Status of Z-Pinch Research

*Refurbished **Z** Facility – September 2007*

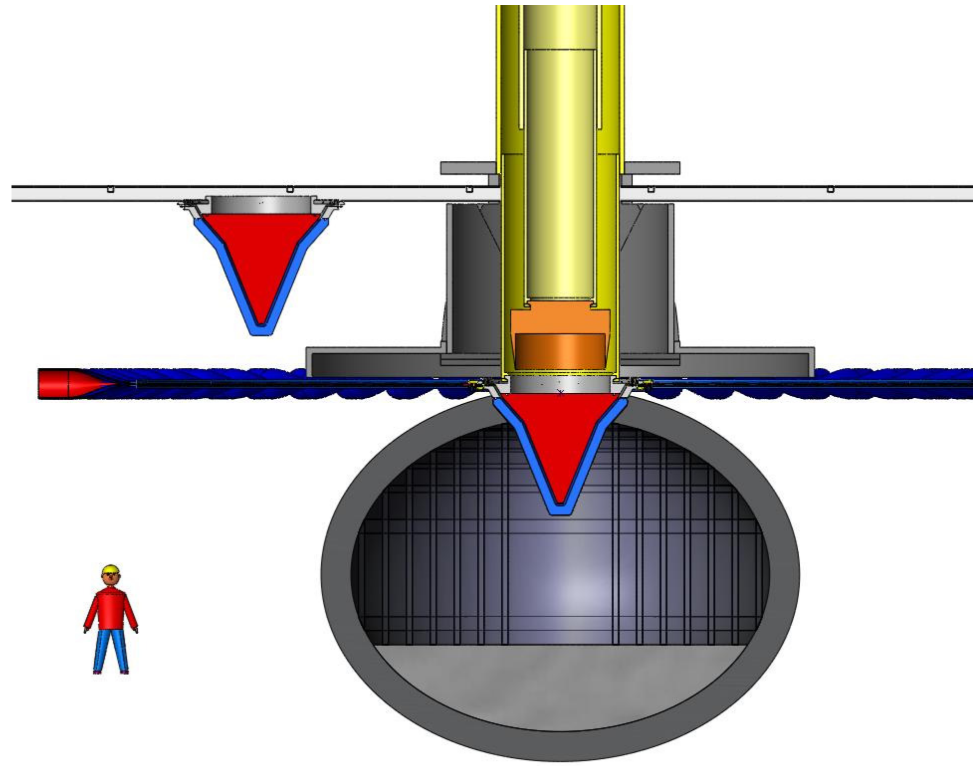
Fusion Power Associates
Annual Meeting and Symposium
Oak Ridge, Tennessee
December 4-5, 2007

Keith Matzen
Director
Pulsed Power Sciences
Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

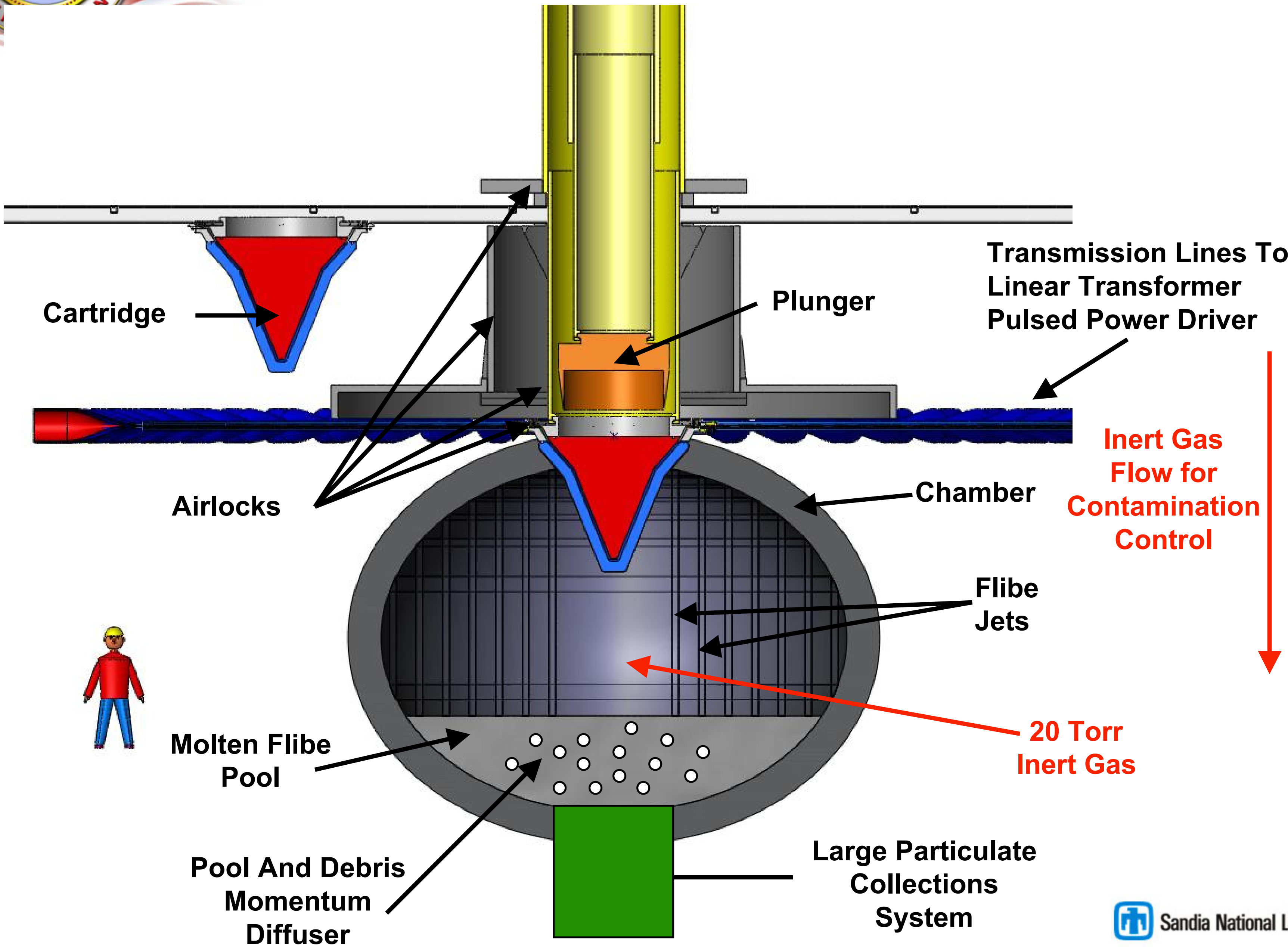
Outline

- **Status of Z-pinch IFE**
  - **No funding; IFE science and technology research "on hold"**
- **Update on refurbished *Z***
- **Update on pulsed power ICF**
- **Advances in pulsed power technology**



Z **is focused on single-shot ICF & HED research; fusion energy is the goal**

The Z-pinch IFE concept uses low rep-rate recyclable transmission lines, high yield targets, thick liquid wa



Many of the important issues and systems have been studied within the Z-IFE program

