SAND2015-8338C

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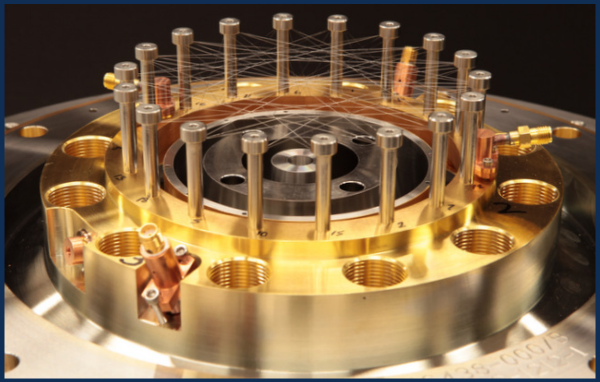

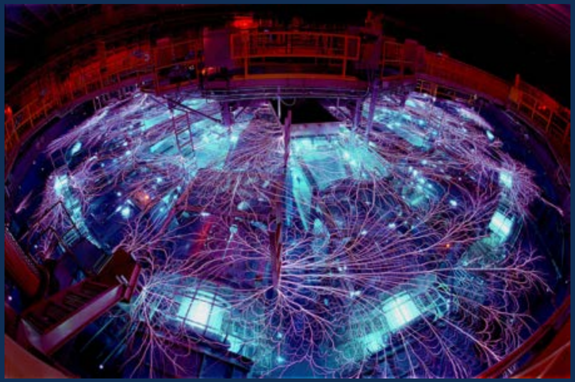

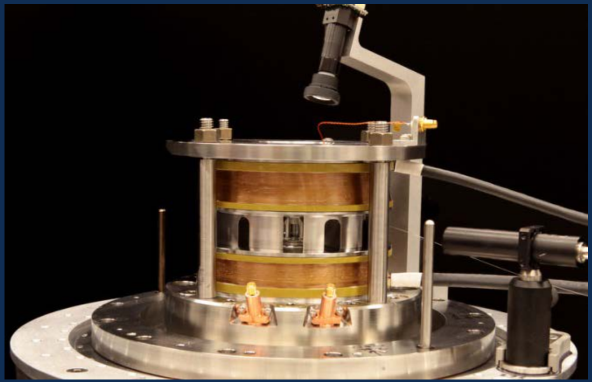

Capability Advances at the Sandia Z Machine

Joel Lash

Senior Manager, Z Facility R&D

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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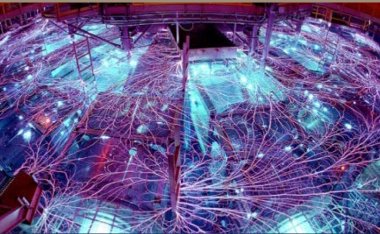

Outline

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- 22 MJ stored energy
- 3 MJ delivered to the load
- 26 MA peak current
- 1 - 100 Megabar
- 100 - 1000 ns pulse length
- ~1 shot per day / ~150 shots per year

Subsystems

- Backlighter
- Cryogenics
- External Magnetic Fields
- Gas Fills
- Explosive Containment for High Z Materials

Experimental Loads

- Wire Arrays – Radiation Sciences
- Liners – Inertial Confinement Fusion, Material Sciences
- Gas Puff – Radiation Sciences
- Flyer Plates – Material Sciences
- Short Circuits – Material Sciences

Diagnostics

- X-Ray
- Neutron
- Optical
- ZBL Backlighter

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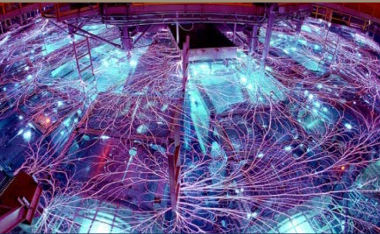

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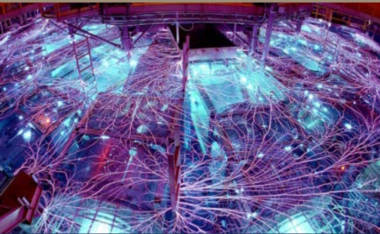
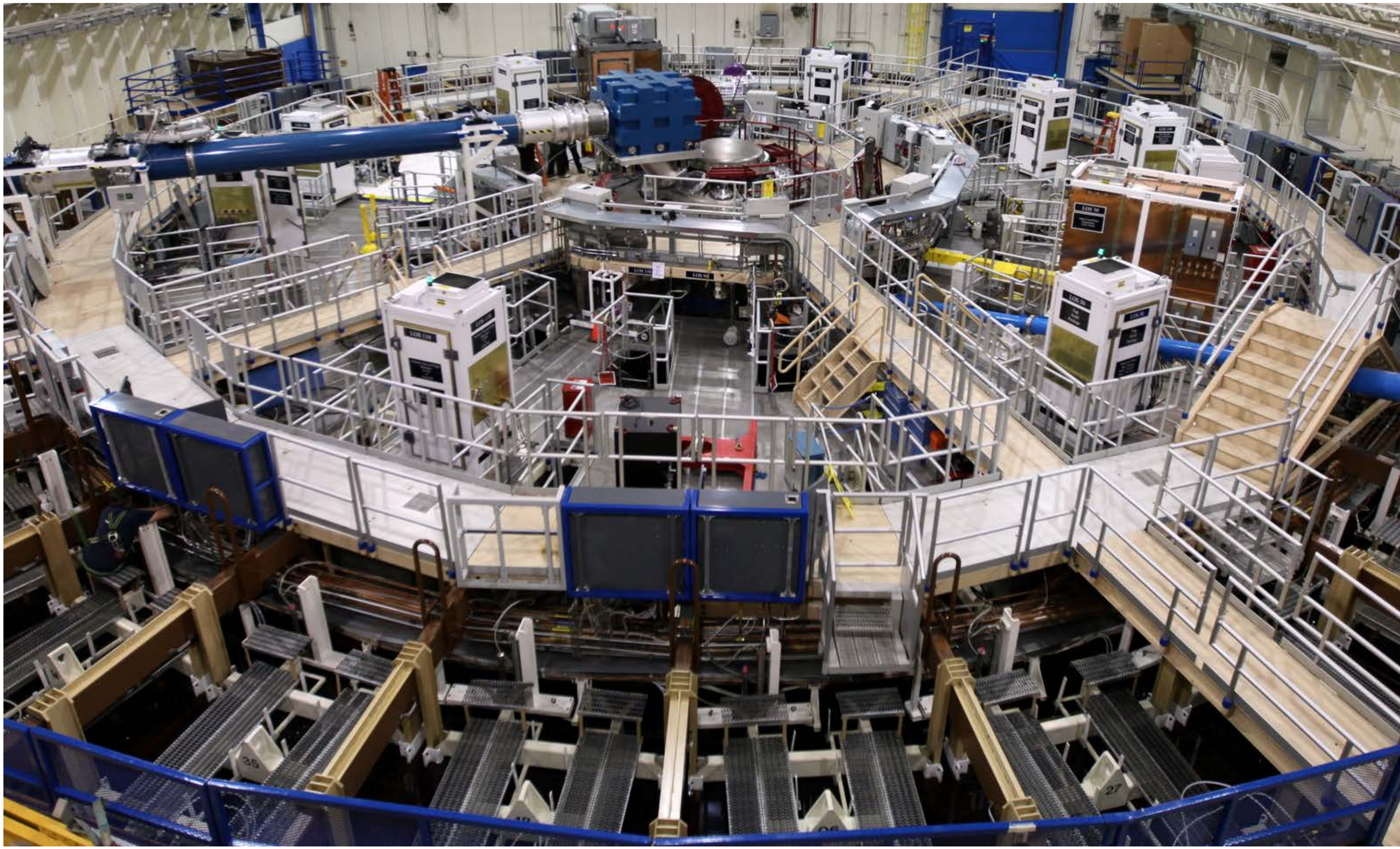


Z is a unique world class pulsed power facility at Sandia National Laboratories



36 Marx generators
2160 capacitors

~ 1M gallons of transformer oil
~ 0.5M gallons of deionized water

100,000 liter
vacuum vessel

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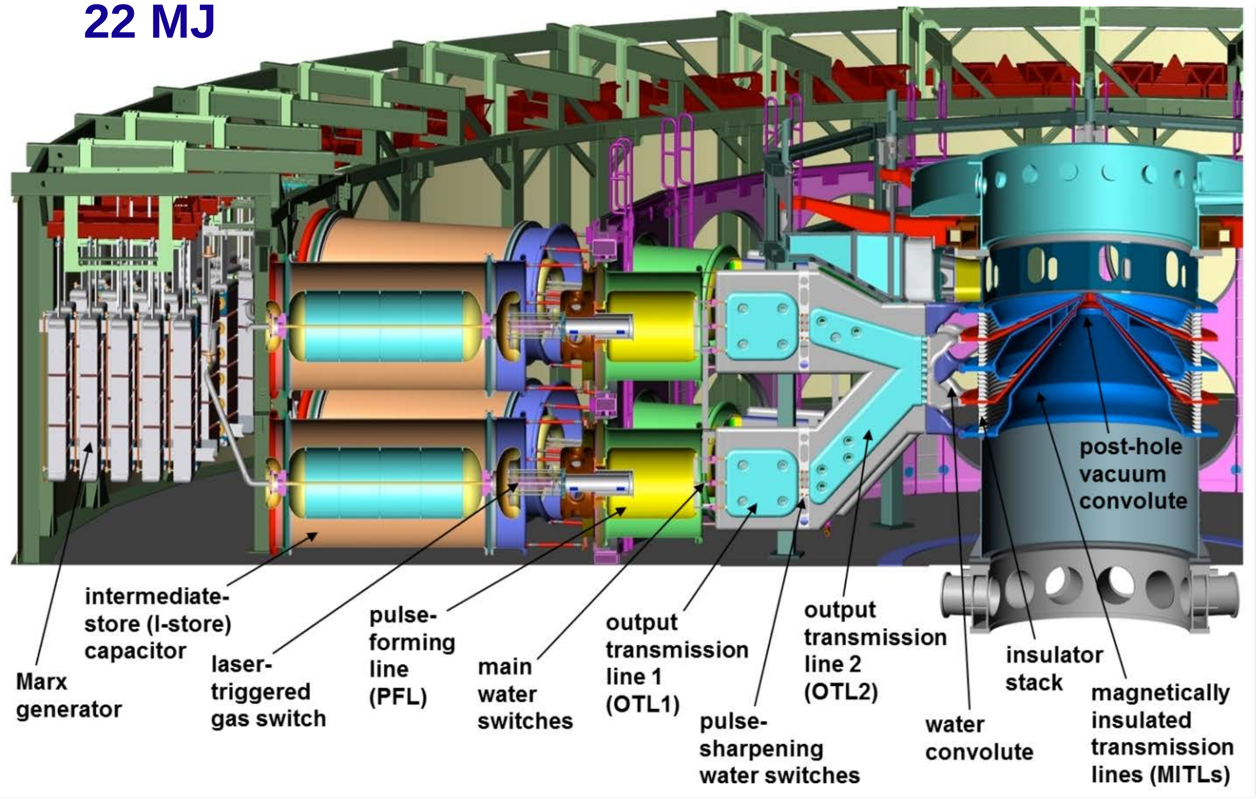
Z compresses electrical energy in both space and time . . .

20 TW
22 MJ

80 TW
8 MJ

Charge for 3 minutes to reach 85 kV



330 TWs & 2.5 MJ of x-ray output in a few ns

. . . and literally shakes the earth almost every day!

