SAND2017-0900PE

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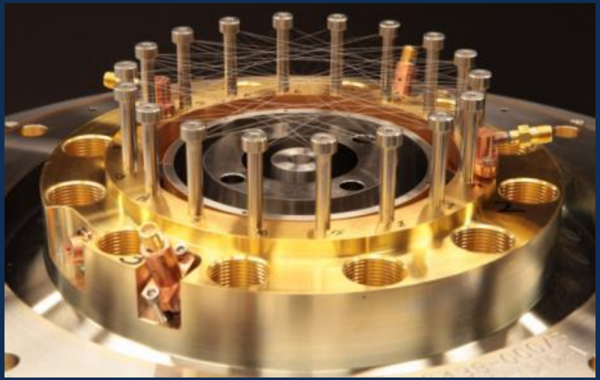
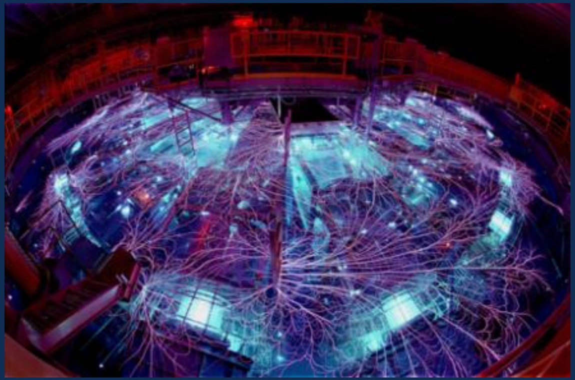
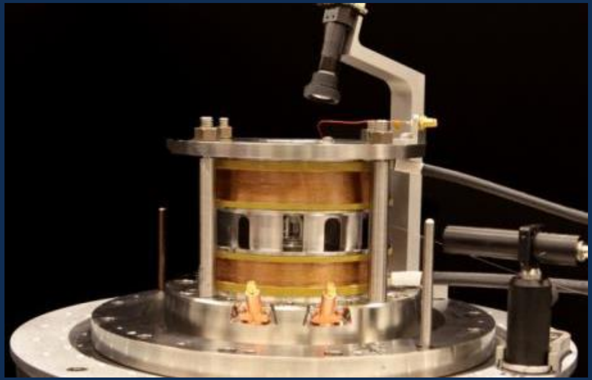






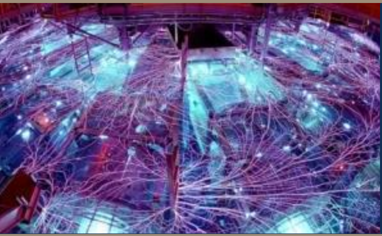
The Sandia Z Machine: an overview of the world's most powerful pulsed power facility

Joel S. Lash, Ph. D.

Senior Manager, Z Facility R&D

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration



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

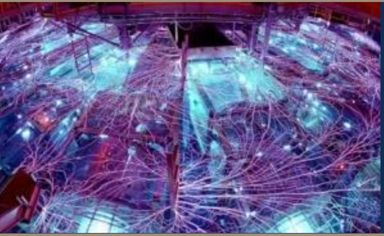
- Backlighter
- Cryogenics
- External Magnetic Fields
- Gas Fills
- Explosive Containment for High-Z Matl's Materials

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 Laser



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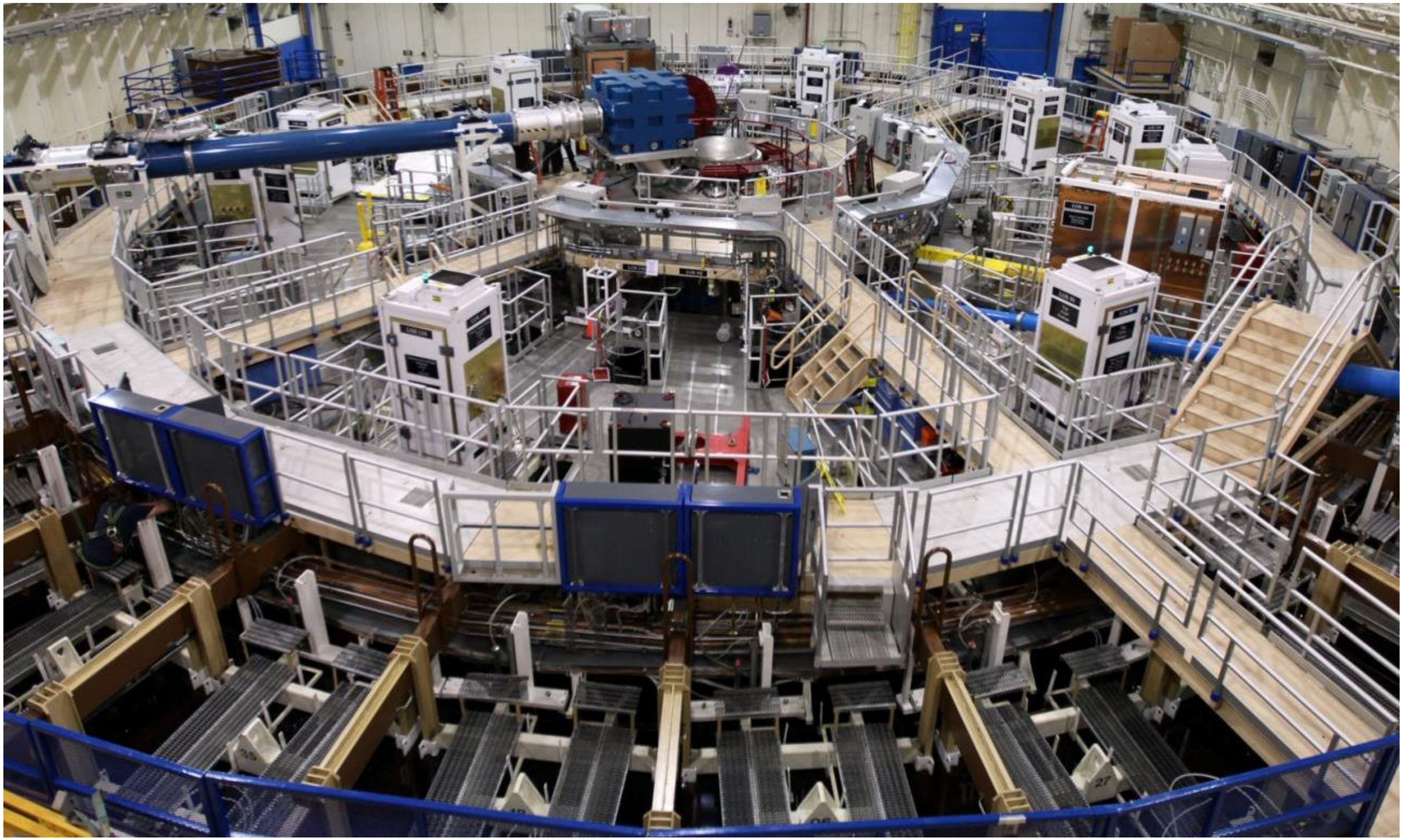
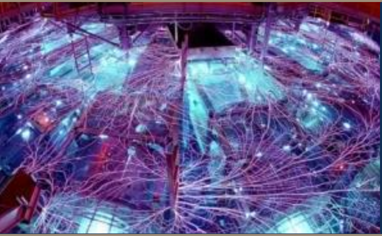
Z is a unique world class pulsed power facility at Sandia National Laboratories



36 Marx generators	**~ 1M gallons of transformer oil**	**66,000 liter**
2160 capacitors	**~ 0.5M gallons of deionized water**	**vacuum vessel**

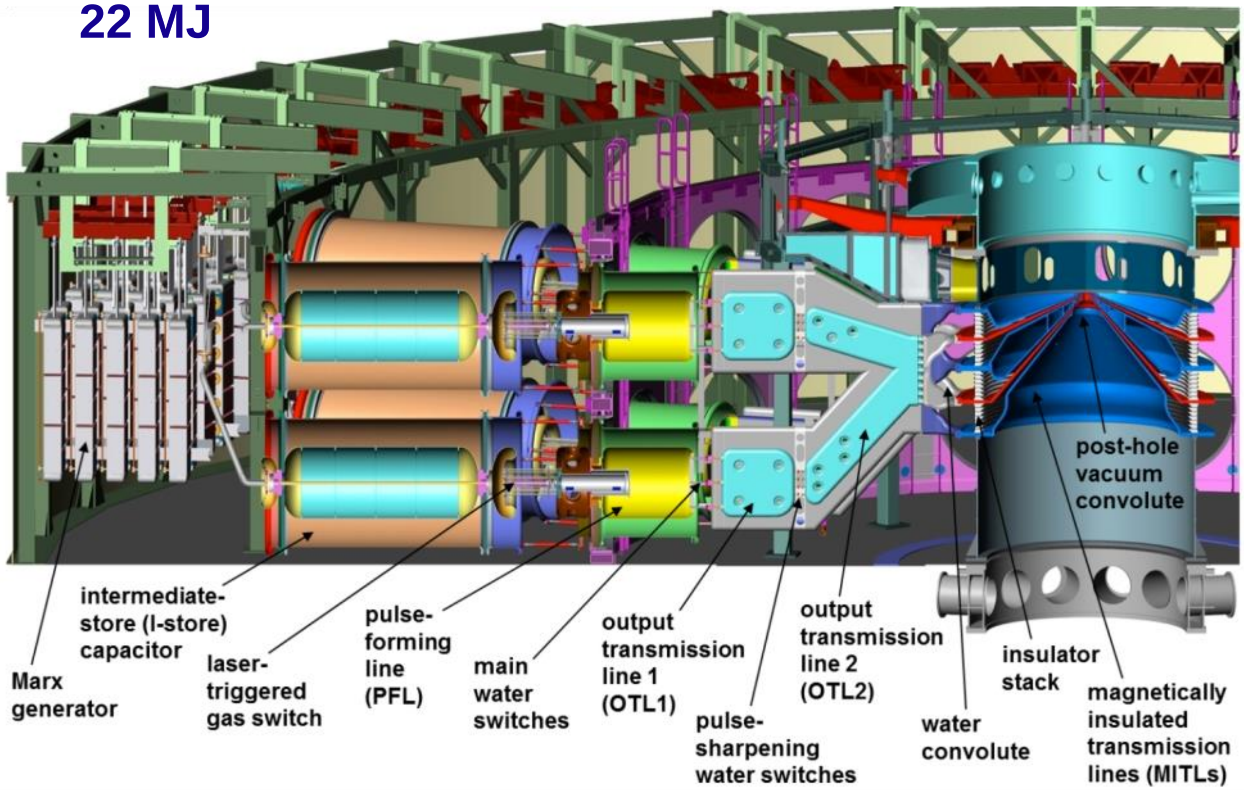


Z compresses electrical energy in both space and time . . .

