The Refurbished Z Facility: Capabilities and Recent Experiments

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Thanks to my colleagues at Sandia for their many important and invaluable contributions

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Presentation Outline

- Refurbishment of Z
  - Objectives
  - Timeline
  - Construction Phase
  - Facility Startup/Commissioning
- Primary Z Applications
  - Magnetic Implosions for X-Rays and Fusion
  - Magnetic Pressures for Dynamic Material Properties
- Z Beamlet and Z Petawatt
- Summary

Sandia Pulsed Power Collaborators and Partners

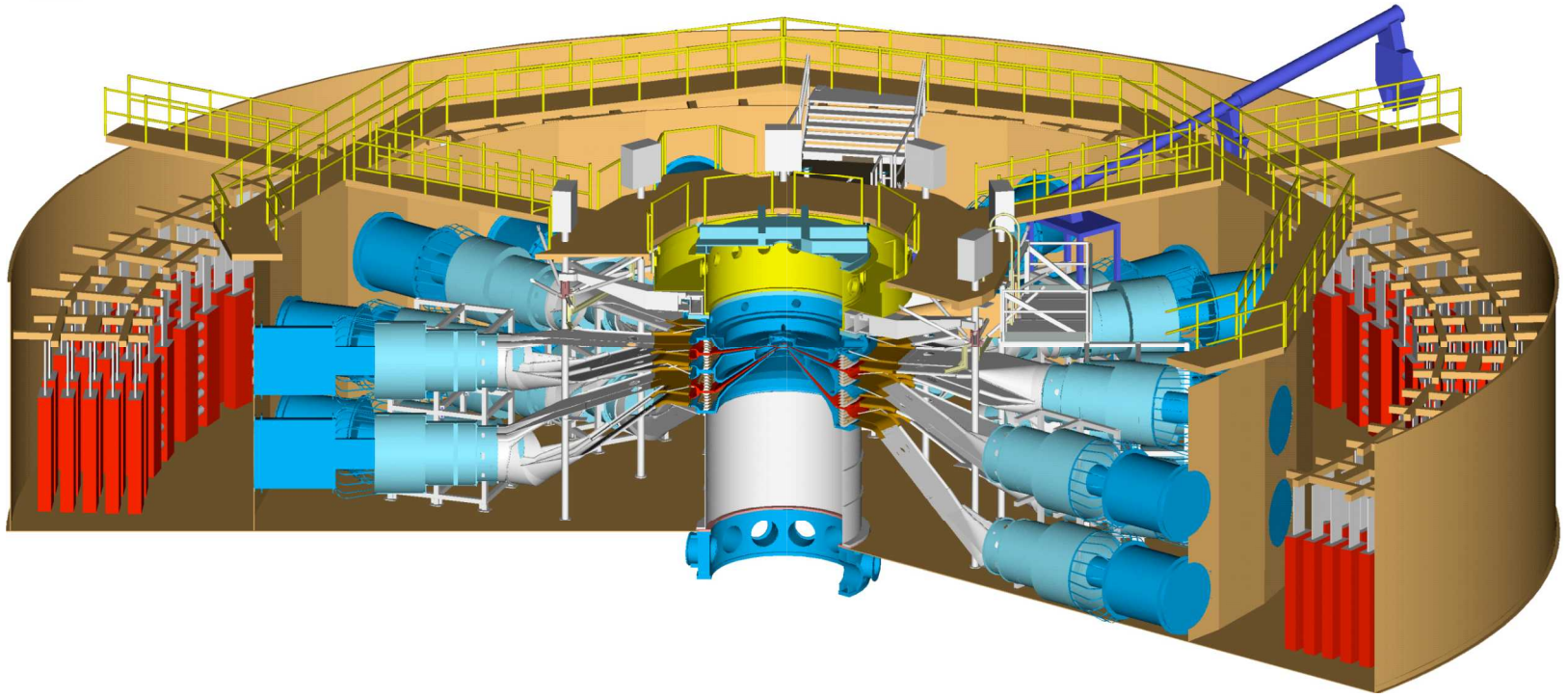
Laboratories

- Laboratory for Laser Energetics (Rochester, NY)
- Lawrence Berkeley National Laboratory (Berkeley, CA)
- Lawrence Livermore National Laboratory (Livermore, CA)
- Los Alamos National Laboratory (Los Alamos, NM)
- Naval Research Laboratory (Washington, DC)

- Atomic Weapons Establishment (Aldermaston, UK)
- Commissariat a l'energie Atomique (France)
- Centre d'Etudes Gramat (Gramat, France)
- High Current Electronics Institute (Tomsk, Russia)
- Kurchatov Institute (Moscow, Russia)
- Lebedev Institute (Moscow, Russia)
- TRINITI (Troitsk, Russia)
- VNIIEF (Sarov, Russia)
- VNIITF (Chelyabinsk, Russia)

- BARC (Mumbai, India)

The Z accelerator was a very successful experimental platform for performing HED science



- First shot in September 1996; last shot in July 2006
- Z has operated at 20 MA and 50 TW_e on over 1700 shots
- Results have been published in over 200 peer-reviewed journal articles

The Z Refurbishment Project pursued a balanced set of objectives

Capability

More Energy & Current Delivered

- Develop and install new capacitors that double the amount of energy stored within the same volume
- Design the pulsed power circuit specifically for z-pinch and material property applications

Capacity

High Operational Reliability

- Design the pulsed power drive system as conservatively as possible while simultaneously increasing delivered energy and current
- Fabricate the hardware from stainless steel instead of aluminum for durability

Precision

Better Repeatability Pulsed Shaping

- Incorporate individual lasers on each of the lines in order to precisely trigger and time each module individually
- Increase the Intermediate Storage Capacitor length for longer pulse options in support of dynamic materials testing

All pulsed power components were replaced as part of the refurbishment project

Robust (Stainless) & Optimized Components:
- Intermediate Storage Capacitors
- Pulse Forming Lines
- Vertical Transmission Lines

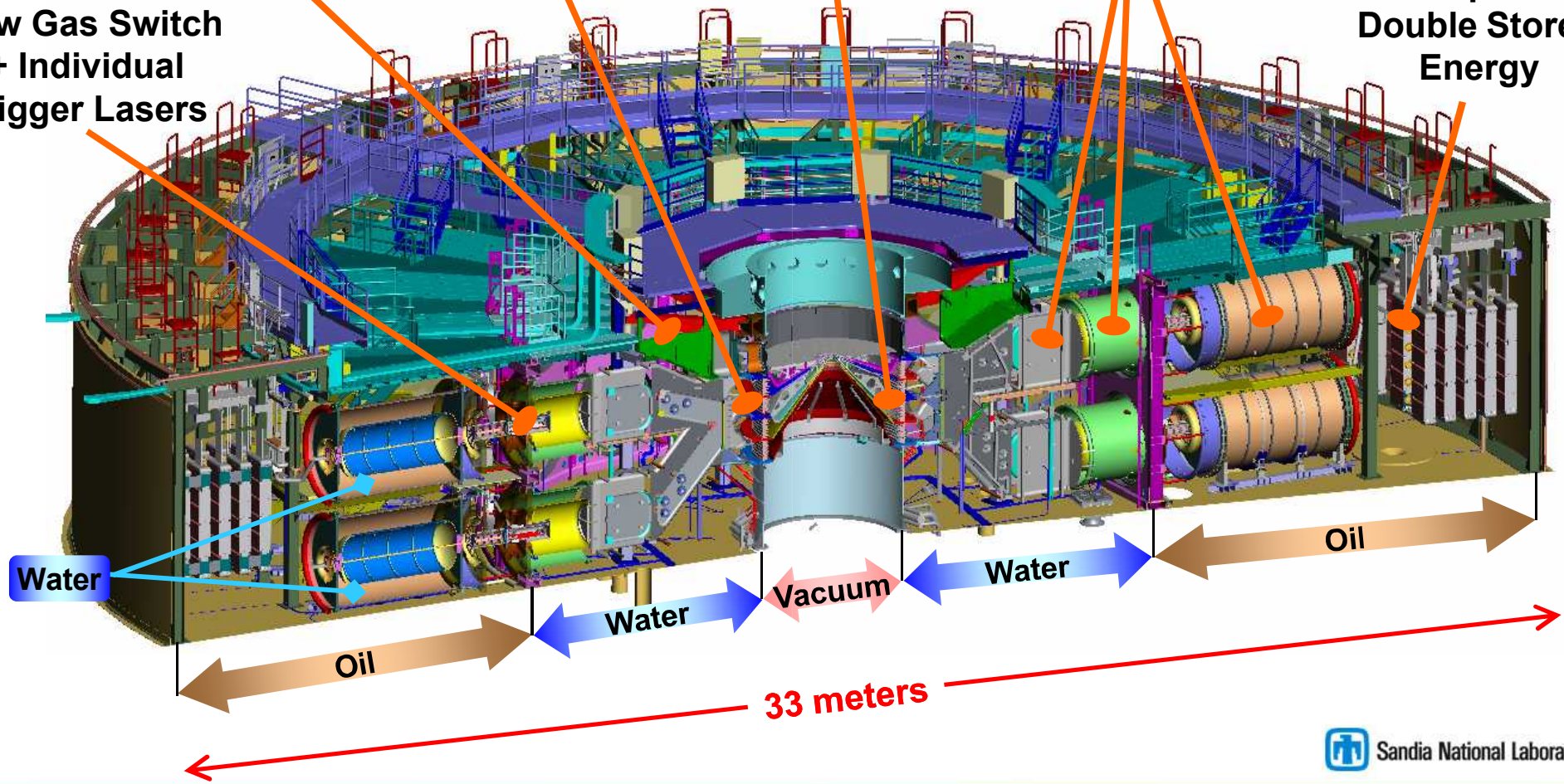
Vertical to horizontal water convolute

New, higher-voltage-capable insulator stack, New MITLs

Enhanced Diagnostics Infrastructure

New Gas Switch + Individual Trigger Lasers

New Capacitors, Double Stored Energy



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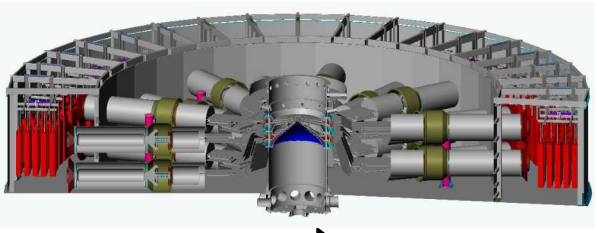
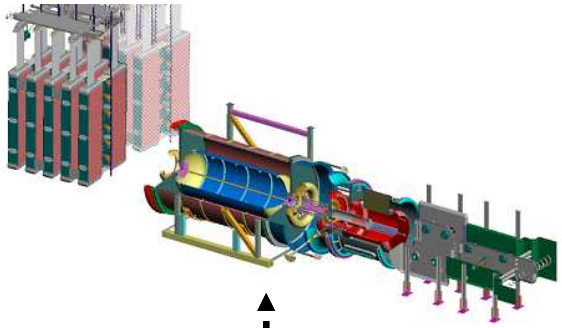
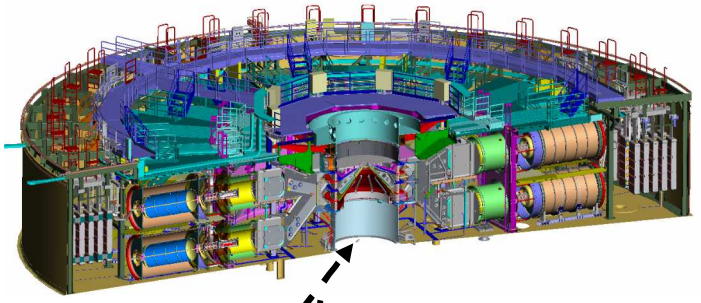
The Z Refurbishment project spanned 7 years from the initial planning efforts







Planning & Architecture Development

Single Line Design & Fab

Single Line Test

Production Design & Fab

Installation & Test

2000	2001	2002	2003	2004	2005	2006	2007

CD0 (2001) · CD1 (2002) · CD2/3a (2004) · CD3b (2006) · CD4 (2007)

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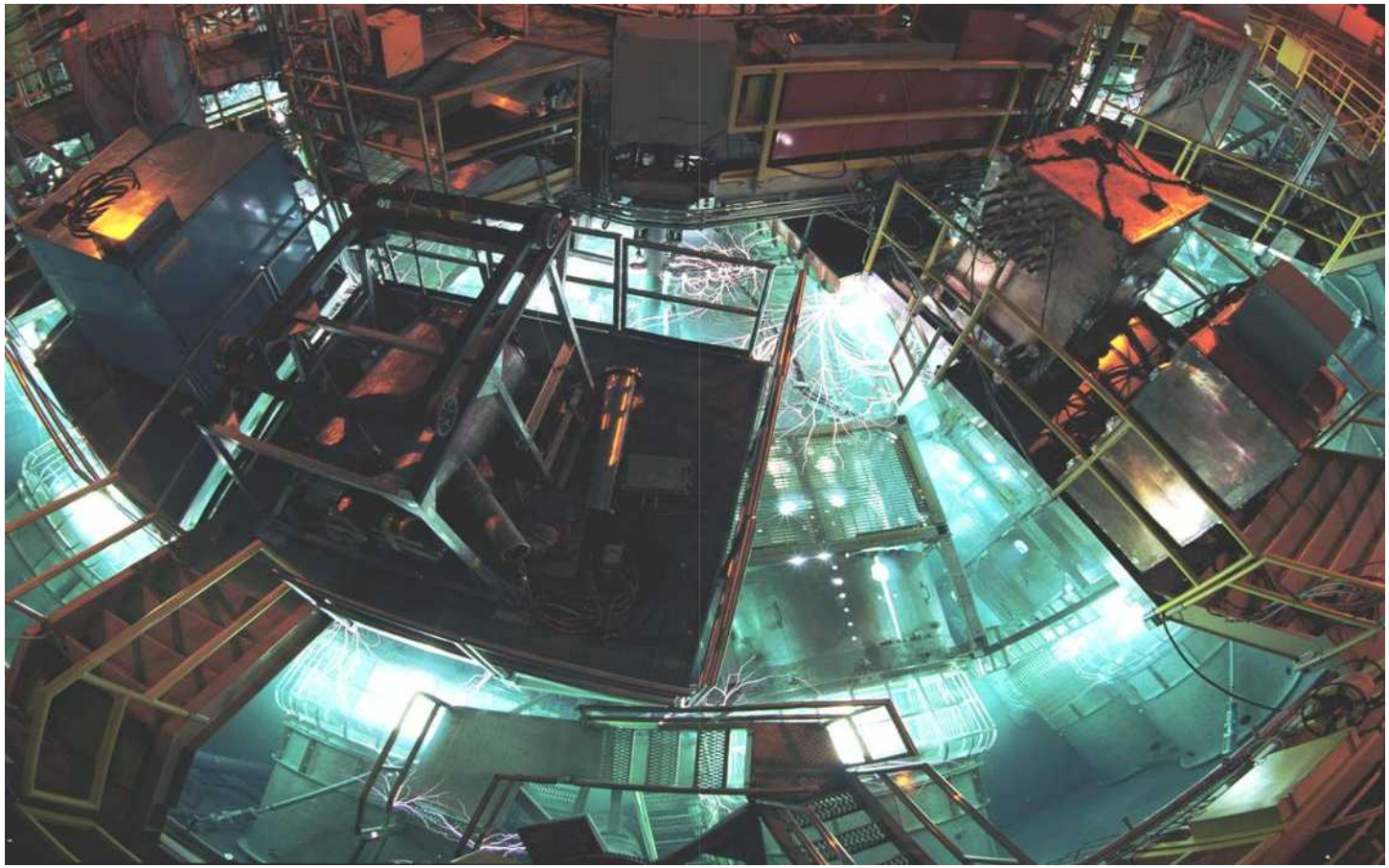
In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