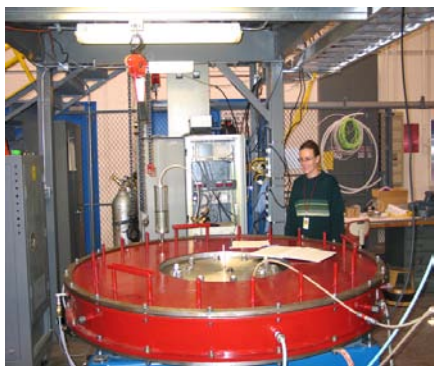
A pre-conceptual Z-pinch power plant design has established baseline parameters

1. Recyclable Transmission Lines (RTLs)

Simulations (> 5 MA/cm works)

Experiments (> 5 MA/cm works)

Fabrication of PoP-size RTLs and pressure testing



2. LTD repetitive driver

0.5 MA, 100 kV LTD cavity fires every 10 seconds

1.0 MA, 100 kV LTD cavities (5) voltage-adder tests

Full IFE driver architectures

3. Shock mitigation

Theory/simulations

Experiments: water ring/explosives
foamed liquids
shock tube/foams

4. Z-PoP planning

Vacuum/electrical connections

Overhead automation animations

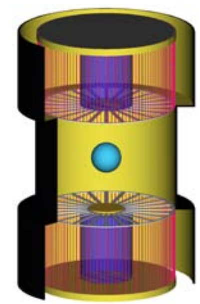
Costing

5. Z-IFE targets for 3 GJ yields

Gains ~ 50-100

Double-pinch/dynamic hohlraum

Scaling studies

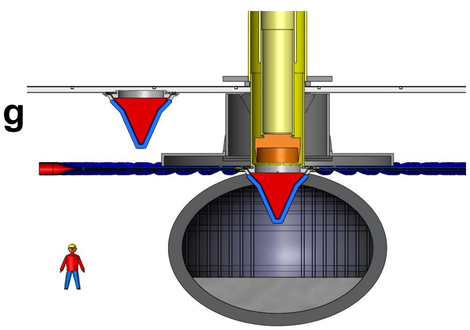


6. Z-IFE power Plant

RTL manufacturing/costing

Wall activation studies: 40 year lifetime

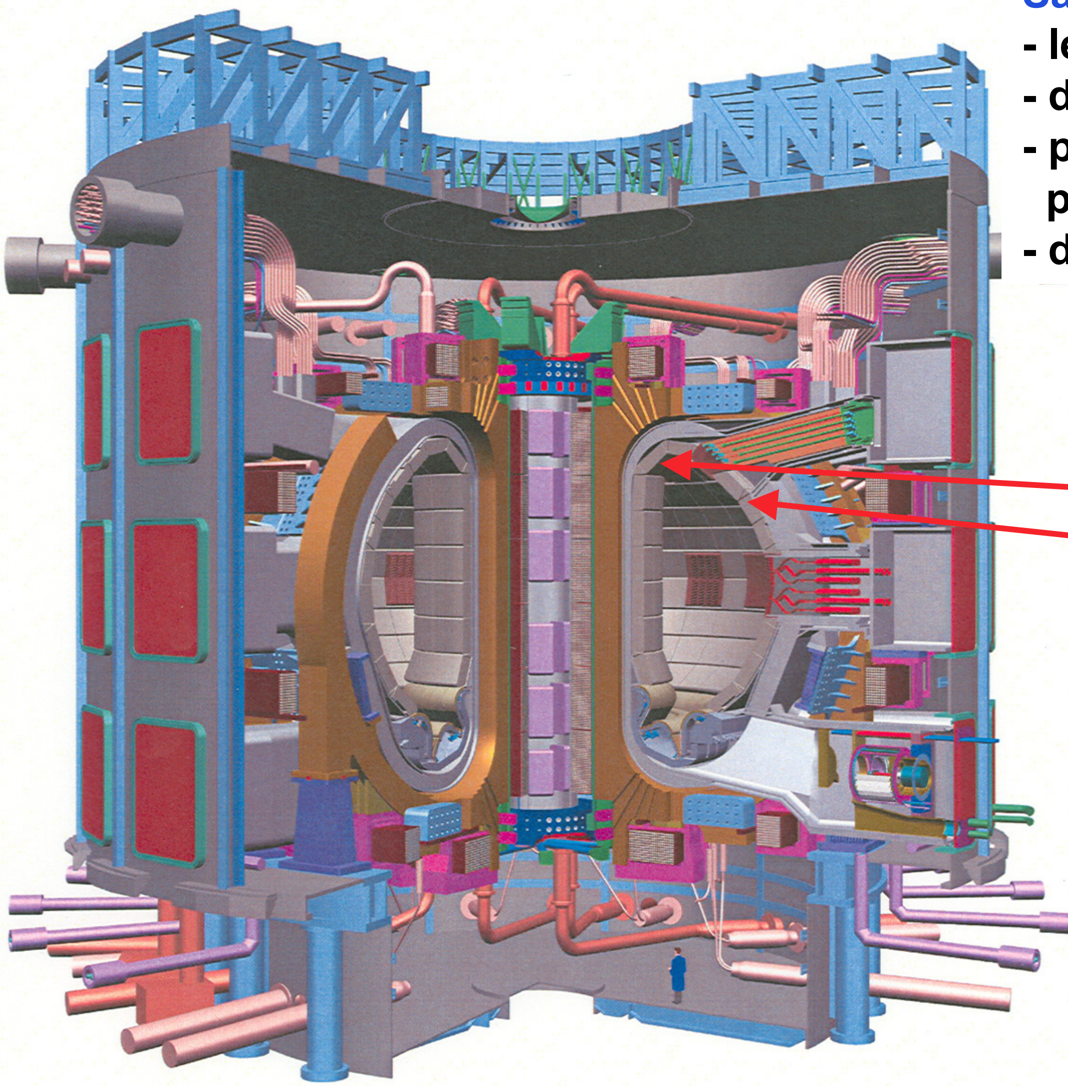
Power plant design +GNEP, transmutation



Results documented on 3 CDs

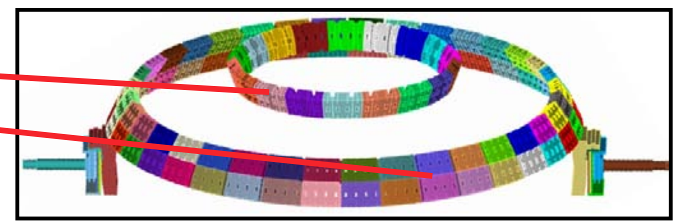
Sandia's ITER activities are within the Pulsed Power Sciences Center

The US is providing 20% of ITER's first wall modules and two port limiters



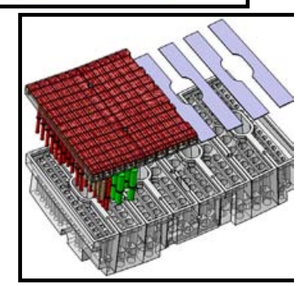
Sandia's role:

- lead design and R&D
- develop US industrial team
- perform R&D on joining of Be & evaluate performance at the PMTF facility
- develop QA procedures and test FW panels