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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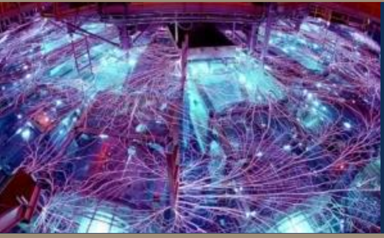
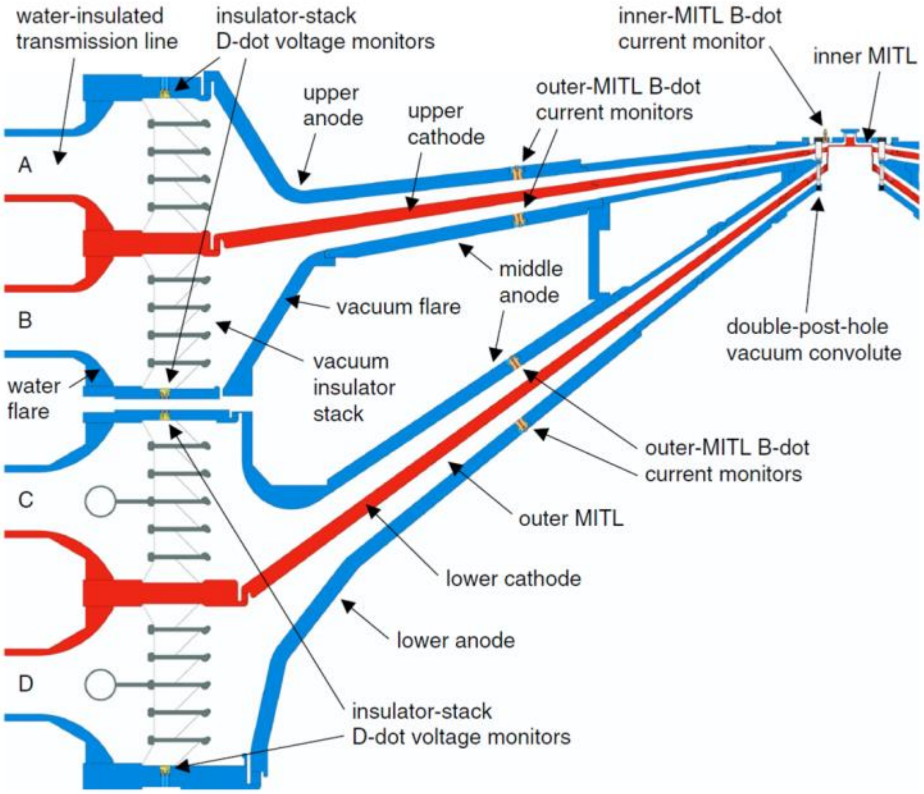
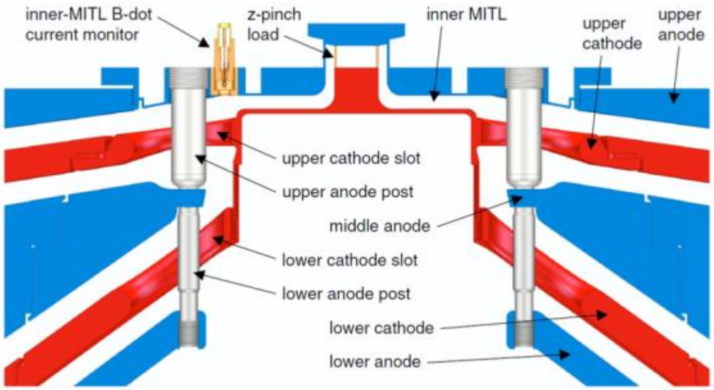
A complex series of conductors combine currents for the load



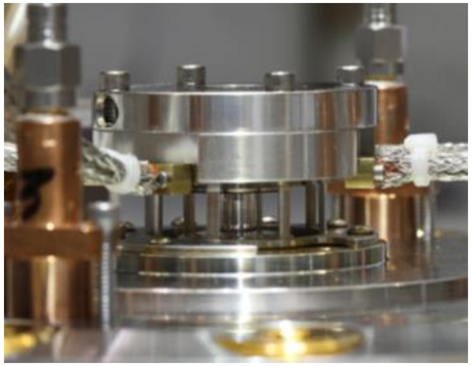
Z vacuum insulator stack and Magnetically Insulated Transmission Lines (MITLs)



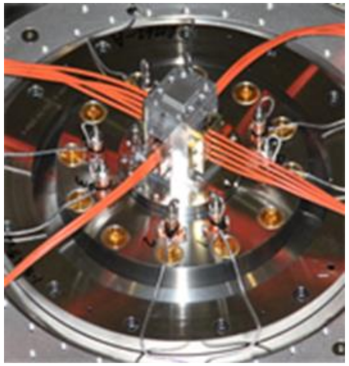
Post hole convolute system and load



ICF liner load



DMP load



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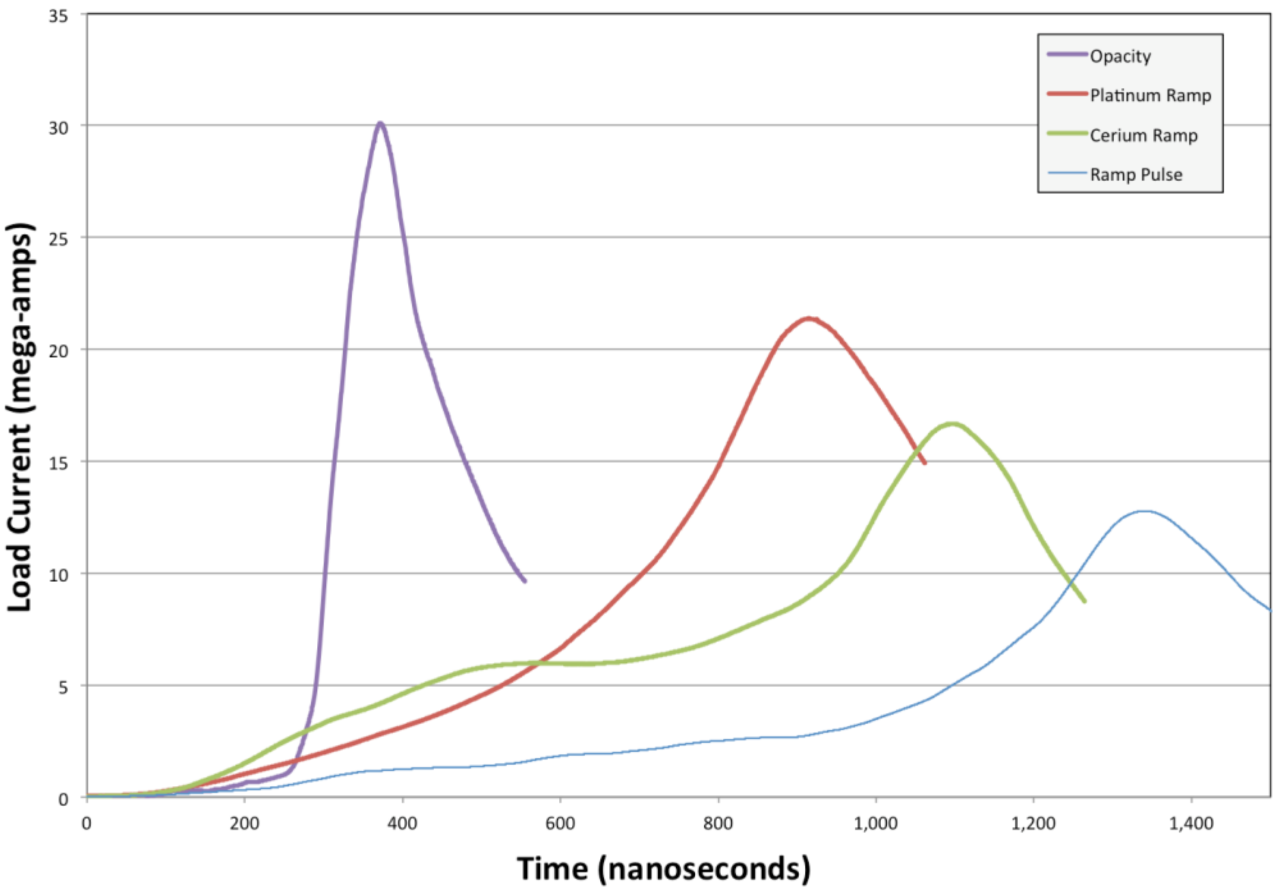
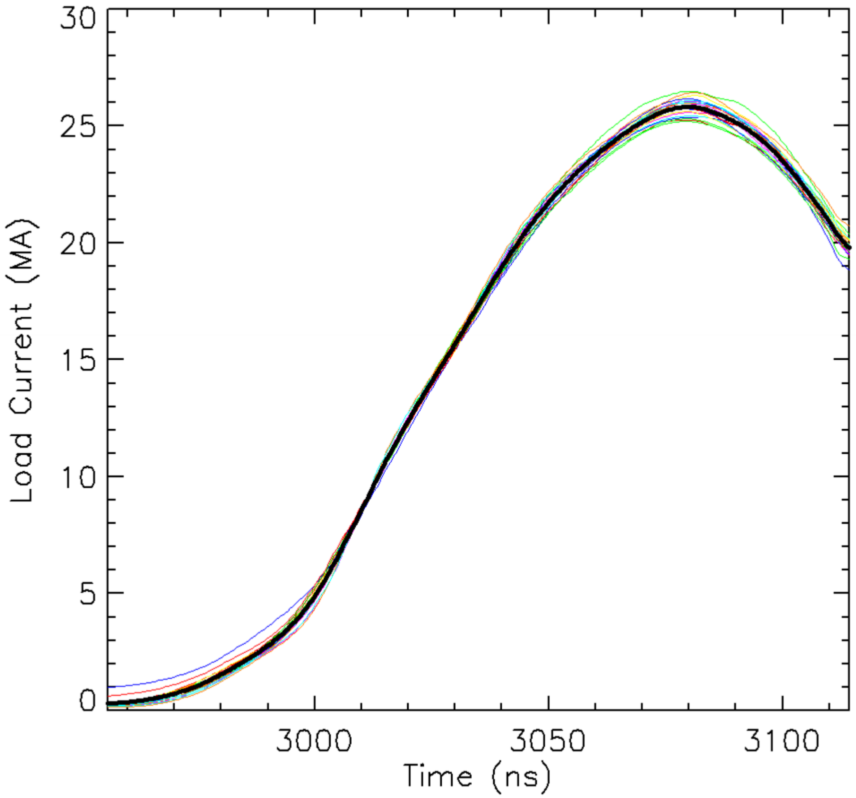
Pulse Shape Flexibility and Reproducibility

- Z was designed to drive dynamic hohlraum experiments.
  - ~150 ns current rise times
- System improvements have enabled precisely tailored pulse shapes with multiple distinct drive characteristics
  - E.g., both shock and ramp drives can be produced by a single pulse shape
  - Up to ~1 μs current rise times
- Each of Z's 36 transmission lines have multiple triggers and switches that can be employed to produce a given pulse.
  - The Sandia developed Laser-Triggered Gas Switches (LTGSs) are central to our pulse shaping capabilities.