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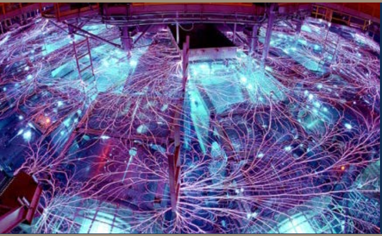
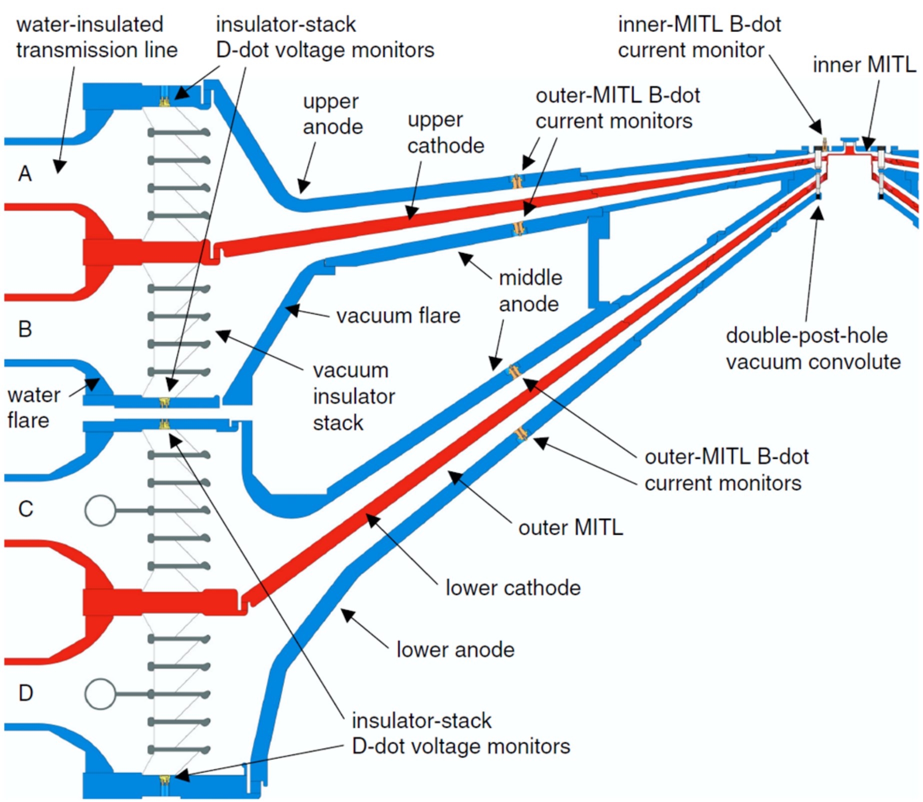
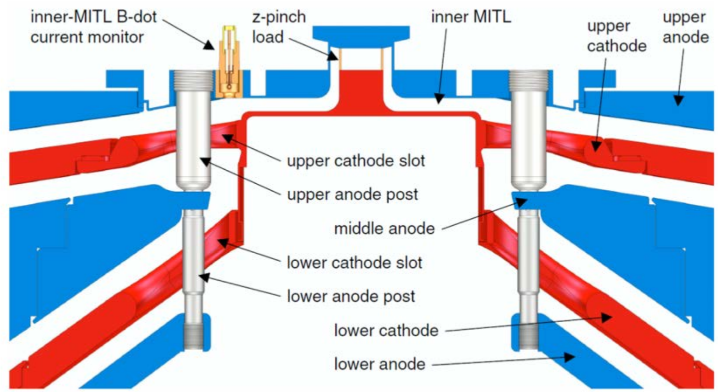


A complex series of conductors combine currents for the load

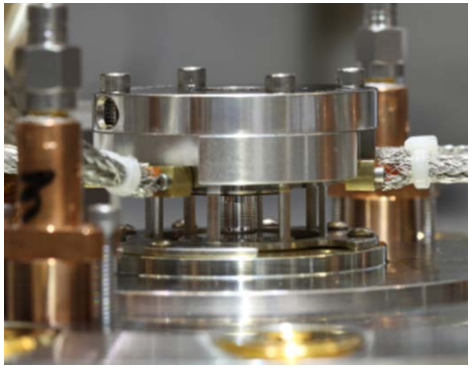
Z vacuum insulator stack and MITLs



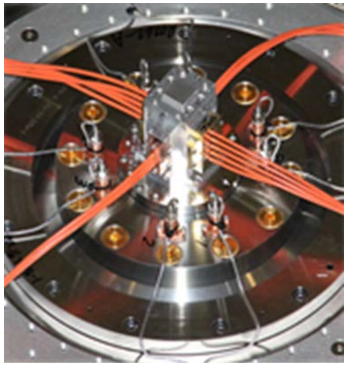
Post hole convolute system and load



ICF liner load



DMP load



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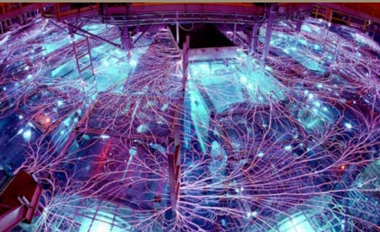


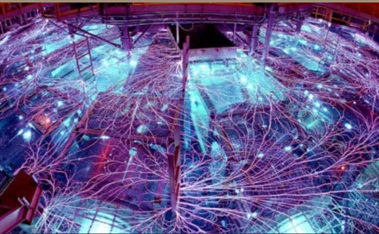
Daily Z Activities: Unload and Refurbishment

- Vent chamber to atmosphere
- Drain ~0.5 million gallons of water
- Drain ~1.0 million gallons of oil
- Inspect, repair, and perform preventative maintenance

Post shot damage

MITL transport

- Remove shot hardware and vacuum chamber diagnostics
- Remove Magnetically Insulated Transmission Lines (MITLs)
- Refurb MITLs and vacuum stack



Daily Z Activities: Load and Downline Preparation

- Fill ~0.5 million gallons of water
- Fill ~1.0 million gallons of oil
- Water dive to remove bubbles from critical surfaces
- Install MITLs

Wire array transport

Target and diagnostic loading

- Install Load Hardware
- Install Diagnostics
- Install FOA, Align Diagnostics
- Pump down vacuum chamber
- Checklists and fire Z!

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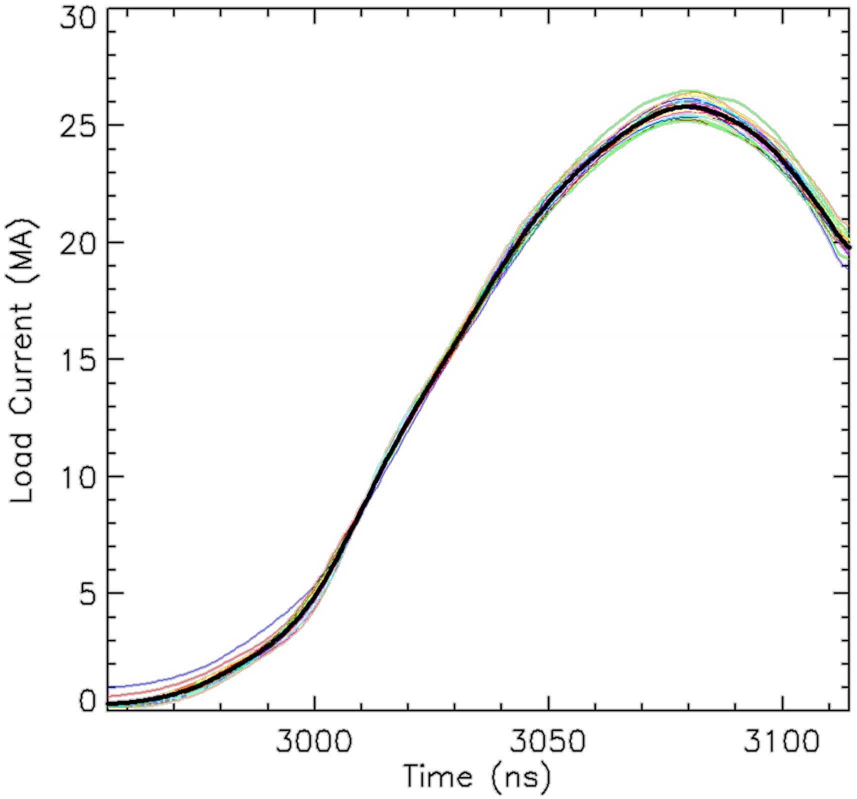
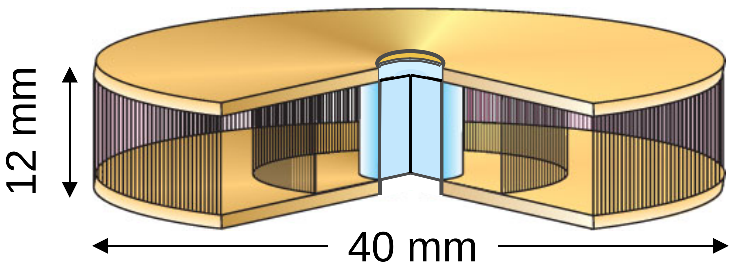
Pulse Shape Flexibility and Reproducibility

Load Currents (20 shot average)



Z-pinch Dynamic Hohlraum



Standard ZPDH Characteristics

360 W wires – 11.4 μm diameter

m = 8.5 mg W total

V_{marx} = 85 kV (20.3 MJ)

I_p = 25.8 ± 0.4 MA [20 shots]

The z-pinch produces record currents of 25.8 MA with 1.5% reproducibility

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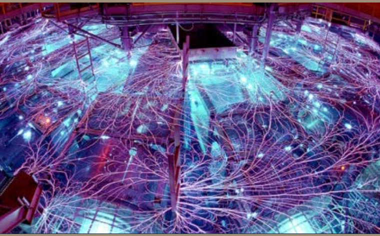
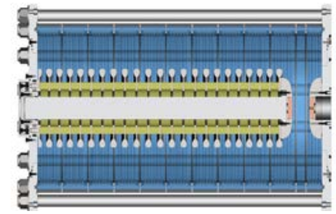
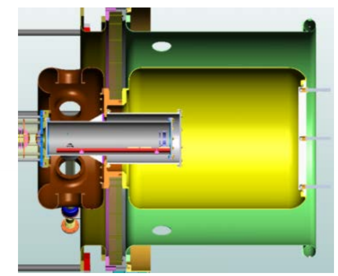


We are increasing the peak current available on Z from 26 to 32 MA

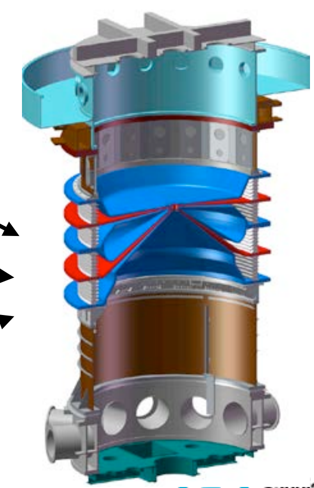
- **6.7 MV laser-triggered gas switches – done!**
  - The new switches allow increasing the Marx voltage from 85 to 95 kV, double the precision of the pulse shape, and increase the shot rate by reducing maintenance.



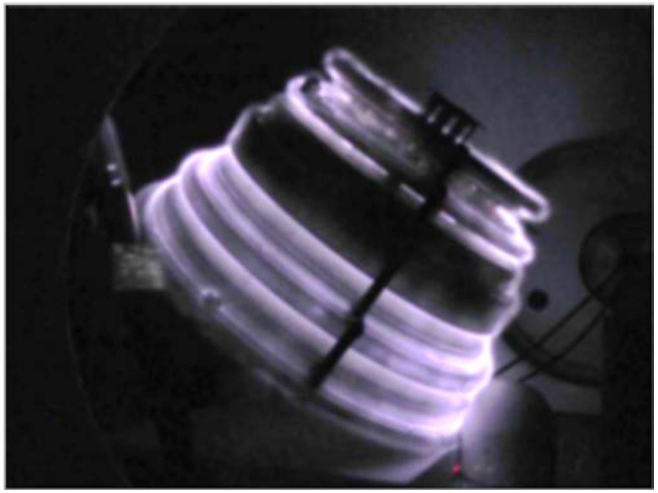
- **6.7 MV pulse-forming lines – done!**
  - The new PFLs will allow us to increase the Marx voltage from 85 to 95 kV, and improve worker safety.