Cooled port limiters

- Retractable, Be/Cu armor, articulation

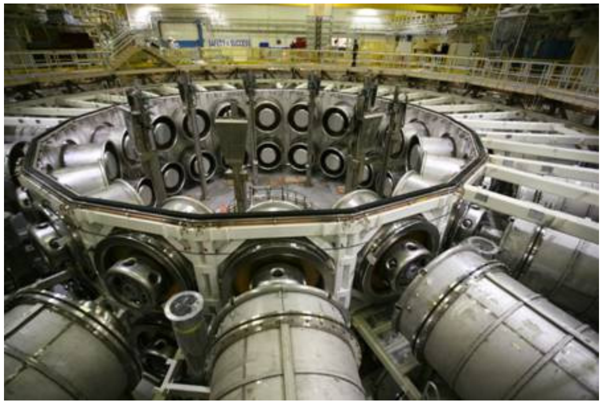


First Wall modules

- Shield blocks (90)
- FW panels (360)

Outline

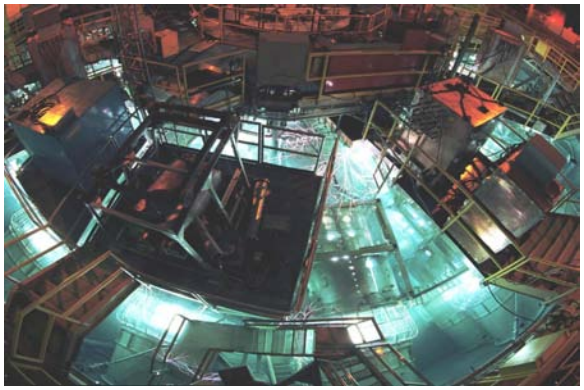
- Status of Z-pinch IFE
- **Update on refurbished *Z***
  - Project completed in September
  - Have delivered 26 MA to ICE load
- Update on pulsed power ICF
- Advances in pulsed power technology



The Z Refurbishment Project Concluded in Sep '07

14 Month Facility Outage

Last Shot Old Z



July '06

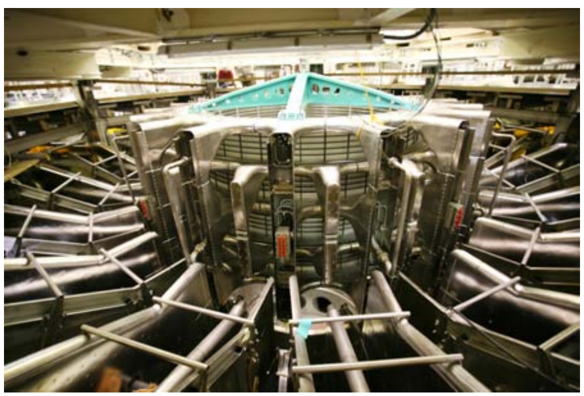
Demolition Completed

Sept '06

Tank Modifications Completed

Jan '07

Center Section Installed

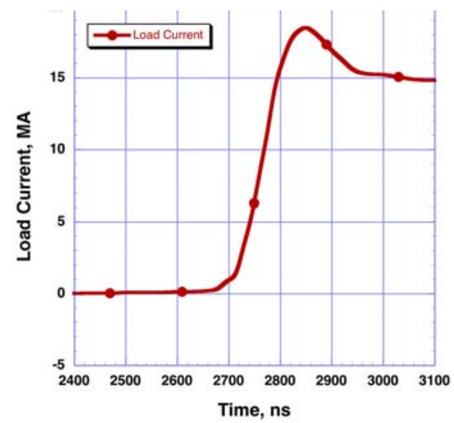


July '07

Installation Completed

Aug '07

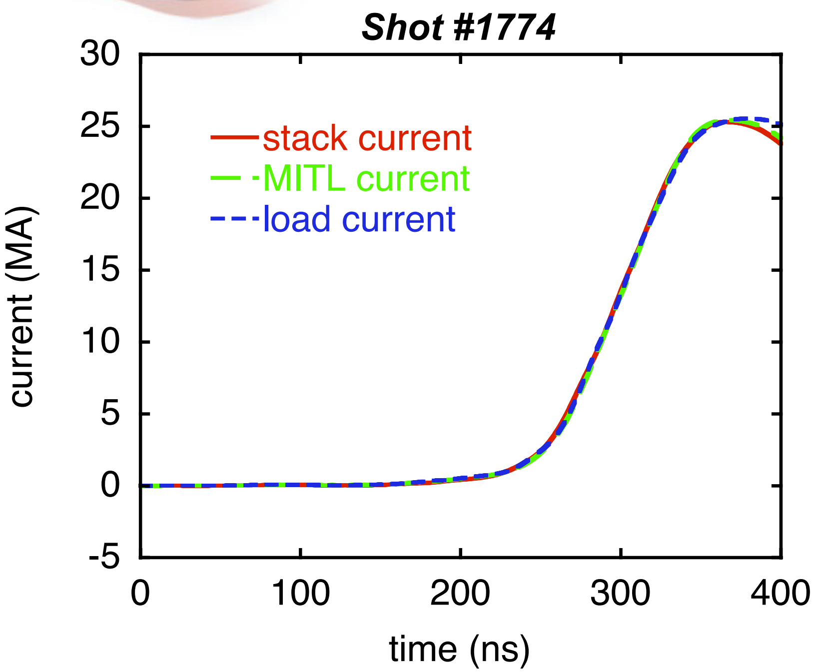
First System Test – New Z



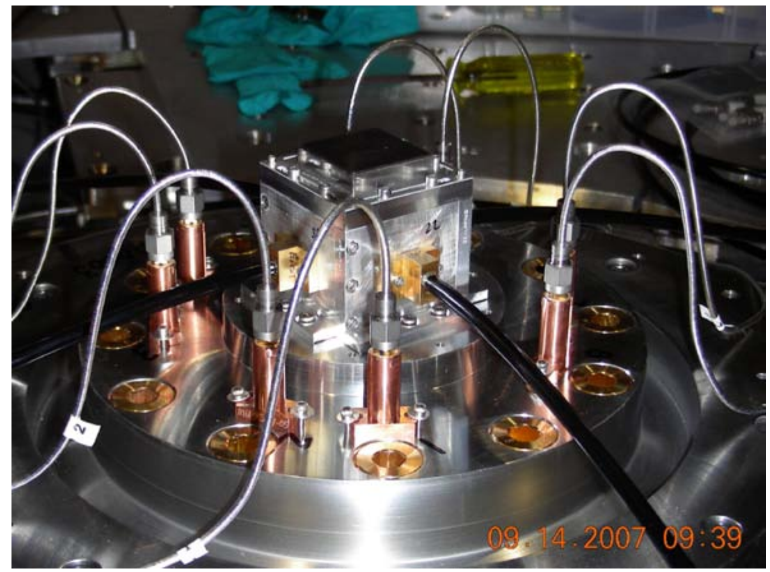
Sept '07

Sandia National Labora

Z-shot #1775 achieved a load current of 26.4 MA



The measured load current is slightly higher than the MITL current, and the MITL is slightly higher than the stack, as expected.