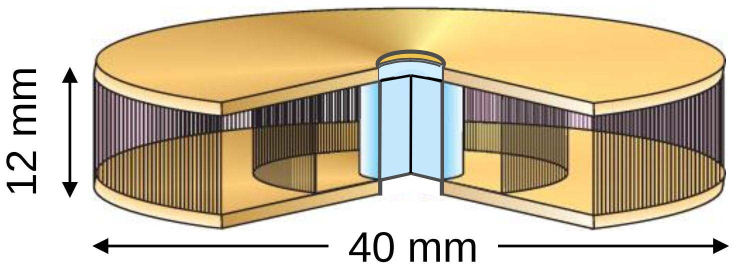


Pulse Shape Flexibility and Reproducibility

Load Currents (20 shot average)



Z-pinch Dynamic Hohlraum



Shot Characteristics

360 W wires – 11.4 μm diameter

m = 8.5 mg W total

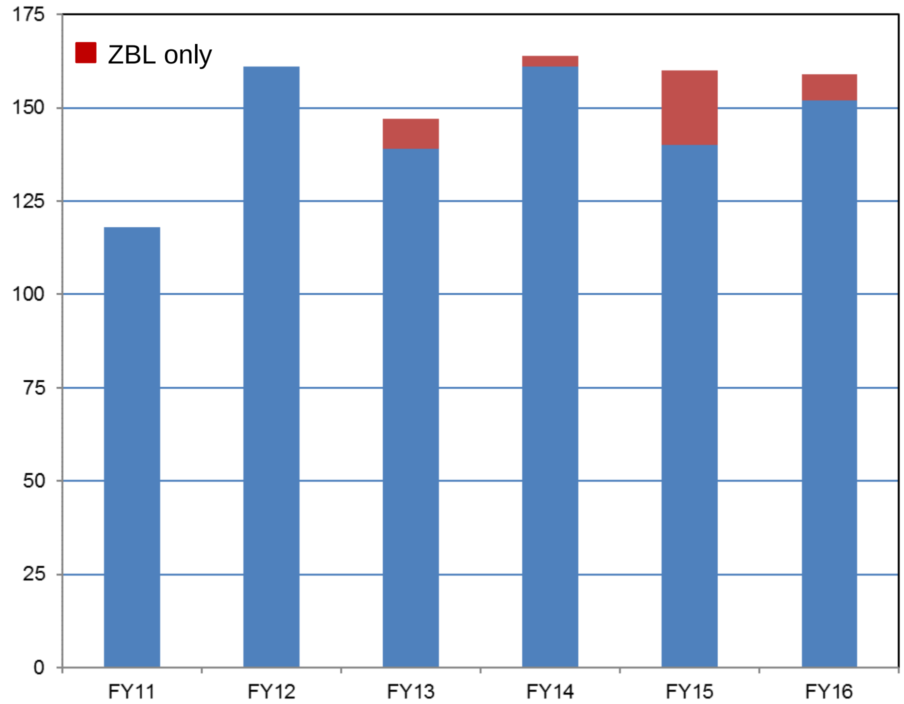
V_{marx} = 85 kV (20.3 MJ)

I_p = 25.8 ± 0.4 MA [20 shots]

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

Z Shot Rate and Shot Planning

Z Shots by Calendar Year



~723 Shot Days were requested by LANL, LLNL, and SNL in CY16 – 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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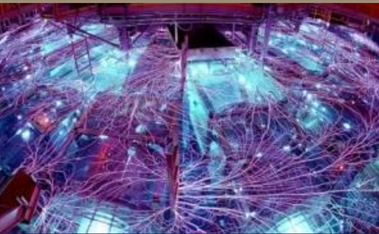
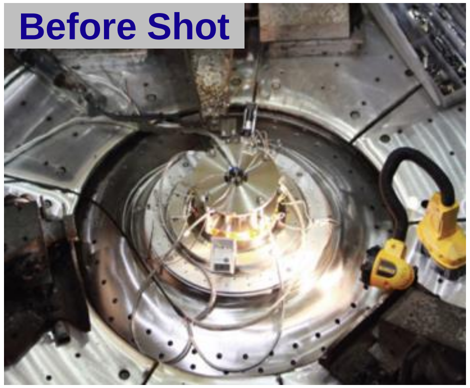


Daily Z Activities: Unload and Refurb of Z's Center Section

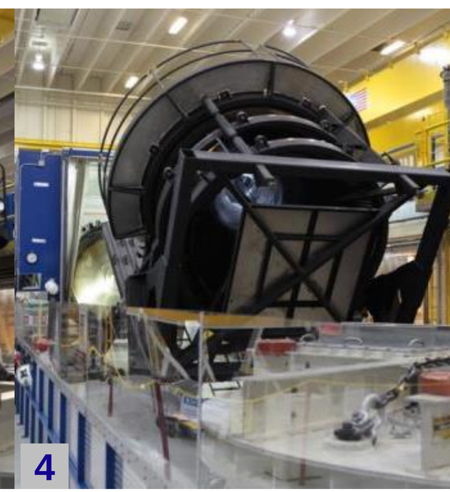
Before Shot

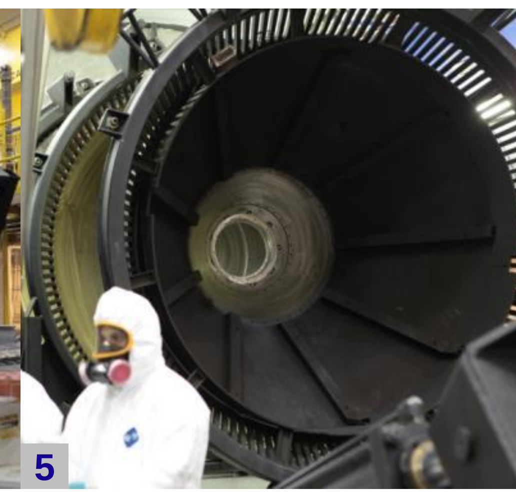


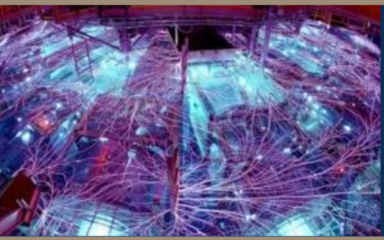
After Shot

During a Z experiment several kilograms of material is destroyed and vaporized. Significant refurbishment activities are required between each shot which consist of:

1. Removal of in-chamber diagnostics and blast shield
2. Removal of Post Hole Convolutes
3. Removal of Magnetically Insulated Transmission Lines (MITL)
4. MITLs are flipped and placed into a HEPA filtered 'garage'
5. Cleaning / Grinding of MITLs and plastic insulator stack. All work requires Tyvek and Respirators due to Beryllium exposure

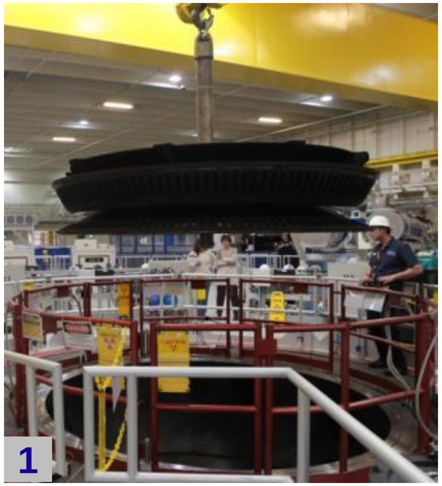


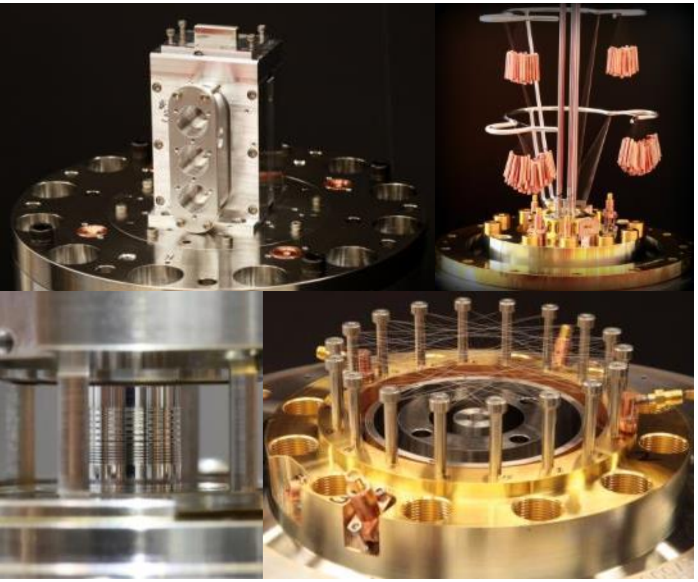


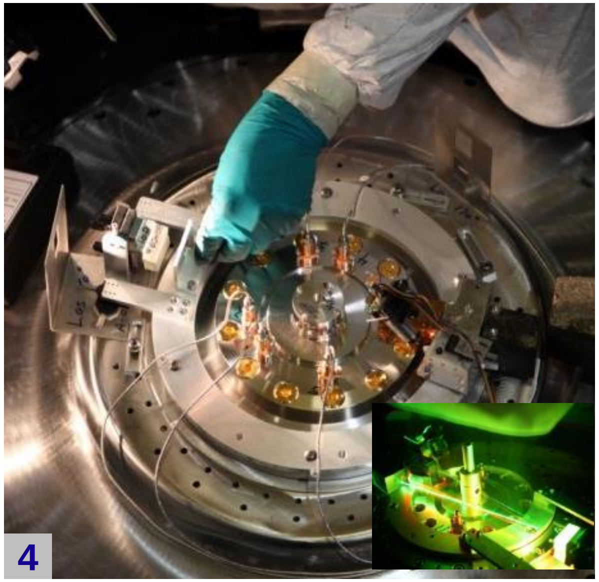


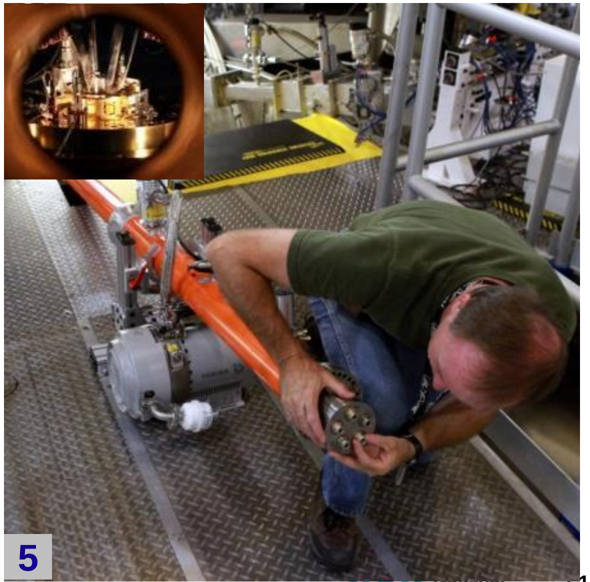
Daily Z Activities: Loading and Diagnostic Activities

