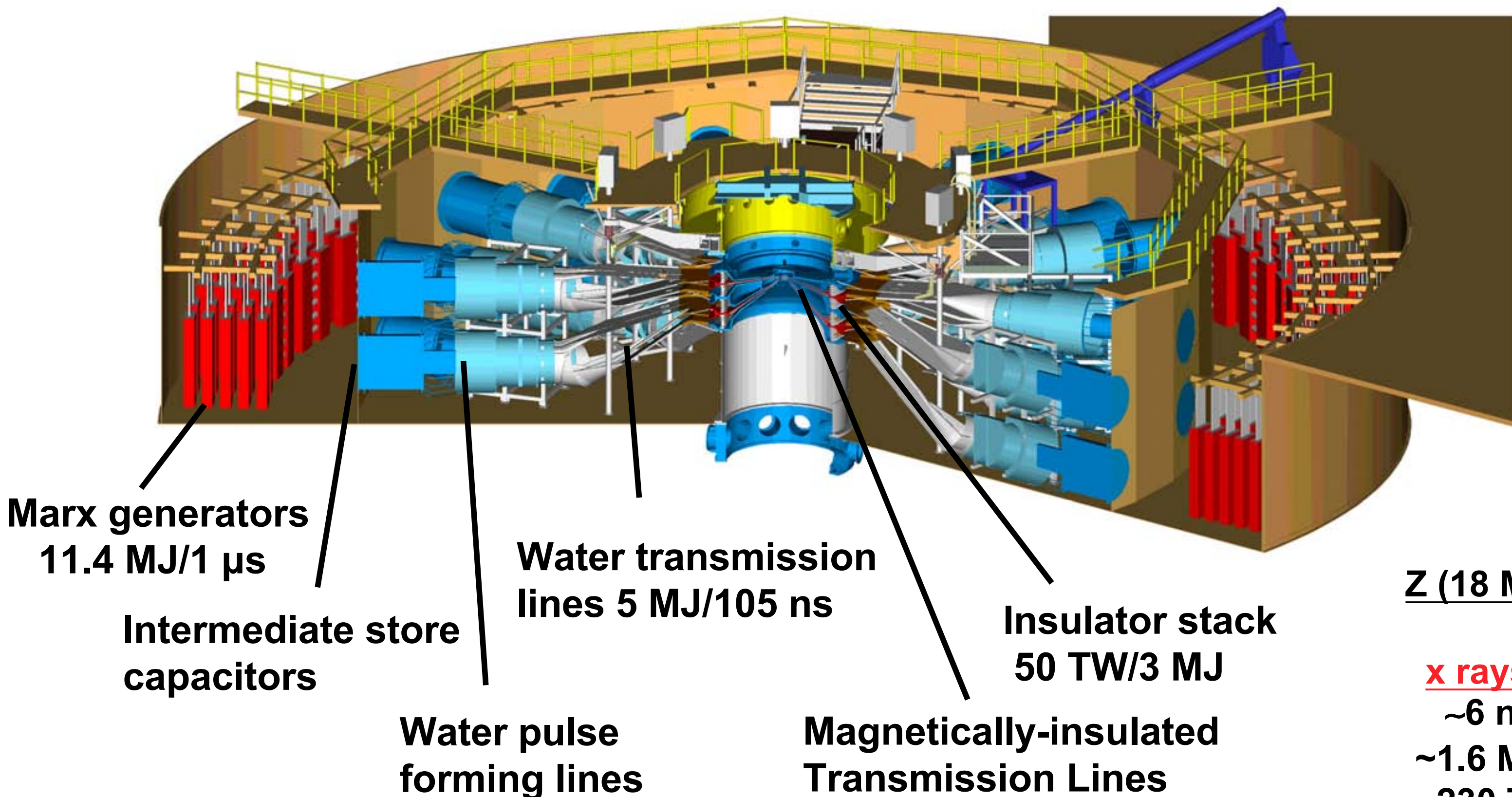


Z-Pinch IFE Road Map
2038
2024
2018
2012
2008
2004
1999
Year
Z-Pinch IFE DEMO
Z-ETF Phase 2
0.5 GJ, repetitive, 0.1 Hz
≥$1B
no new neutron test facilities required
Laser indirect-drive Ignition
NIF
High Yield Driver
"Z-ETF Phase 1"
(50-60 MA)
0.5 GJ
≥$1B
Z-PoP Phase 2
(ten 1 MA legs)
~ $20M/year
Z-Pinch IFE target design
~ $5M /year
Z-Pinch IFE target fab., power plant technologies
~ $10M /year
FI
ZR
(26 MA)
Z
(18 MA)
Z- PoP Phase 1
(two 1 MA legs)
~ $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 –
Completed $4M for FY04
Completing $4M for FY05
Single-shot, NNSA/DP
Repetitive for IFE, VOIFE/OFES

Z-Pinch ICF with Z/ZR

(single shot)

Z uses Marx/water-line technology to produce a ~100 ns pulse to drive the world's most powerful z-pinch x-ray source



Z (18 MA)

x rays
~6 ns
~1.6 MJ
~230 TW
conversion efficiency
~15% (wall-plug to x-rays)

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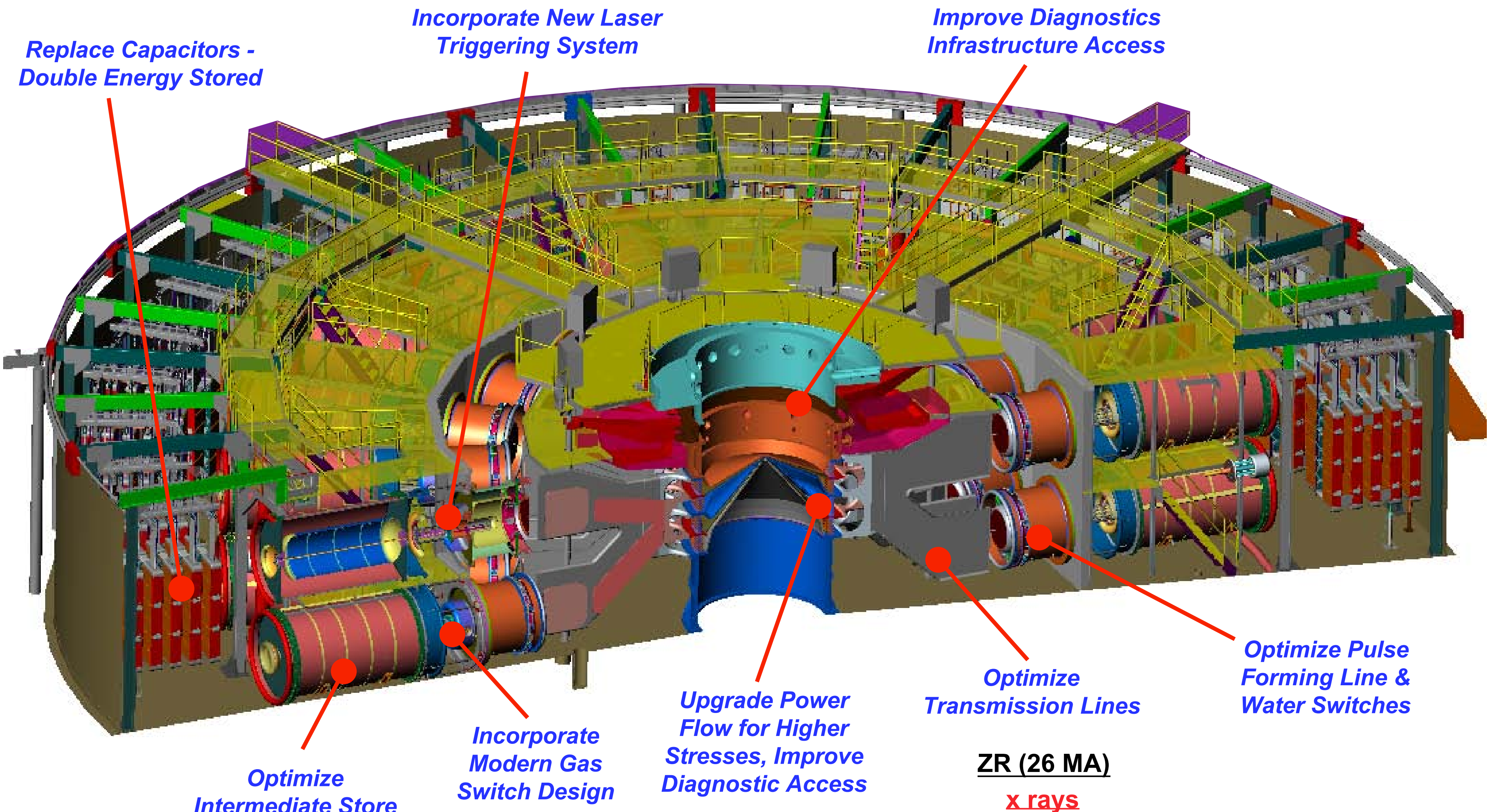
ZR - Refurbishing the Entire Accelerator