Z-shot number	Marx-Charge voltage	Peak load current
1770	70 kV	20.6 MA
1772	75 kV	22.8 MA
1773	80 kV	23.8 MA
1774	85 kV	25.6 MA
1775	90 kV	26.4 MA

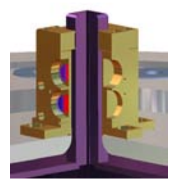
Experimental benefits of Refurbished *Z*

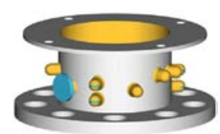
Precision & pulse flexibility will enable:

- New experimental regimes
- Improved timing with Z Backlighter & Z Petawatt

More current than on *Z* will enable up to:

- 50% increase – x-ray power radiated
- 70% increase – x-ray energy radiated
- 15-20% increase - temperature
- 3x increase - peak ICE pressure
- 40% increase - flyer plate velocity


Equation of State


Radiation Flow


Radiation Effects


ICF

Z-Petawatt will enable high photon energy backlightin and fast ignition physics experiments on *Z*

Z Backlighter

ZBeamlet

- λ = 527 nm
- June 2001:
  - τ = 0.3 – 8 ns
  - ϕ ~75 μm spotsize
  - E < 2 kJ
  - I < 10^{17} W/cm^2
- Goal in 2008
  - Multi-frame @ 6.151 keV

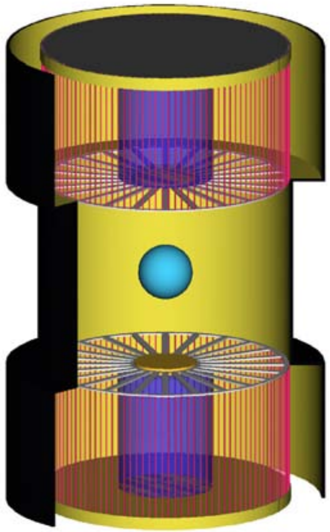
ZPetawatt

- λ = 1054 nm
- December 2007:
  - τ = 500 fs min
  - ϕ ~30 μm spotsize
  - E < 500 J
  - I > 10^{20} W/cm^2
- Goal in 2009
  - 2 kJ/10 ps

Compression chamber installation

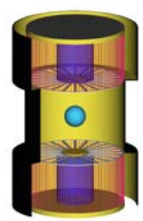
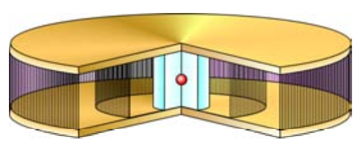
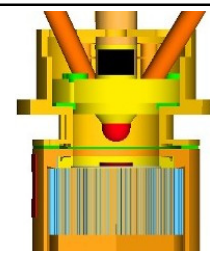
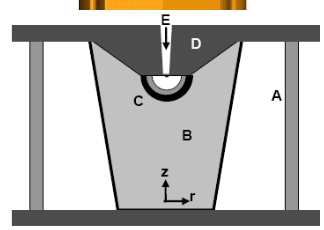
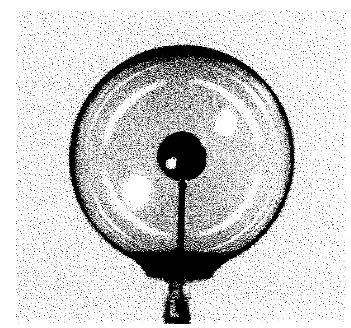
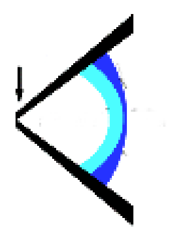
Outline

- Status of Z-pinch IFE
- Update on refurbished *Z*
- **Update on pulsed power ICF**
  - Experimentally demonstrated symmetry, pulsed shaping, energy coupling, and capsule implosions
  - Integrated 2D high fusion yield designs
- Advances in pulsed power technology

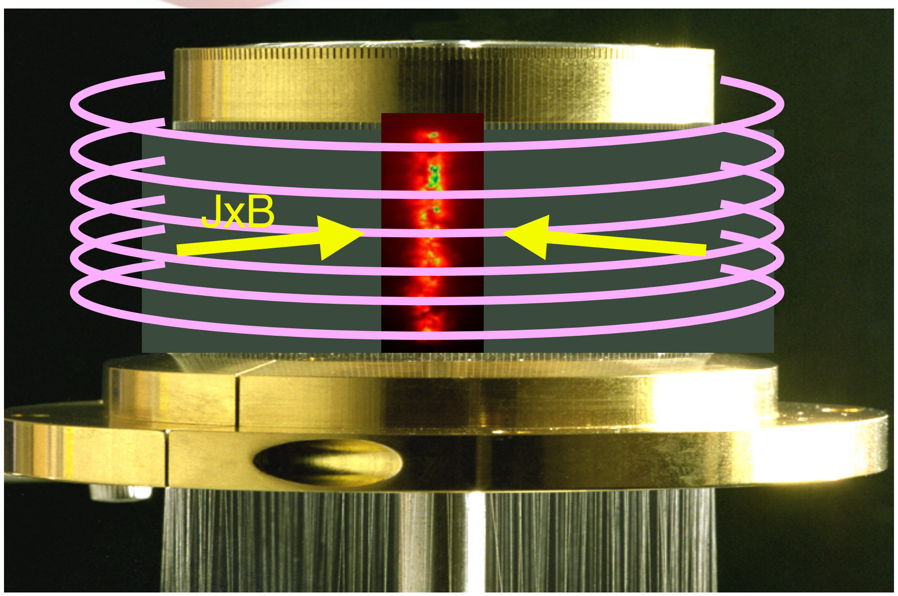


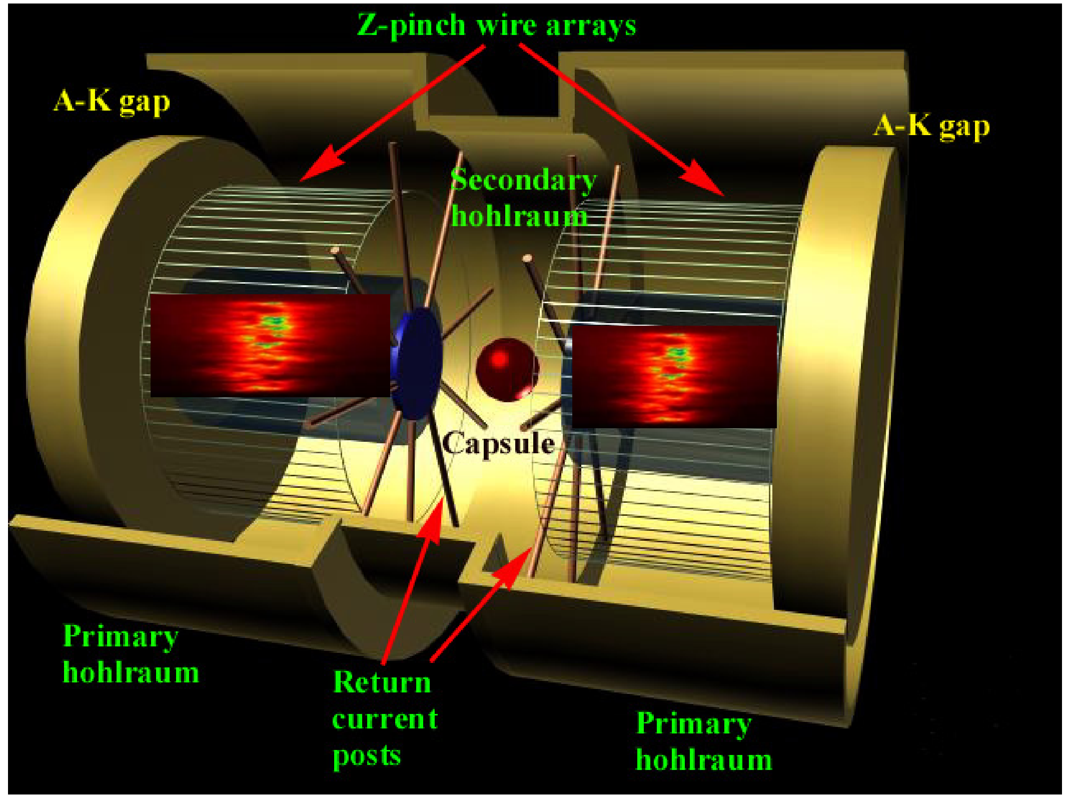
Double-ended hohlraum

Z and Z-Beamlet/Petawatt support a diverse researc portfolio of ignition & high yield ICF options