1. Install Magnetically Insulated Transmission Lines
2. Install post hole convolutes
3. Install the target
4. Install in-chamber diagnostics
5. Align diagnostics









Daily Z Activities: Oil & Water Processing

Oil System Control Panel (circa 1985)

- Drain/Fill ~400,000 gallons of water
  - 30 minutes to drain or fill
- Drain/Fill ~600,000 gallons of oil
  - 80 minutes to fill and 65 minutes to drain

- Water is stored in twelve 50,000 gallon underground tanks
- Oil is stored in four 250,000 gallon tanks outside of the building

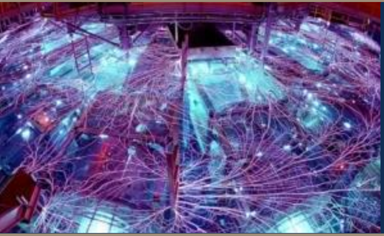
Daily Z Activities: Pulsed Power Inspections, Repairs & Configuration

- Drain oil and water tanks
- Teams will first 'ground' the machine
- Inspection of over 4000 components consisting of capacitors, resistors, gas switches, laser alignment, plastic rods
- Perform repairs and preventative maintenance as needed

Shorting of Marx Banks

Removal of a Pulse Forming Line (PFL)

Inspection of a Marx Trigger Generator (MTG)



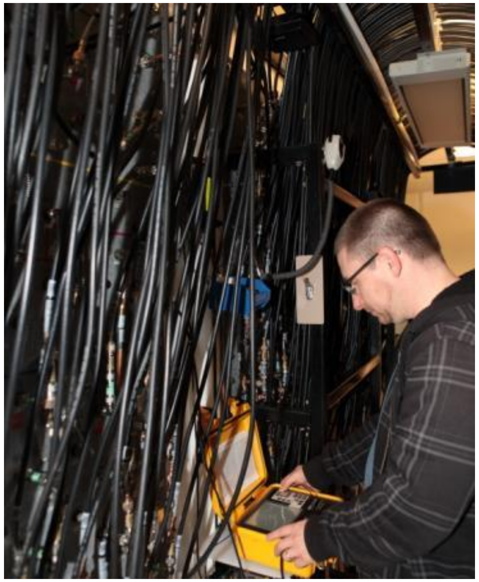
Daily Z Activities: Shot Preparations

Vacuum System

- 20 Vacuum Pumps (Cryo, Turbo & Roughing) on a 66,000 liter vessel
- Able to achieve shot pressure in 90 minutes ($3x10^{-5}$Torr)
- Control system is circa 1985

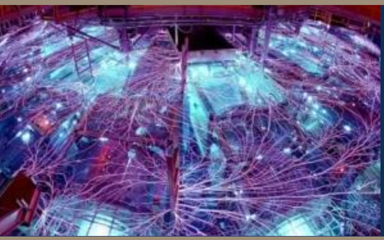
Sulfur Hexafluoride (SF6) System

- System contains ~3000 lbs. of SF6
- SF6 is used as an insulating gas for laser trigger gas switches, Marx spark gaps, and Marx trigger generators.
- Infrastructure is circa 1985



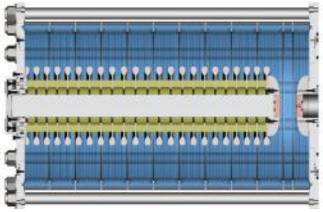
Control Monitor & Data Acquisition System

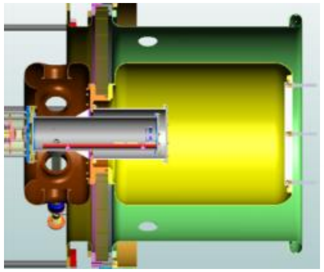
- We record ~800 fast signals on each shot.
- A 2-man team operates the machine for downline activities

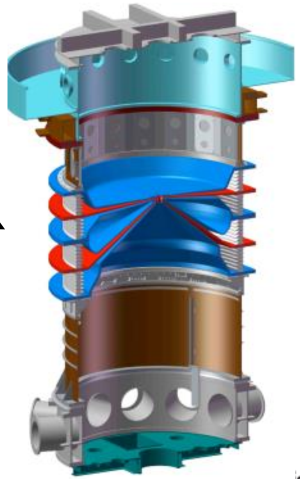


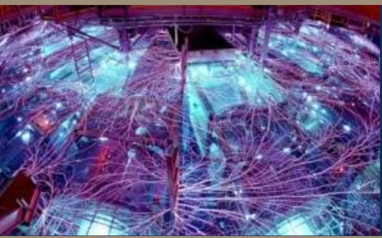
We are increasing the peak current available on Z from 26 to 32 MA

- **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 kV to 95 kV, and improve worker safety.
- **Next generation vacuum insulator stack – in progress**
  - The new stack will allow short-pulse 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% and lower convolute costs by $1M each year.
- **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%.

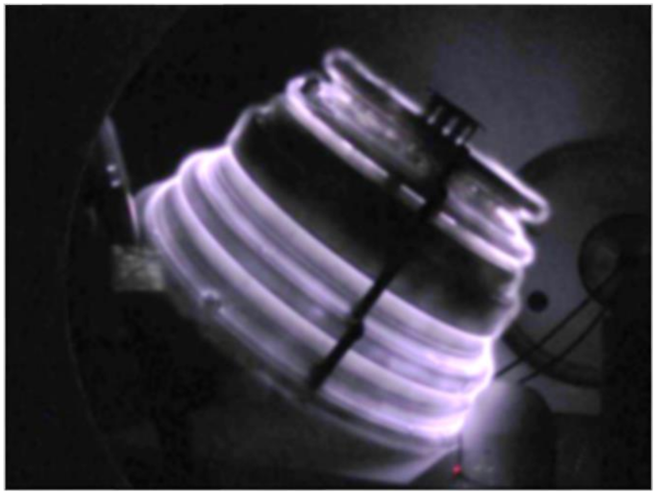




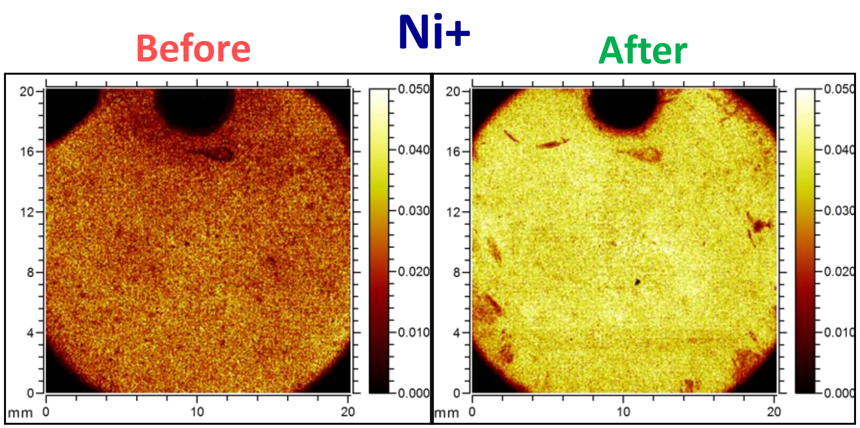




We are working to improve current delivery to the experimental load

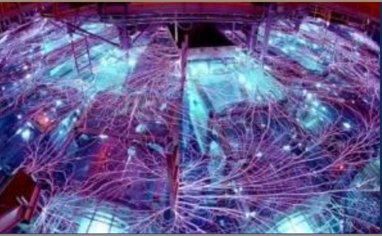


Plasma cleaning development on Z Convolute hardware



*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

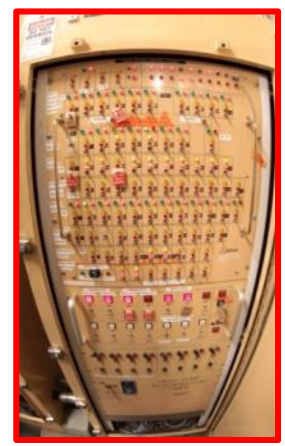
Vacuum Chamber Air Exchange

Replacing the Be Refurbishment Tent

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.

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

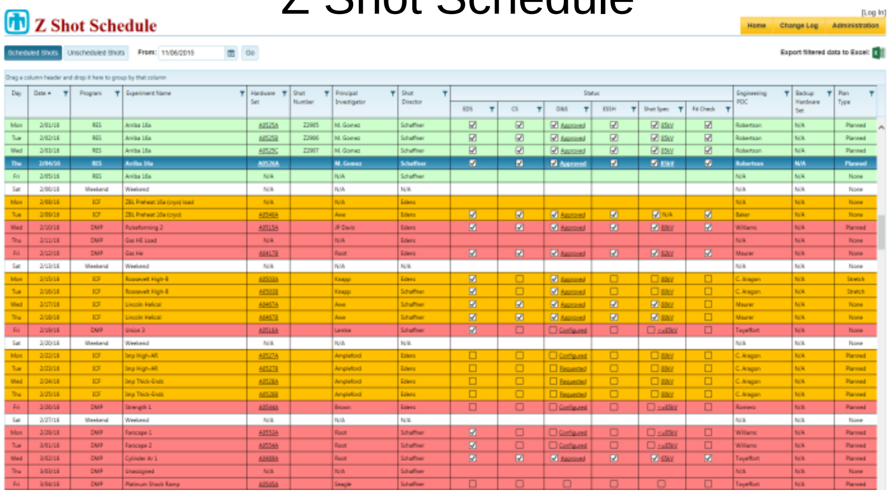


Z's vacuum control system In place since 1985.