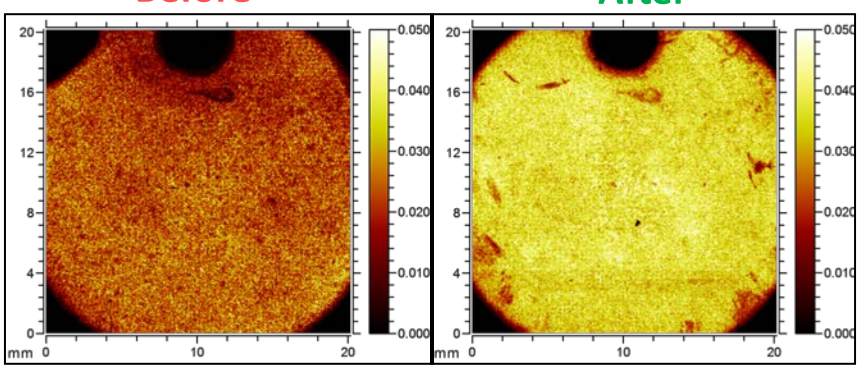
- **Next generation vacuum insulator stack – in progress**
  - The new stack will allow operation at 95 kV, and eliminate flashovers that can affect the pulse shape.
- **Lower-inductance MITL-convolute system**
  - A new system would increase the peak current 5%, lower convolute costs by $1M each year, and increase the shot rate by 5%.
- **Horizontal water triplates that connect the PFLs to the stack**
  - The new triplates will eliminate the 3D water convolute, which will increase the current by 7%.



We are working to improve current delivery to the experimental load

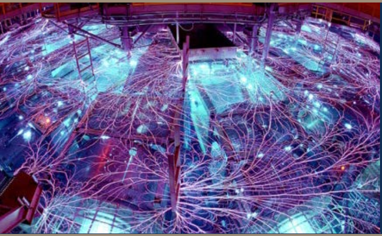


Plasma cleaning development on Z Convolute hardware



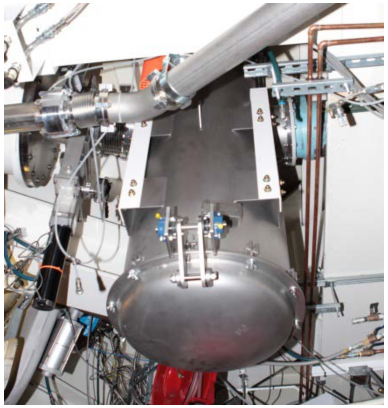
*Coupon with environmental exposure survey, shown **Before** and **After** plasma cleaning. Increase in detected bulk nickel indicates reduced surface contaminants on SS304 sample.*

- **Increased load current will benefit nearly all Z experiments**
  - Achievable pressure in dynamic materials experiments
  - Radiated power in wire array experiments
  - Fuel compression in MagLIF experiments
- **An *in-situ* plasma cleaning system will remove surface contaminants from highest power density surfaces**
  - Delay or mitigate creation, evolution of cathode and anode plasmas
  - Hydrocarbons and desorbed water likely culprits
  - Quantitative testing underway to evaluate removal rates for surface contamination materials



Safety and Facility Upgrades

Vacuum Chamber Air Exchange

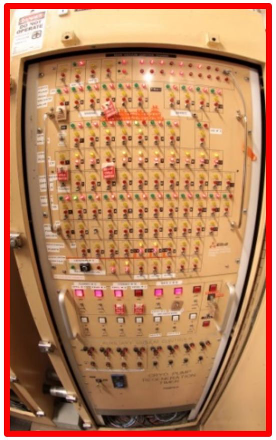


Replacing Aging/Legacy Equipment

- Over the past few years, many legacy control and monitoring systems have been replaced and/or upgraded.
- We are developing new systems to improve the capability, safety and reliability of control and data acquisition systems for Z.

Replacing the Be Refurbishment Tent

Z's control system computer. In place since 1993. Replaced May 2015



Z's vacuum control system In place since 1985.

Z's water drain/fill control system In place since 1985.

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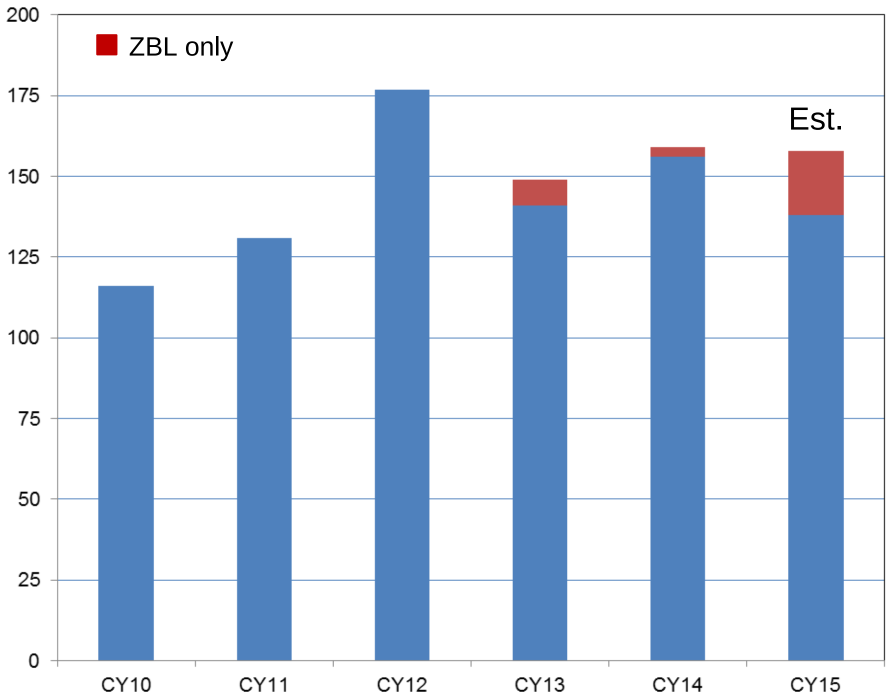
Z Shot Rate and Shot Planning

Z Shots by Calendar Year



~550 Shot Days were requested by LANL, LLNL, and SNL in CY15 – 3X more shot requests than available!

Z Shot Planning

- Typically plan for 140 – 160 shots a year based on budget
- Single shift operation:
  - 6 am work day start
  - 5 pm shot window closes
- Nominally 1 shot per shot day
  - 3 – 6 days for containment shots
- Most maintenance performed in parallel with daily shot preparations
- External PIs work with internal PIs for planning and execution

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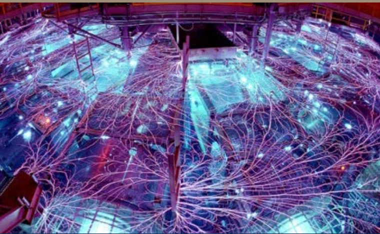

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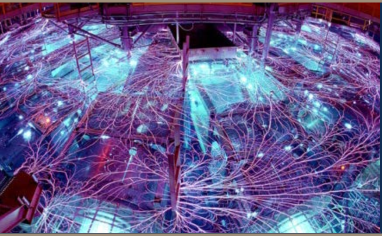
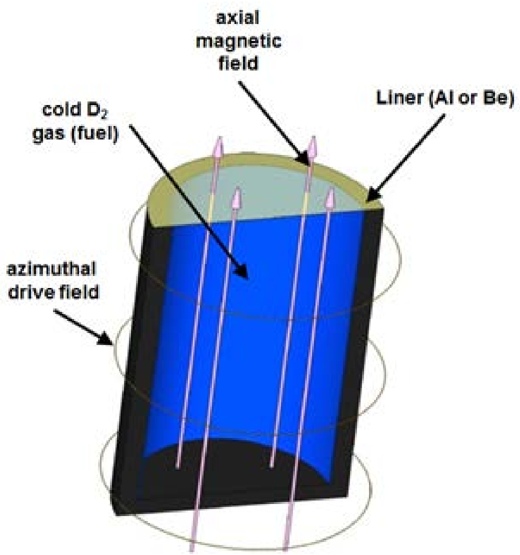


Flexibility in Experimental Platforms: Inertial Confinement Fusion

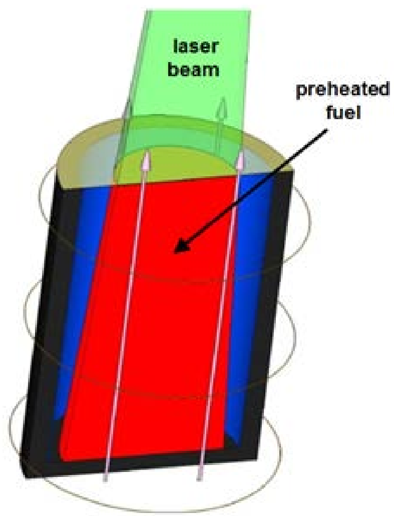
Magnetization



An initial ~10T axial magnetic field is applied

- Inhibits thermal conduction losses
- Enhances alpha particle energy deposition
- May help stabilize implosion at late times

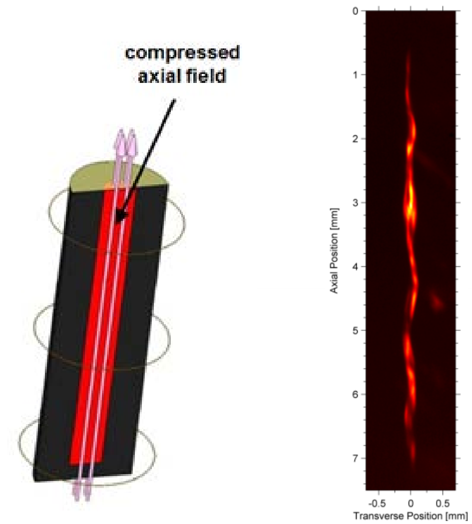
Laser Heating



During implosion, deuterium fuel is heated using the Z-Beamlet laser

- Preheating reduces the compression needed to obtain ignition temperatures to 20 - 30
- Preheating reduces the implosion velocity needed to “only” 100 km/s (slow for ICF)
- Stagnation pressure required is a few Gbar, not a few hundred Gbar