	Driver	ICF Target		
		Cryogenic		Non-cryogenic
		Hot spot ignition	Fast ignition	Double shell
X-ray drive	Vacuum hohlraum Dynamic hohlraum	 	 	
Direct drive	Magnetic field			

The double-ended hohlraum concept separates capsule, hohlraum, and z-pinch physics issues



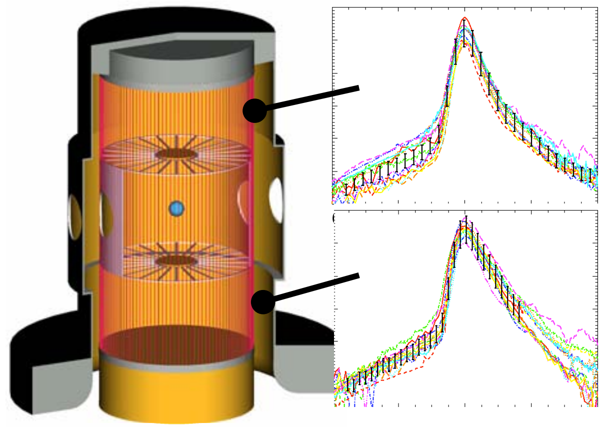


- Demonstrated ignition in 2D hohlraum + capsule simulations for the first time
- Robustness of 220 eV capsules is suitable for Z-pinch driven hohlraum
- Developed strategy to control time-dependent hohlraum symmetry
- Capsule absorbs 7% of the z-pinch-generated x-ray energy

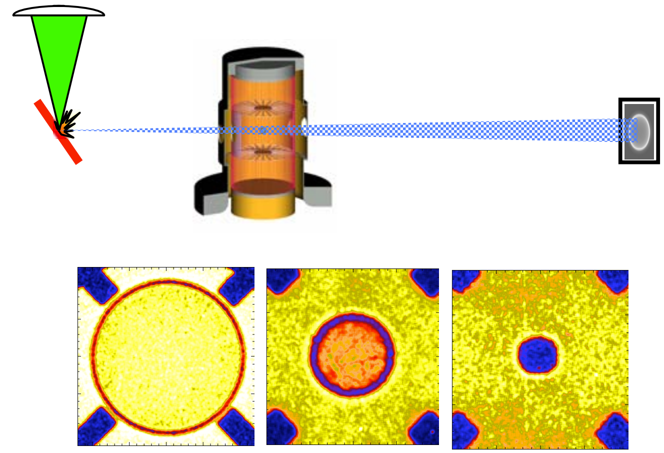
Sandia National Labora

The integrated target design builds on several years of validation experiments on *Z*

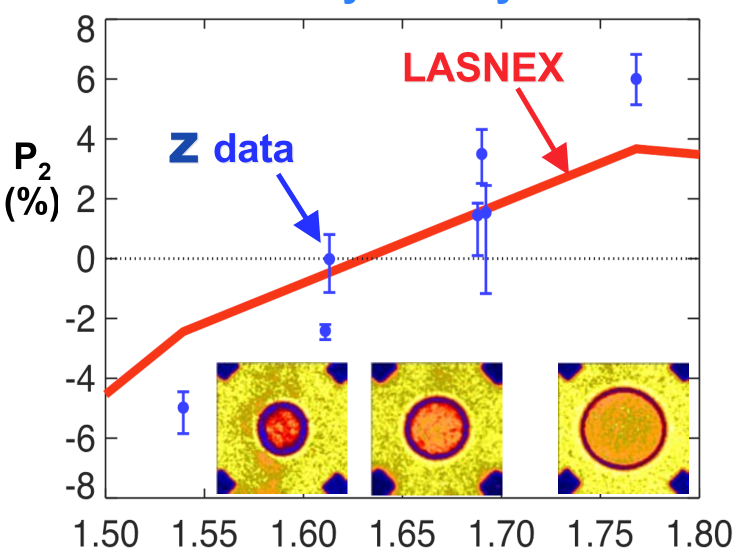
Double pinch development



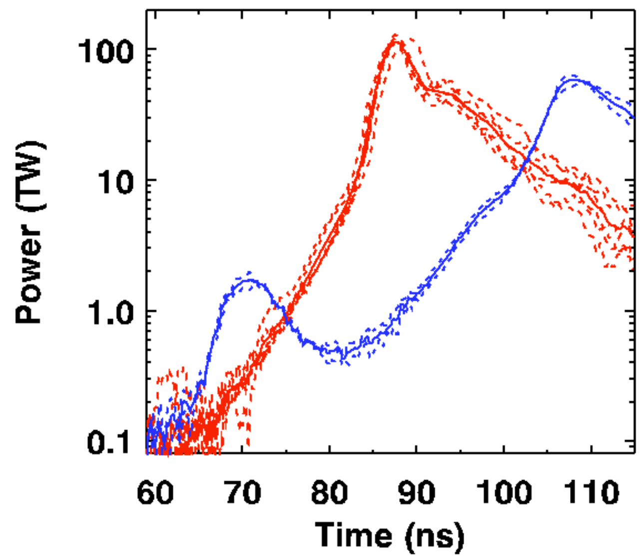
Z-Backlighter development



Symmetry

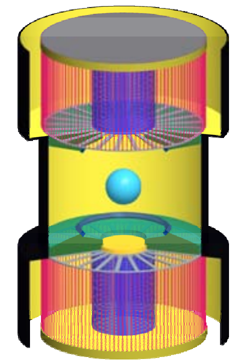


Pulse shaping



Sandia National Labora

We have developed a modern high-yield target desig for the z-pinch-driven double-ended hohlraum