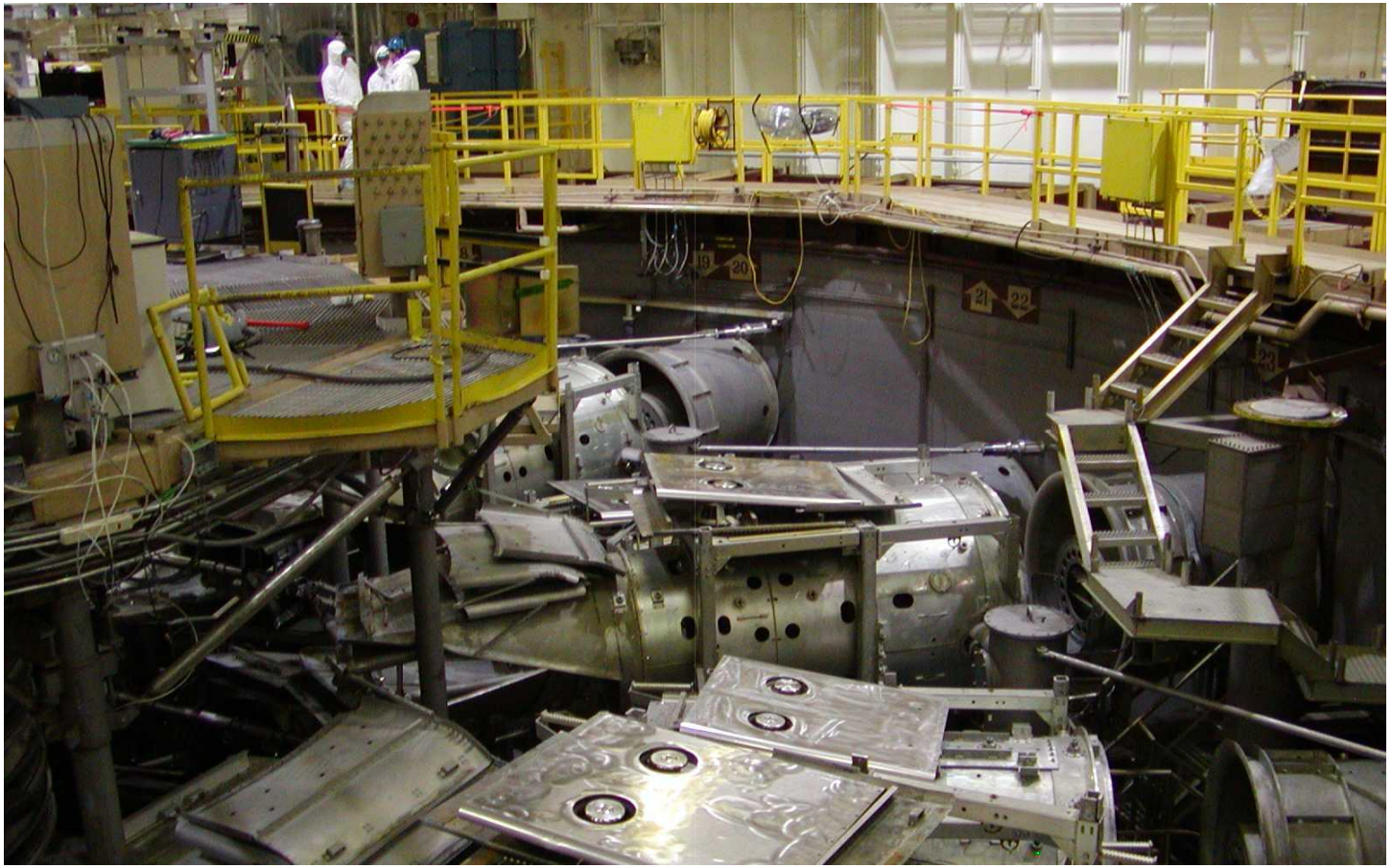
July 2006



Last Experiment on Z

In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

August 2006



Dismantlement of Old Z Underway

In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

September 2006

Teardown Complete, Rebuild Underway

In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

November 2006

New Oil/Water Separation Wall Nearly Done

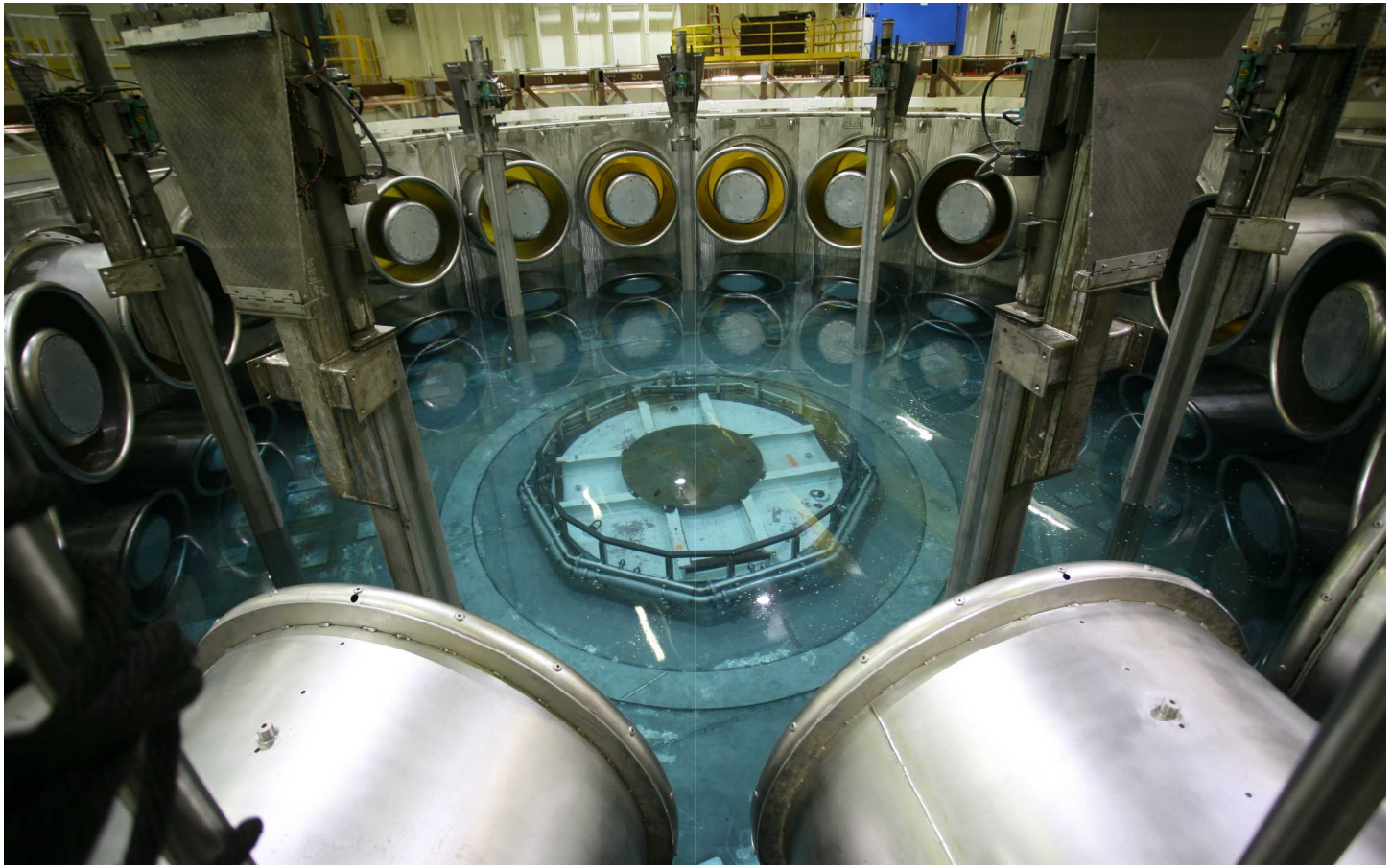
In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