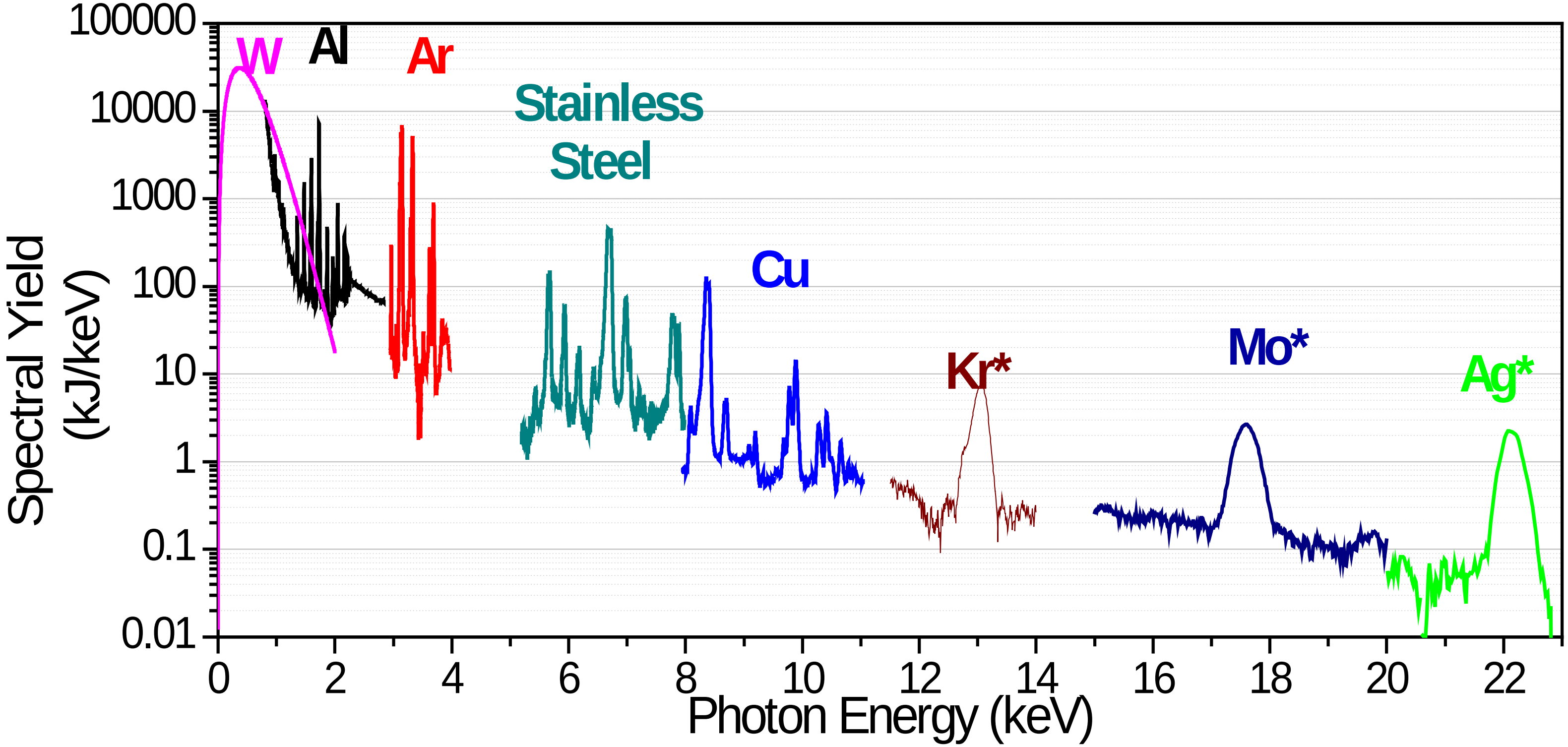
Compression



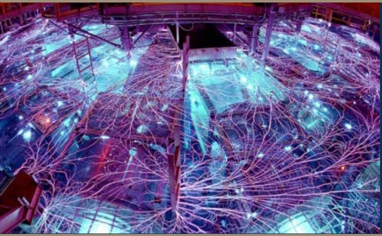
The Z machine efficiently drives a z-pinch implosion which produces high fuel compression producing approximately 10^{12} fusion neutrons

Flexibility in Experimental Platforms: Radiation Sciences

Radiation Effects Sources



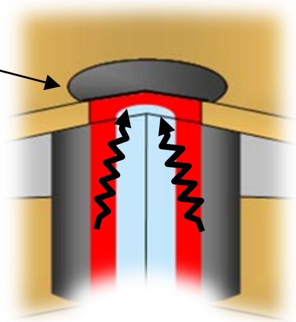
Z provides intense x-ray sources at different energies for radiation effects studies



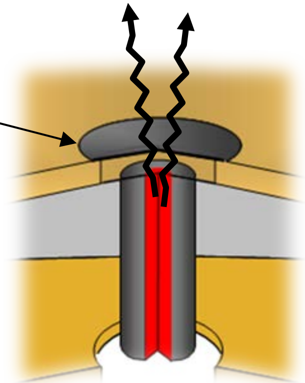
Flexibility in Experimental Platforms: Radiation Sciences

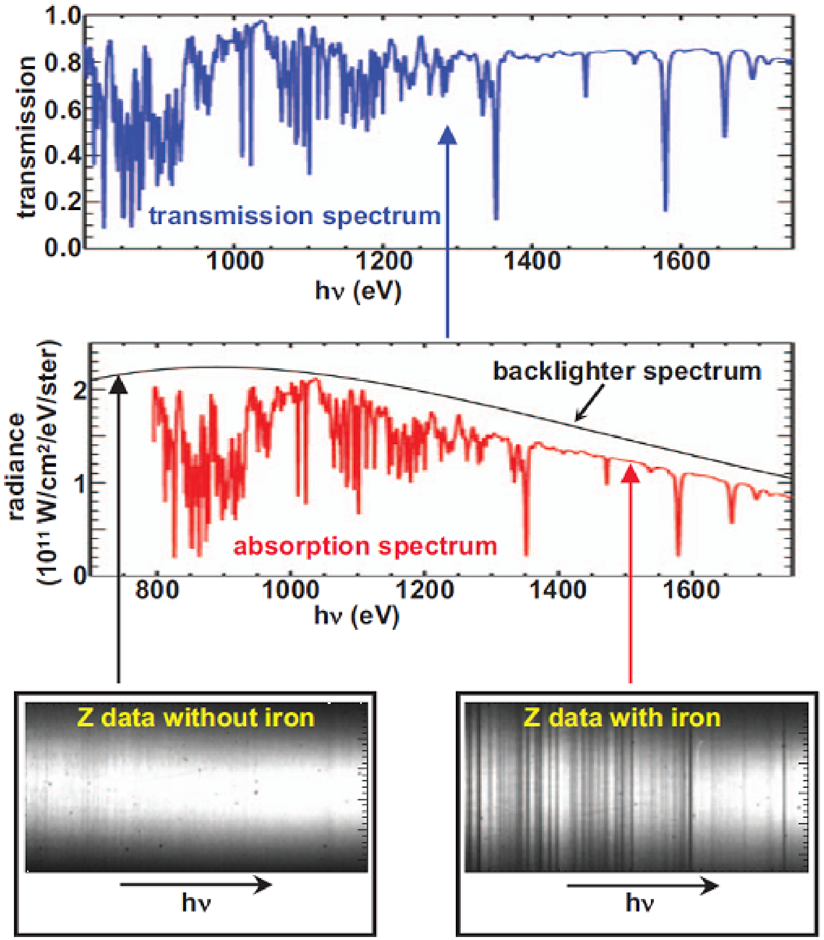
Opacity Measurements with a Z Pinch Driven Dynamic Hohlraum

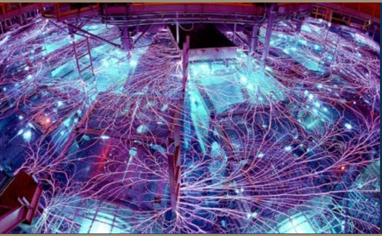
Foil heated during Dynamic Hohlraum implosion



Foil backlit at shock stagnation

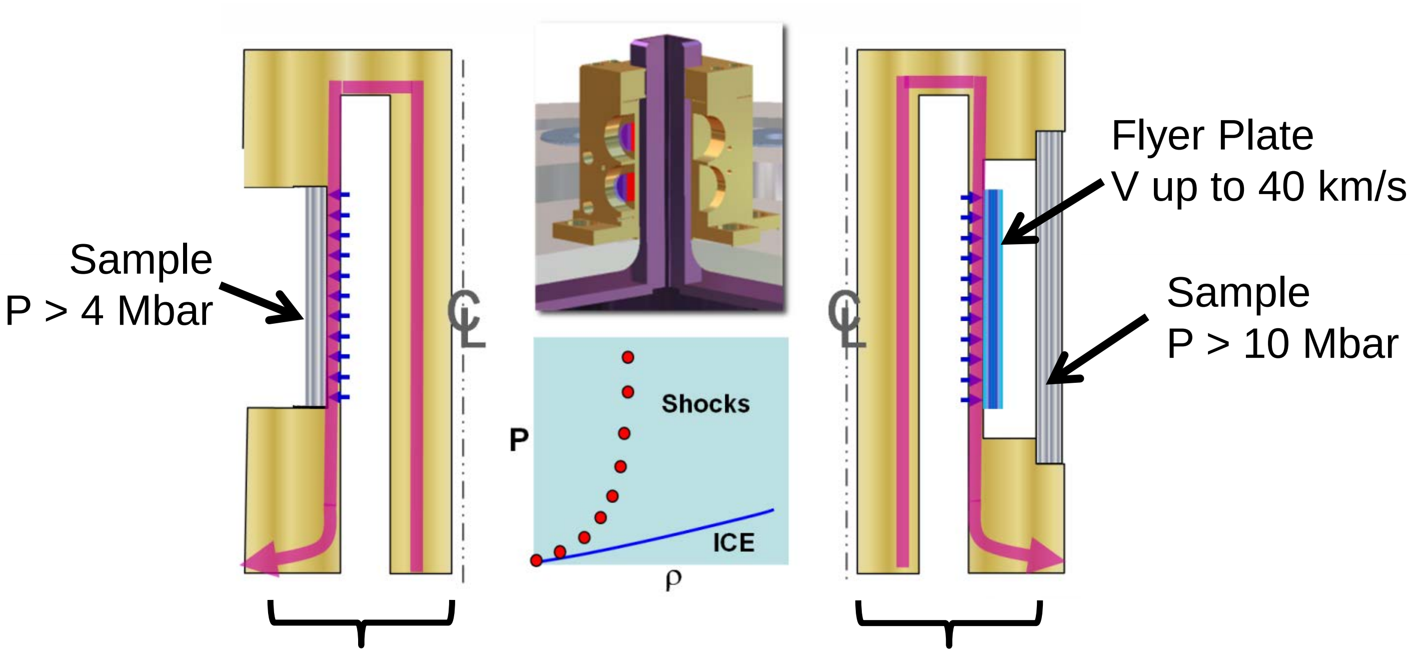






Flexibility in Experimental Platforms: Dynamic Materials

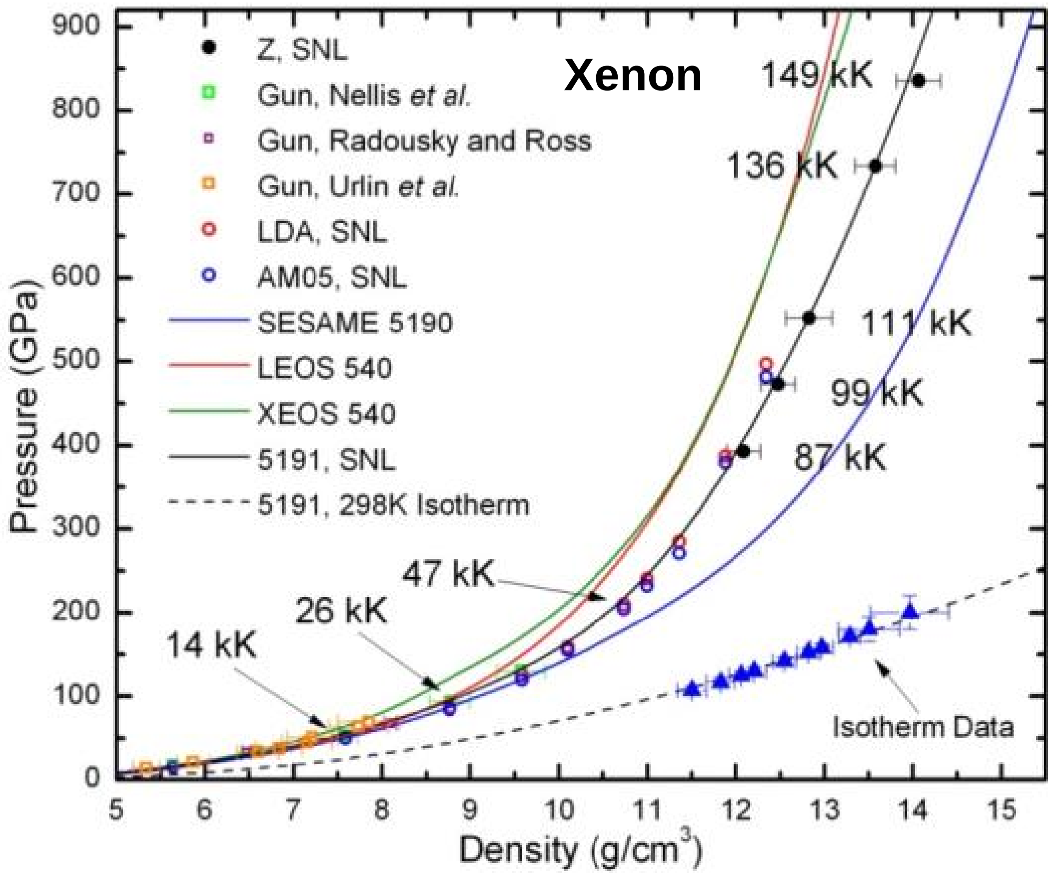
Z isentropic compression and shock wave experiments enable access to key equation of state regions for many materials, including Uranium and Plutonium