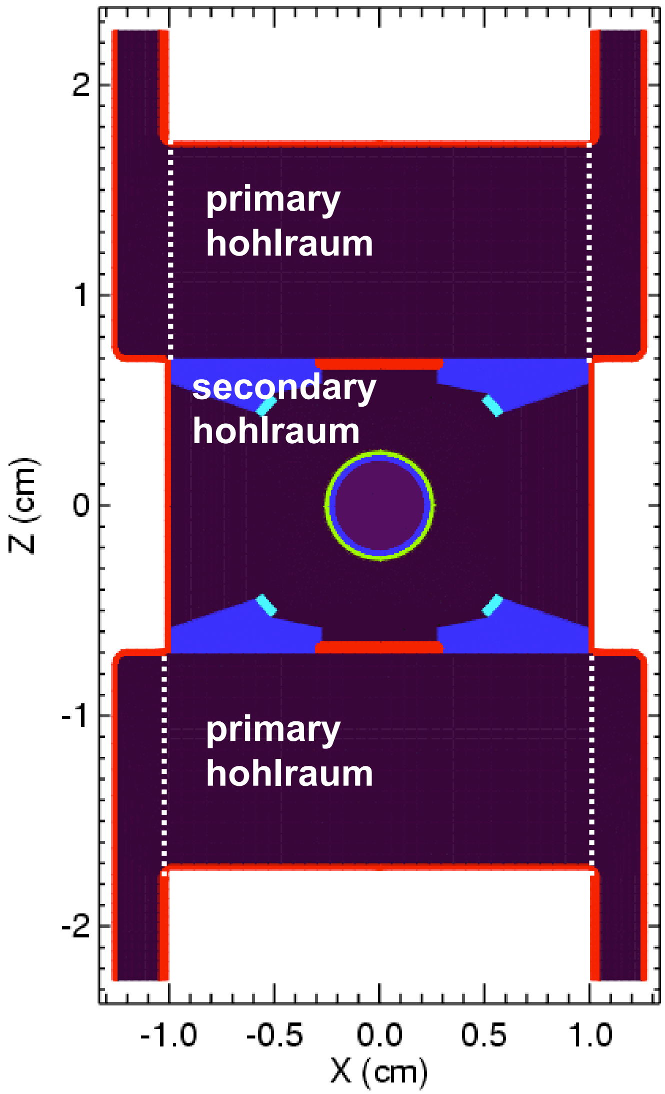


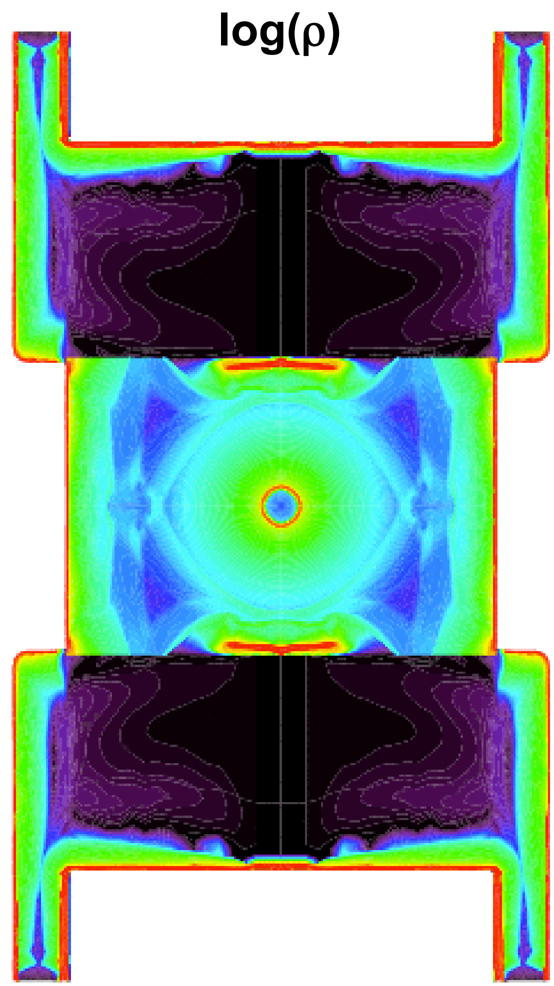
J. Hammer, M. Tabak, S. Wilks, *et al., Phys. Plasmas* **6**, 2129 (1999)

R. A. Vesey, M. C. Herrmann, R. W. Lemke et al., *Phys. Plasmas* **14**, 056302 (2007)

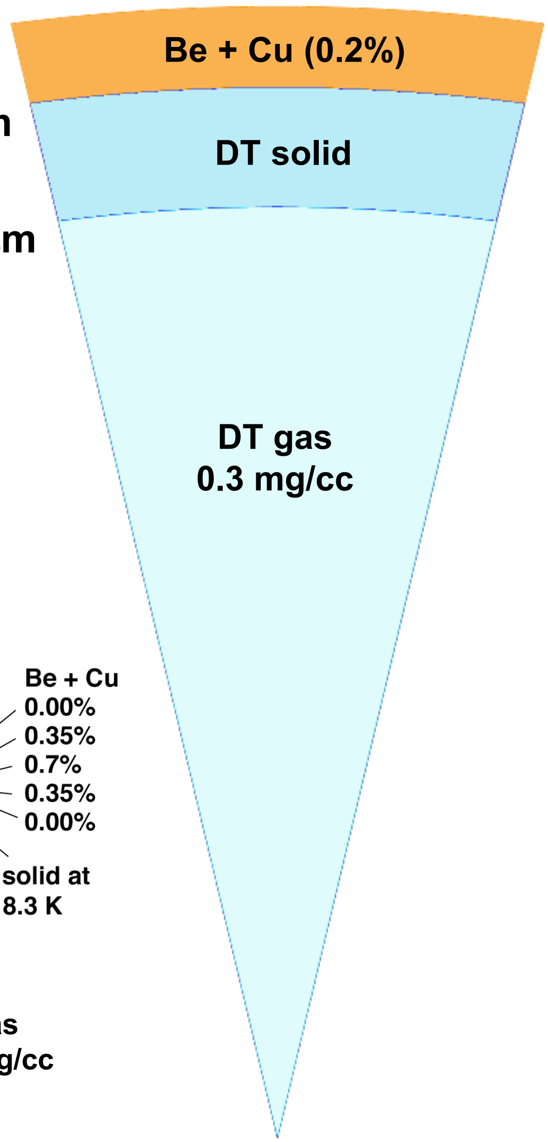
- **Demonstrated ignition in 2D LASNEX hohlraum+capsule simulations for the first time**
- **Developed strategy to control time-dependent hohlraum symmetry**
- **Robustness of 220 eV capsules is suitable for z-pinch driven hohlraum**
- **Defining Z-pinch and accelerator requirements based on the capsule and hohlraum requirements**
- **Extending target design work to smaller scale vacuum hohlraums including advanced compact x-ray sources**

2D LASNEX hohlraum + capsule simulations capture th essential physics of radiation coupling and symmetry

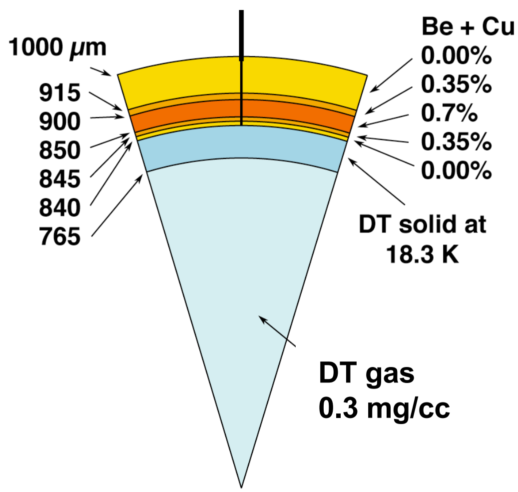




The current high yield target design centers around a beryllium ablator capsule with 500 MJ fusion yield



NIF Layered Be capsule



1D capsule parameters

Capsule	NIF Rev1[1]	DEH capsule
Ablator outer radius (mm)	1.0	2.65
Peak drive temperature (eV)	300	220
Ablator thickness (μm)	160	190
DT fuel thickness (μm)	75	280
DT fuel mass (mg)	0.15	4.74
Absorbed energy (MJ)	0.14	1.21
Yield (MJ)	13	520
Peak ρr (g/cm^2)	1.9	3.1
Implosion velocity (cm/μs)	36.4	26.0
Fuel KE margin	33%	29%
Hot spot convergence ratio	36	34