January 2007

Tank Painting Completed

In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

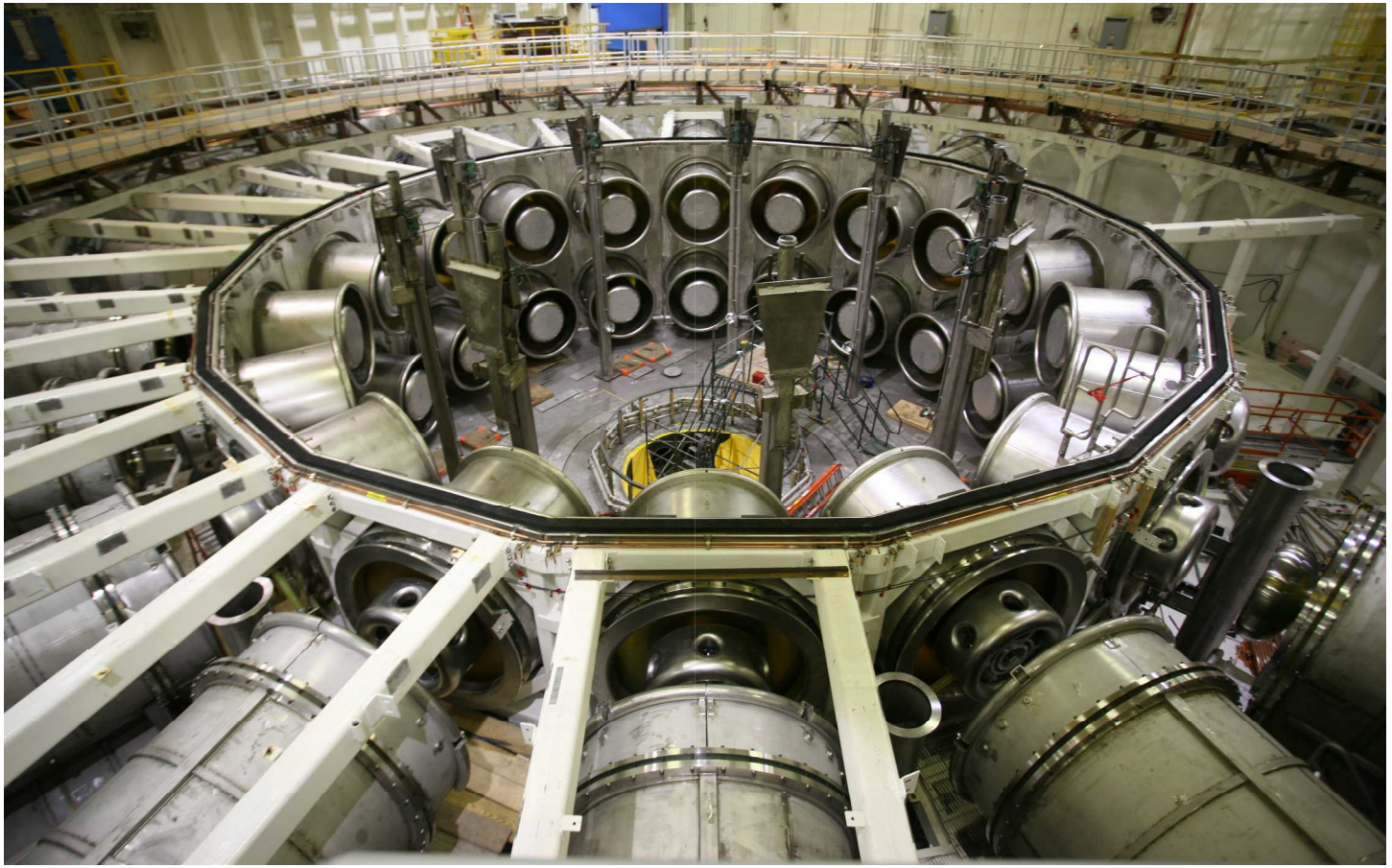
February 2007



Pulse Forming Lines In – Water Leak Test

In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

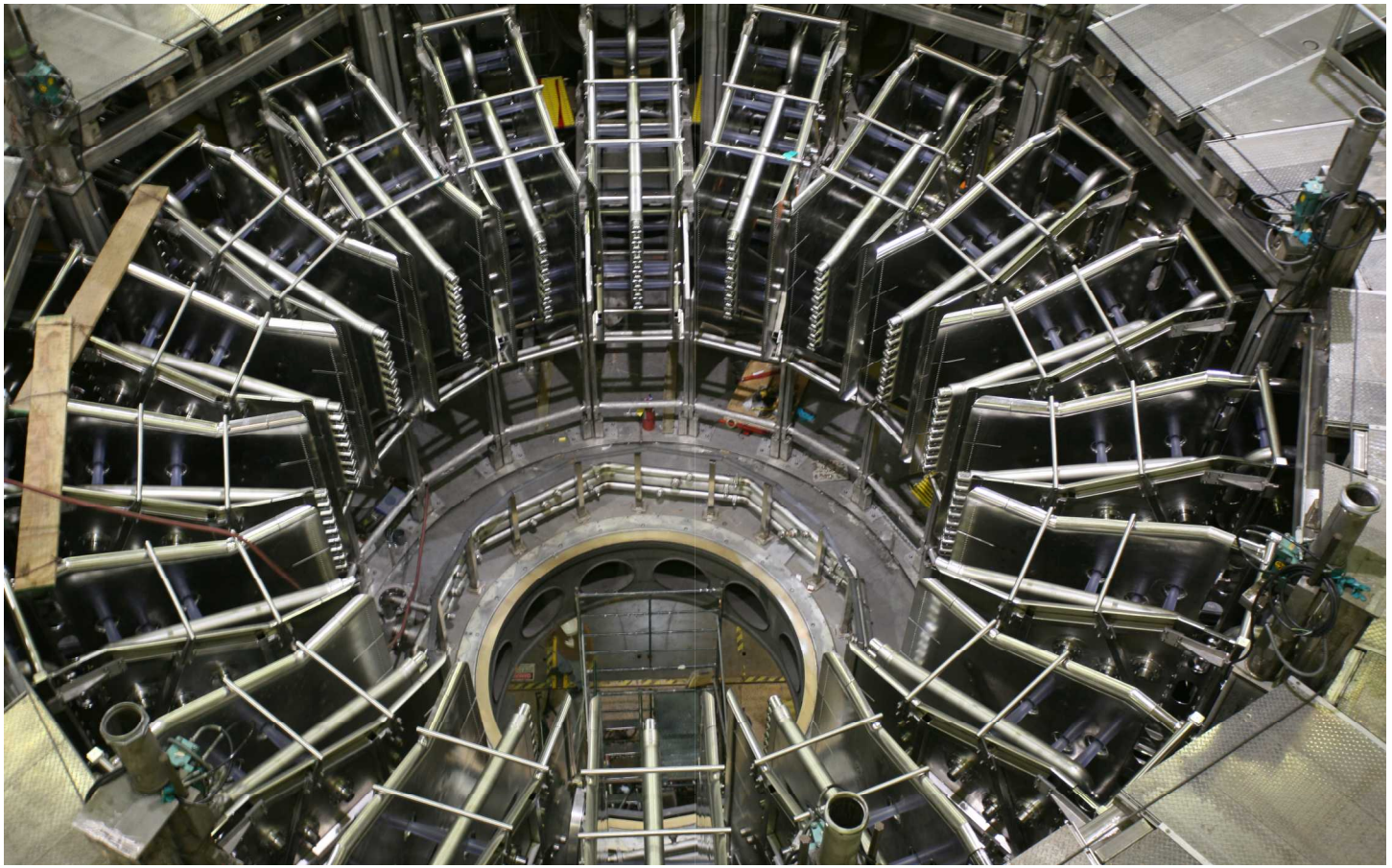
March-April 2007



Intermediate Storage Capacitor Installation Underway

In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

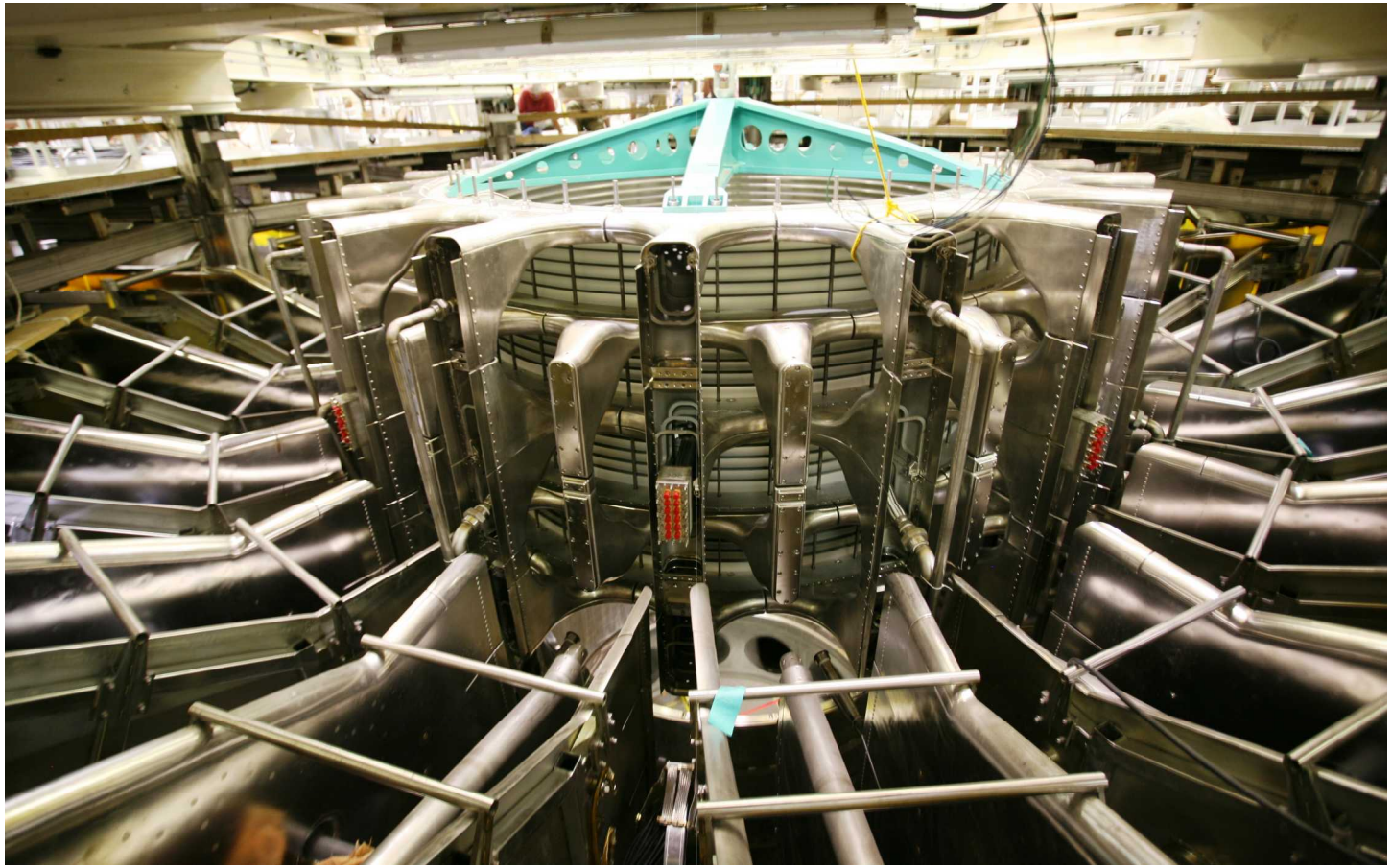
May 2007



Transmission Lines Installation Completed

In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

June 2007



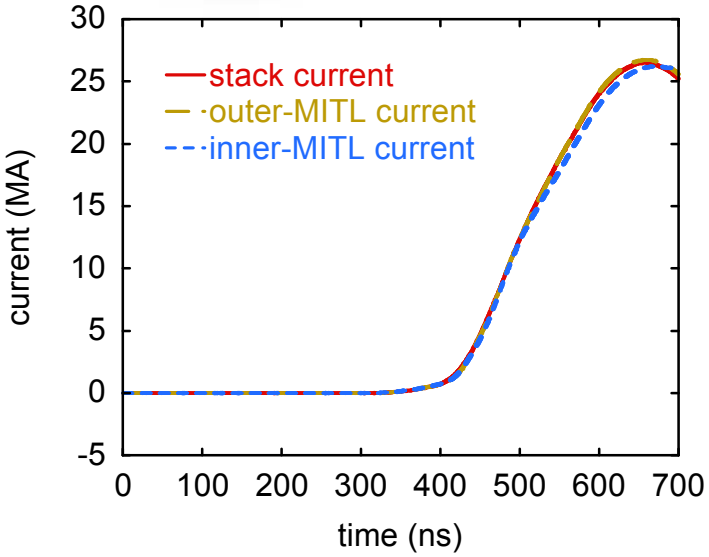
Insulator Stack/Water Convolute Installed

In only 14 months, Z was dismantled, reconstructed, and all new subsystems installed and tested

September 2007

Subsystem Testing Completed, First Shot on Refurbished Z

On the tenth shot we achieved the goal of a peak load current of 26 MA



Peak stack, outer-MITL, and inner-MITL currents agree to within 2%.

ICE load hardware for shots 1770-1775

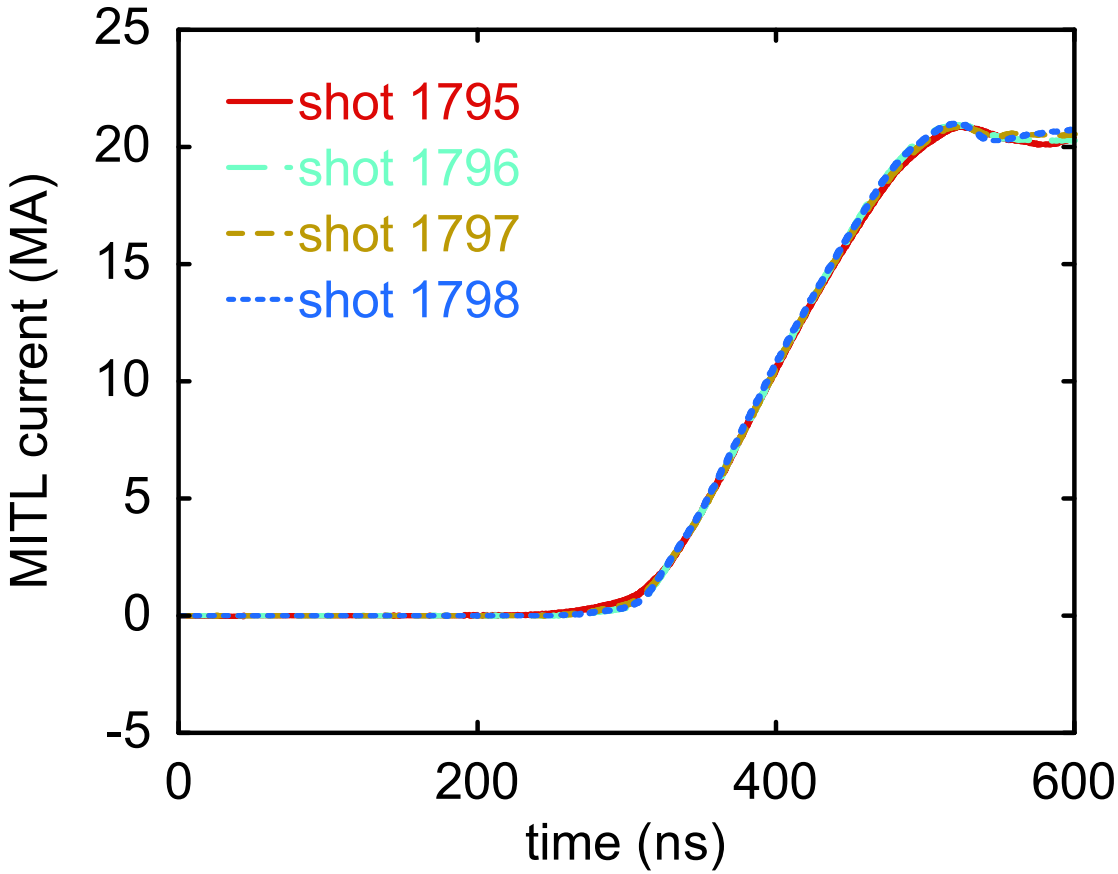
shot number	pulse length	Marx-charge voltage	peak load current
1770	short	70 kV	**20.6 MA**
1772	short	75 kV	**22.8 MA**
1773	short	80 kV	**23.8 MA**
1774	short	85 kV	**25.6 MA**
1775	long	90 kV	**26.4 MA**

We also demonstrated that the peak MITL current can be reproduced to within 1%

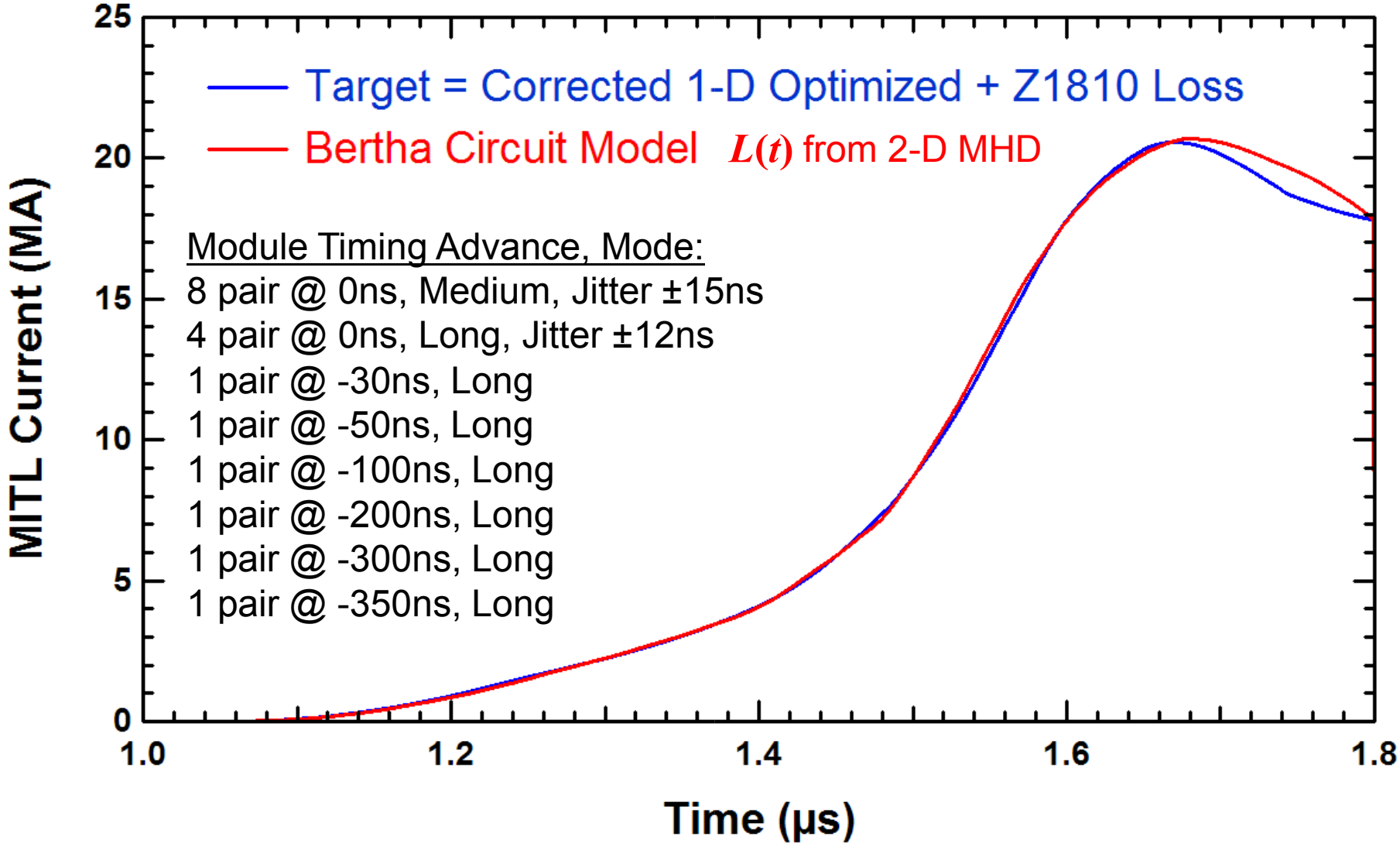
We were required to demonstrate 3% reproducibility for an NNSA milestone

The stretch goal was 2%

We've demonstrated 1%

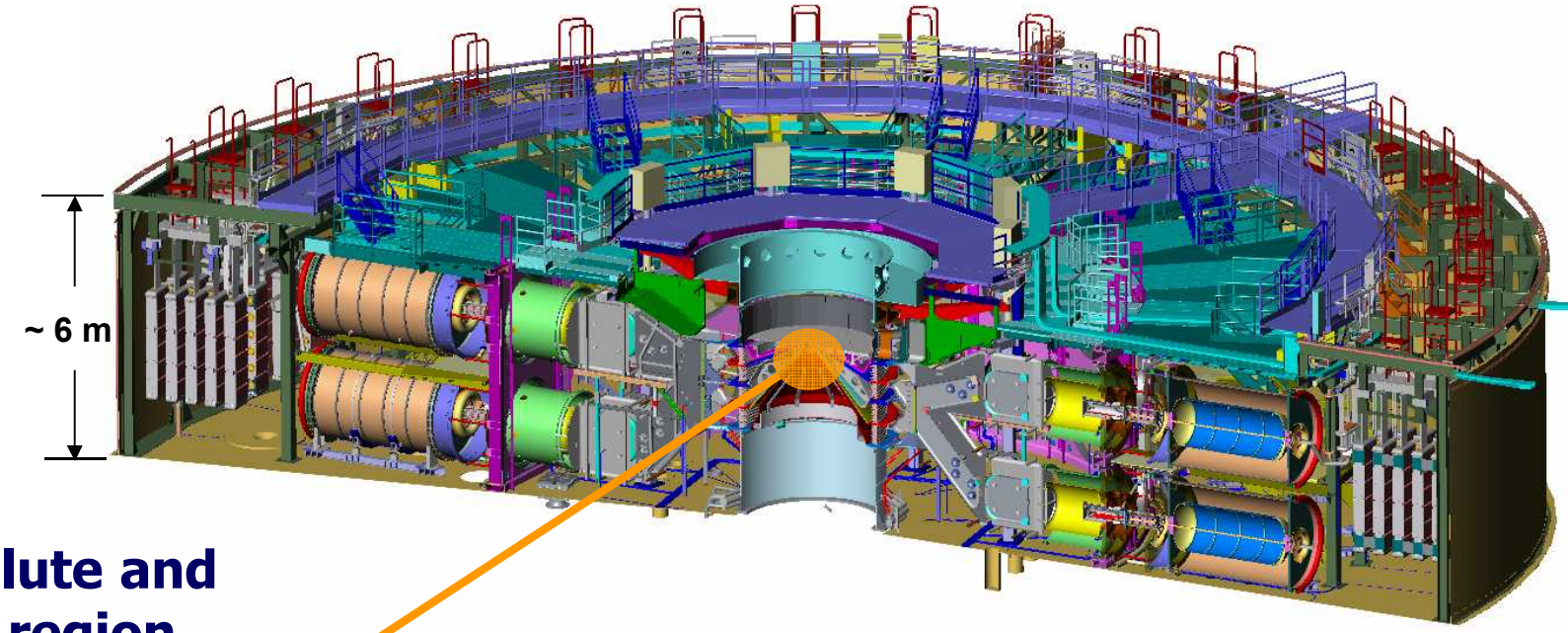


By shorting water switches and adjusting switch timings we can achieve tailored long-pulse current profiles

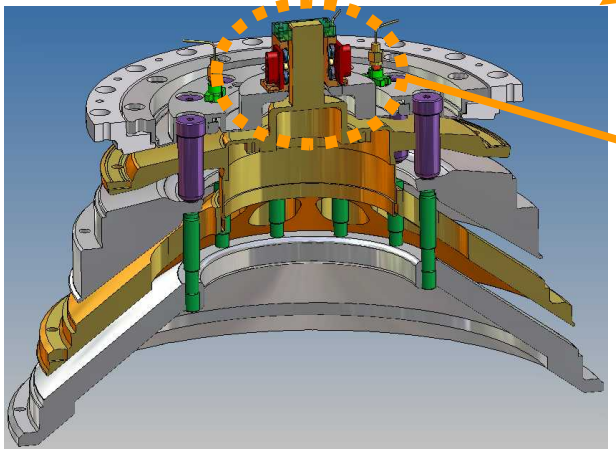


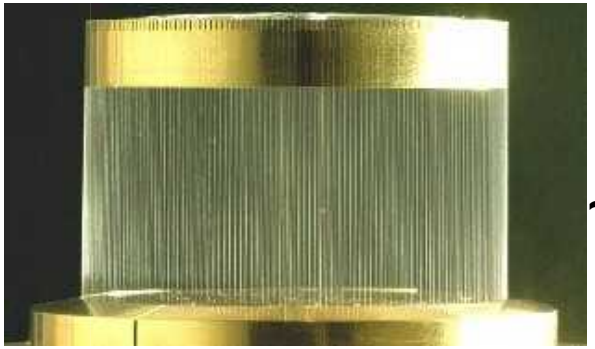
High Energy Density Physics experiments are mounted at the center of the Z accelerator

Z accelerator



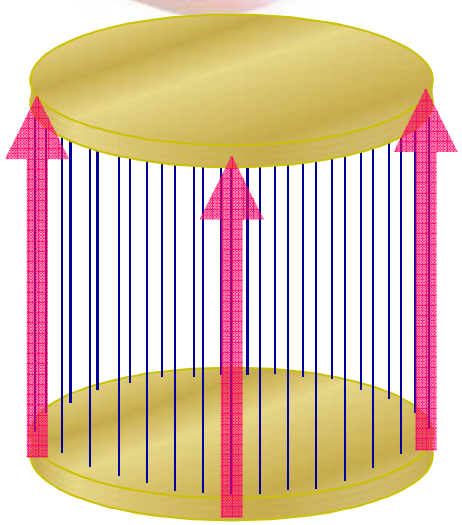
Convolute and load region



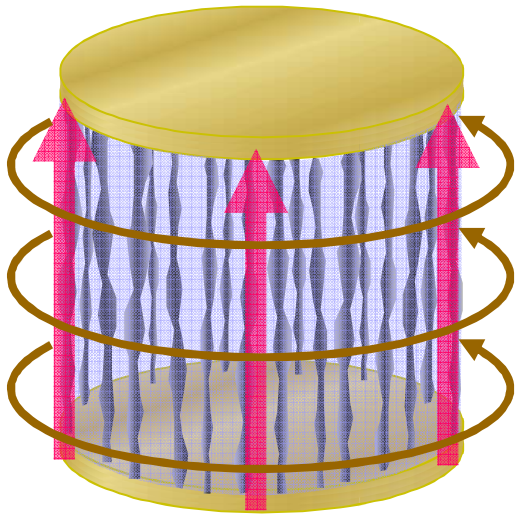


Wire-array z-pinch implosion

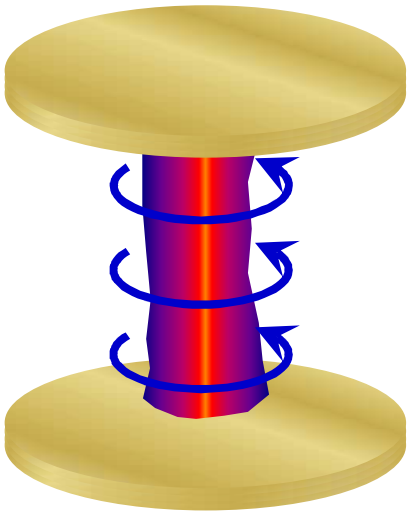
Magnetically-driven z-pinch implosions efficiently convert electrical energy into radiation