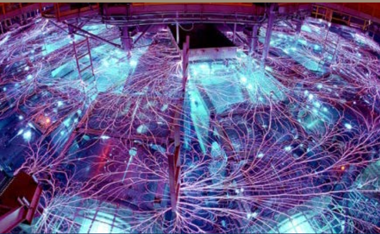
Isentropic compression: gradual pressure rise in the sample

Shock Compression: shock wave launched in sample at impact

Flexibility in Experimental Platforms: Dynamic Materials



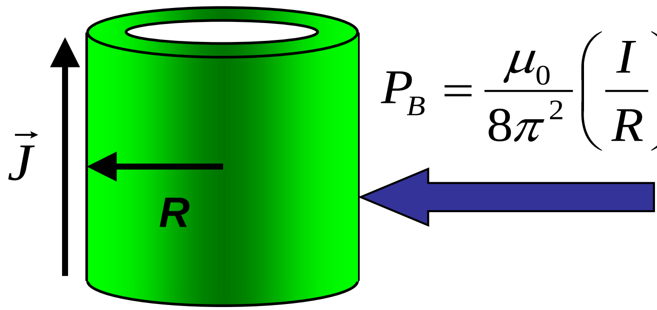
Z acquires data never seen before and is resolving fundamental EOS differences



Flexibility in Experimental Platforms: Dynamic Materials

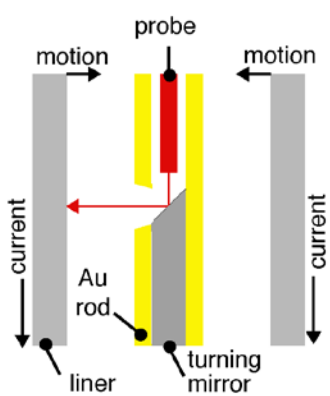
Quasi-isentropic Compression to Stresses ≈20 Mbar in Cylindrical Implosions

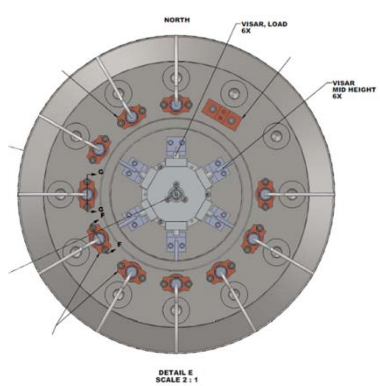
Liner Z-Pinch Implosion



$$P_B = \frac{\mu_0}{8\pi^2}\left(\frac{I}{R}\right)^2$$

I = 20 MA; R = 0.1 cm; $P_B \approx$ 64 Mbar





- 3 - 4 times higher pressure than can be achieved in planar geometry
- Material stress increases monotonically
- Shockless compression by shaping the current profile
- A key challenge is diagnosing the compressed state
- *Successfully fielded internal radial photonic Doppler velocimetry (PDV) to measure the implosion velocity to very high precision*
- *A remaining challenge remains in obtaining accurate drive conditions to infer the pressure in an unfold*

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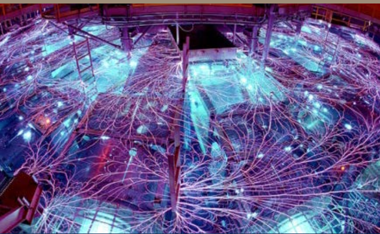

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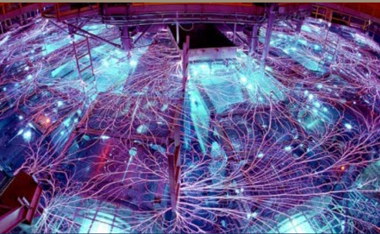
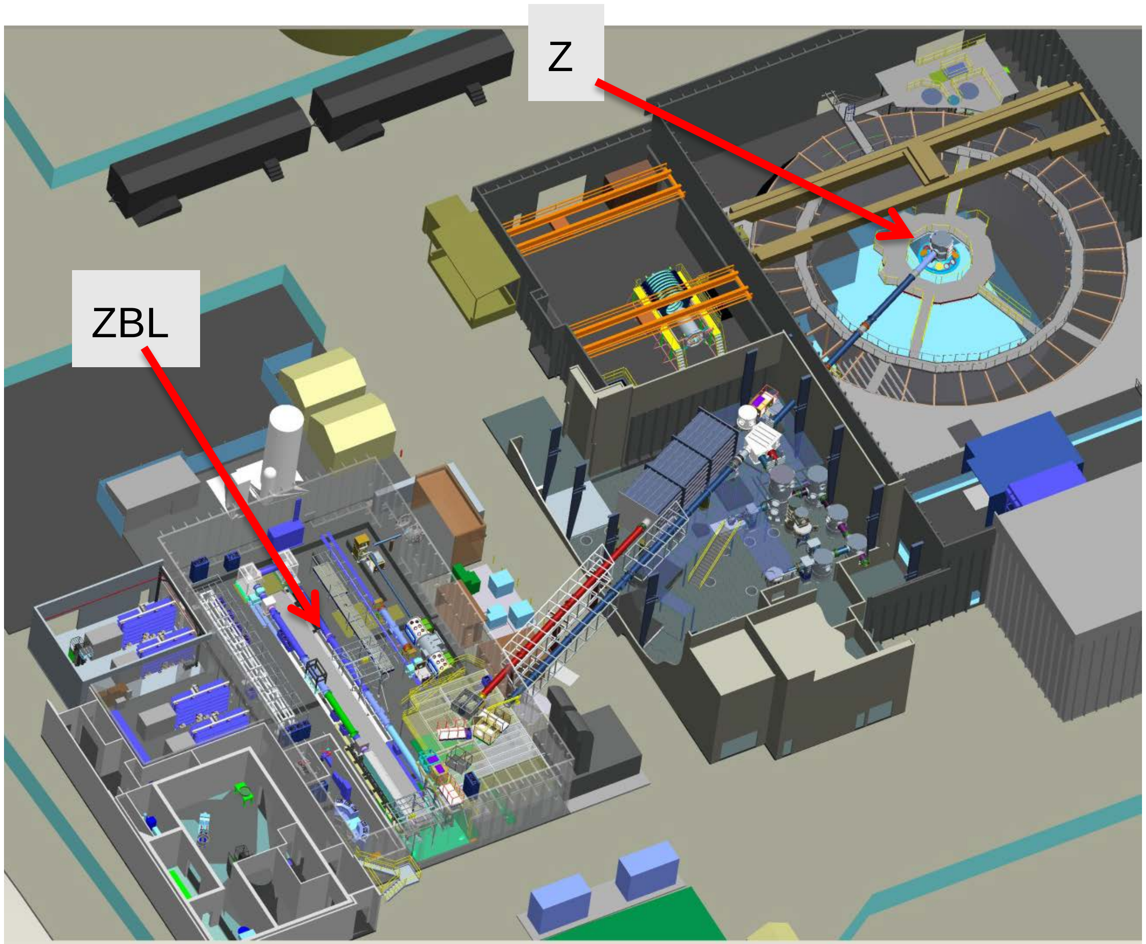


Z Core Capabilities: ZBL

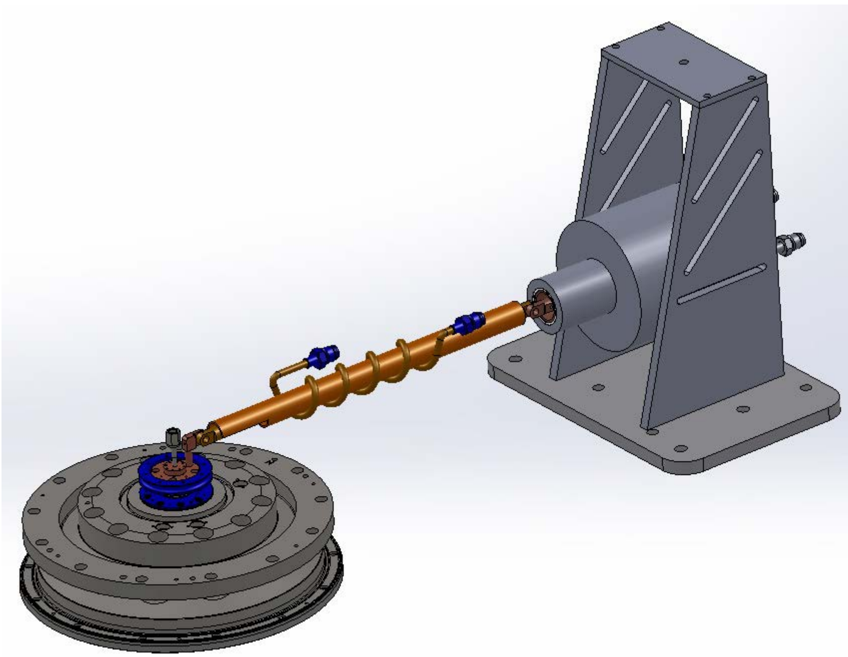
Z-Beamlet Basics



- The Z-Beamlet Laser (ZBL) was the LLNL NIF Prototype (1992-1998) and is now used on Z
  - 1st shots into Chamber: 3/0
  - 1st Z radiographs: 6/01
- The two facilities are co-timed to within 500 ps
- ZBL Parameters:
  - Up to 6kJ @ 1053nm
  - Up to 4kJ @ 527nm
  - Up to 4 shots per day
  - Typically 0.3 – 4 ns pulse length in a 31x31 cm^2 beam
  - 1 - 9 keV radiography

Z Core Capabilities: Cryogenics

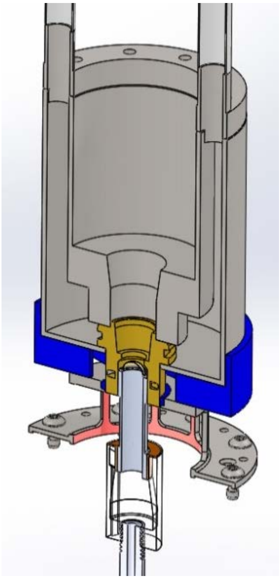
Standard Configuration (Mini Cryostat)



- Assembly outside blast shield.
- Cooled with liquid helium or nitrogen
- Achievable temperature range 200K to 18K
- Cooling time 20 - 45 min depending on configuration

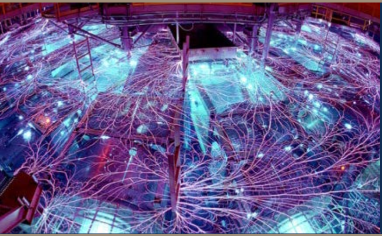
MagLIF Cryostat

- Liquid helium cooled
- Integrated into the assembly of the target
- Achievable temperature range 100K to 25K with current configuration
- Allows cooling of MagLIF target with coil assembly