ZR (26 MA)

x rays
~2.7 MJ
~350 TW

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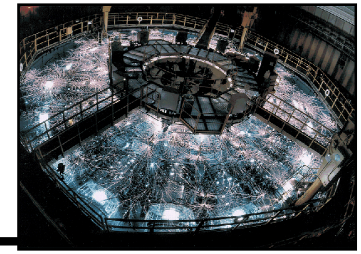
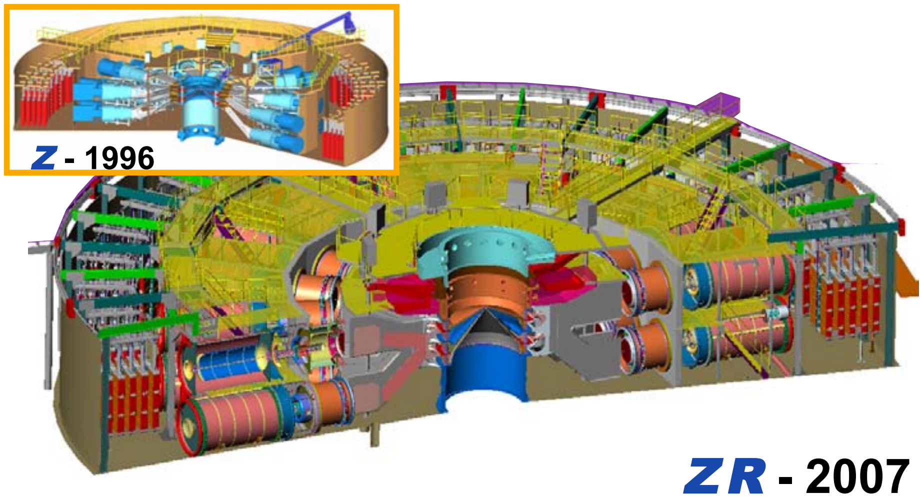
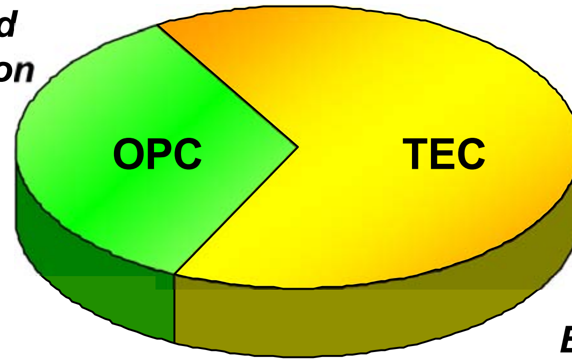
ZR Project – Refurbishing Sandia's *Z* machine -- the worlds most powerful and energetic x-ray source for SSP applications





Total Cost (TPC) $90.4M

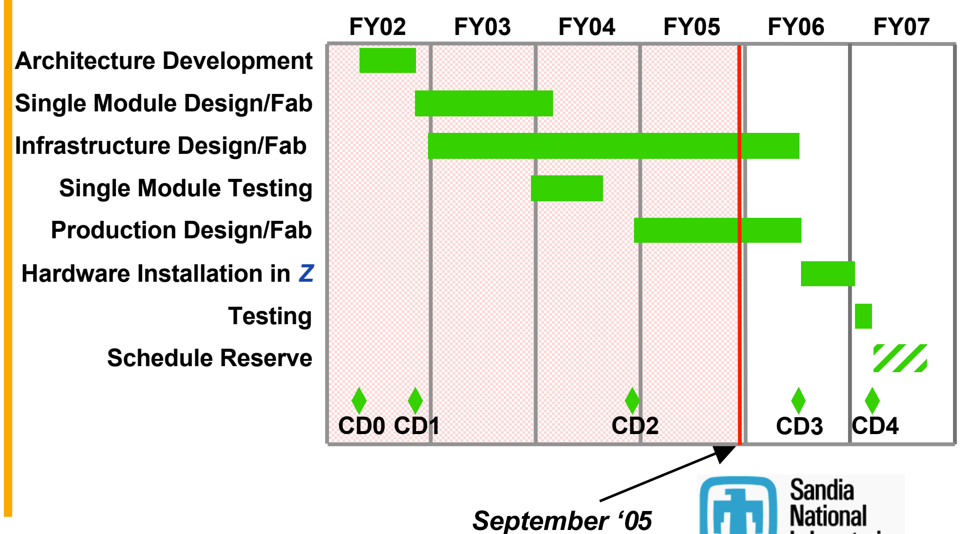


Balanced Objectives

Cost effective refurbishment / optimization, realizing

with minimum impact to ongoing programs.

6 Year Project



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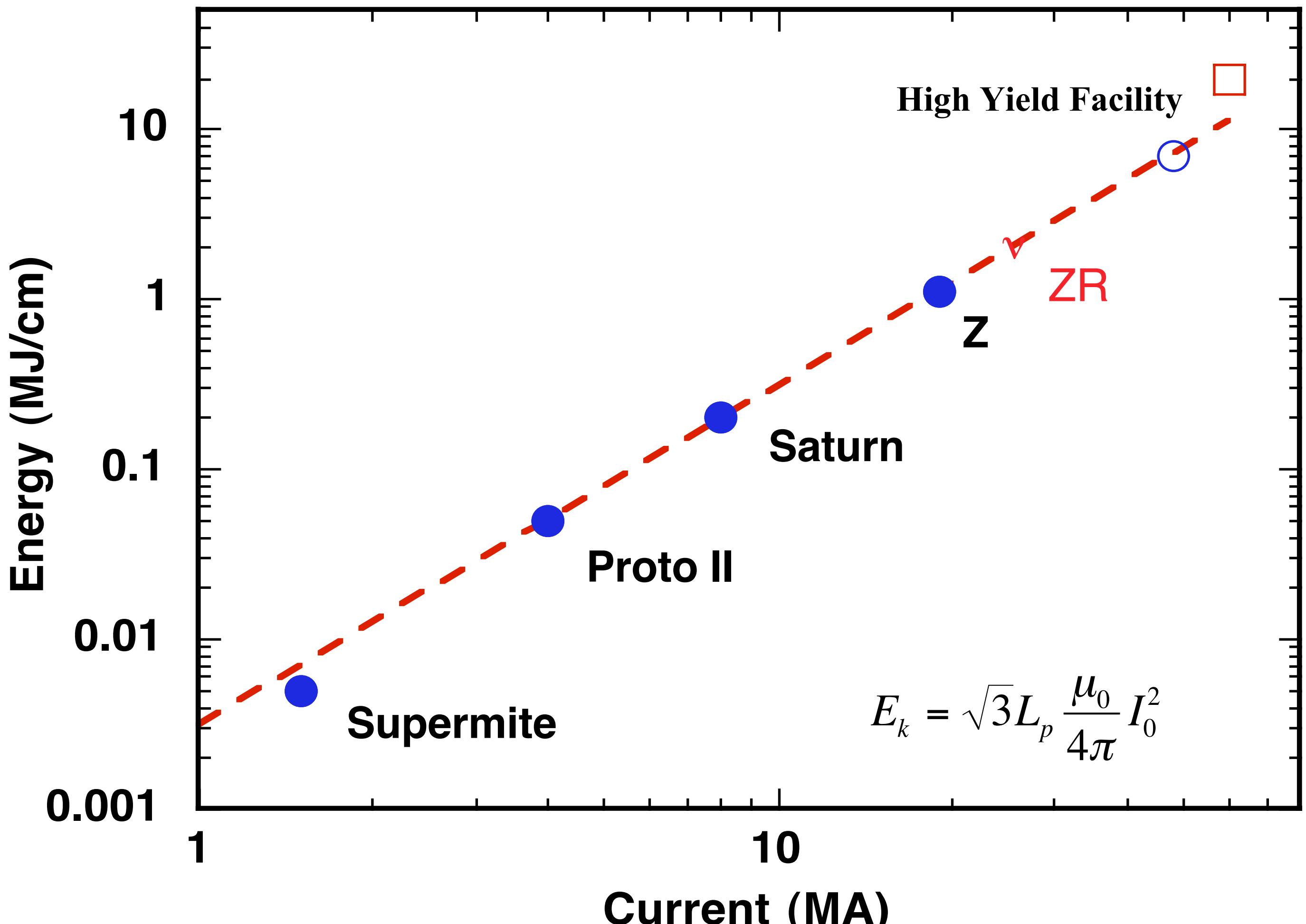
Z-pinches offer the promise of a cost-effective energy-rich source of x-rays for IFE

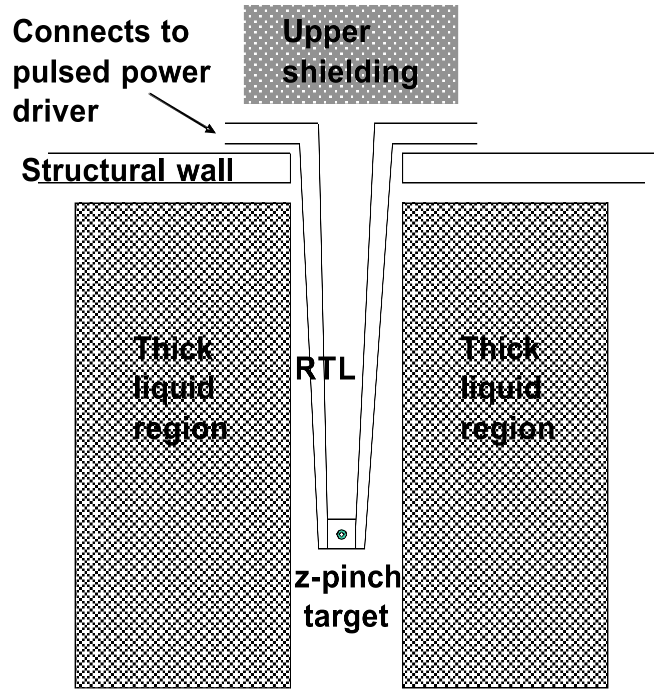


ZR will be within a factor of 2-3 in current (4-9 in energy) of a High Yield driver.