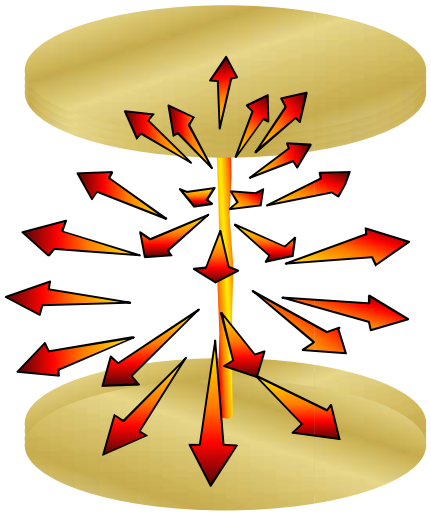
Initiation



Ablation



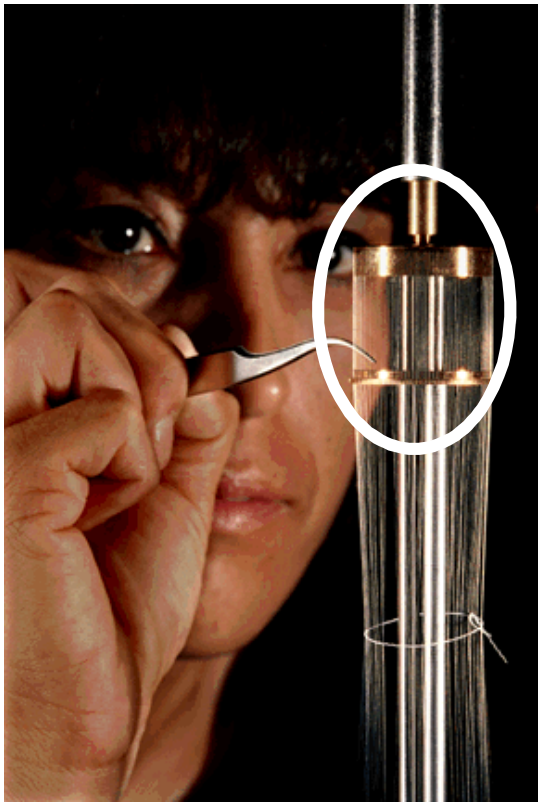
Implosion



Stagnation

On Z:

- **Energy: x-ray ≈15% of stored electrical**
- **Power: x-ray ≈2- 4 times electrical**



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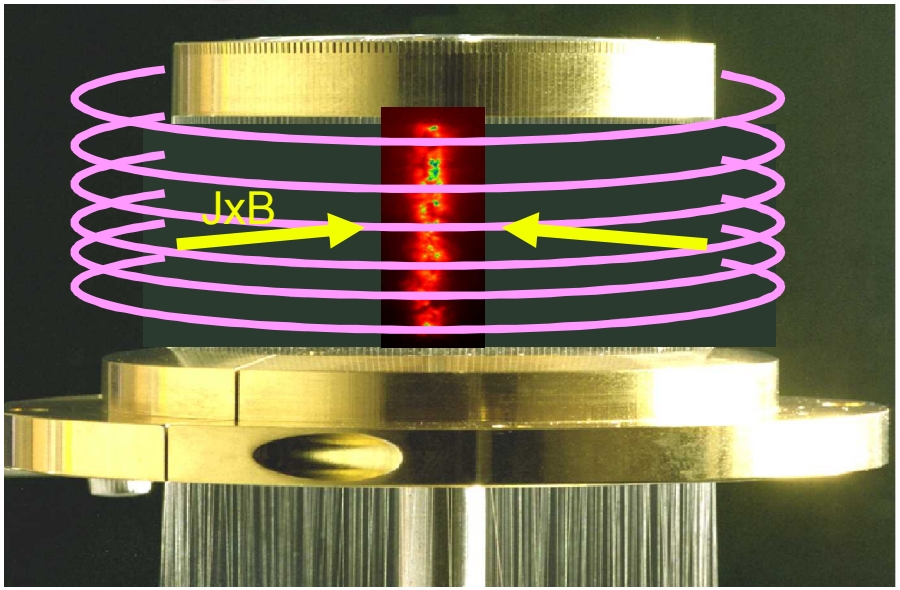
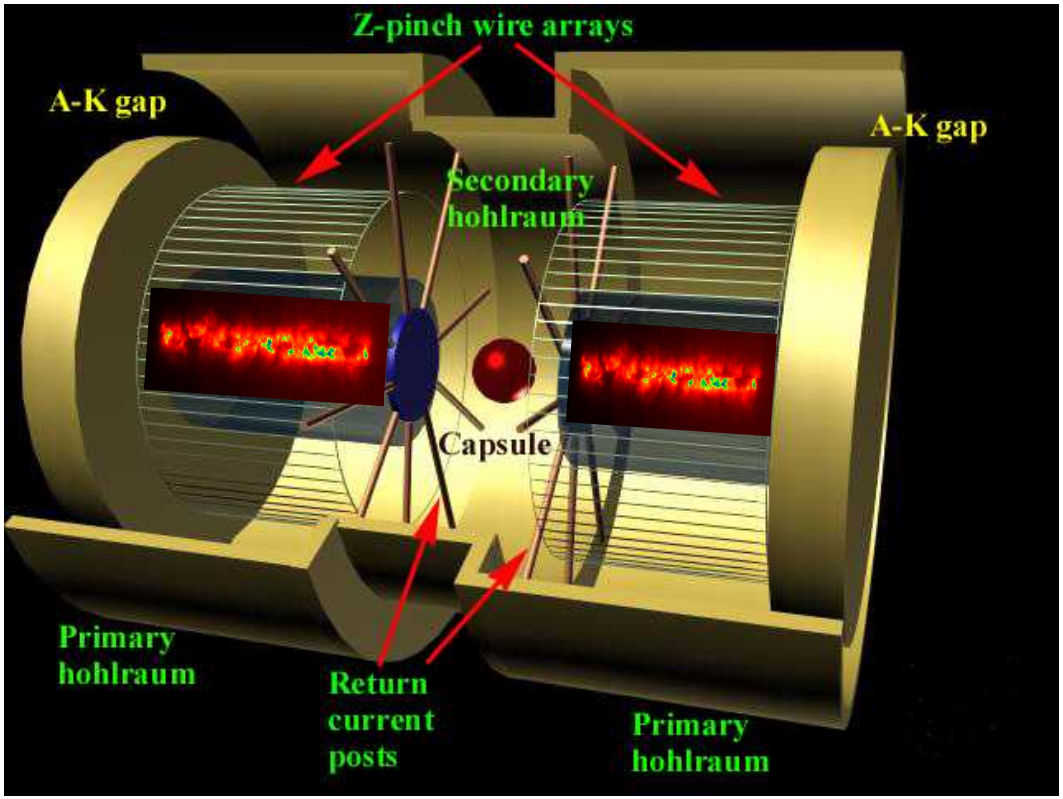
The double-ended hohlraum concept separates capsule, hohlraum, and z-pinch physics issues

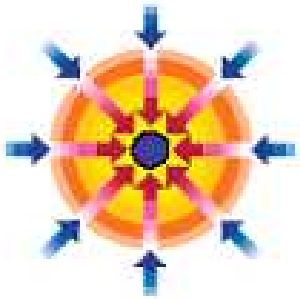




Target heating

Compression

Ignition



Burn

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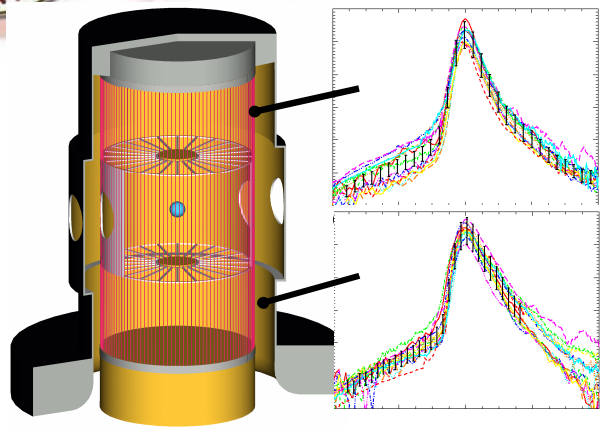
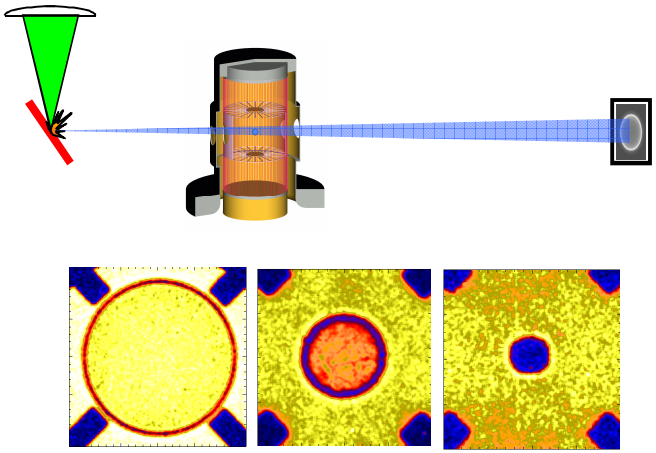
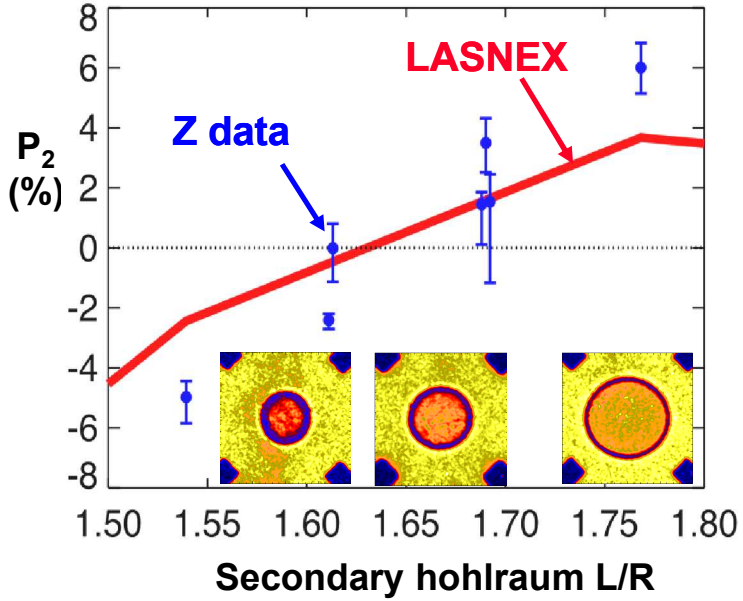
The integrated target design builds on several years of validation experiments on Z



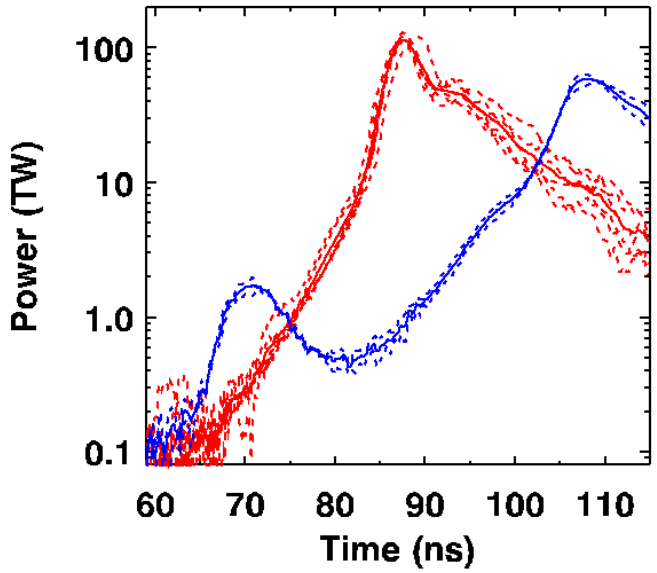
Double pinch development



Z-Backlighter development



Symmetry



Pulse shaping

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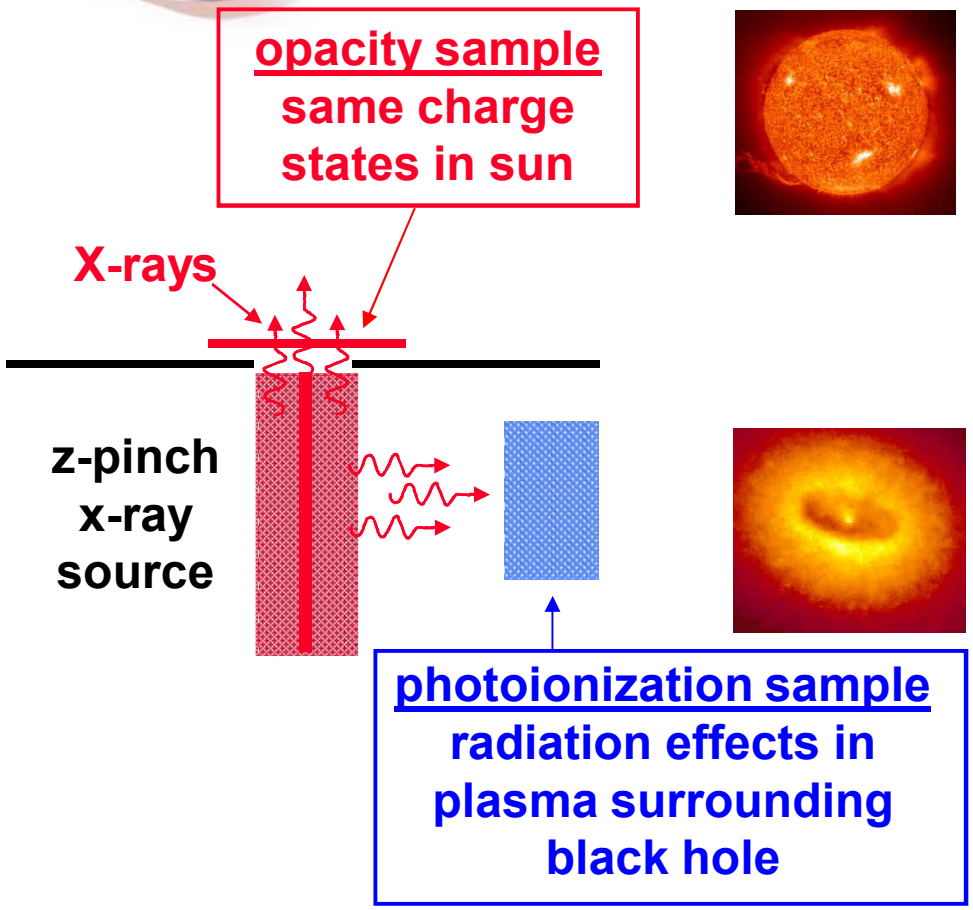
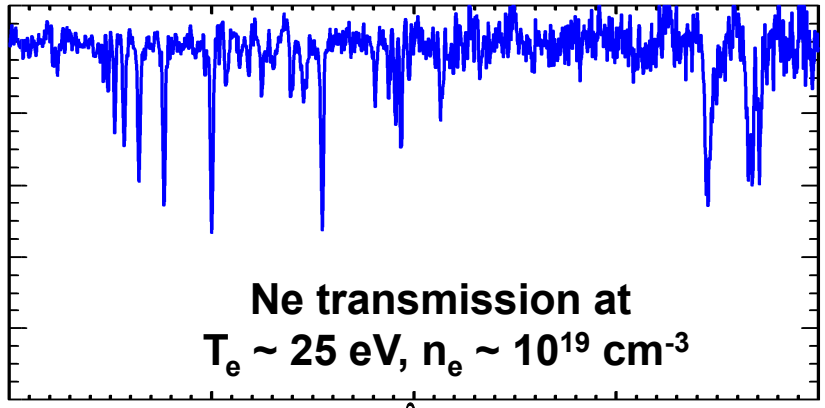
Z is being used to measure the opacity of materials at high temperatures and pressures