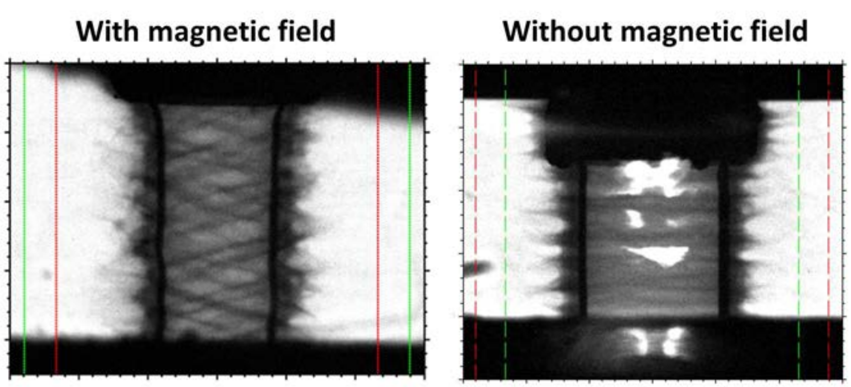
Liquid Helium Reservoir Cryostat

- Achievable temperature range 4.2K to 2.17K
- Cooling time 60 – 90 min
- Cryostat must have vacuum applied at 4.2K to achieve lower temperatures

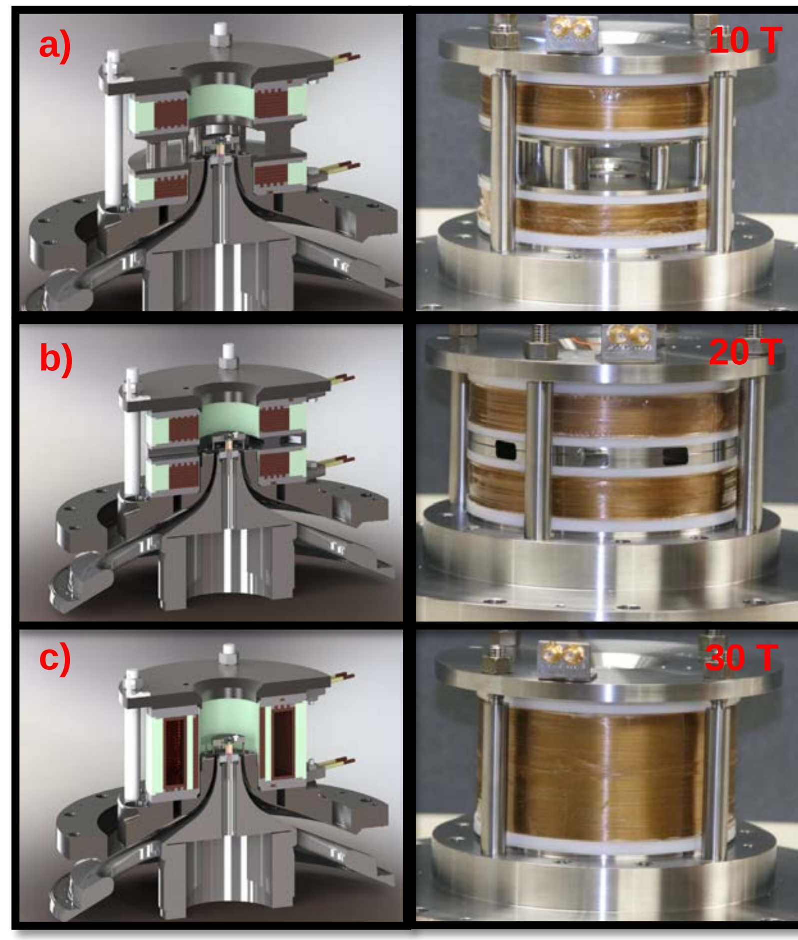


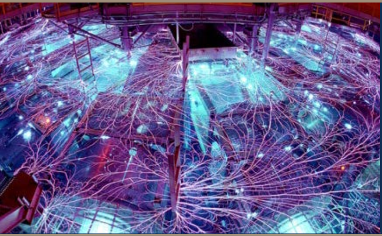
Z Core Capabilities: Applied B-Field

- Applied B on Z (ABZ) system enables HED magnetized target experiments on Z
- Since February 2013, over 75 HED experiments have used magnetization
- External capacitor bank can store up to 900 kJ for coil load in target chamber
- Different coil geometries have been designed and implemented to trade radial diagnostic access with field strength



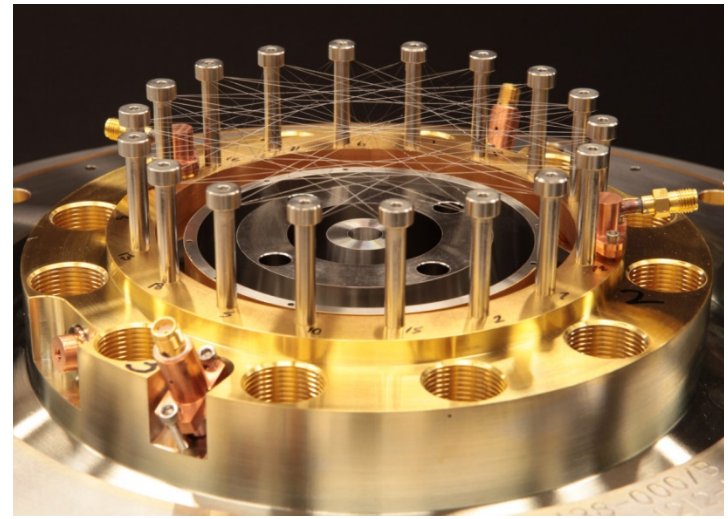
ABZ Field Coil Configurations

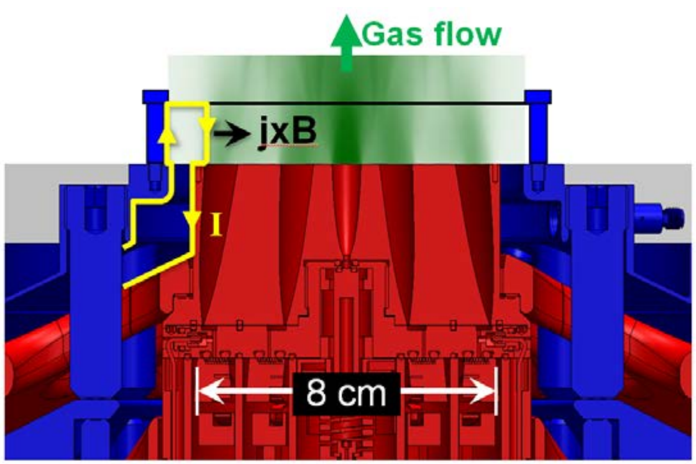


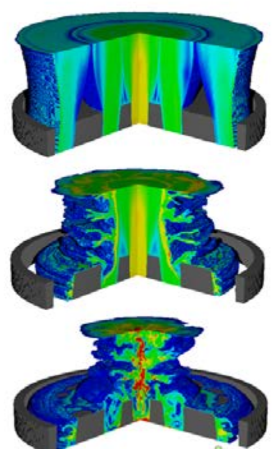


Z Core Capabilities: Gas Puffs

- Gas Puffs provide unique loads for tailoring x-ray outputs through judicious choice of gases
- Nozzle design and characterization is critical with development being done at the Sandia Systems Integration Test Facility
- Record K-shell x-ray outputs are robustly generated on Z







- The use of deuterium gas creates a neutron source producing ~4e13 DD neutrons
- A gas puff neutron source enables studying stagnation physics for comparison with MagLIF
- Robust yields also support diagnostic development

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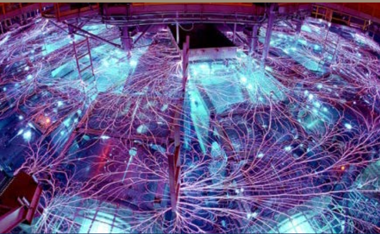
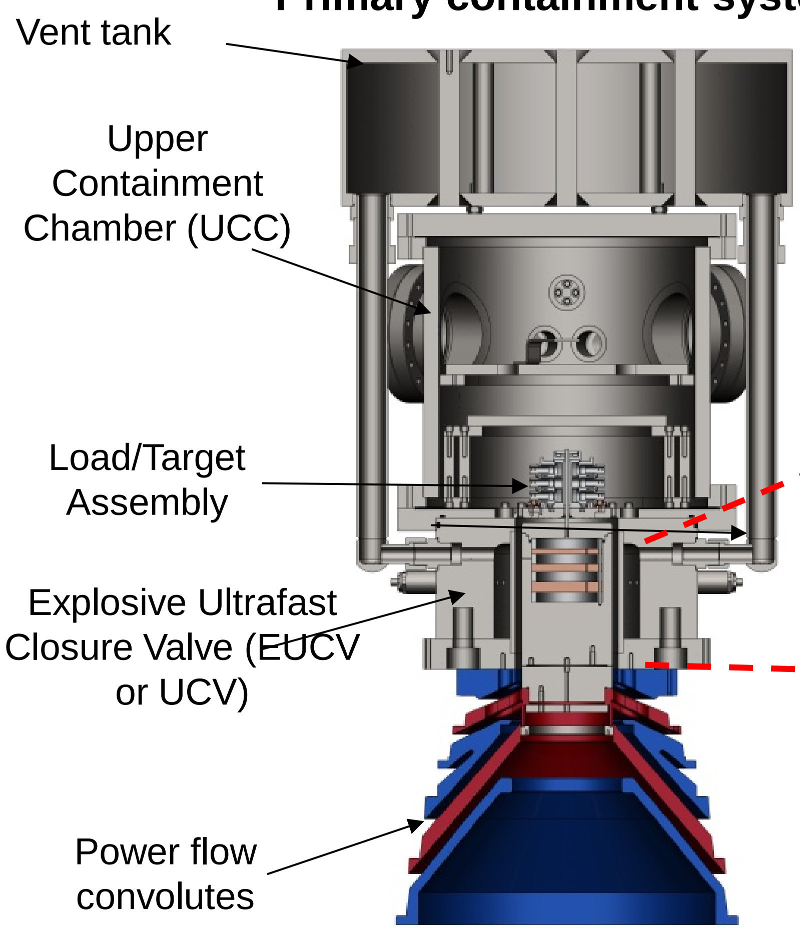


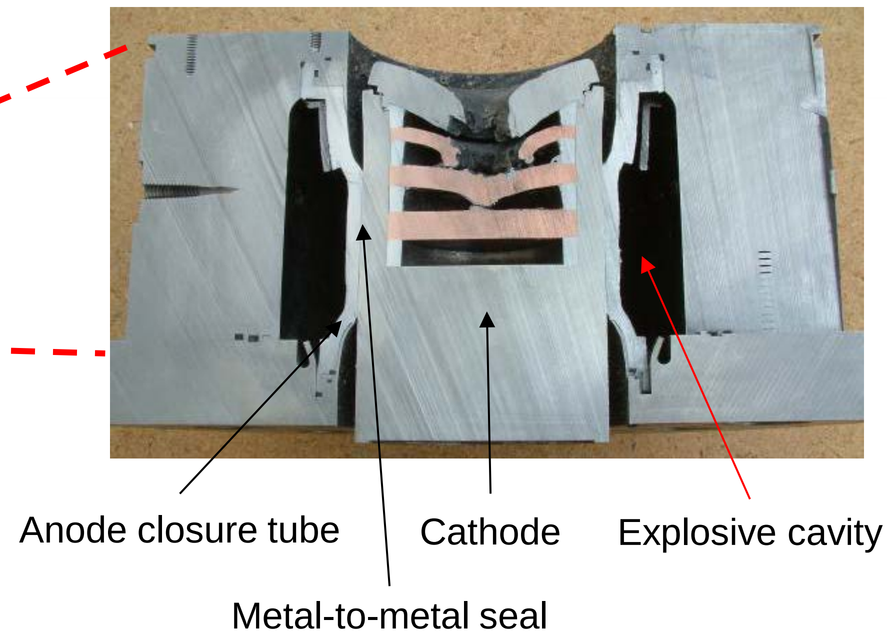
Z Core Capabilities: High Z

Primary containment system

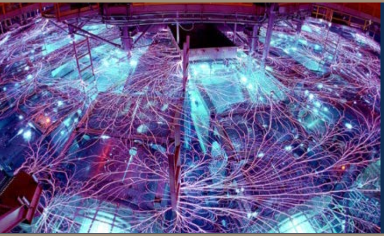


Post-shot cross section of UCV showing metal to metal seal between anode closure tube and cathode