Z-Pinch IFE

(repetitive for energy)

Recyclable Transmission Line (RTL) Concept for Z-Pinch IFE



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 40 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

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

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Z-Pinch IFE Power Plant has a Matrix of Possibilities

Repetitive 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)

Recent Results in Z-IFE

1. RTLs

simulations (5 MA/cm works)

experiments (5 MA/cm works)

pressure testing (20 Torr works)

2. LTD repetitive driver

0.5 MA, 100 kV cavity fires every 30 seconds

1.0 MA, 100 kV cavity tested

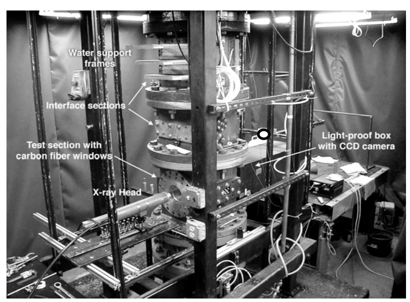
full IFE driver architectures

3. Shock mitigation

theory

experiments

simulations

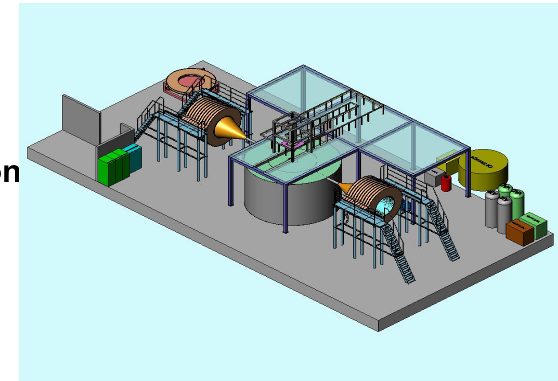


4. Z-PoP planning

vacuum/electrical connections

overhead automation

animations/costing

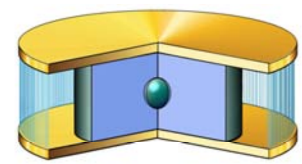


5. Z-IFE targets for 3 GJ yields

gains ~ 50-100

double-pinch/dynamic hohlraum

scaling studies

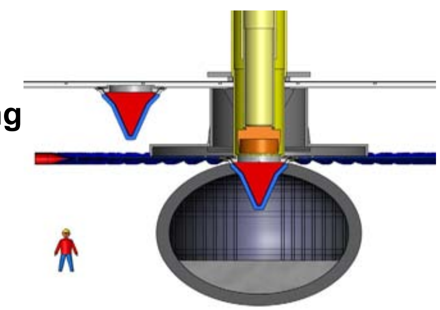


6. Z-IFE power Plant

RTL manufacturing/costing

wall activation studies: 40 year lifetime

power plant design



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 mass handling	comparison with coal plant
RTL structural properties	ANSYS simulations, buckling tests
RTL shrapnel formation	under study
RTL vacuum connections	annular 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 estimates: ~$5 for steel, ~$0.80 for Flibe
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

…

On-going Research

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There are many tradeoffs in optimizing the RTL

<u>RTL material</u>: electrical conductivity, structural properties, low activation, interaction with coolant, recycling, etc. (carbon steel - back-up is Flibe)

<u>RTL mass</u>: movement, size/cost of recycle plant, total inventory mass, etc. (50 kg)

<u>RTL radius at top</u>: minimum inductance, vacuum and electrical connections, minimal hole into chamber, etc.
(100 cm for power plant)

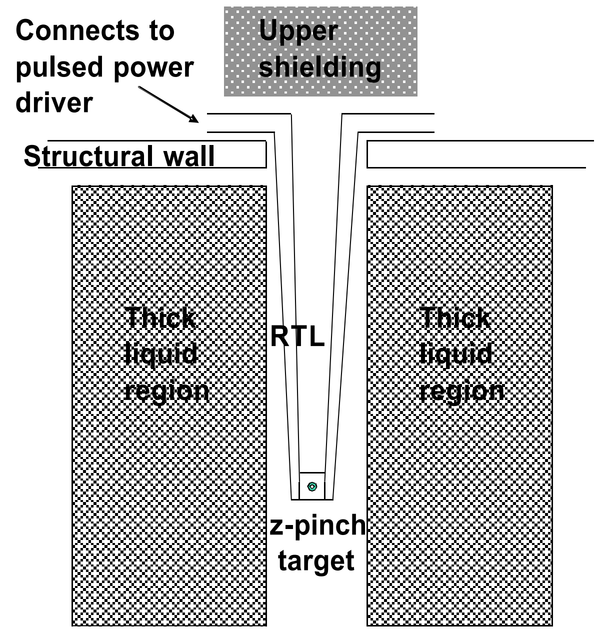
<u>RTL radius at bottom</u>: about target radius, ~ 2- 5 cm.
(5 cm for power plant)

<u>RTL length</u>: long for blast, short for inductance, affects voltage requirement of driver, etc.
(200 – 500 cm for power plant)

<u>RTL shape</u>:

best for low inductance   best for structural strength
(using conical RTL for now)

<u>RTL interface with power flow</u>: many LTD modules (coax), to triplate, to biplate, to connection with RTL
(using biplate to coax RTL for now)

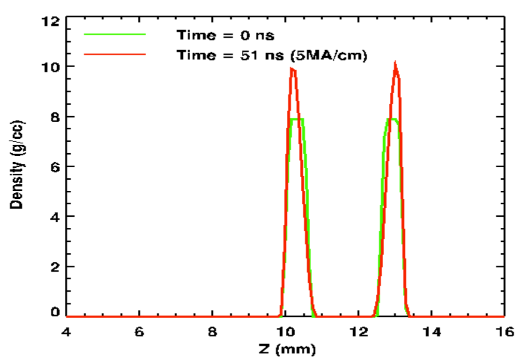


MITL/RTL Issues for 20 MA ⇒ 60 MA ⇒ 90 MA
(now on Z) *(high yield)* *(IFE)*

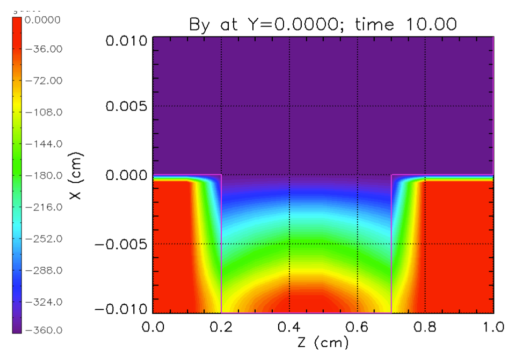
SNL, ATK-MRC, NRL, Kurchatov

Issues that become most critical near the target:
- **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**

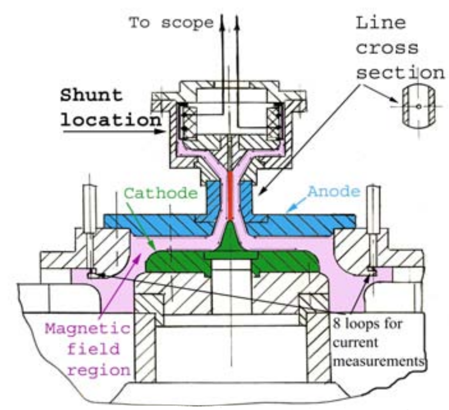
I	20 MA	60 MA	90 MA
R_{array} (z-pinch)	? 2 cm	? 2 cm	? 5 cm
I / (2 ? R_{array})	? 1.6 MA/cm	? 4.8 MA/cm	? 2.9 MA/cm
MITL	Works on Z	?	?
RTL	?	?	?



ALEGRA MHD simulations of thin-walled (0.6 mm thick), small AK gap (2 mm) at 60 MA show no disruption at 5 MA/cm



Scaling of LSP simulations for 90 MA at 2.9 MA/cm show acceptable cathode B field penetration (1-1.6 μm/ns for 100 ns rise)



Experiment on S-300 at Kurchatov at 6 MA/cm shows plasma did not reconnect the MITL gap

Present experiments and simulations indicate RTLs should work at 5 MA/cm or more

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RTLs made and pressure tested for structural strength: results compare favorably with code calculaions

- RTLs manufactured for tests (radius 50 cm, length 200 cm, thickness 0.635 mm)
- Pressure tests to buckling (U. Alabama)
- Analysis
  ANSYS (U. Wisconsin)
  ABAQUS (SNL)
  Singer Closed Form Solution
- Experiment results and code results predict buckling at about 70 Torr (as anticipated)
- Chamber pressure of 10-20 Torr has large safety margin

Studies to make stronger and lighter RTLs (stiffners, various shapes, etc.) under study

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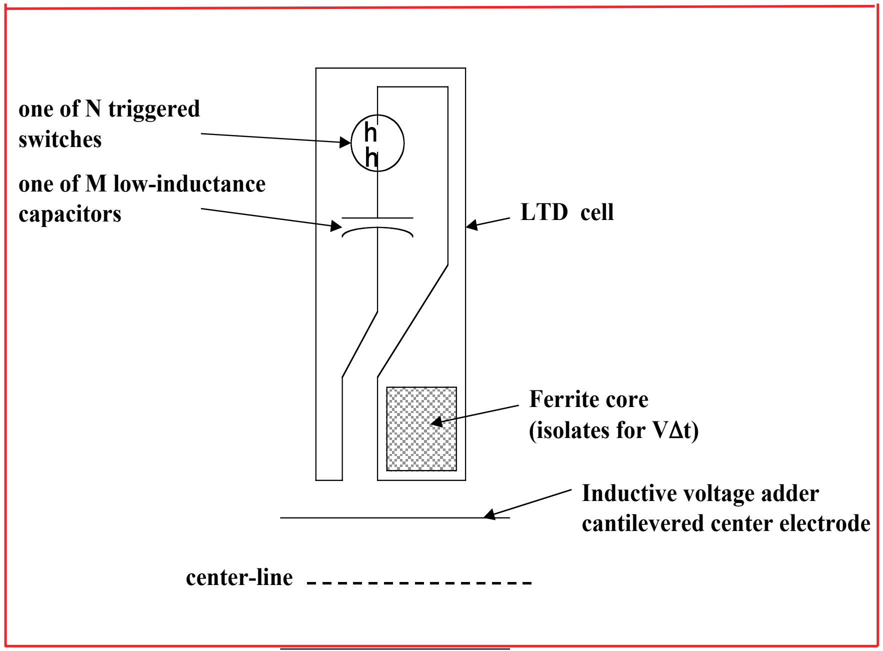
Linear Transformer Driver (LTD) technology is compact and easily rep-rateable

- 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 accelerator volume about 1/4 -1/3 the volume of Marx/water line technology (as used in Saturn and Z)
- LTD pioneered at Institute of High Current Electronics in Tomsk, Russia