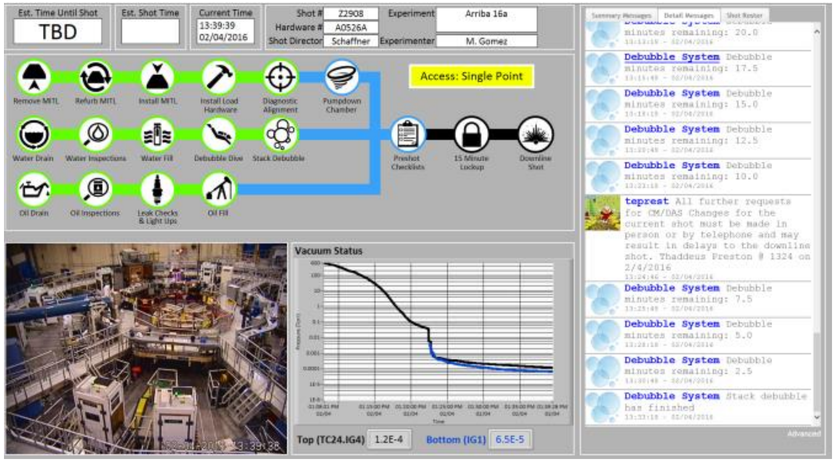
Z's water drain/fill control system In place since 1985.

Improved Information Management and Communications

Z Shot Schedule



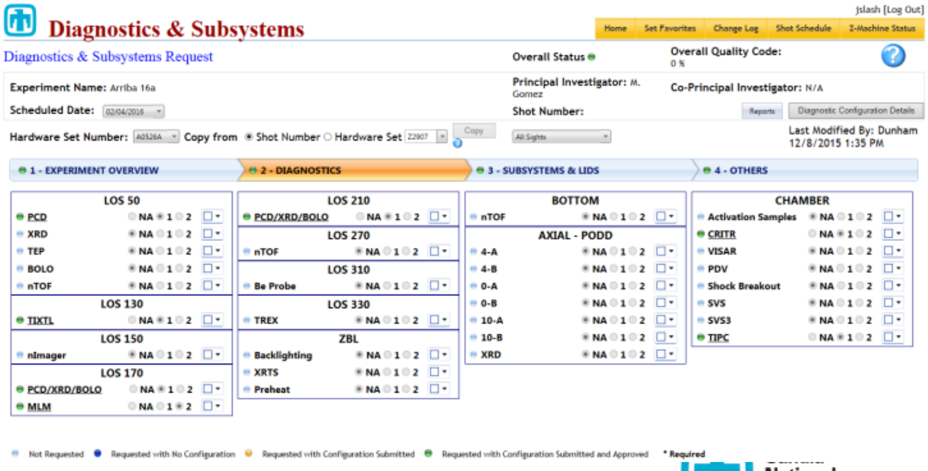
Lab-Wide Z Status Page

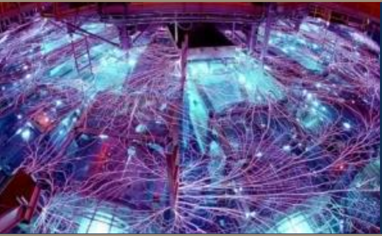


Z Shot Roster

	Mon 04/20/2015	Tues 04/21/2015	Wed 04/22/2015	Thurs 04/23/2015	Fri 04/24/2015
Experiment Name	D2 Puff	D2 Puff	Hydroliquid	Union 2	Pulseshaping 3
Shot Director	De Luna	De Luna	De Luna	De Luna	De Luna
Principal Investigator	Knapp	Knapp	Knudson	Lemke	JP Davis
Engineering POC	Reneker	TBD	Williams	Twyeffort	Williams
CM Operator	Baker	Baker	Radovich	Preston	Bock
CM Coordinator	Ploor	Ploor	Preston	Ploor	Preston
DAS Operator (CM POC)	Baker	Ploor	Preston	Ploor	Preston
Vacuum Shot Support	Bock	Bock	Bock	Bock	Bock
ESS Shot Support	Roznowski / Rakes	Divett / Jojola	Cortez / Speas	McCarthy / Avila	Cortez / Avila
LTS Shot Support	Potter	Potter	Potter	Potter	Potter
Access Evacuator (Top)	Roznowski / Potter	Jojola / De Luna	Speas / Potter	Avila / De Luna	Cortez / Potter
Access Evacuator (Bottom)	De Luna / Ploor	Divett / Baker	Cortez / De Luna	McCarthy / Potter	Avila / Bock
MITL Refurb & Wipe	York / Citrin / White	York / Citrin / White	York / Citrin / White	York / Citrin / White	York / Citrin / White
Stack Refurb & Wipe	Justus / Roebuck / White	Justus / Roebuck / Macrunnels	Justus / Roebuck / Macrunnels	Justus / Roebuck / Macrunnels	Justus / Roebuck / Macrunnels
Lab 101	York / Olivas	York / Olivas	York / Olivas	York / Olivas	York / Olivas
Top Side Load	York / Citrin	Macrunnels / Citrin	Macrunnels / Citrin	Macrunnels / Citrin	Macrunnels / Citrin
Bottom Side Load	White / Roebuck	Roebuck / White	Roebuck / Olivas	Roebuck / Justus	Roebuck / White

Z Diagnostic Request System





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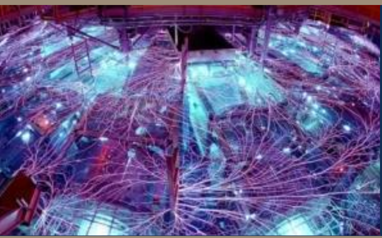
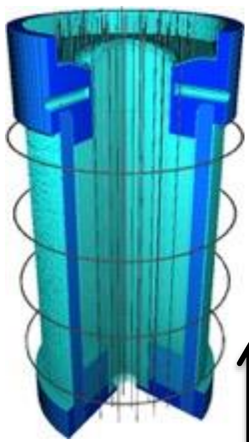
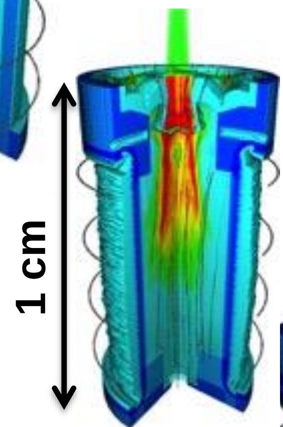


Flexibility in Experimental Platforms: Inertial Confinement Fusion



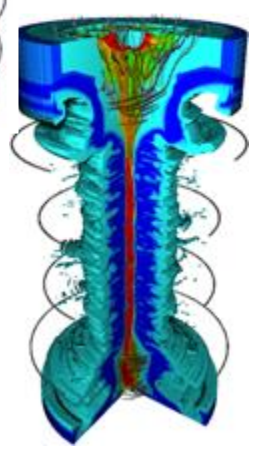
Axial Magnetic Field (10 T initially; 30 T available)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Fusion products magnetized



Laser heated fuel (2 kJ initially; 6-10 kJ planned)

- Initial average fuel temperature 150-200 eV
- Reduces compression requirements (R_0/R_f ~ 25)
- Coupling of laser to plasma in an important science issue



Magnetic compression of fuel (~100 kJ into fuel)

- ~70-100 km/s, quasi-adiabatic fuel compression
- Low Aspect liners (*R/DR*~6) are robust to hydrodynamic (MRT) instabilities
- Significantly lower pressure/density

Goal is to demonstrate scaling: $Y\ (B_{z0},\ E_{laser},\ I)$
DD equivalent of 100 kJ DT yield possible on Z

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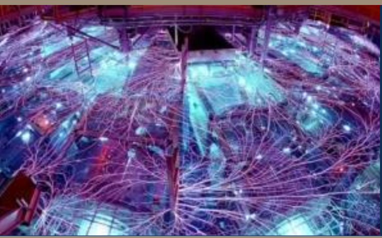
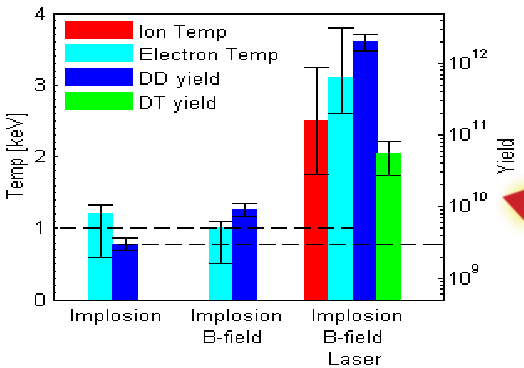
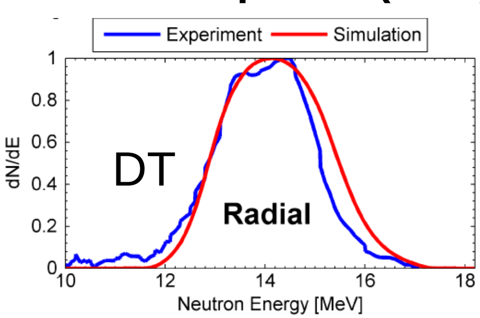
Flexibility in Experimental Platforms: Inertial Confinement Fusion

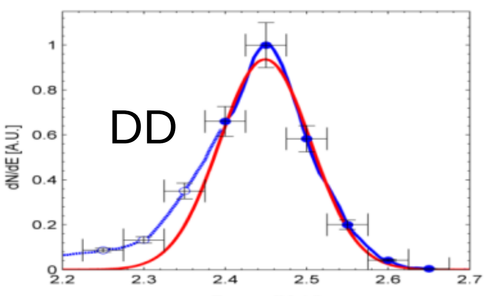


Nuclear Activation (yield)

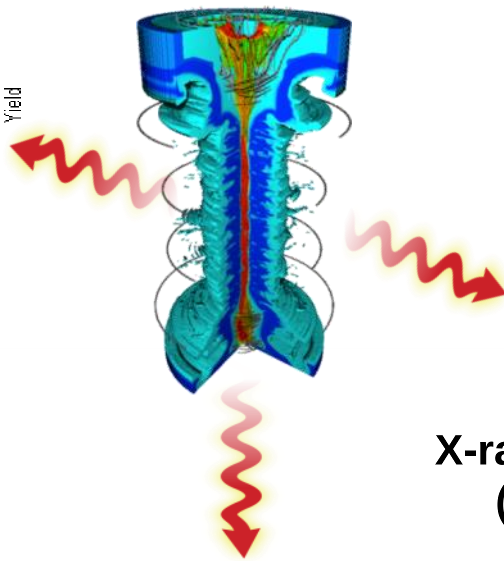


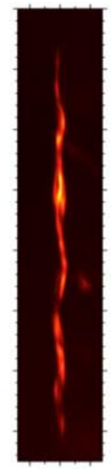
Neutron spectra (Tion)