Fe + Mg transmission
T_e ~ 156 eV, n_e ~ 10^{22} cm^{-3}
λ

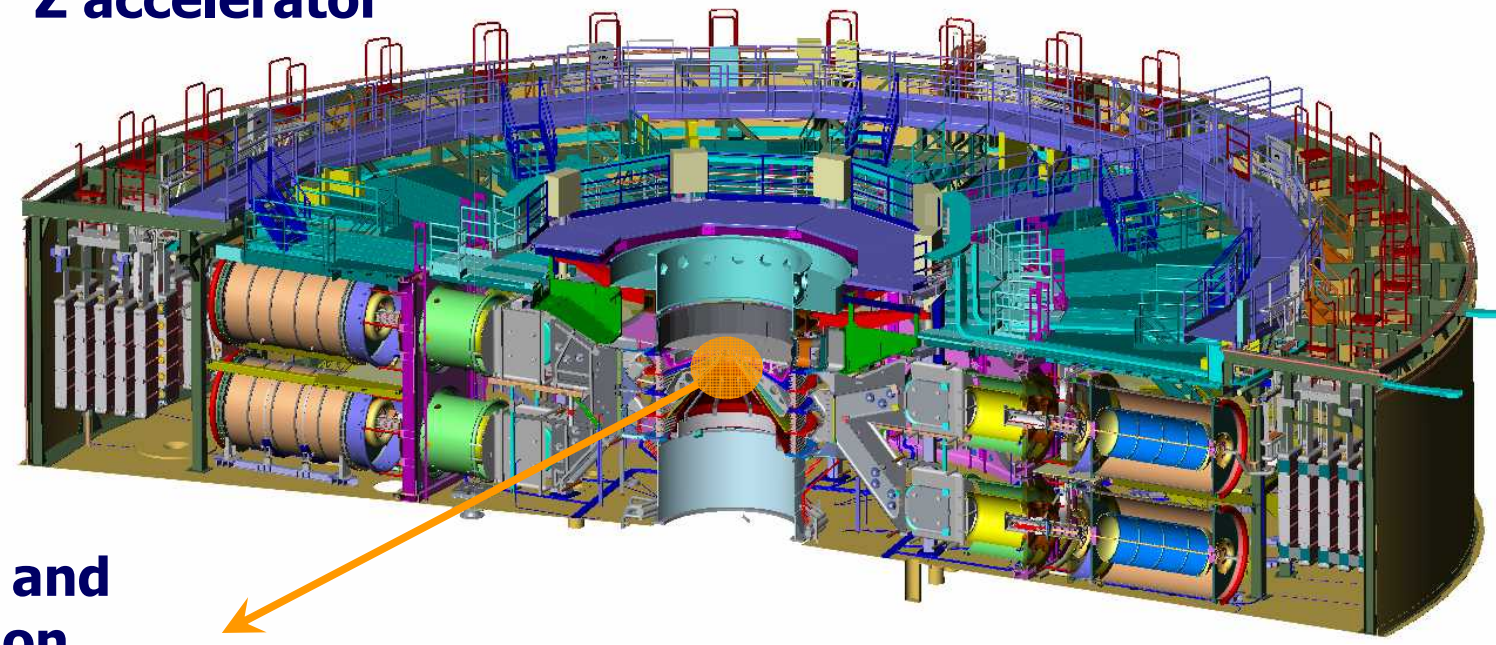


Ne transmission at
T_e ~ 25 eV, n_e ~ 10^{19} cm^{-3}
λ

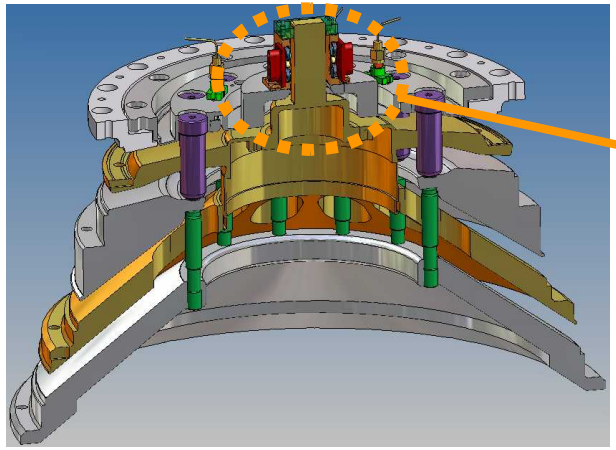
Modeling of stellar interiors and accretion powered objects depend on material opacities at high temperatures and pressures that have never been measured

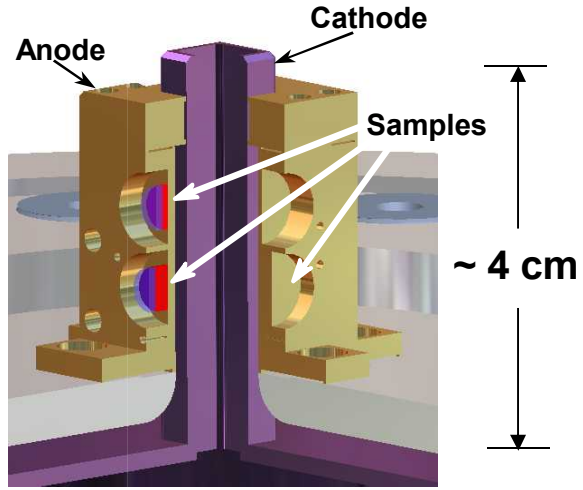
Replacing the wire array with an "ICE cube" enables material property experiments on Z

Z accelerator



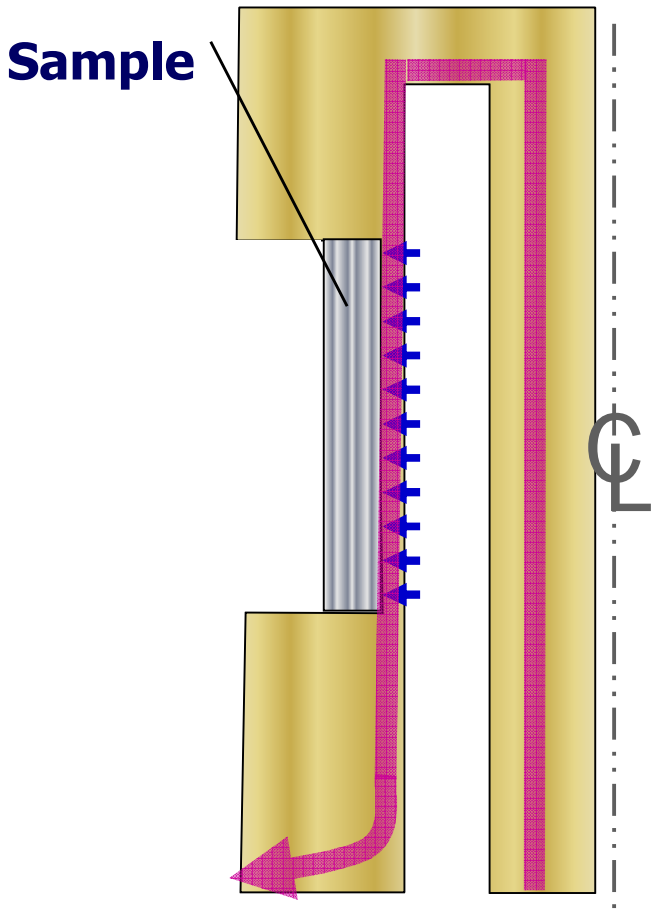
Convolute and load region

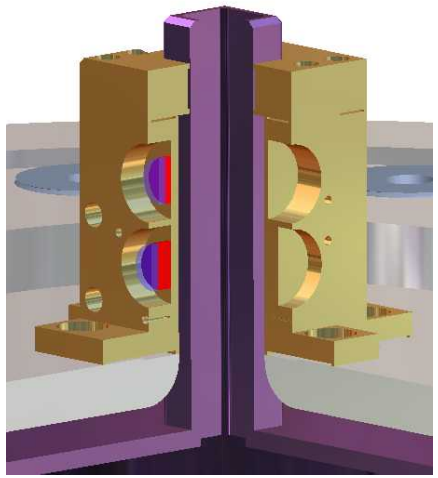


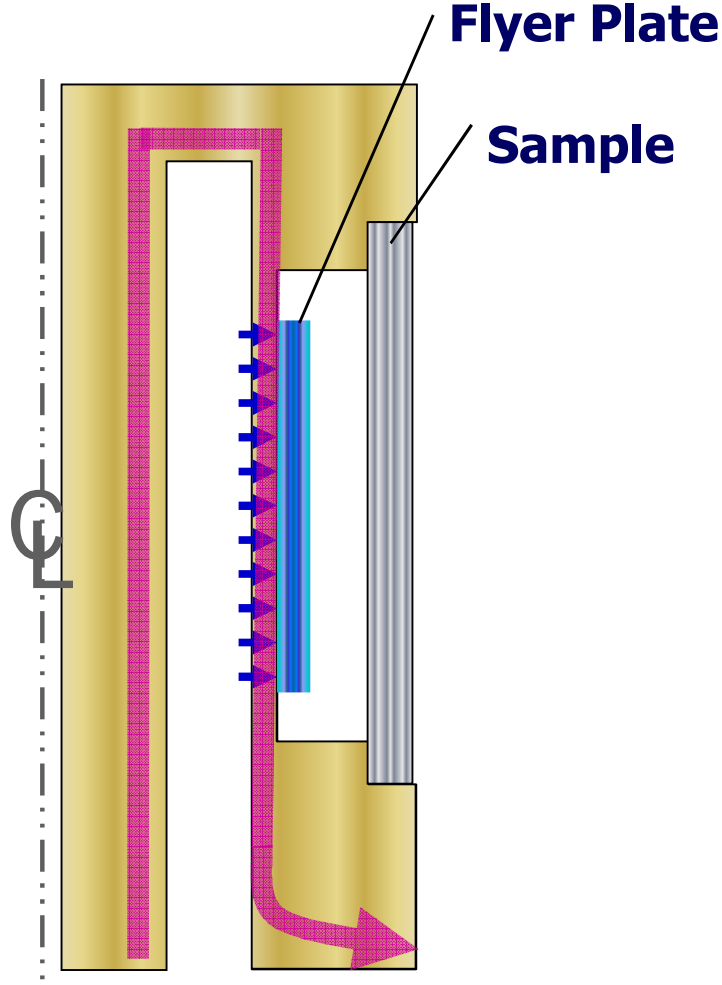


Material property experiment

Magnetic pressure associated with the high current can be used directly for material property experiments





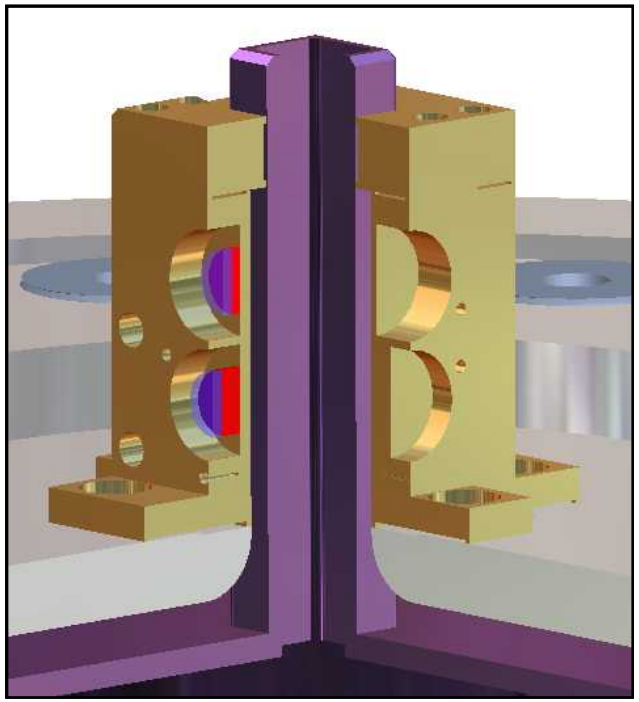


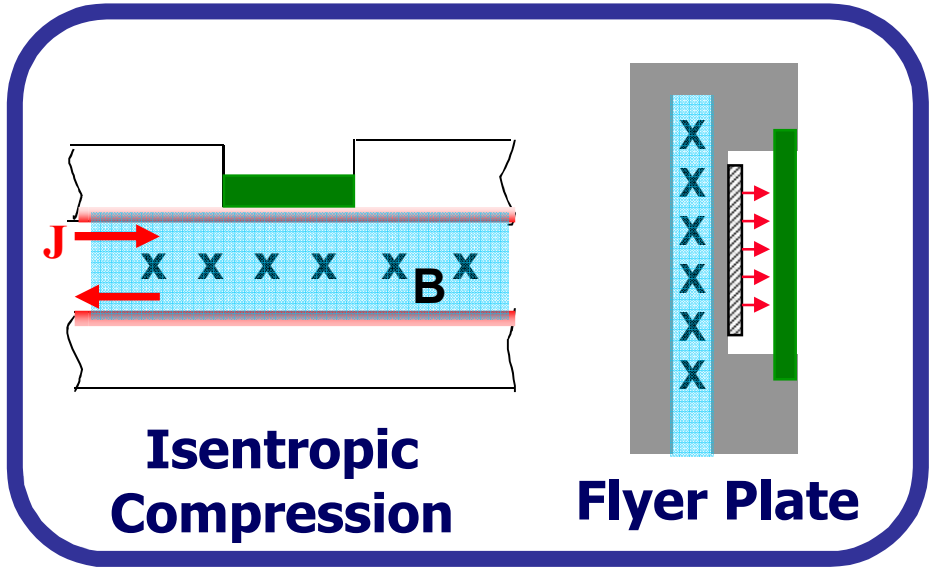
Isentropic Compression Experiments:
direct pressure wave through sample

Shock Hugoniot Experiments:
flyer plate launched to shock sample

Shaping the current pulse enables high ICE pressures and flyer plate velocities

Magnetic pressure drive

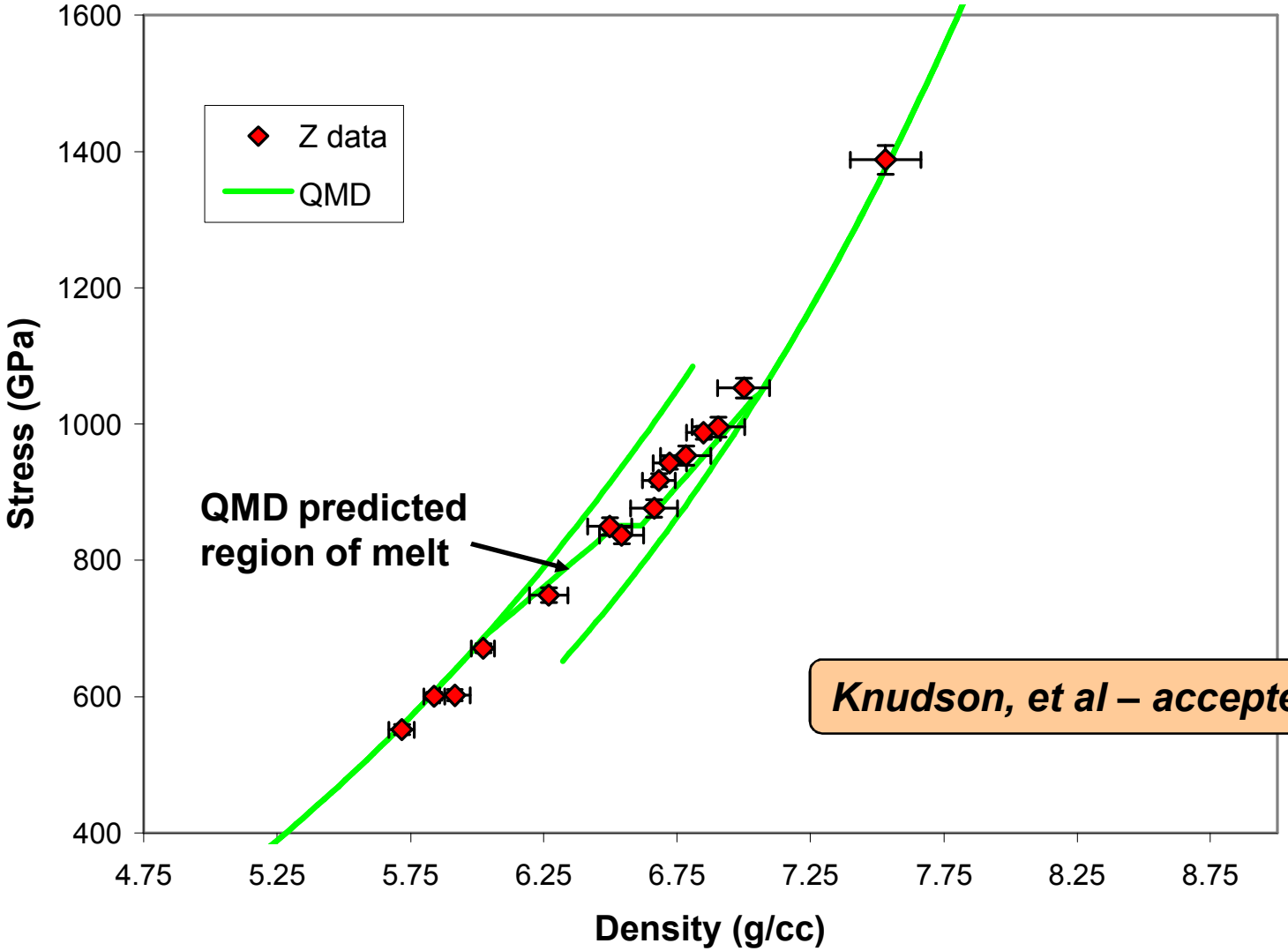




- Flyer plates to velocities of 34 km/s
  - » Deuterium EOS to 1.8 Mbar
  - » High-Z Hugoniot expts to > 20 Mbar
- Isentropic Compression Experiments
  - » Off-Hugoniot EOS measurements to 4 Mbar
  - » Al strength measurements to 2.4 Mbar
  - » Solid-solid and liquid-solid phase transitions