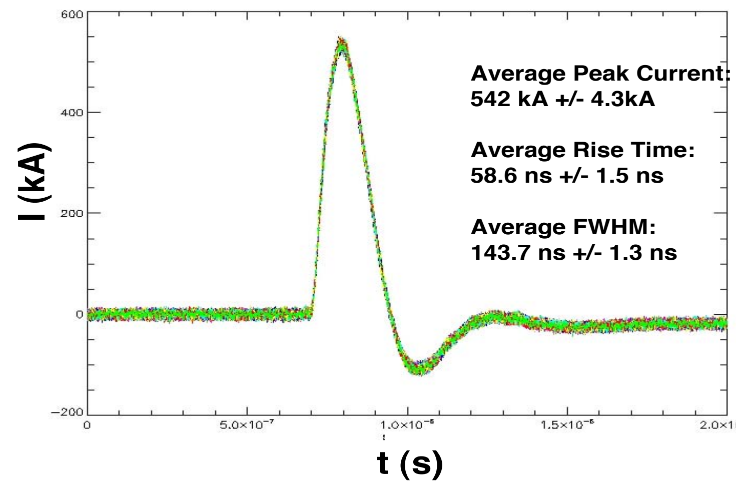
Modular

High Efficiency

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

Easily made repetitive for 0.1 Hz

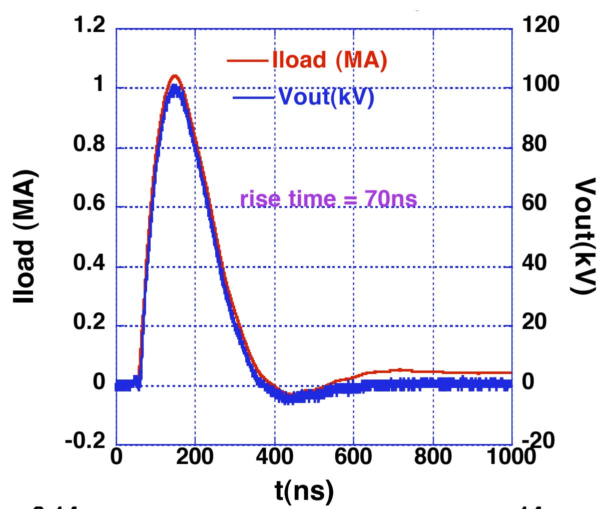
Repetitive, 0.5 MA, 100-kV LTD Cavity in operation at SNL

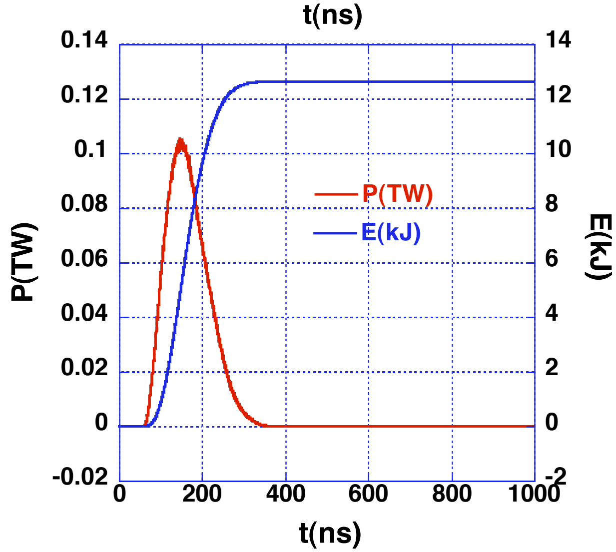


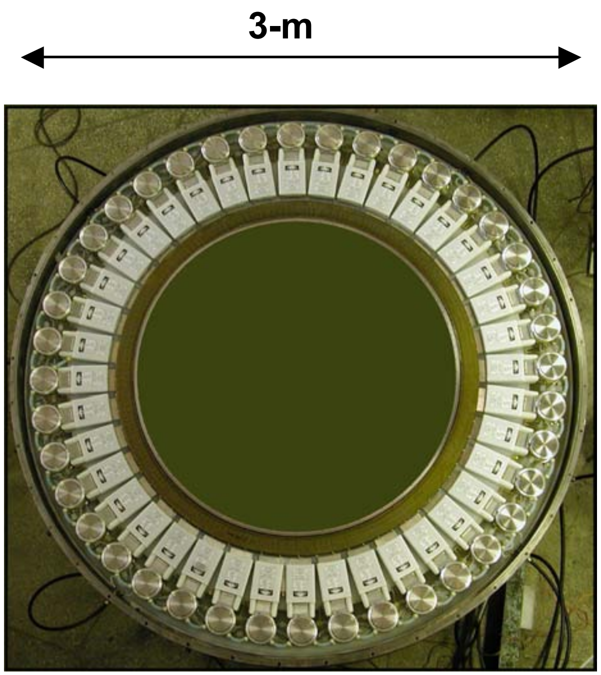
Overlay of 100 shots at 0.03 Hz for 90 kV charging

This 0.5 MA cavity has exceeded 1000 shots in rep-rated mode at 0.03 Hz (one shot every 30 seconds)

1.0 MA LTD cavity built - performs as expected during first 100 shots (this is the building block for Z-PoP and future Z-IFE drivers)







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

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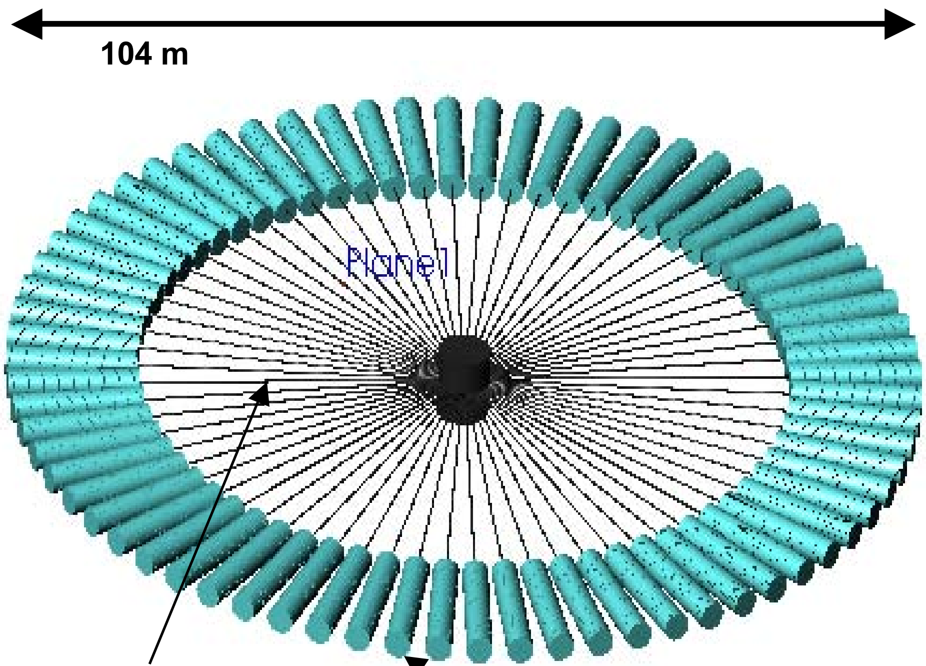
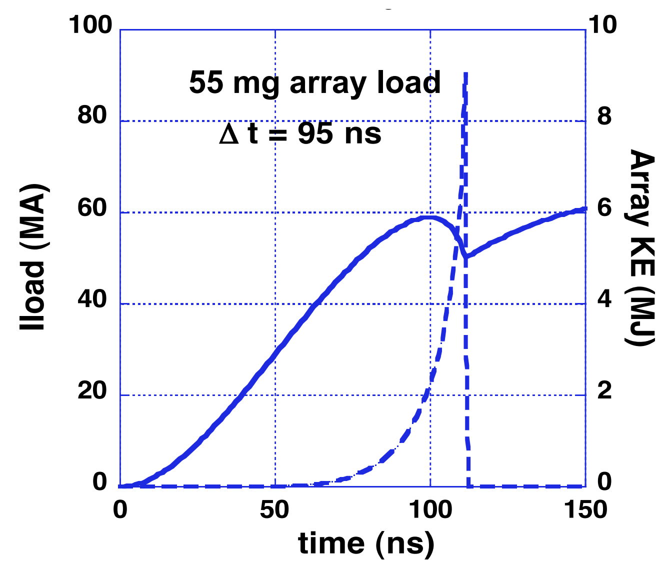
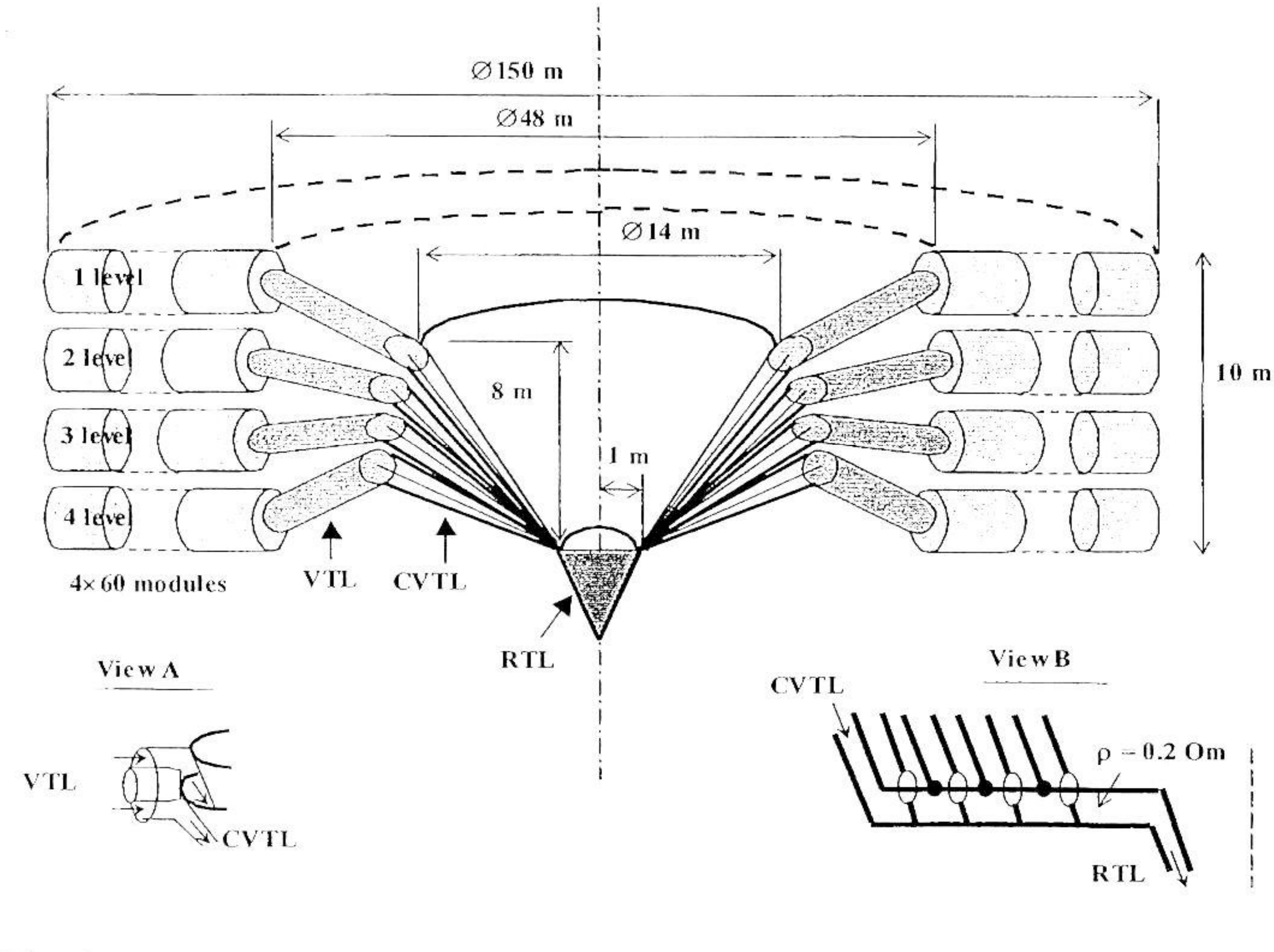
An IFE driver with seventy 1-MA voltage adder modules, each with 70 LTD cavities