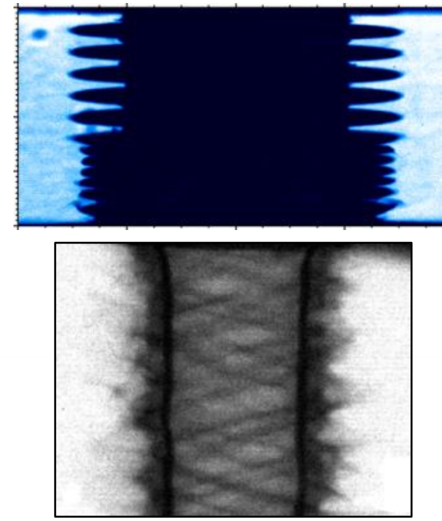
MagLIF Z pinch



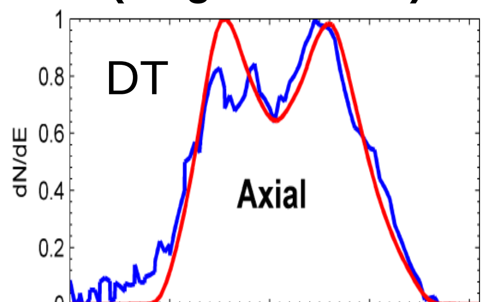


X-ray Imaging (plasma shape)

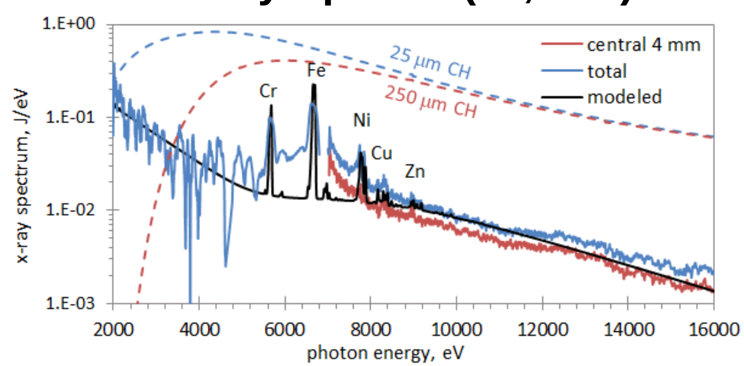
Magneto-Rayleigh-Taylor growth



DT Neutron spectra (magnetization)

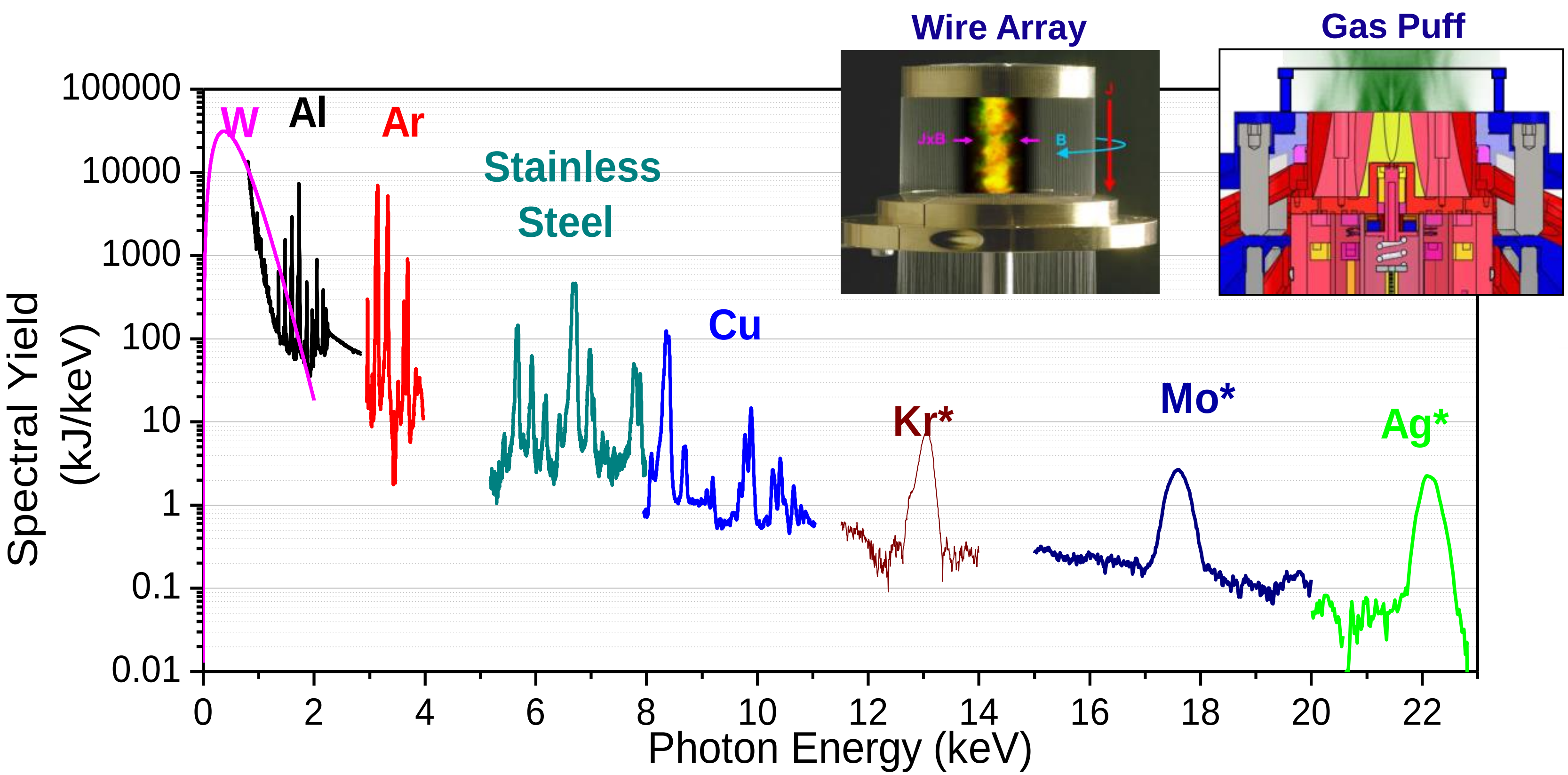


X-ray Spectra (Te, mix)

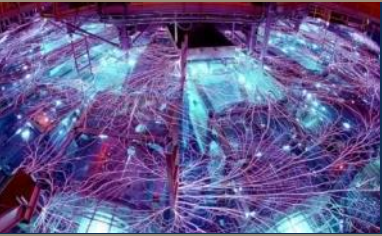


Flexibility in Experimental Platforms: Radiation Sciences

Radiation Effects Sources



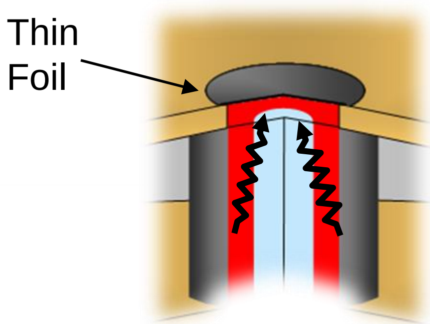
Z provides intense x-ray sources at different energies for radiation effects studies



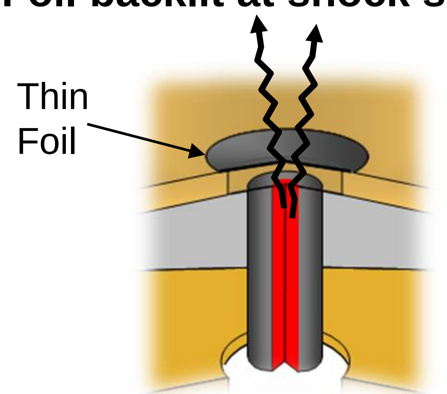
Flexibility in Experimental Platforms: Radiation Sciences

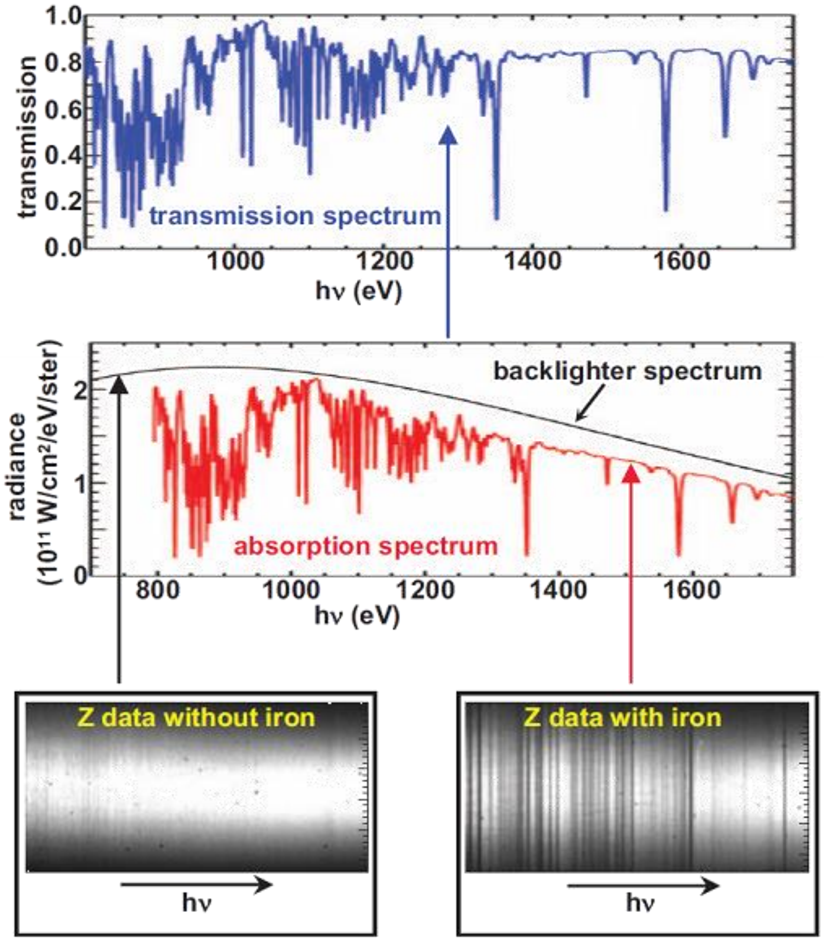
Opacity Measurements with a Z Pinch Driven Dynamic Hohlraum