- Valve closes in ~ 40 μs
- Leak spec is < 1e-5 atm-cc/sec
- Typical leak rates are 1e-8 atm-cc/sec



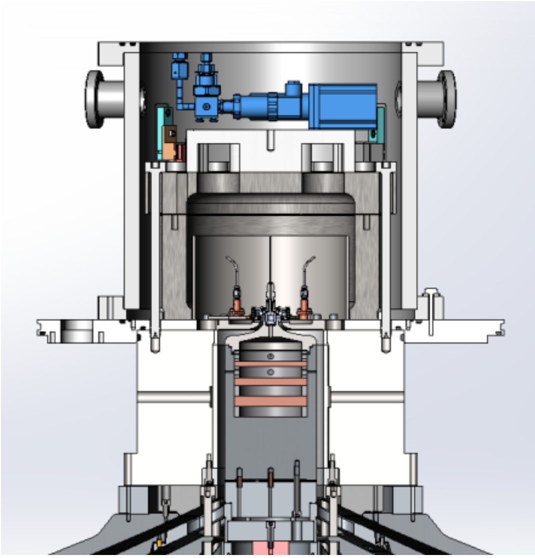
We have a proven containment system for Pu experiments used many times

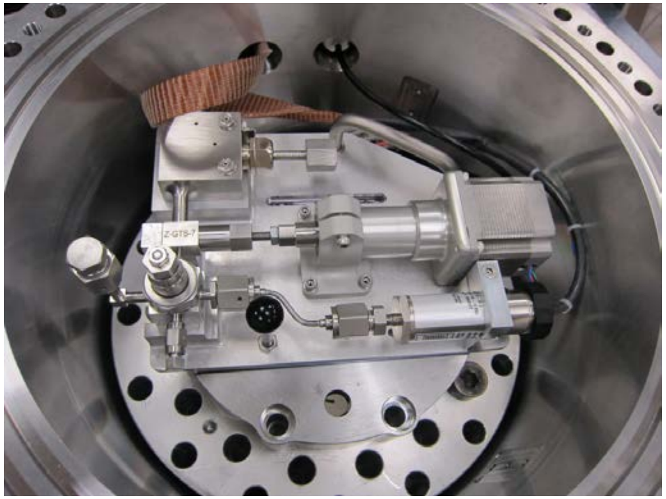


Z Core Capabilities: Tritium

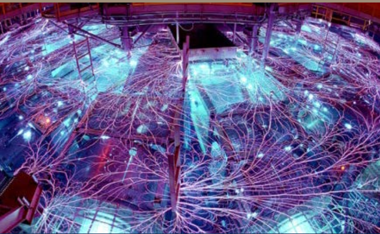
A Sandia Grand Challenge LDRD project is assessing the feasibility of using an explosive containment system

- Conducted three tritium containment development experiments using light gas surrogates
- Validated use of the existing hazardous material containment system as a viable test platform for tritium





- Developed and demonstrated the Z Gas Transfer System (ZGTS)
- Planning to conduct two trace tritium (0.1% - 1.0%) experiments in CY16 using the ZGTS in a containment system



Outline

Pulsed Power / Facility

- 22 MJ stored energy
- 3 MJ delivered to the load
- 26 MA peak current
- 1 - 100 Megabar
- 100 - 1000 ns pulse length
- ~1 shot per day / ~150 shots per year

Subsystems

- Backlighter
- Cryogenics
- External Magnetic Fields
- Gas Fills
- Explosive Containment for High Z Materials

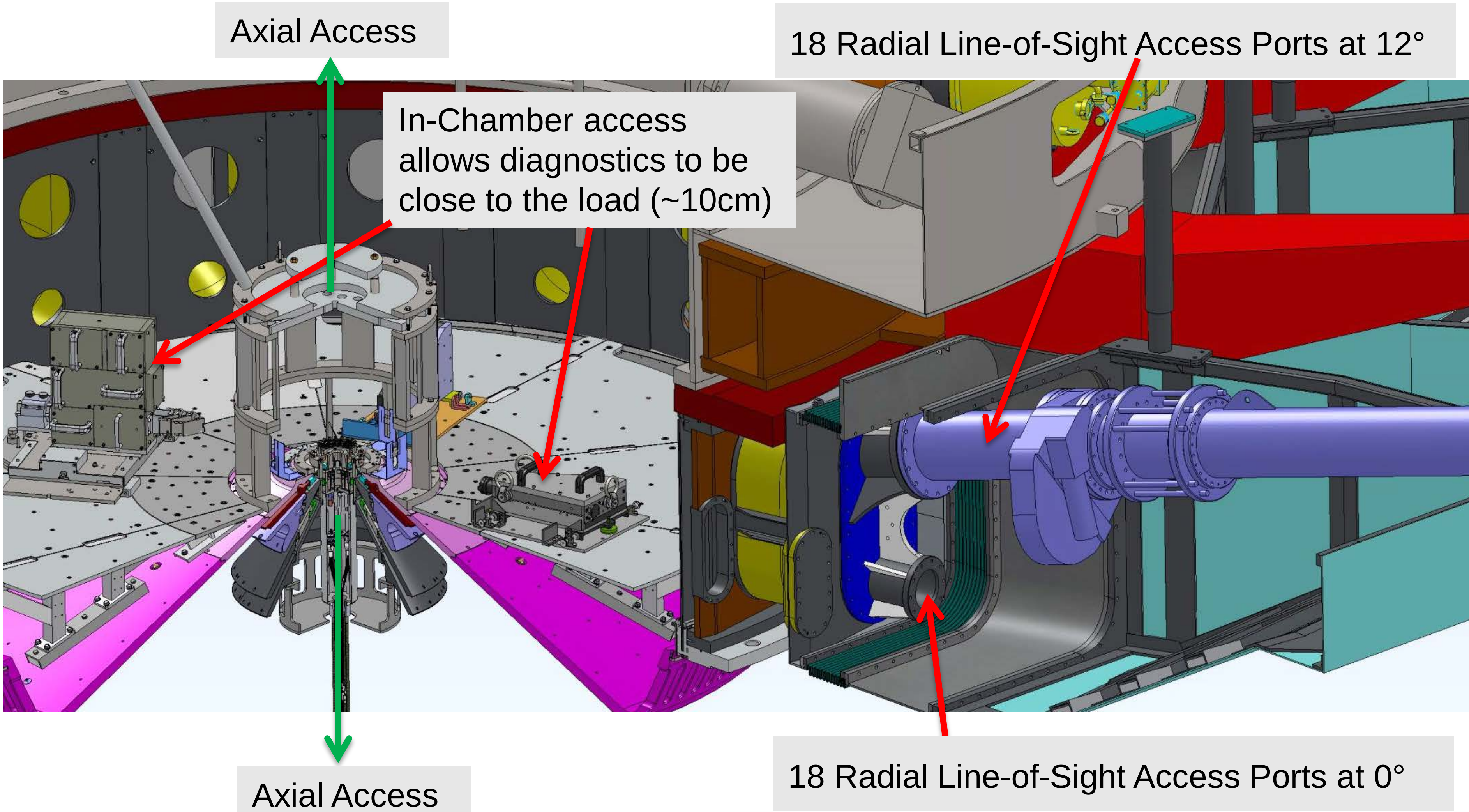
Experimental Loads

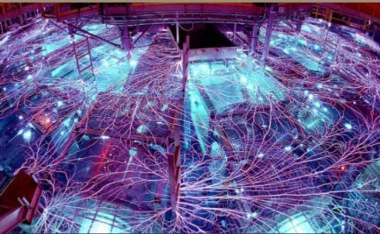
- Wire Arrays – Radiation Sciences
- Liners – Inertial Confinement Fusion, Material Sciences
- Gas Puff – Radiation Sciences
- Flyer Plates – Material Sciences
- Short Circuits – Material Sciences

Diagnostics

- X-Ray
- Neutron
- Optical
- ZBL Backlighter

Diagnostics: Overview





Diagnostics: Overview

X-Ray Diagnostics

- Time Resolved X-ray Power and Energy
- Time Resolved Pinhole Cameras
- Time Integrated Pinhole Cameras
- Time Resolved Multi-Layer Mirror Cameras
- Time Integrated Spectrometers
- Time Resolved Spectrometers

Visible / Shock Diagnostics

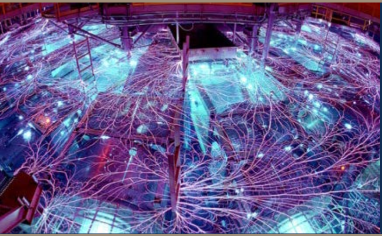
- VISAR
- Photonic Doppler Velocimetry (PDV)
- Streaked Visible Spectrometry (SVS)

Neutron Diagnostics

- Neutron Activation
- Neutron Time of Flight
- Neutron Imaging
- CR-39 in progress
- MRS under study

Z-Beamlet Laser

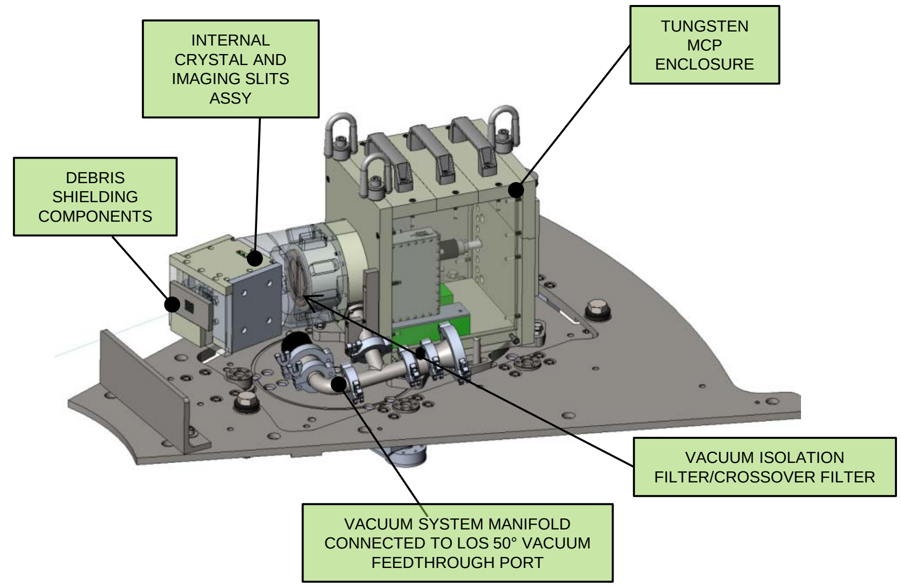
- Monochromatic Crystal Backlighting
  - Typically 6.151 or 1.865 keV
- X-Ray Thomson Scattering
- Diffraction under study

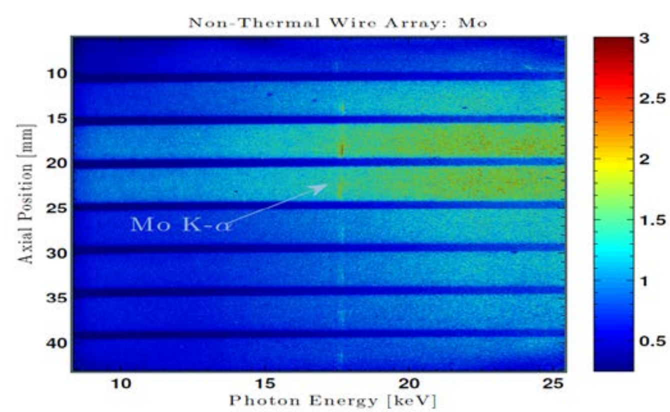


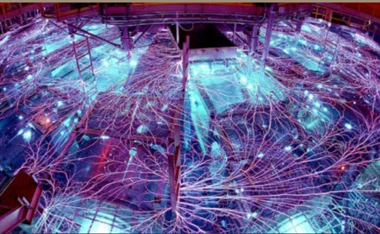
Diagnostics: New Deployments

TiGHER: Time-Gated High-Energy Radiation Spectrometer

- TiGHER was designed to address gaps in our ability diagnose certain experiments with high fidelity and time resolution
- Design requirements are based on physics needs:
  - Spectral range and resolution:
    - ICF: Diagnose temperature and density in fusion plasmas using Kr and/or Br K-shell radiation (12 - 15 keV)
    - RES: Diagnose conditions in K-shell and non-thermal sources at >10 keV photon energy
    - Requires spectral resolution $\lambda/\Delta\lambda$>500
  - Spatial resolution and FOV:
    - FOV 8 - 10 mm at most (mag. 0.5 configuration)
    - Resolution of 100 µm or better (mag 0.8 configuration)