Precision measurements on Z quantified properties of Be & diamond for the National Ignition Campaign

Stress versus density for diamond

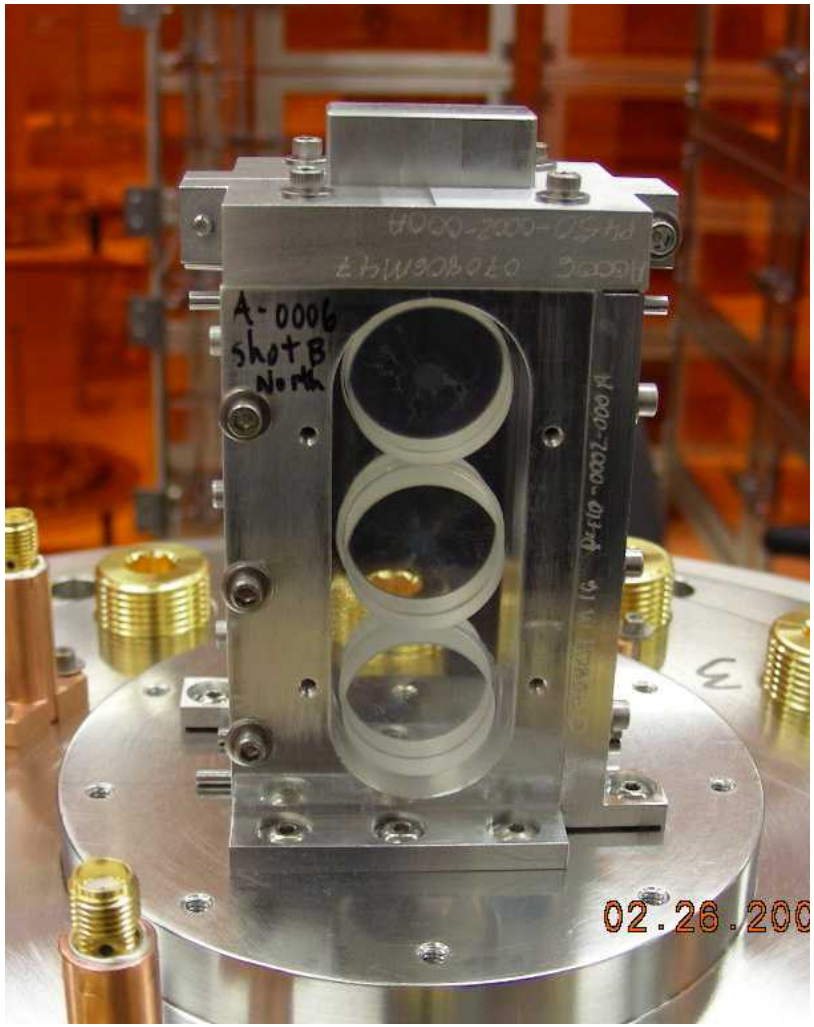


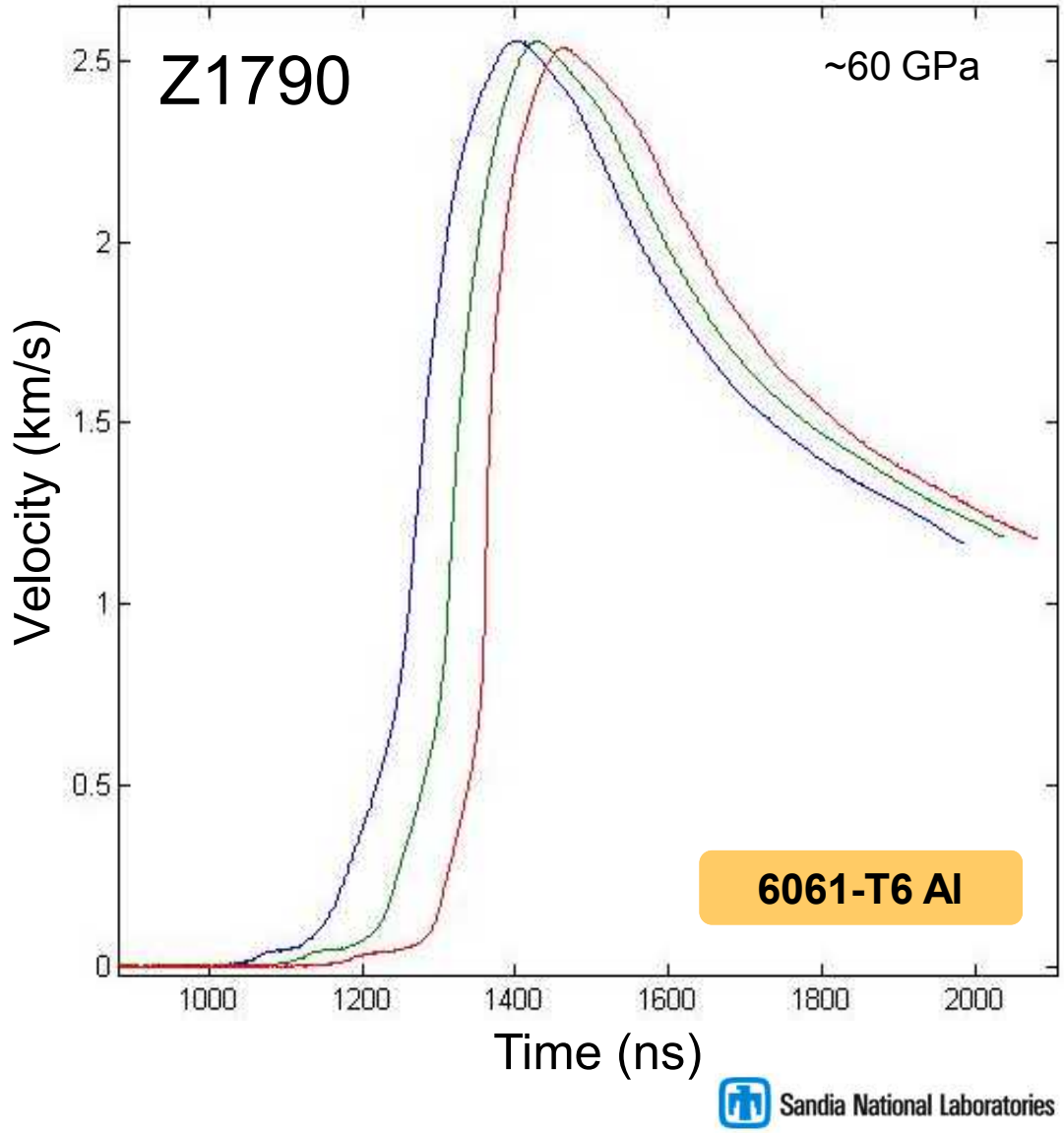
- Z data obtained in 1 week
- Measurements on Z have an accuracy of ≤ 1%

Knudson, et al – accepted for review - Science

Initial Z experiments were designed to obtain wave profiles to infer strength

Coax strength load hardware





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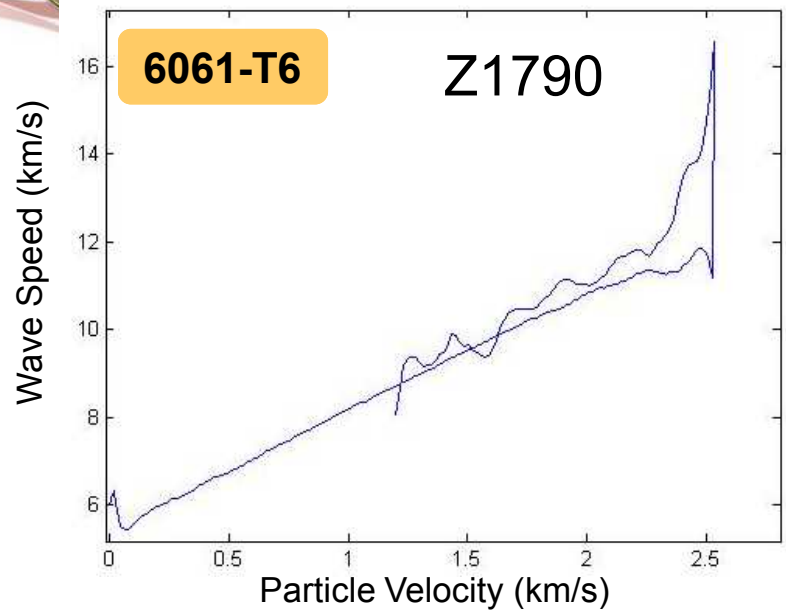
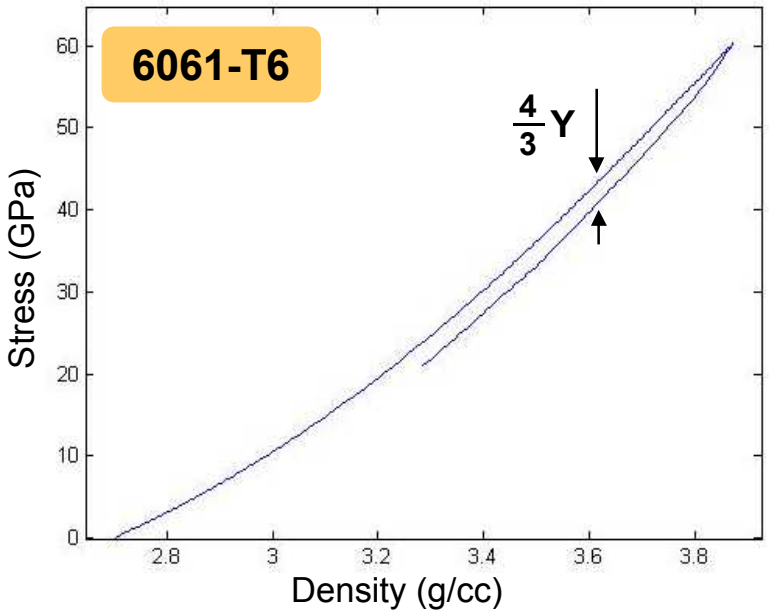
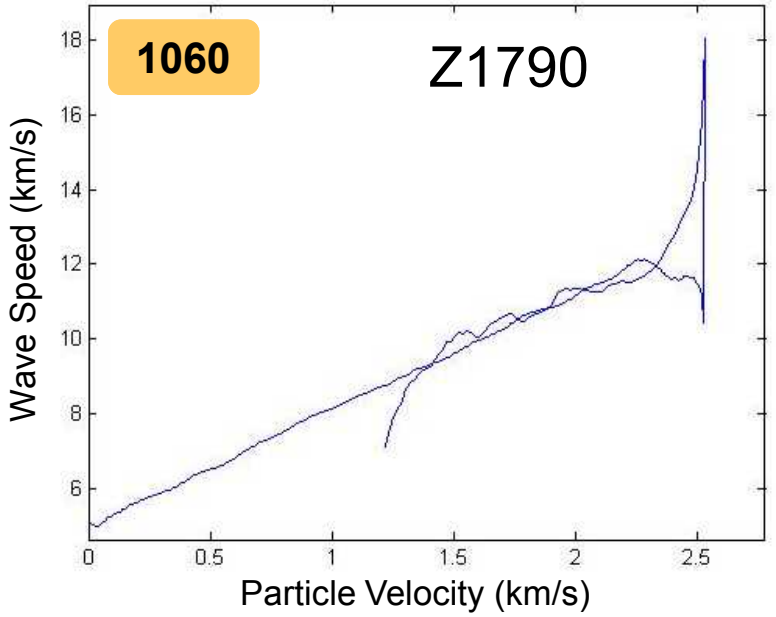
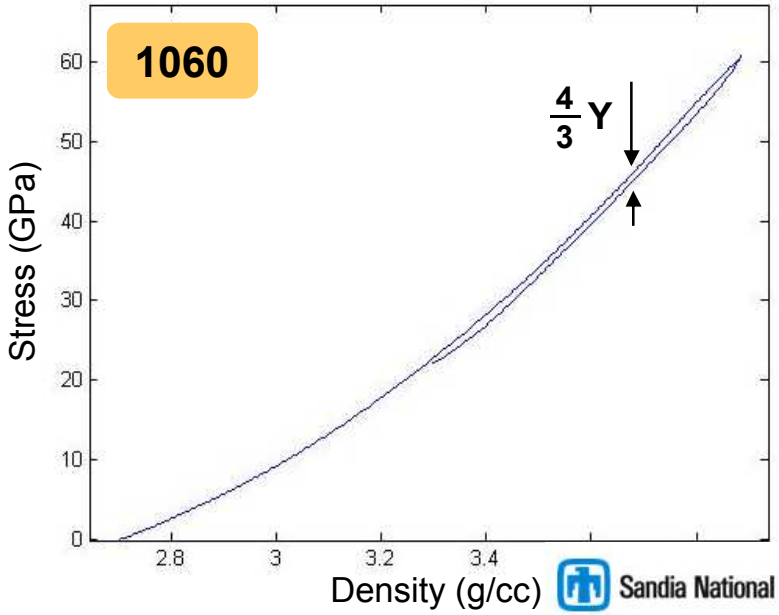
Wave profile analysis is providing reasonable estimates of strength at high pressure