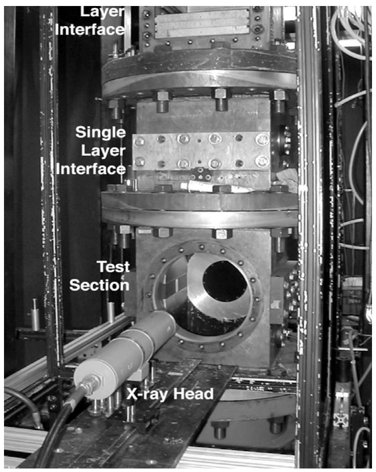


90-MA IFE Driver (model 1) concept from the Kurchatov Institute, Moscow



Shock mitigation experiments in progress

Shock tube tests with water layers, Al foams

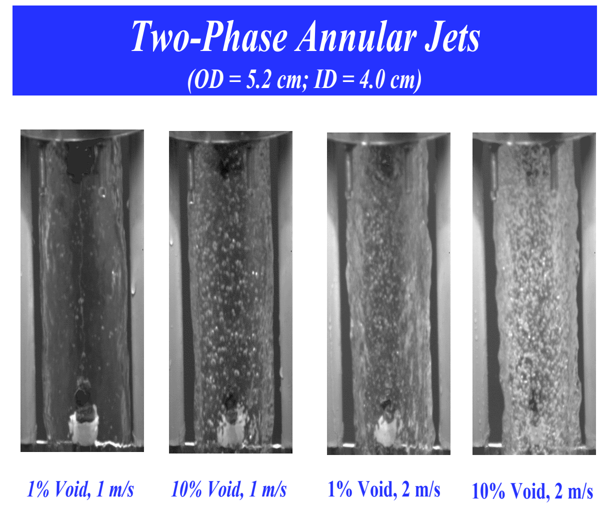


Shock tube facility at the University of Wisconsin

Explosives with water curtain

Vacuum Hydraulics Experiment (VHEX) at UCB

Foamed liquid sheets

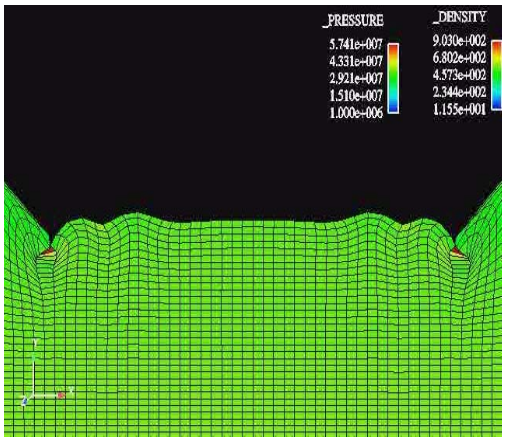


Georgia-Tech annular foamed jet

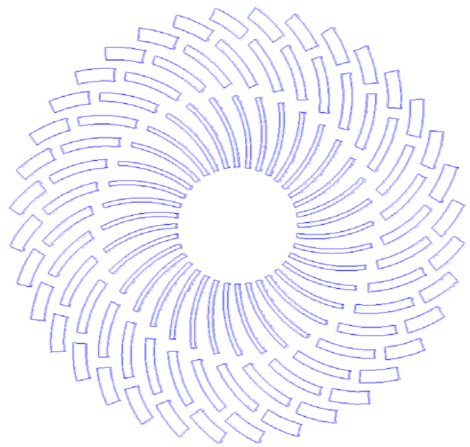
exploding wire creates shock

Shock mitigation code calculations in progress

3. Shock mitigation



ALEGRA simulation of shocked Al metal foam sheet (SNL)