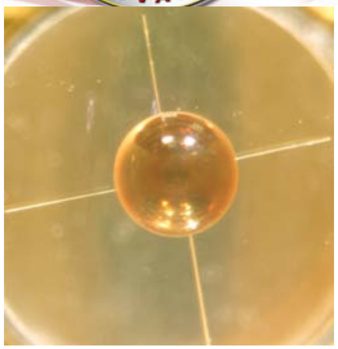
[1]NIF ignition point design layered Be capsule Rev 1

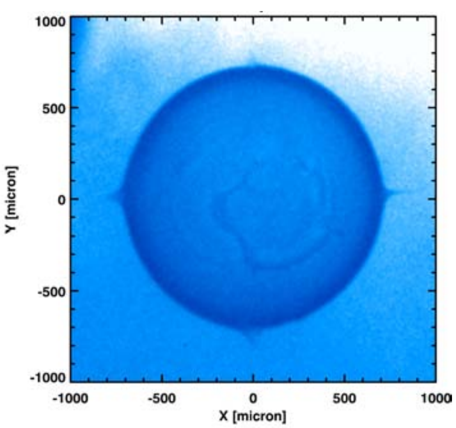
Recent Publications

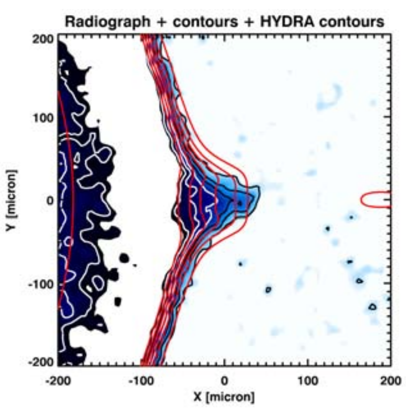
Recent Publications Relevant to the Double Z-Pinch Target Design:

- D. B. Sinars et al., *Phys. Plasmas* **12**, 056303 (2005) -- Wire array radiography
- M. E. Cuneo et al., *Phys. Rev. E* **71**, 046406 (2005) -- Wire array trajectories
- W. A. Stygar et al., *Phys. Rev. E* **72**, 026404 (2005) -- High yield system scaling
- M. E. Cuneo et al., *Phys. Rev. Lett.* **95**, 185001 (2005) -- Z-pinch pulse shaping experiments
- M. E. Cuneo et al., *Plasma Phys. Control. Fusion* **48**, R1 (2006) -- Concept review
- R. A. Vesey et al., *J. Phys. IV France* **133**, 1167 (2006) -- 2D hohlraum model validation
- M. E. Cuneo et al., *Phys. Plasmas* **13**, 056318 (2006) -- Nested wire array dynamics
- R. A. Vesey et al., *Phys. Plasmas* **14**, 056302 (2007) -- 500 MJ high yield target design
- W. A. Stygar et al., *Phys. Rev. ST Accel. Beams* **10**, 030401 (2007) -- Accelerator architecture

Double-ended hohlraum experimental platform enable experiments on NIC-capsule fill tube hydrodynamics







Issue: How well do simulations model the perturbations arising from the presence of fill tubes on inertial confinement fusion capsules?

Ignition scale capsules with multiple ignition-scale tubes attached were made and characterized

Experiments on Z imaged the perturbation growth with ~10 μm resolution using 6.151 keV backlighting

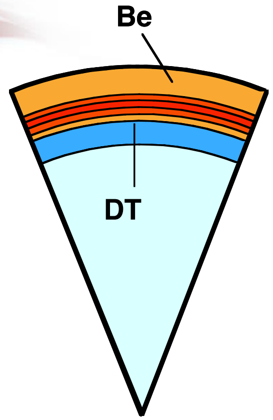
HYDRA simulations are within ~ 30% of the experimental measurements

This level of agreement increases our confidence that perturbations from fill tubes will not be a problem for the first ignition experiments

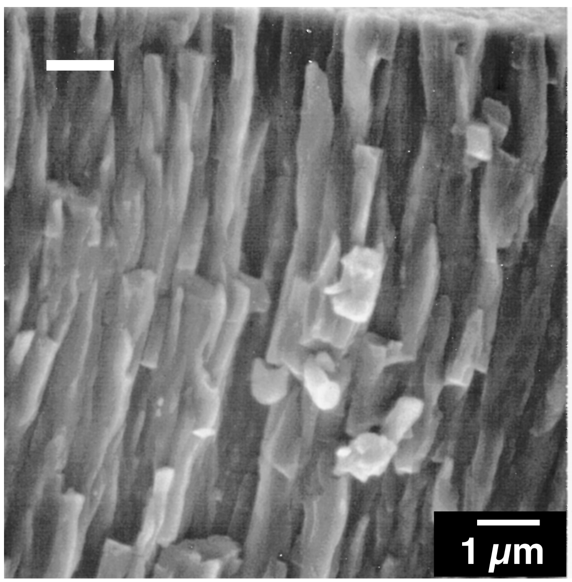
GENERAL ATOMICS Sandia National Labora

Accurate material models are critical to the success of the National Ignition Campaign

300 eV graded-dopant Be design:



Sputtered Be has grains

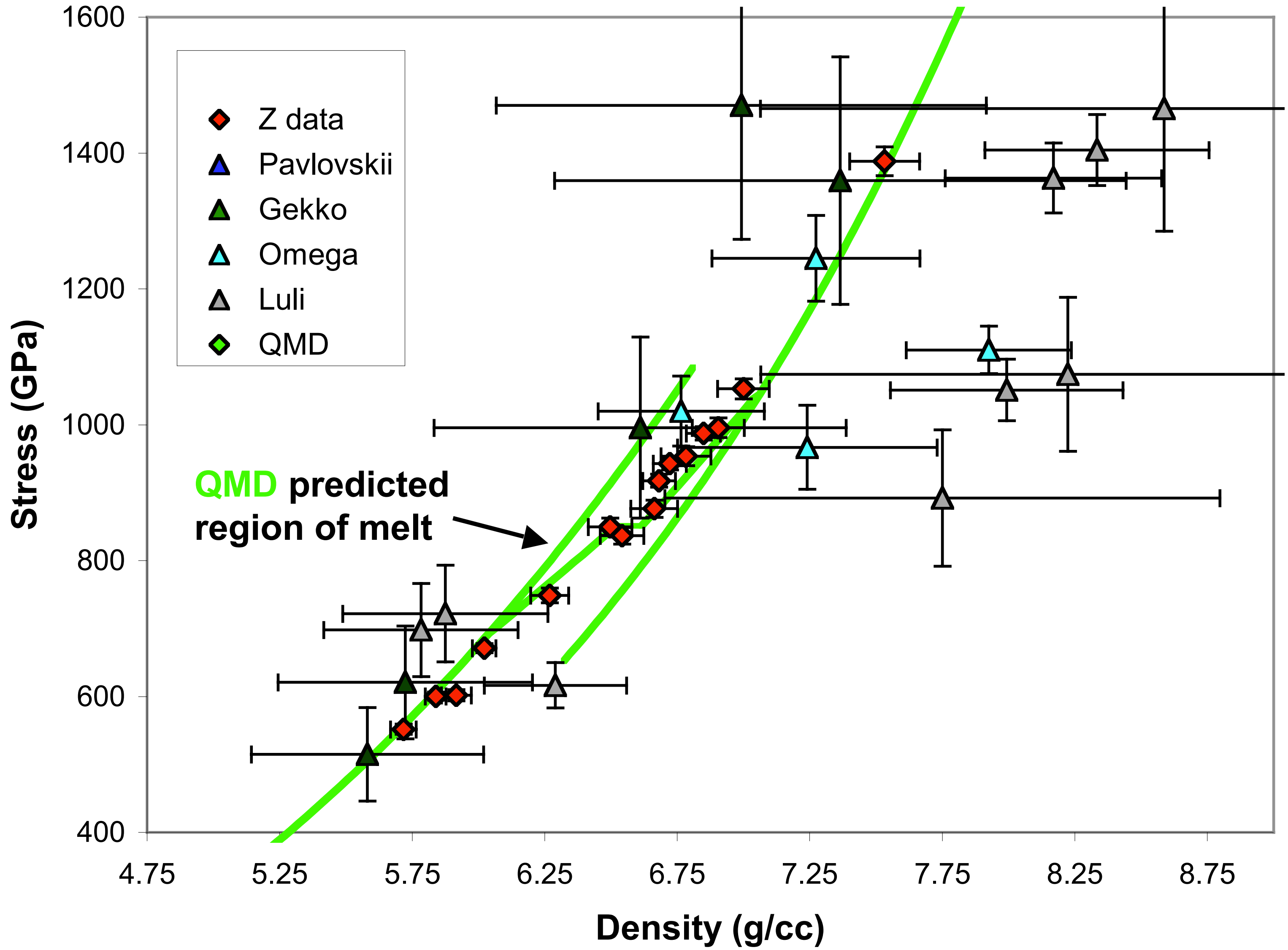


This is predicted to be of no consequence when the Be melts

- Beryllium and diamond capsule ablators both have microstructure that could seed instabilities that would prevent ignition
- The risk reduction strategy is to ensure that both ablators are melted, significantly reducing the seed for instabilities
- Strong shocks, created through pulse shaping to maintain the DT on a low adiabat, can also be used to melt the beryllium and diamond ablators
- Accurate, experimentally verified models are needed
- NIC requested Z experiments for both beryllium and diamond to develop these models

Z answered important questions about the properties of Be and diamond for the National Ignition Campaign

Stress versus density for diamond



- **Z data was obtained in 1 week**
- **Measurements on Z have an accuracy of ≤ 1%**

Outline

- Status of Z-pinch IFE
- Update on refurbished ***Z***
- Update on pulsed power ICF
- **Advances in pulsed power technology**
  - **Demonstrated improved efficiency and reliability**

Linear Transformer Driver cavity

Linear Transformer Drivers (LTDs) are a major advance in pulsed power technology

LTD cavity

- Rise time ≥ 70 nsec
- Rep rate = 1 shot every 10 seconds
- Timing jitter = 2 ns (1σ)
- Voltage and current reproducibility = 0.3% (1σ)
- Peak power = 0.1 TW
- Output energy = 11.3 kJ
- Electrical efficiency = 70%

- LTDs compress stored electrical energy to the desired pulse length in a single stage
- LTDs are composed of simple modules of fast capacitors and 200-kV switches
- LTDs have an efficiency of 70% and can be fired once every 10 seconds

LTD switch

LTD capacitor

We have developed an architecture that can be appli to the design of petawatt-class z-pinch drivers*

E_{stored} = 180 MJ

$P_{electrical}$ = 1050 TW

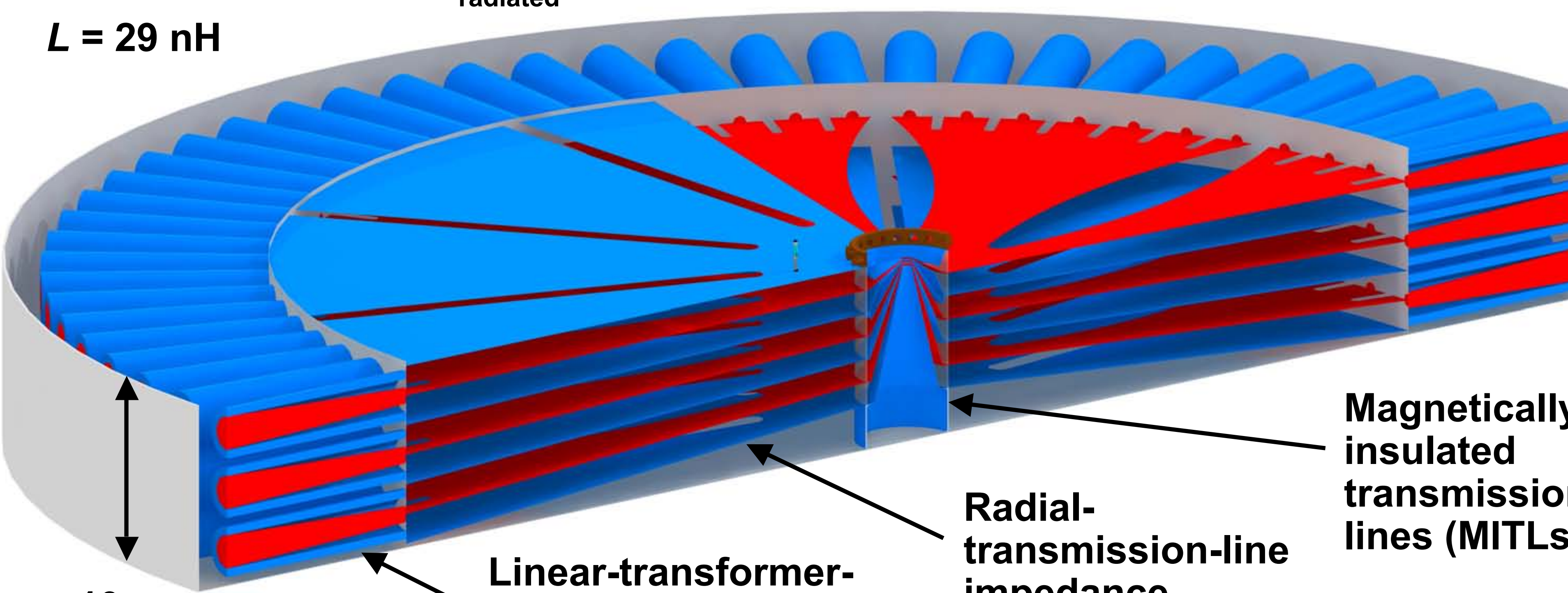
V = 24 MV

L = 29 nH

I = 68 MA

$\tau_{implosion}$ = 95 ns

$E_{radiated}$ ~ 20 MJ



*W. A. Stygar, M. E. Cuneo, D. I. Headley, H. C. Ives, R. J. Leeper, M. G. Mazarakis, C. L. Olson, J. L. Porter, T. C. Wagoner, and J. R. Woodworth, Phys. Rev. ST Accel. Beams 10, 030401 (2007).

Summary

- The Z-Pinch IFE research program is presently on hold due to lack of funding
- Integrated 2D calculations predict fusion yields in excess of 500 MJ and define the pulsed power generator design requirements for high fusion yield
- The *Z* Refurbishment Project was completed in September and the *Z* facility has delivered over 26 MA to ICE loads
- LTDs are a promising next generation pulsed power driver with demonstrated improvements in efficiency and reliability with the capability to be repetitively pulsed