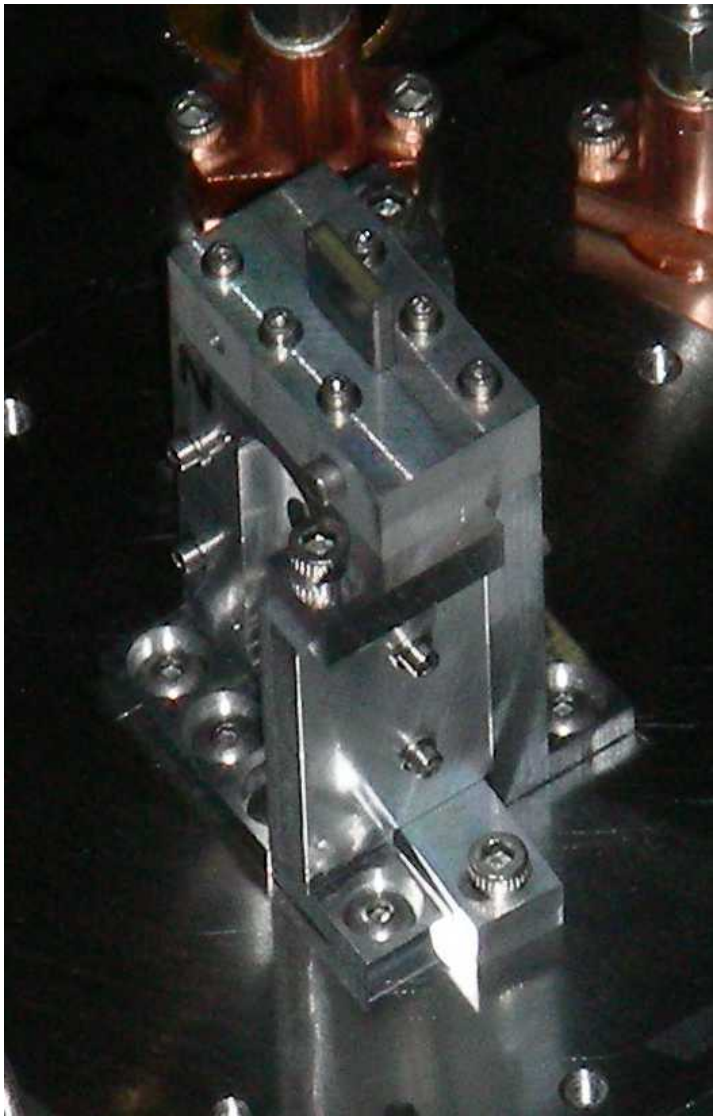


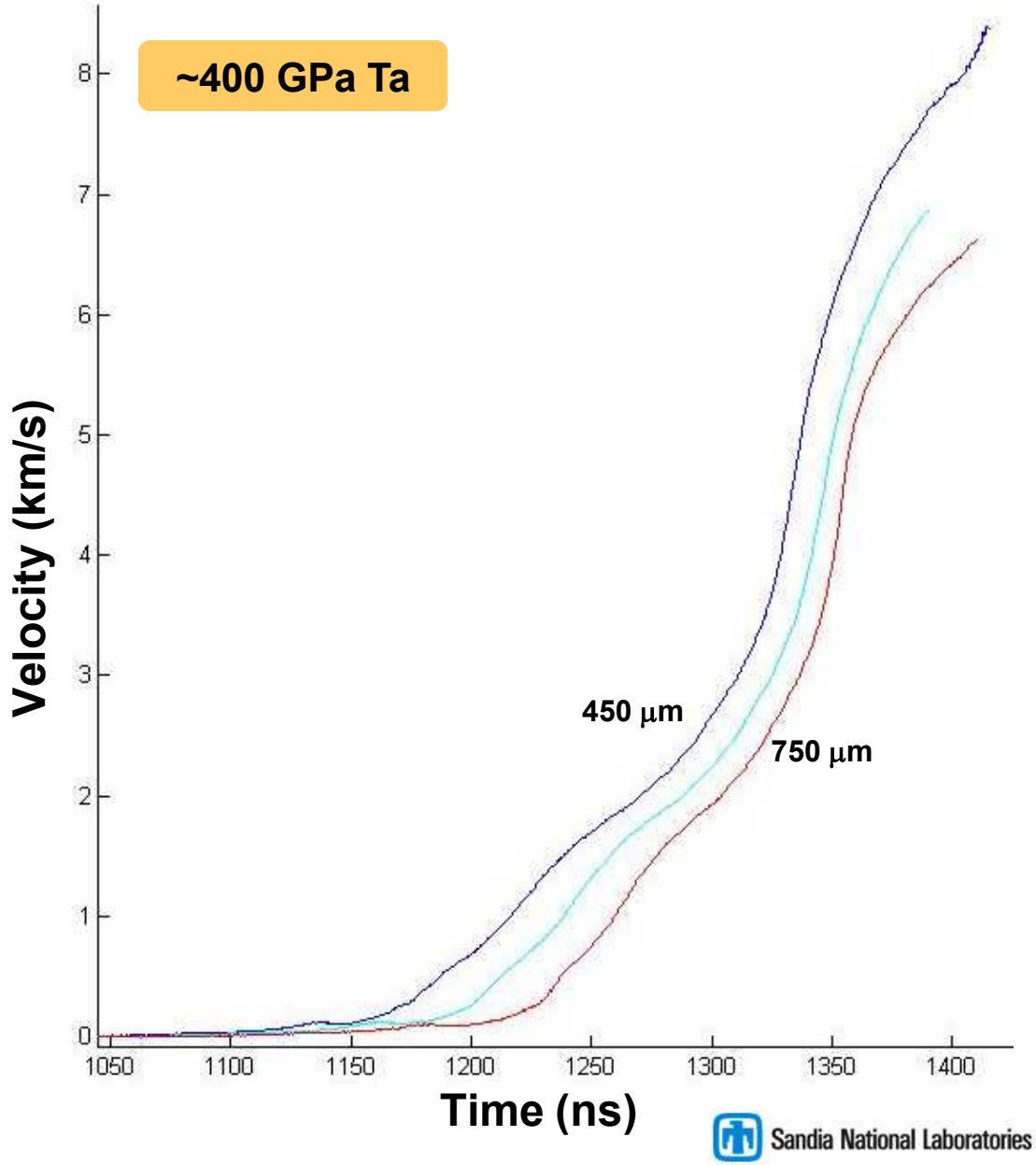




Sandia National Laboratories

Coaxial geometry has produced Isentropic compression to ~400 GPa





Sandia National Laboratories

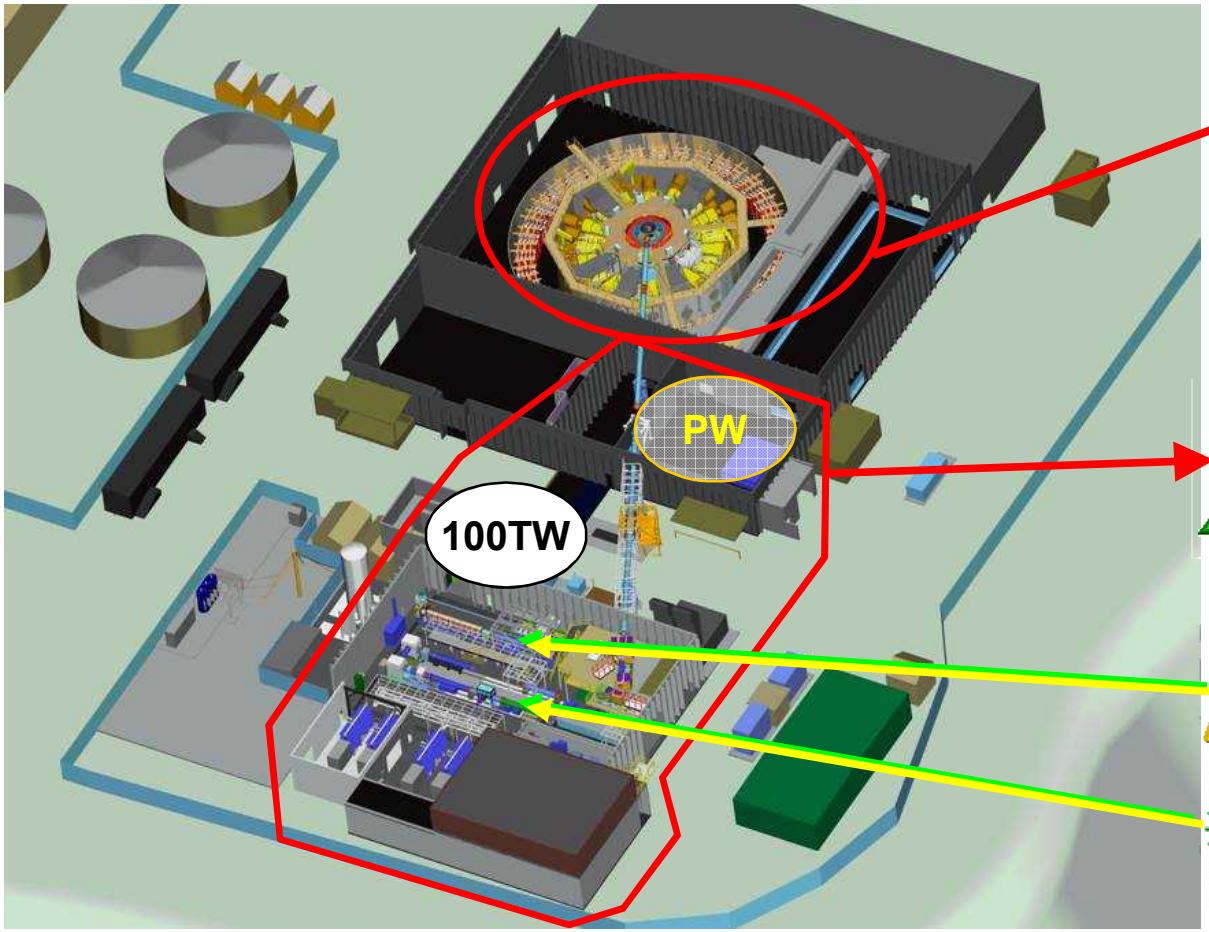
Available Laser Systems

- λ=527nm
- τ=0.3-8ns (2ns common)
- ϕ~75μm spotsize
- E<2kJ
- I<10^{17} W/cm^2
- ~3 hr/shot
- 2 pulse MFB

- λ=1054nm
- τ=500fs min
- ϕ~30μm spotsize
- E<60J (<500J pending)
- I>10^{19} W/cm^2
- ~3 hr/shot
- Sub-ps probe @ 527nm, <20mJ

- λ=1064nm (532nm option)
- τ=150ps
- ϕ~5μm spotsize
- E<10J
- I<10^{17} W/cm^2
- ~20 min/shot
- Pending: 8-10ns operations at >100J @1ω

Facility Overview



Z

Z Backlighter

Z Petawatt

Z Beamlet

Both Z Beamlet and Z-Petawatt are part of the Z Backlighter Facility

Z Backlighter

Z Beamlet

- λ = 527 nm
- November 2007
- τ = 0.3 – 8 ns
- ϕ ~75 μm spotsize
- E < 2 kJ
- I < 10^{17} W/cm^2

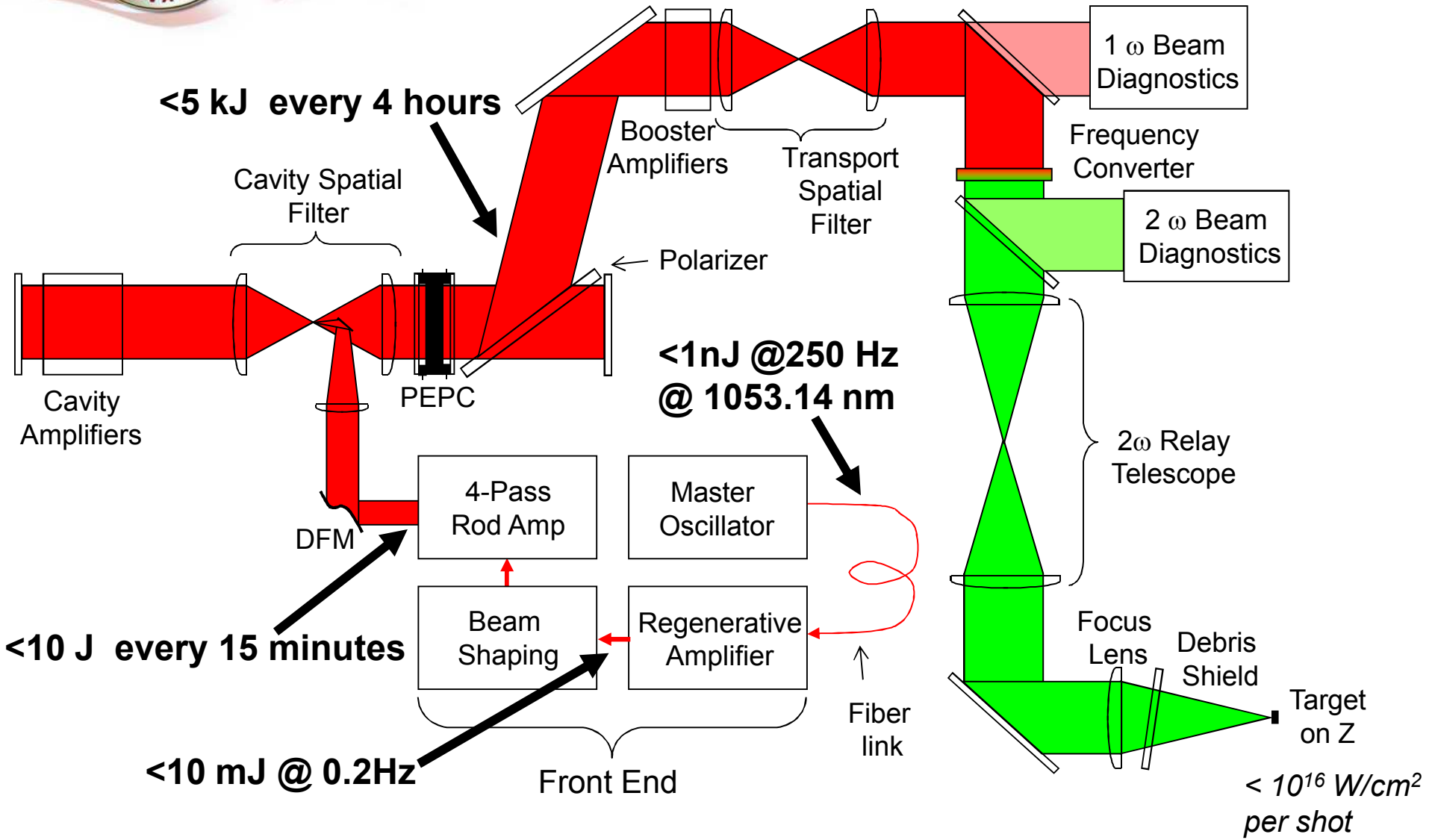
Z Petawatt

- λ = 1054 nm
- November 2007
  - τ = 500 fs min
  - ϕ ~30 μm spotsize
  - E < 500 J
  - I > 10^{19} W/cm^2
- Goal in 2010
  - 2 kJ/10 ps

Compression chamber installation

Sandia National Laboratories

The Z-Beamlet Laser system



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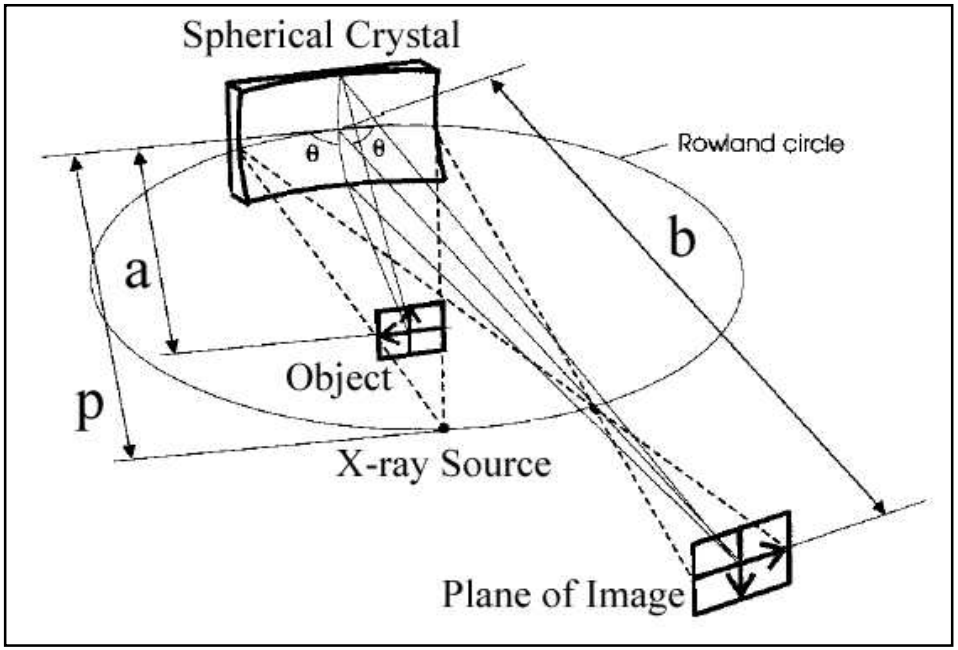
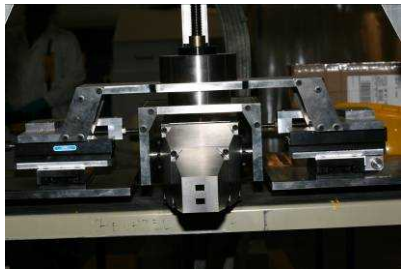
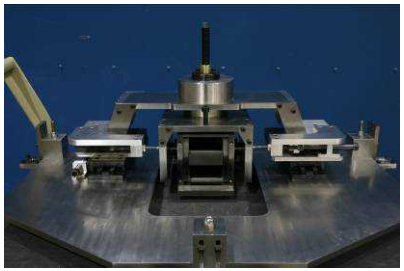
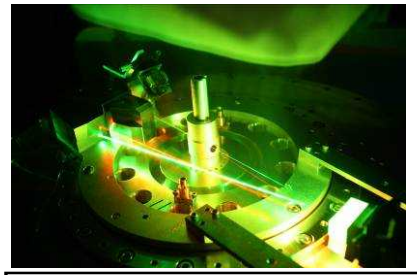
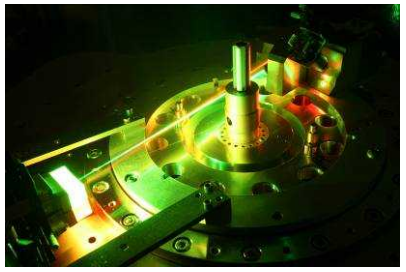
Curved-crystal imaging offers an elegant solution for backlighting in hostile environments











Bent-crystal Imaging

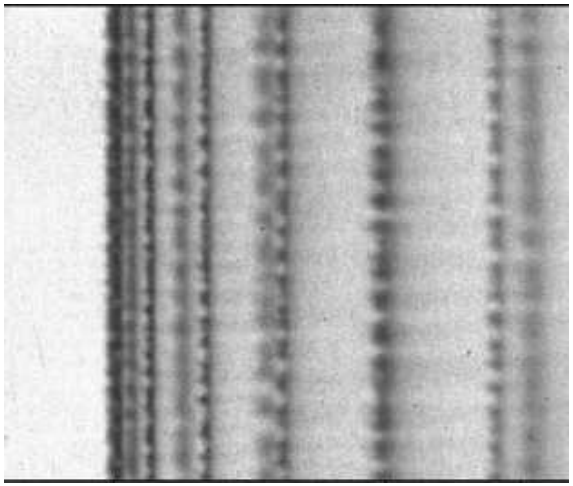
- **Monochromatic (~0.5 eV bandpass)**
- **10 micron resolution**
- **Large field of view (e.g. 20 mm x 4 mm)**
- **Debris mitigation**

- **Concept proposed in mid-1990s.**
  - S.A. Pikuz *et al.,* Rev. Sci. Instrum. **68**, 740 (1997).
- **A 1.865 keV backlighter built at NRL**
  - Y. Aglitskiy *et al.*, Rev. Sci. Instrum. **70**, 530 (1999).
- **Crystal imaging techniques proposed for microscopy/backlighting on NIF**
  - J.A. Koch *et al.*, Rev. Sci. Instrum. **70**, 525 (1999).
- **1.865 and 6.151 keV diagnostics successfully implemented on Z facility**
  - D.B. Sinars *et al.*, Rev. Sci. Instrum. **75**, 3672 (2004).