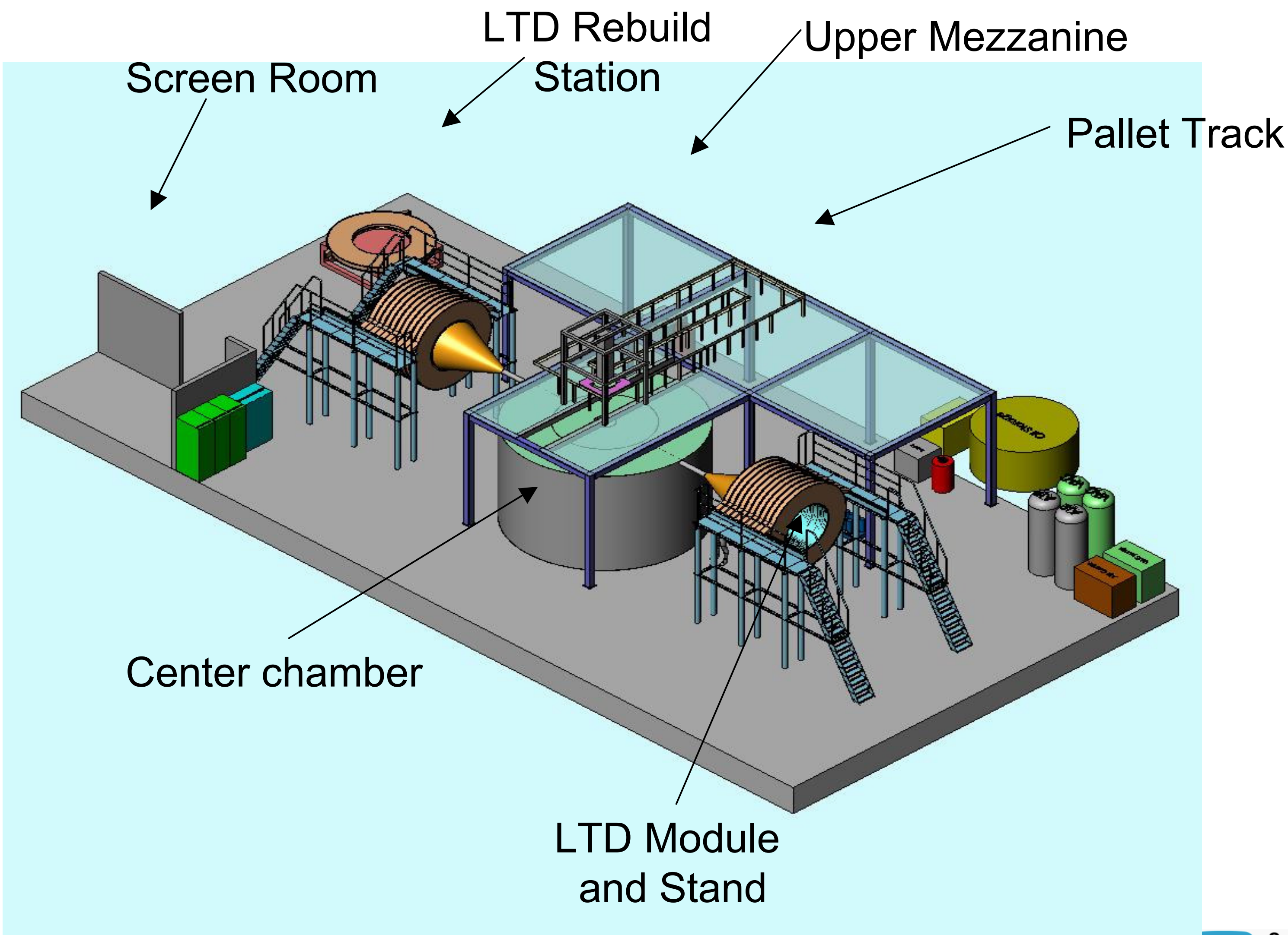


Flibe jet geometry for shock mitigation (LLNL) - 3 GJ yield contained

- Liquid walls
- Foamed Flibe
- Liquid pool
- Bubbles

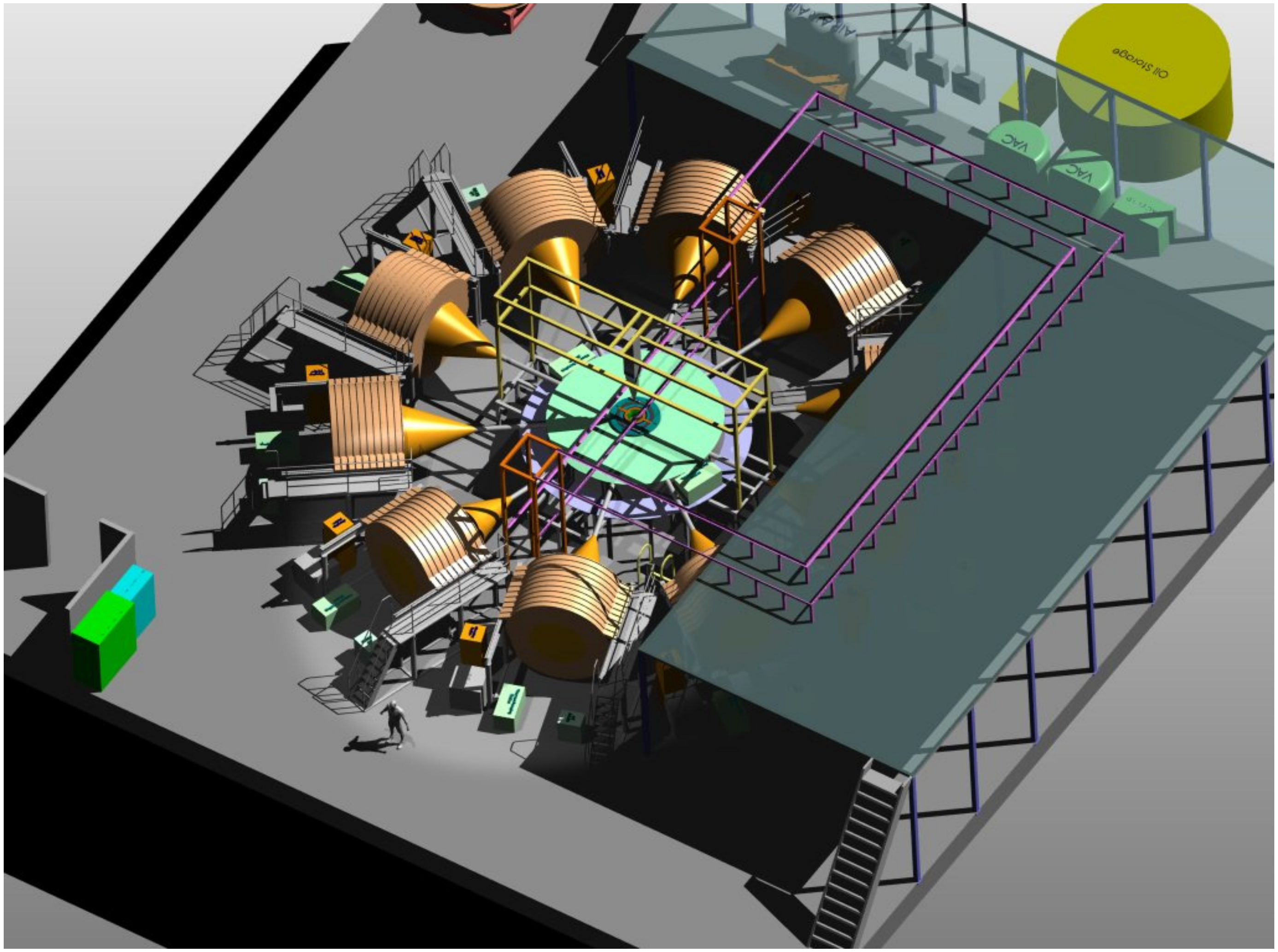
Dyna2D simulations (GA)

Z – PoP (two 1 MA legs)



Z – PoP (ten 1 MA legs)

comparable to a rep-rated Saturn at 10 MA



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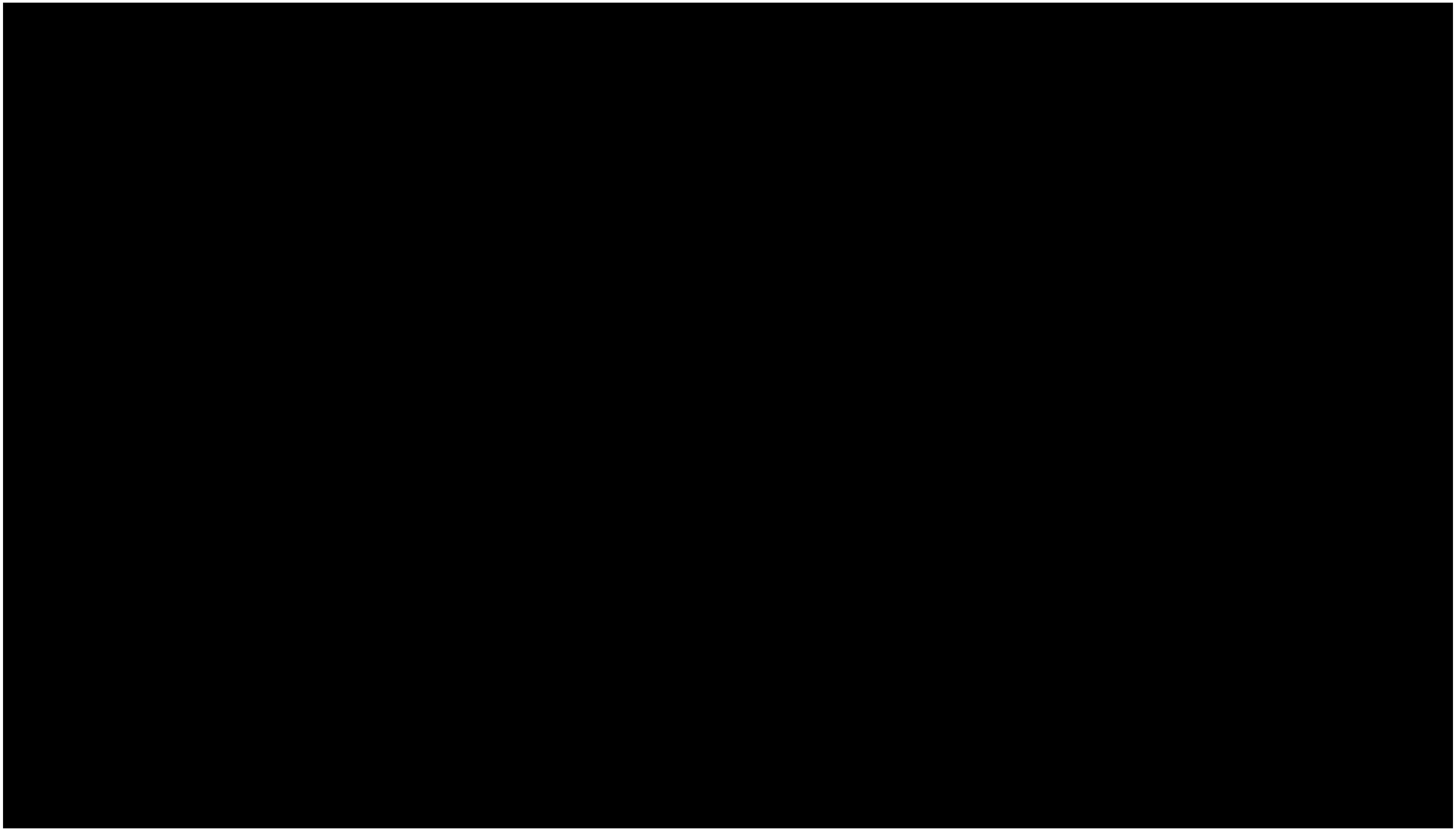
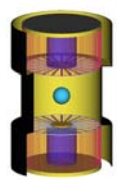
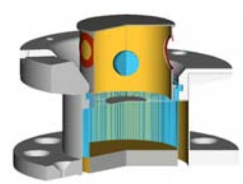
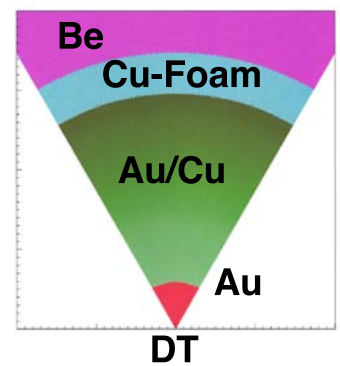
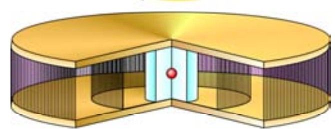
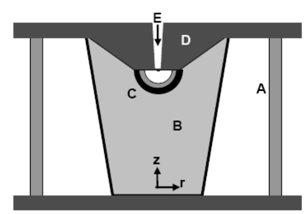
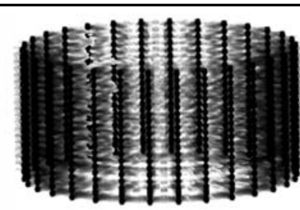
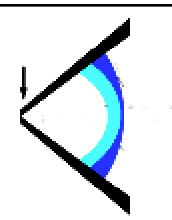
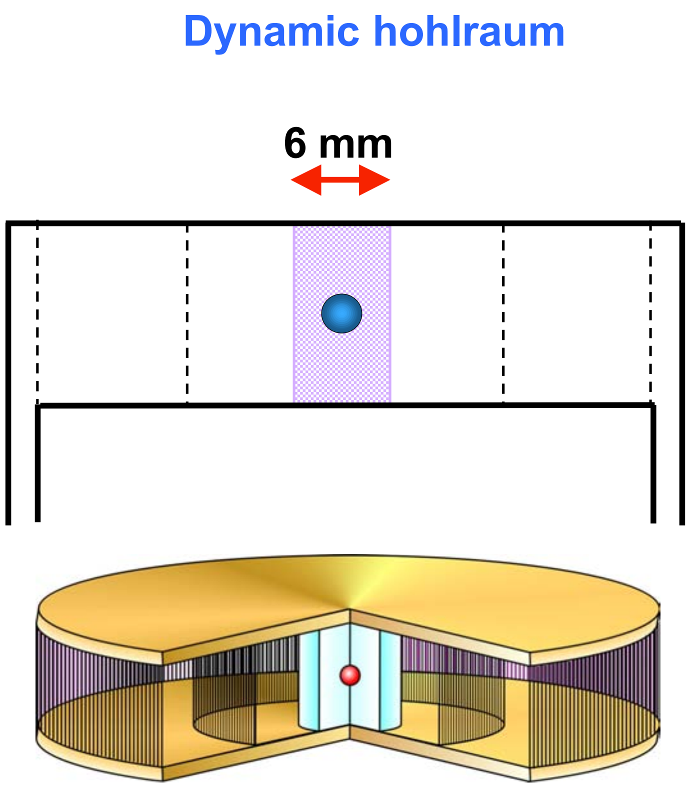
Z-PoP Movie