Foil heated during Dynamic Hohlraum implosion



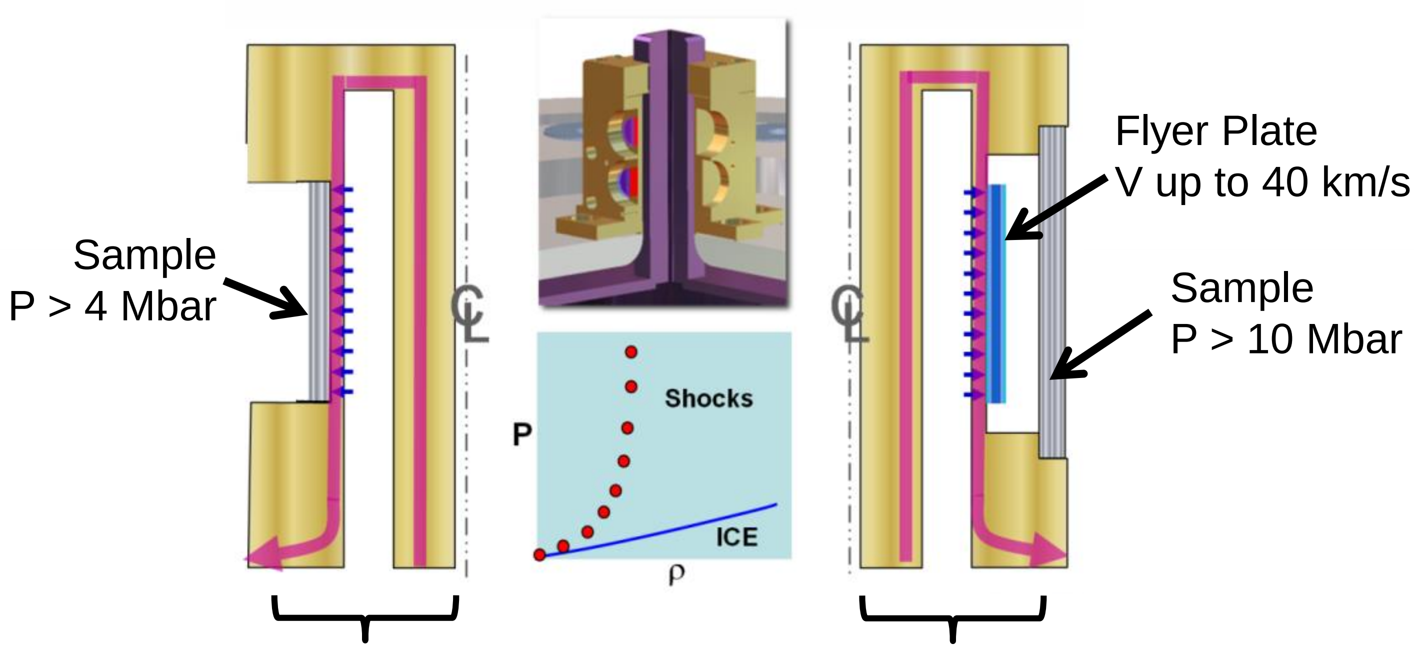
Foil backlit at shock stagnation





Flexibility in Experimental Platforms: Dynamic Materials

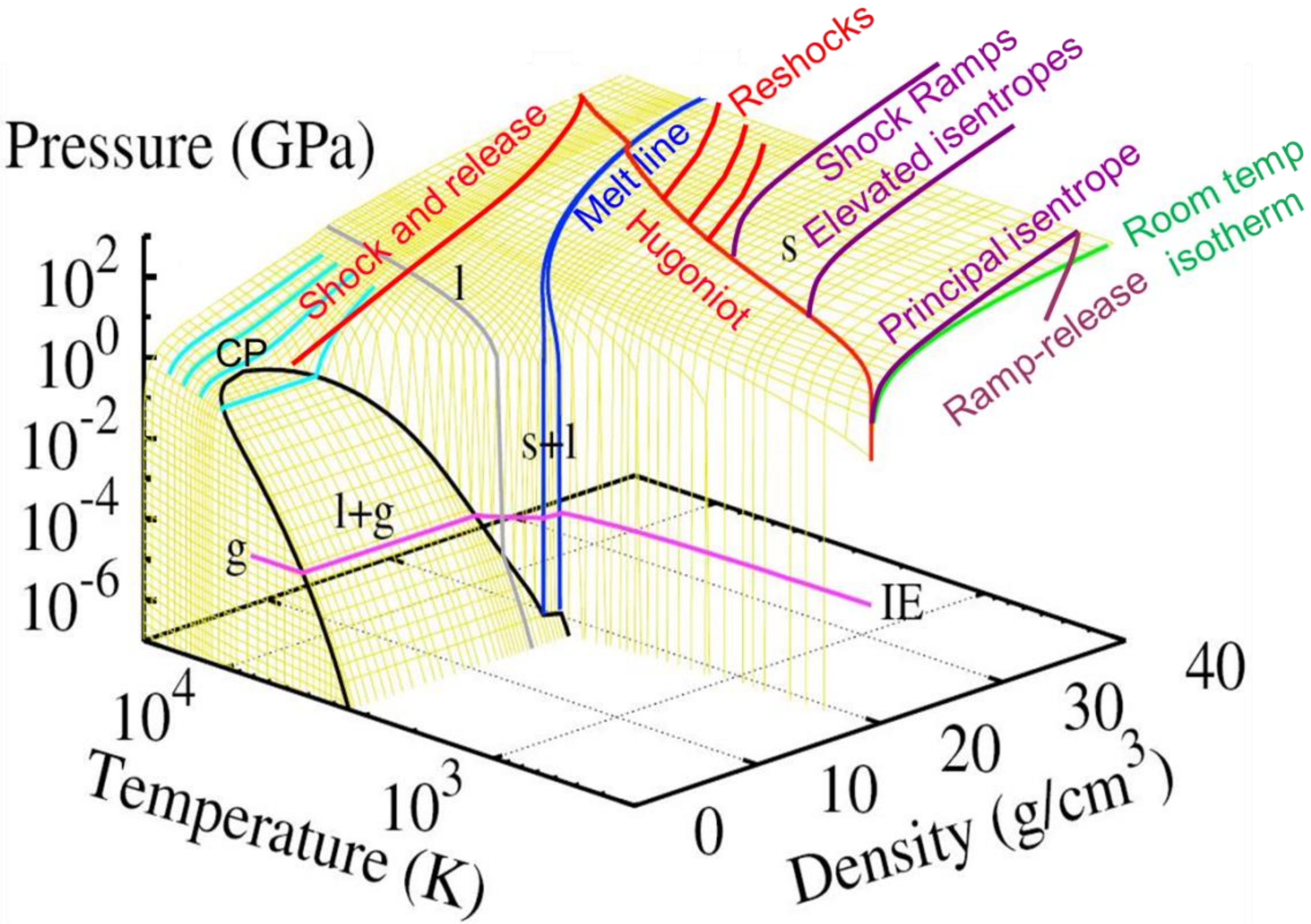
Z isentropic compression and shock wave experiments enable access to key equation of state regions for many materials, including Uranium and Plutonium



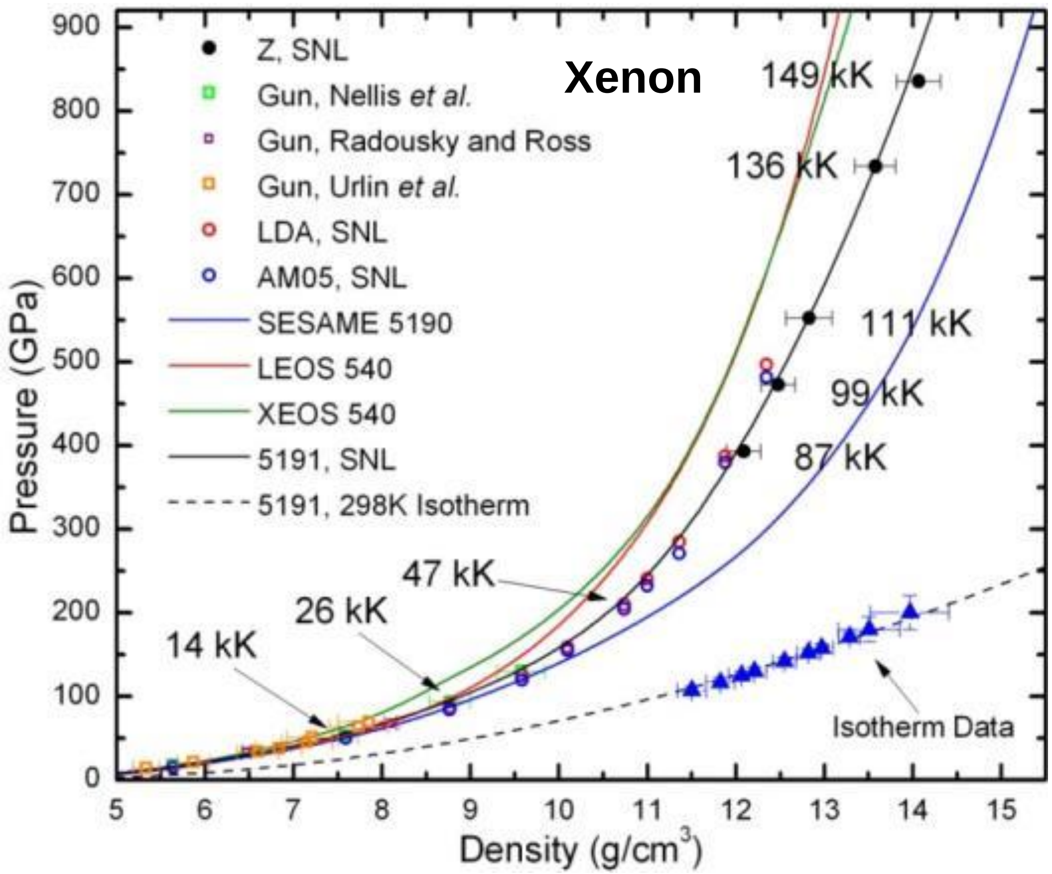
Isentropic compression: gradual pressure rise in the sample

Shock Compression: shock wave launched in sample at impact

Flexibility in Experimental Platforms: Dynamic Materials



Flexibility in Experimental Platforms: Dynamic Materials



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

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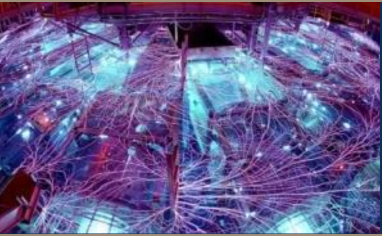
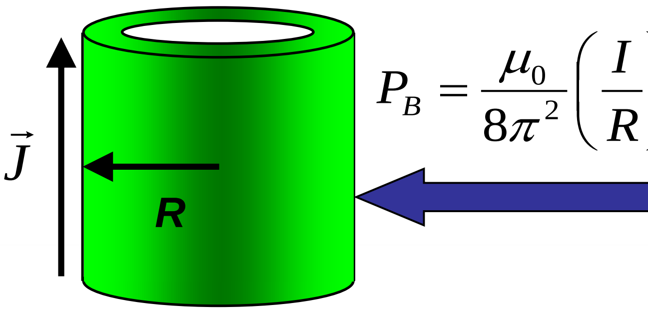