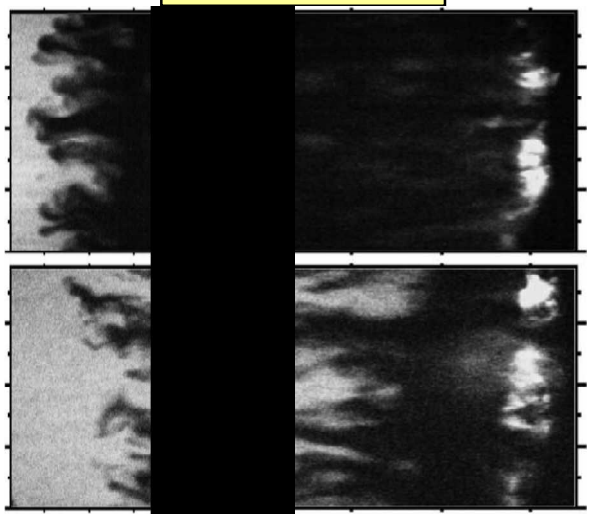
X-ray backlighting has led to rapid progress in the understanding of wire-array magnetically-driven implosions

Tungsten Wire Array implosions radiographed at 6.151 keV

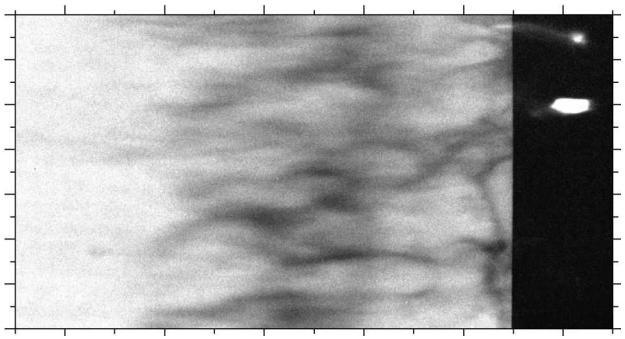
Ablation

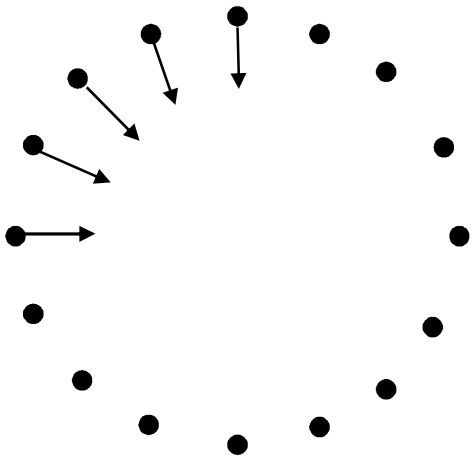


Implosion



Stagnation & X-ray production





Magnetic Rayleigh-Taylor and other instabilities strongly affect wire array zpinches from the very beginning

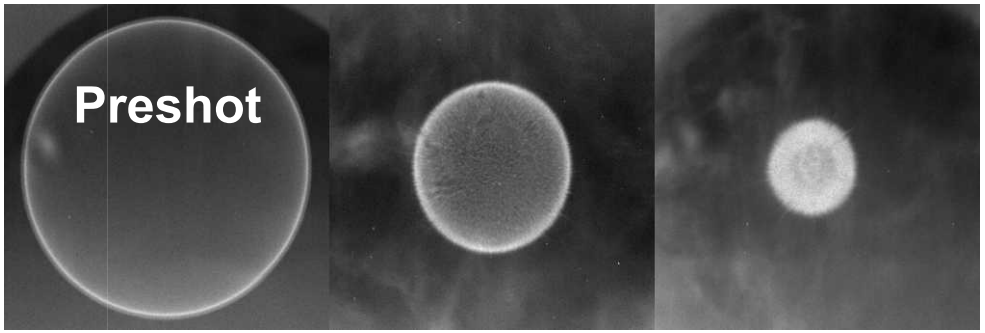
Few carefully benchmarked magnetic Rayleigh-Taylor experiments have been done

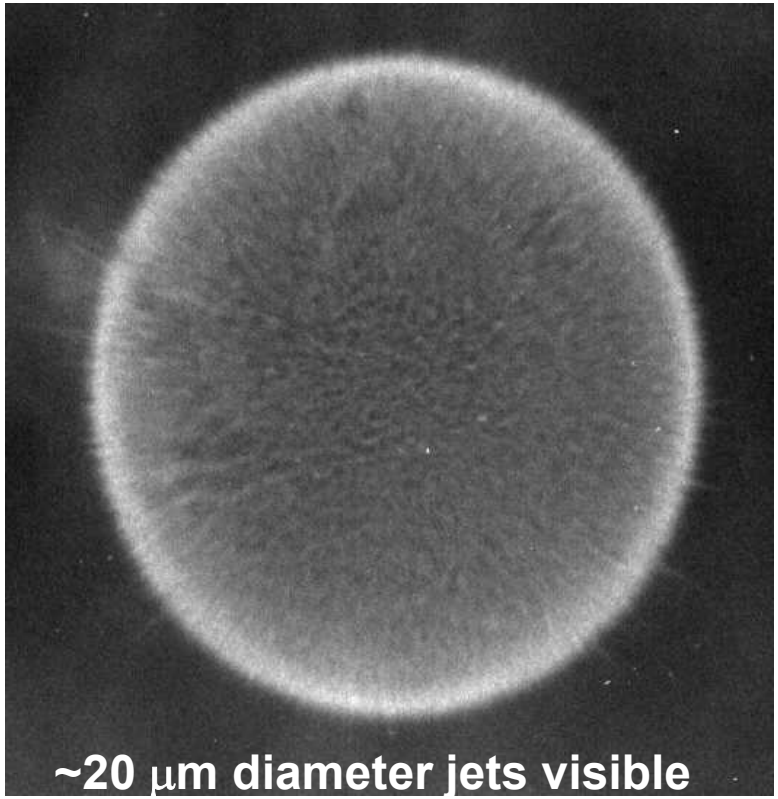
Late in time current delivery to small radius is limited by mass "left behind"

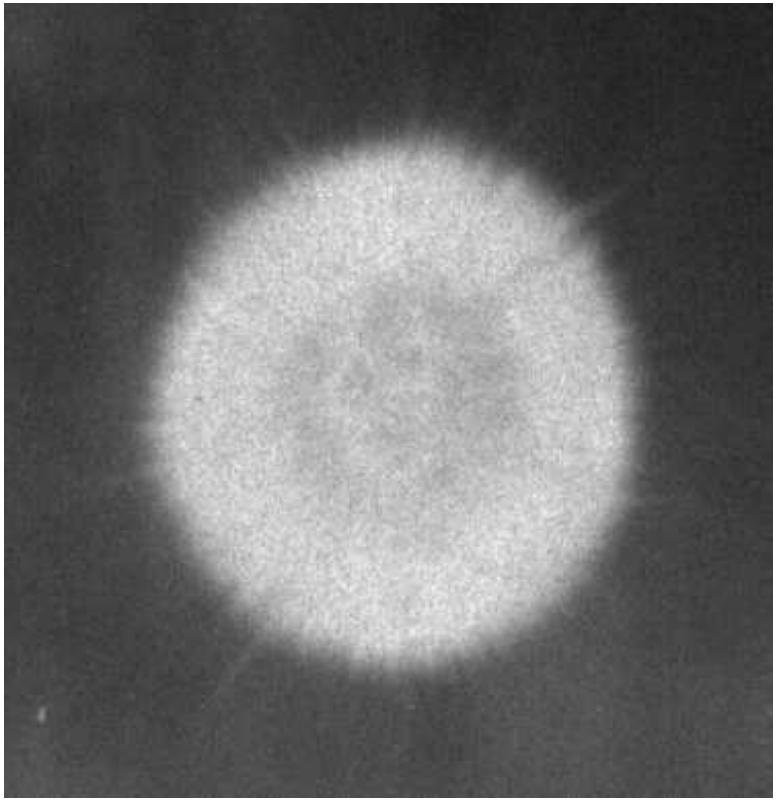
The higher spatial resolution bent-crystal imaging system revealed new features in imploding capsules

3.4-mm diameter plastic ICF capsule

Capsules had 100s of known defects on surface that apparently produced a myriad of small jets



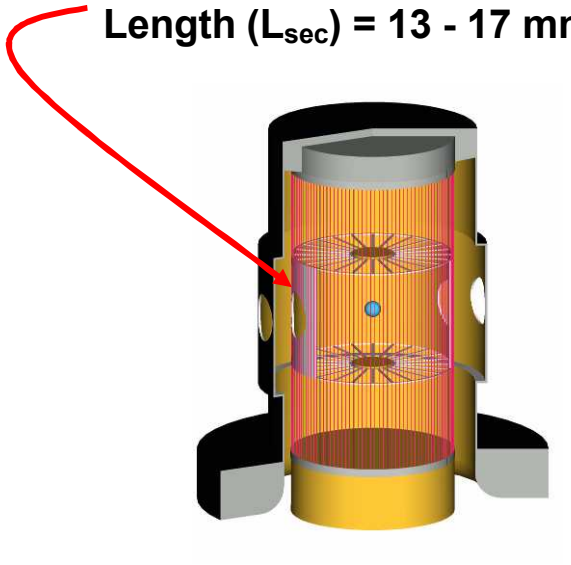




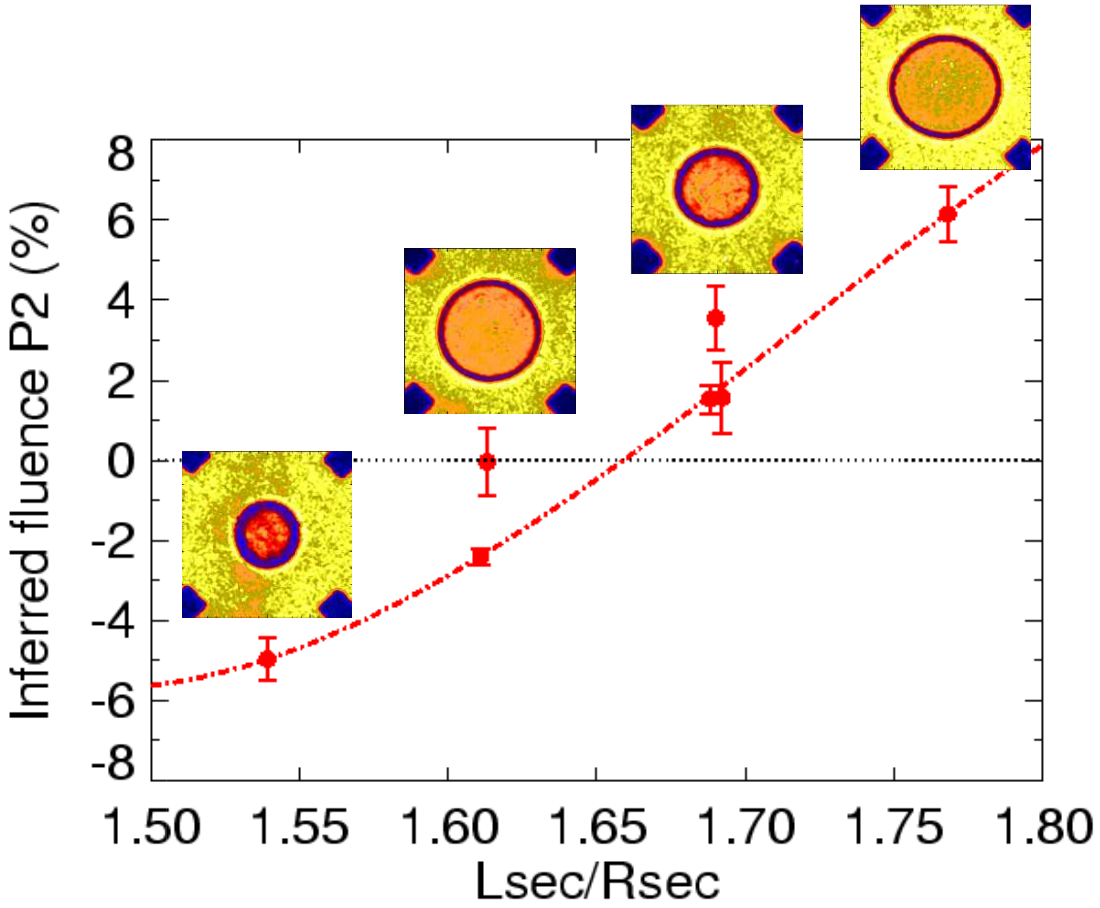
X-ray backlighting enabled us to optimize the symmetry of capsule implosions on Z

Secondary hohlraum dimensions

Radius (R_{sec}) = 9.6 mm
Length (L_{sec}) = 13 - 17 mm

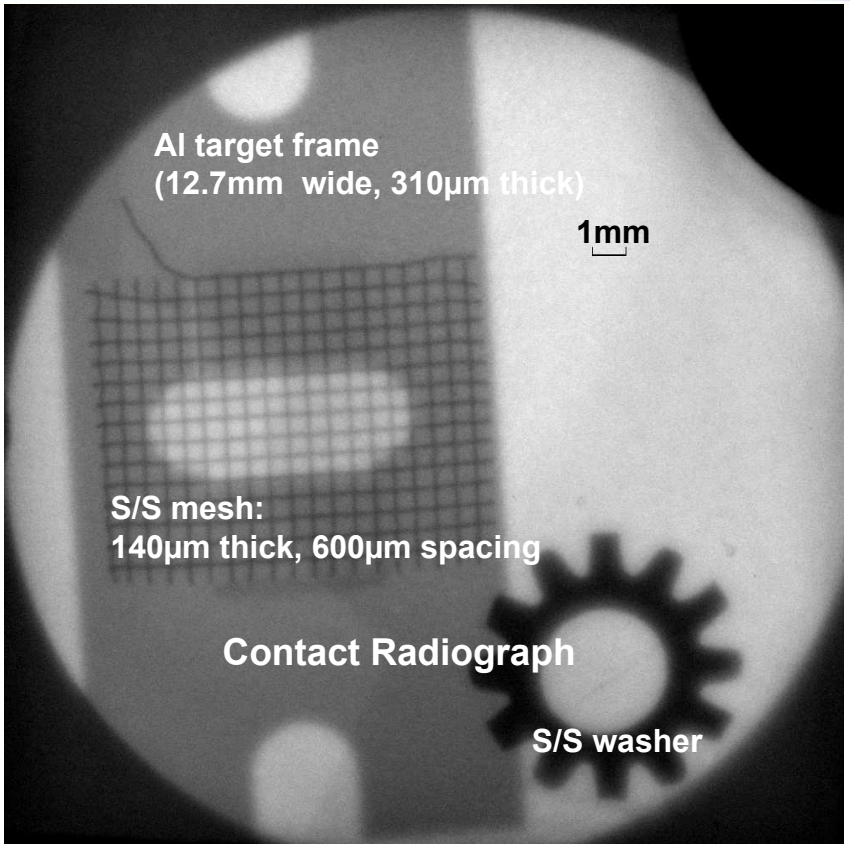


Time-integrated P_2 radiation symmetry



In late 2007, Z-Petawatt delivered ~125 J compressed pulse to an inactive Z-Accelerator

- **Z-Petawatt will enable:**
  - New radiography options
    - » X-rays for radiography up to 100 keV range
    - » Proton radiography
    - » Sub-picosecond resolution radiography
  - Fast Ignitor fusion research on Z
- **ZPW enhances Z backlighting abilities**
  - 43.5 cm beamsize
  - Applies 1480 l/mm 94 cm gold gratings (Nova)
  - Demonstrated up to 414 J uncompressed
  - Demonstrated 125 J compressed in initial shots
  - Limit: ~1 PW (500 J / 500 fs)
- **Future backlighting on active Z to include:**
  - A complete diagnostics suite
  - A fully active Final Optics Assembly
  - Active and passive debris mitigation
  - Active back-reflection isolation



Cu K_α x-rays yielded a contact radiograph and x-ray spectra with better signal to noise than 100 TW scale tests

Summary

- The Z accelerator has been a very successful experimental platform for performing HED science
  - Inertial confinement fusion
  - Dynamic material properties
  - Radiation hydrodynamics, radiation effects, and basic science
- The Z Refurbishment Project was completed in September 2007 and has delivered over 26 MA to ICE loads
- Commissioning of refurbished Z is going well – no barriers to full performance
- Refurbished Z combined with Z-Beamlet and Z-Petawatt provide an exciting experimental platform for future work