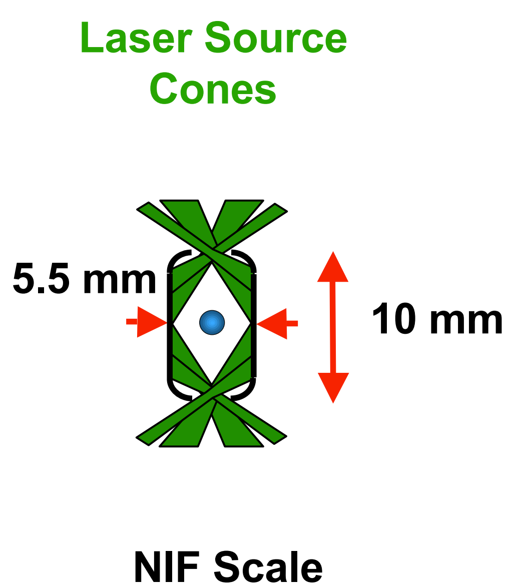


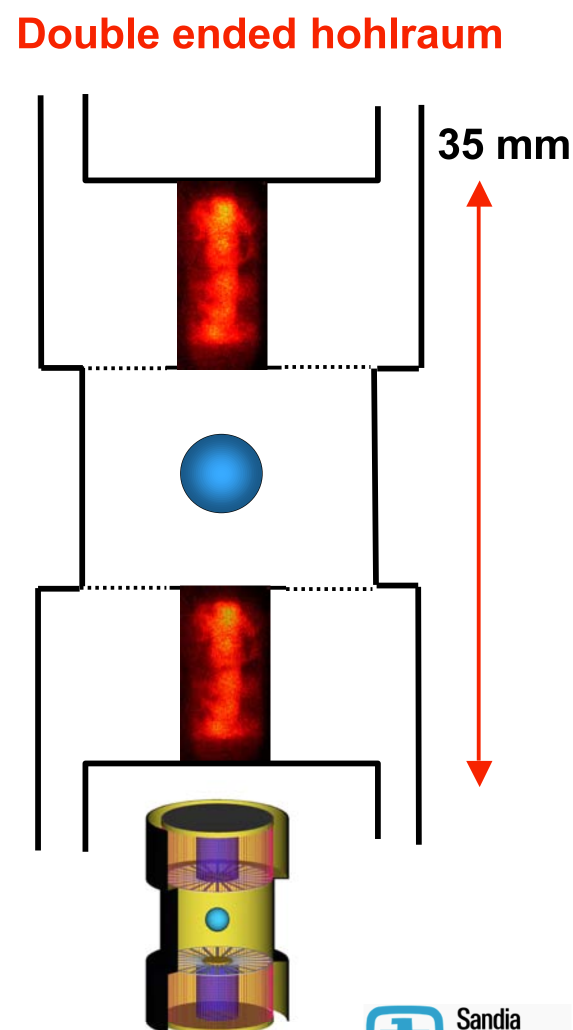
We are continuing to evaluate a diverse portfolio of ICF options for Z-pinch IFE

	Driver	ICF Target		
		Cryogenic		Gas fill
		Hot spot ignition	Fast ignition	Double shell
Indirect drive	Vacuum hohlraum			
Indirect drive	Dynamic hohlraum			
NEW →	Hybrid Hohlraum			
Direct drive	Magnetic field			

Z-pinch-driven-hohlraums have similar topology to laser-driven-hohlraums, but larger scale-size







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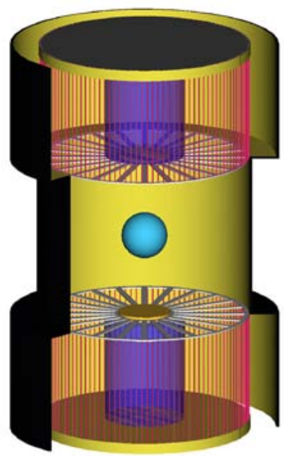
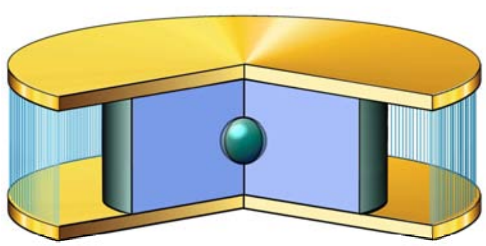
We are exploring 2 complementary Z-pinch indirect-drive target concepts for high-yield ICF and Z-IFE

Double-Ended Hohlraum



	ICF _ IFE
Peak current	2 x (62 – 116) MA
Energy delivered to pinches	2 x (19 – 67) MJ
Z-pinch x-ray energy output	2 x (9 – 33) MJ
Capsule absorbed energy	1.2 – 8.6 MJ
Capsule yield	400 – 4500 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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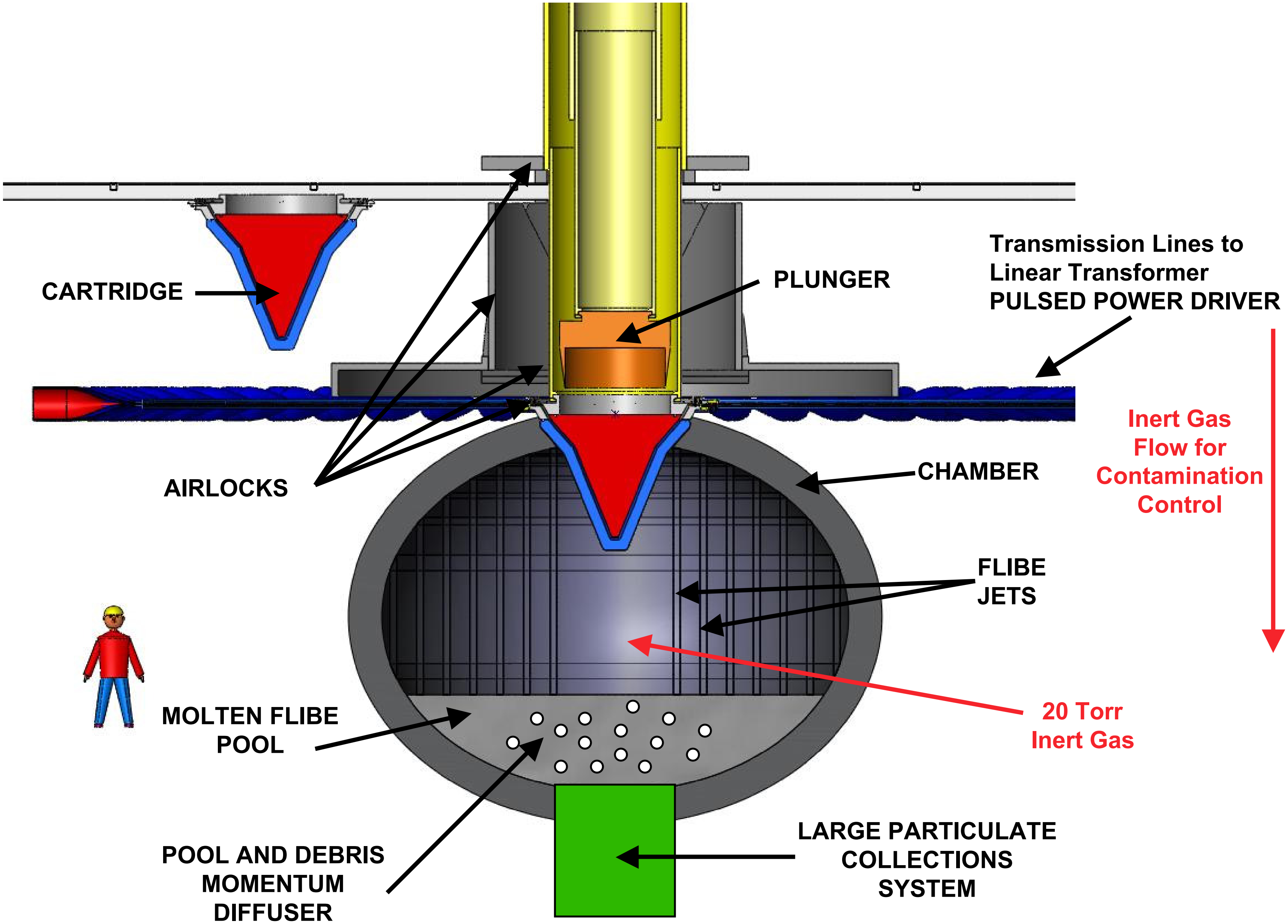
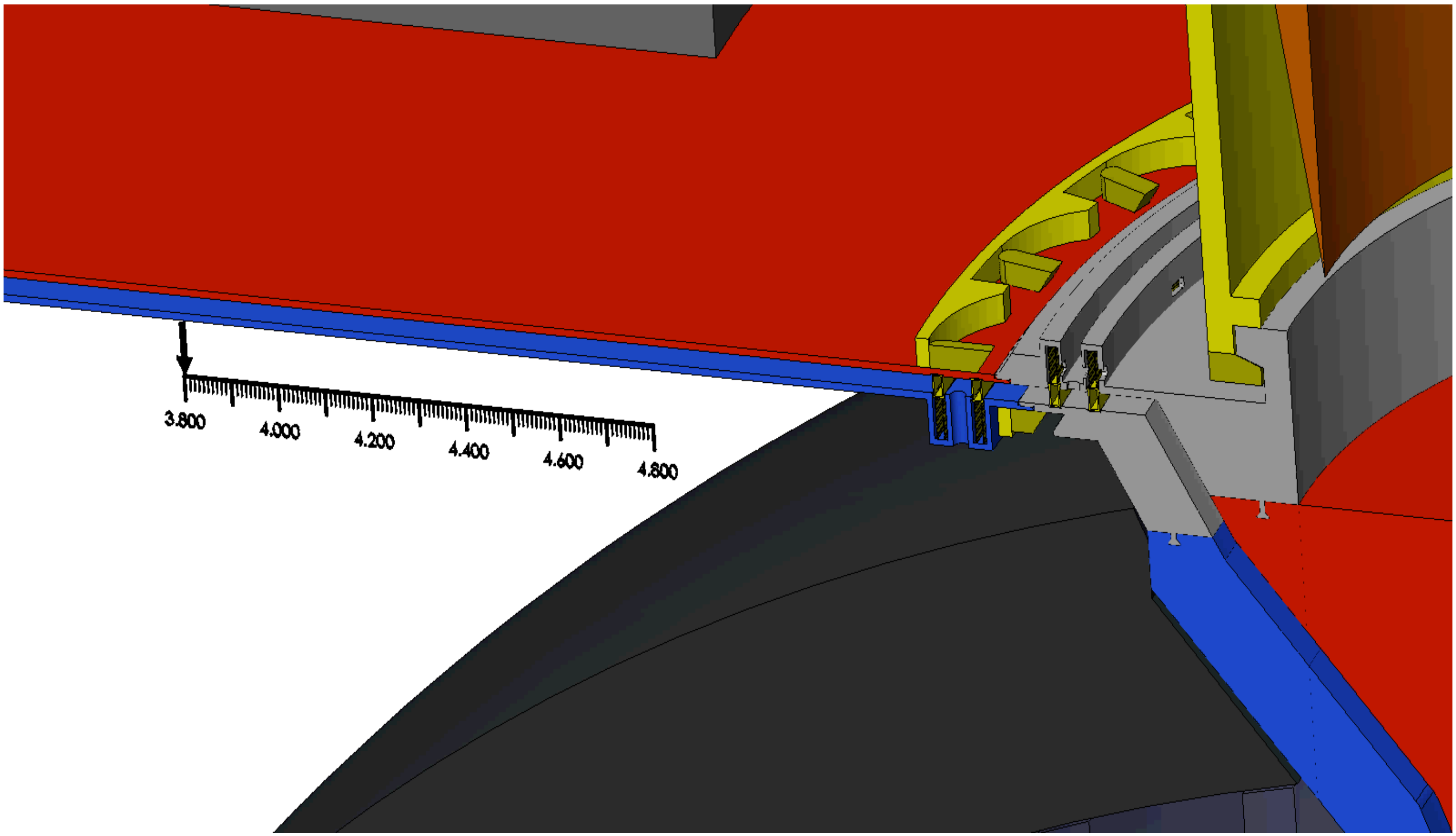
BASE Z-IFE UNIT