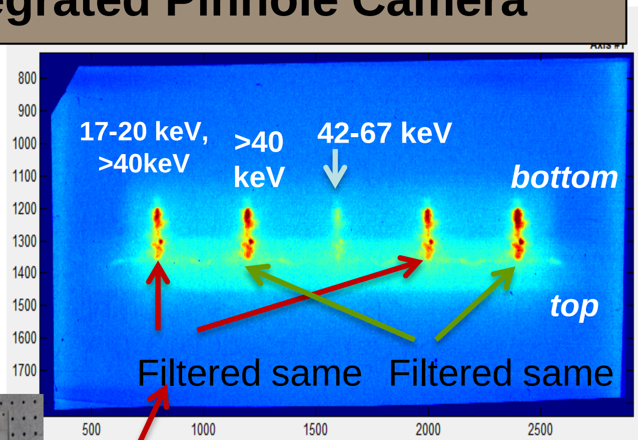


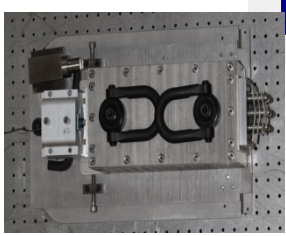


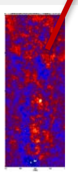


Diagnostics: New Deployments

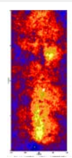
Time-Integrated Pinhole Camera







Subtracting images that are filtered the same

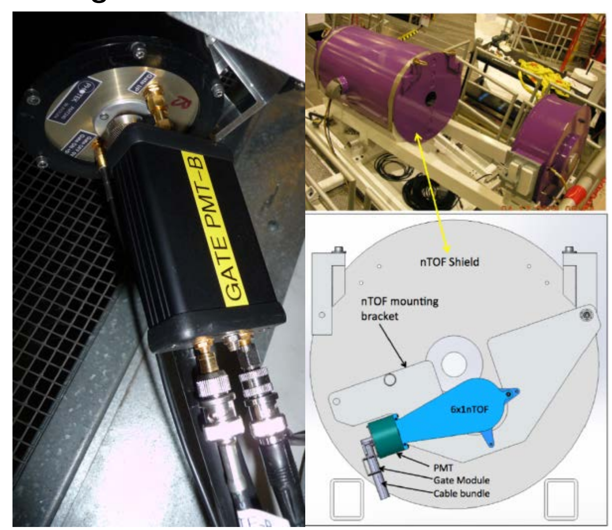


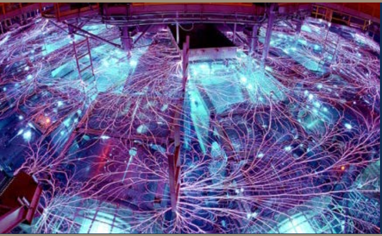
Subtracting different filtered images to get 17-20 keV window

- In-chamber pinhole camera designed for imaging warm x-rays (15 -100 keV)
- 5 filtered pinhole images per experiment
- Developed under hostile environments LDRD to identify where in the source warm x-rays are produced
- Currently used broadly in ICF and RES programs

Gated nTOF detectors

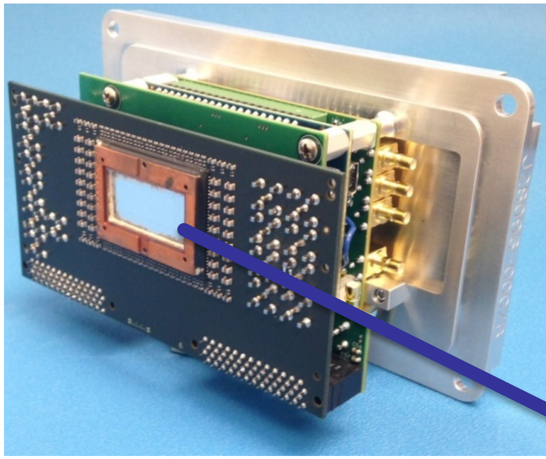
- Collaboration with LLE based on Omega fielding experience (Glebov), and NSTec to implement Z detectors
- Gating out brems pulse will allow higher signal-to-noise measurement of secondary DT spectrum
- Improved BR measurement for MagLIF
- Gate unit function has been demonstrated in Z electromagnetic environment





Diagnostics: CMOS imaging

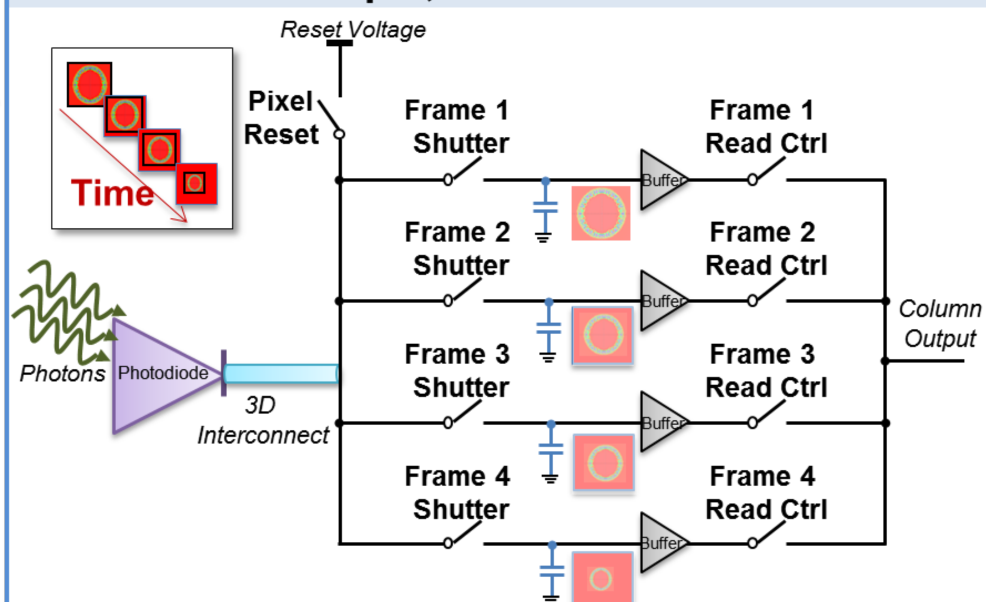
hybrid gated CMOS camera

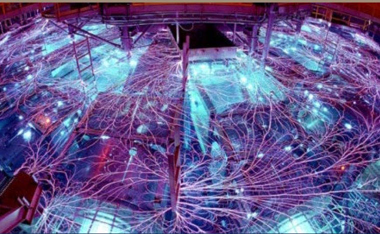


designed and built in collaboration with the MESA facility

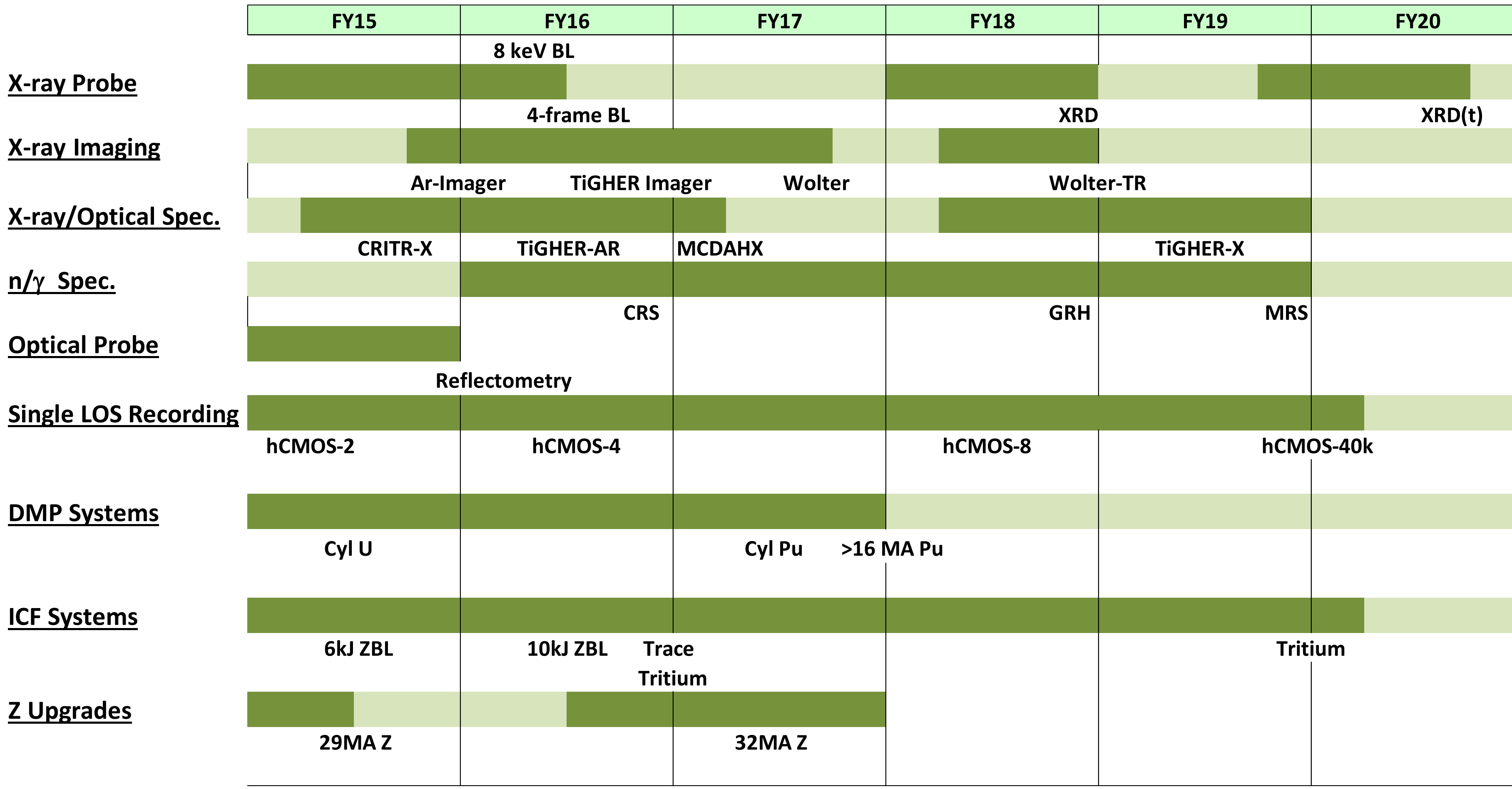
- Up to 4 frames of data on a single line-of-sight
- 1.5 ns minimum gate time
- 448 x 1024 pixel array
- 25 um x 25 um per pixel
- Sensitive to visible light and 0.7 - 6 keV x-rays

Each Of The 448 x 1024 Pixels Has This Four Sample, Hold & Read-Out Circuit





We have a diagnostics and capability roadmap to guide our investments



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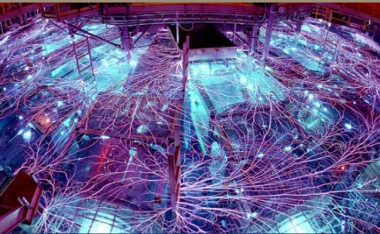

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Questions?