RTL Operation



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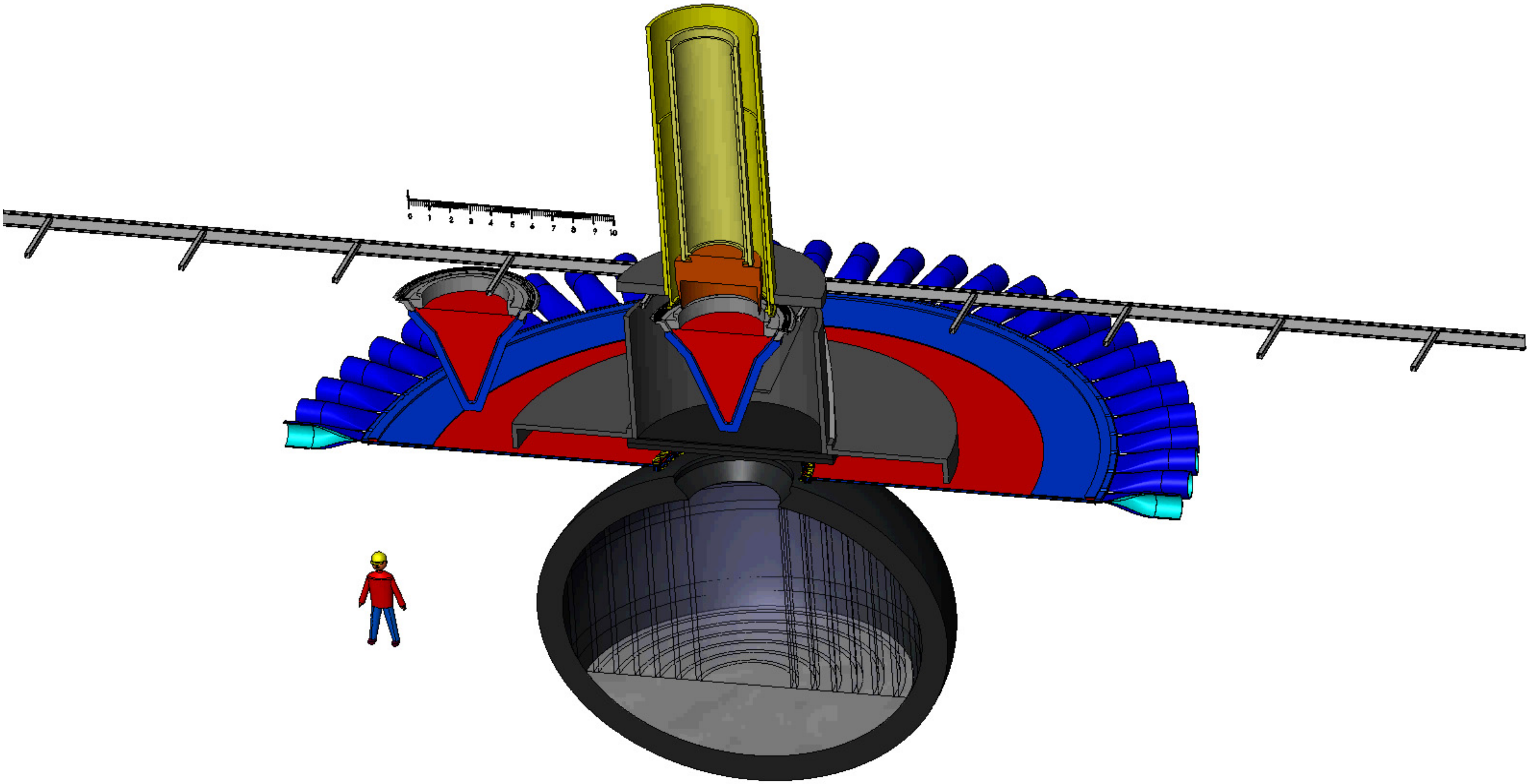
6. Z-IFE Power Plant



Z-Pinch Power Plant Baseline Parameters

Target Yield	3 GJ
Rep. Rate (per chamber)	0.1 Hz
Fusion Power per chamber	300 MWth
Number of Chambers	10

Chamber

Shape	Spherical or
Ellipsoidal	
Dimension	4 m internal radius
Material	F82H Steel
Wall Thickness	15-30 cm

Coolant

Coolant Choice	Flibe
Jet Design	Circular Array
Standoff (Target to First Jet)	0-2 m
Void Fraction	0.05 – 0.67
Curtain Operating Temperature	950 K
Average Curtain Coolant Flow	12 m^3/s
Heat Exchanger Coolant Flow	0.47 m^3/s
Heat Exchanger Temp. Drop	133 K
Pumping Power	1.3 MW/chamber
Heat Cycle	Rankine
Heat Exchanger Type	Shell and Tube

Tritium Recovery

Breeding Ratio	1.1
Tritium Recovered per Shot	0.017 g
Extraction Type	Countercurrent

RTL

RTL Material	1004 Carbon Steel
Cone Dimensions	1 m Ø x 0.1 m Ø x 2 m h
Outer Cone Thickness	0.9 mm _ 0.52 mm
Inner Cone Thickness	0.52 mm
Mass per RTL (2 cones)	50 kg _ 34 kg

RTL Manufacturing

Furnace	Electric Arc
Production	Sheet Metal to Deep Draw
Energy Demand	184 MW for ten chambers

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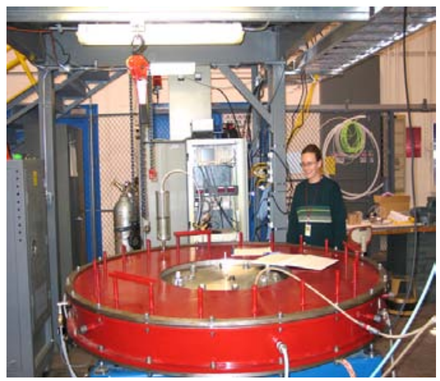
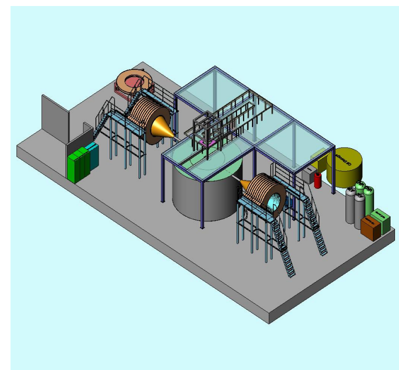
Z-Pinch Inertial Fusion Energy

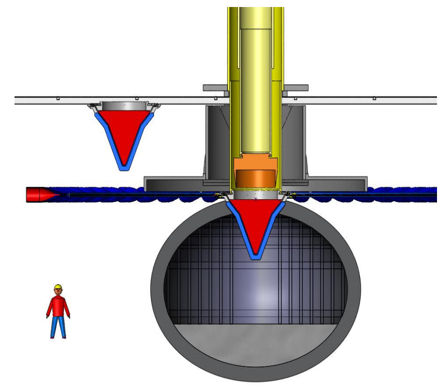
RTL



LTD driver



Z-PoP



Chamber

- **Substantial progress is being made in all area of Z-Pinch IFE**
- **A growing Z-Pinch IFE program is envisioned**