Flexibility in Experimental Platforms: Dynamic Materials

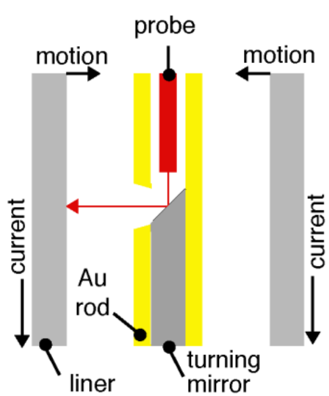
Quasi-isentropic Compression to Stresses ≈20 Mbar in Cylindrical Implosions

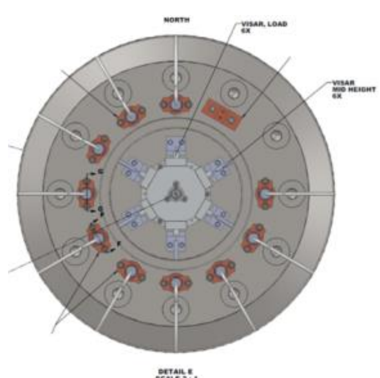
Liner Z-Pinch Implosion



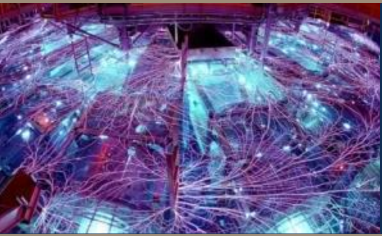
$$P_B = \frac{\mu_0}{8\pi^2}\left(\frac{I}{R}\right)^2$$

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*



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

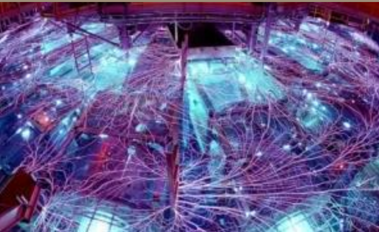
- Backlighter
- Cryogenics
- External Magnetic Fields
- Gas Fills
- Explosive Containment for High Z Materials

Experimental Loads

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

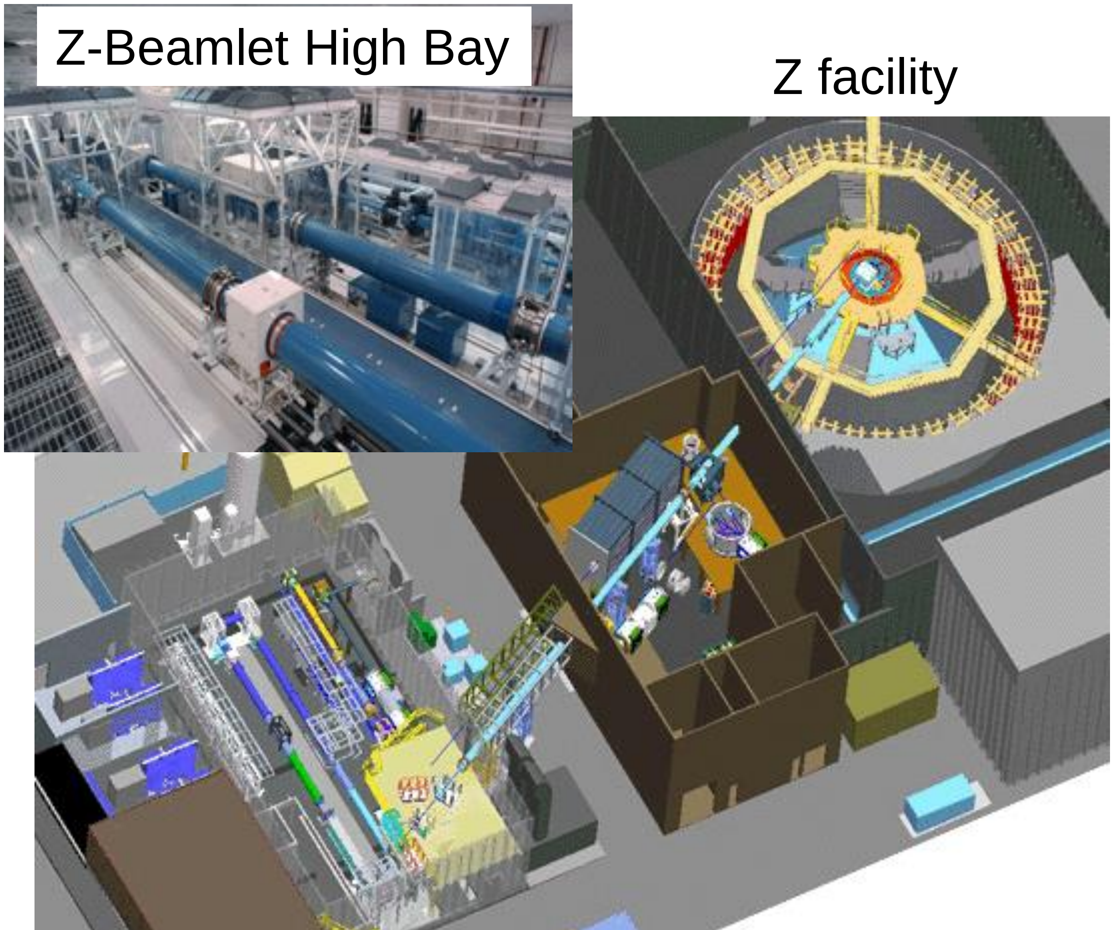
Diagnostics

- X-Ray
- Neutron
- Optical
- ZBL Backlighter

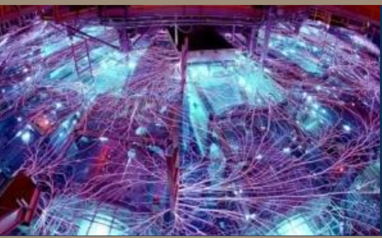


Z Core Capabilities: Z-Beamlet Laser

Z-Beamlet Basics

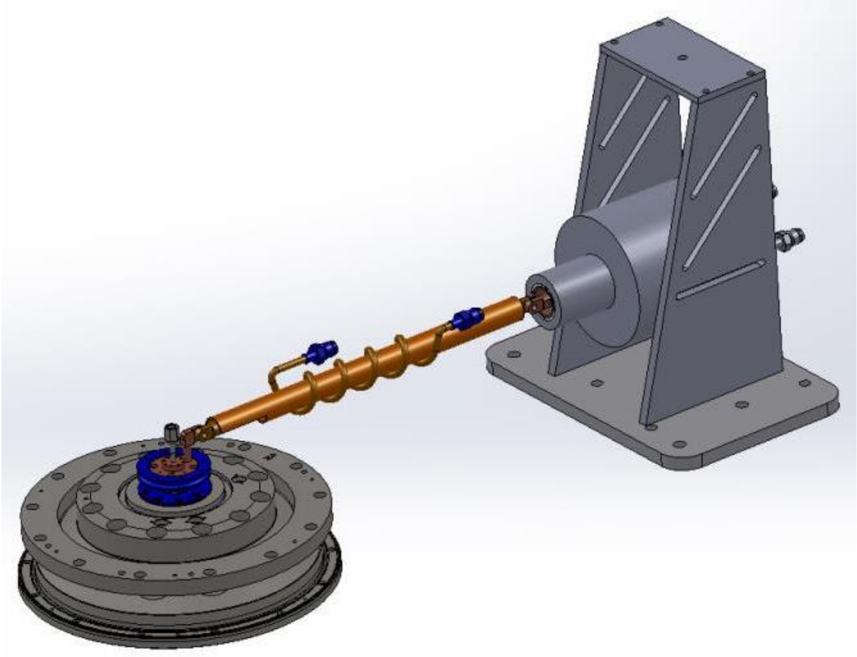


- ZBL is routinely used to deliver ~ 2.4 kJ of 2ω light in 2 pulses for backlighting experiments on Z
- In 2014 we added bandwidth to the laser; can now deliver ~4.5 kJ of 2ω in a 4 ns pulse.
- It should be possible to reach 6-10 kJ of laser energy (e.g., as on the NIF)
- ZBL Parameters:
  - Up to 6 kJ @ 1053nm
  - Up to 4.5 kJ @ 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

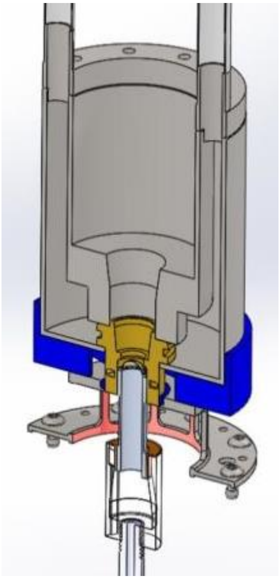
Standard Configuration (Mini Cryostat)



- 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



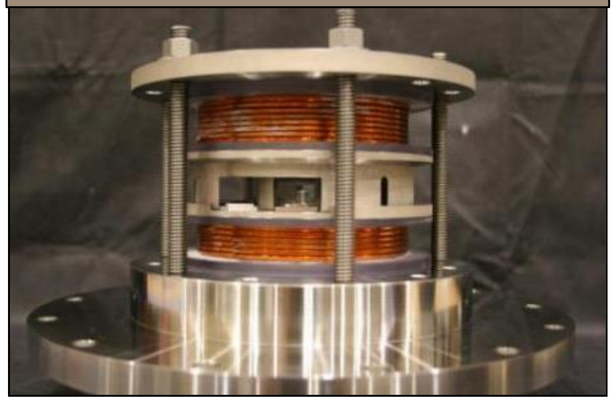
Liquid Helium Reservoir Cryostat

- 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

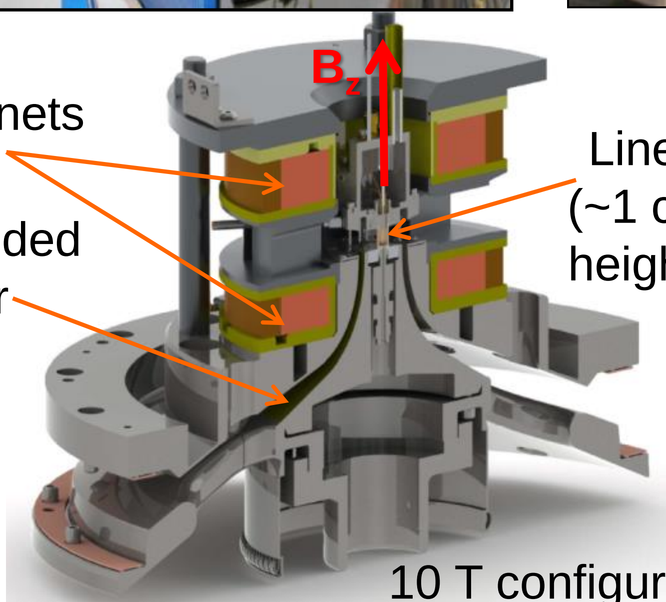
Z Core Capabilities: Applied B-Field

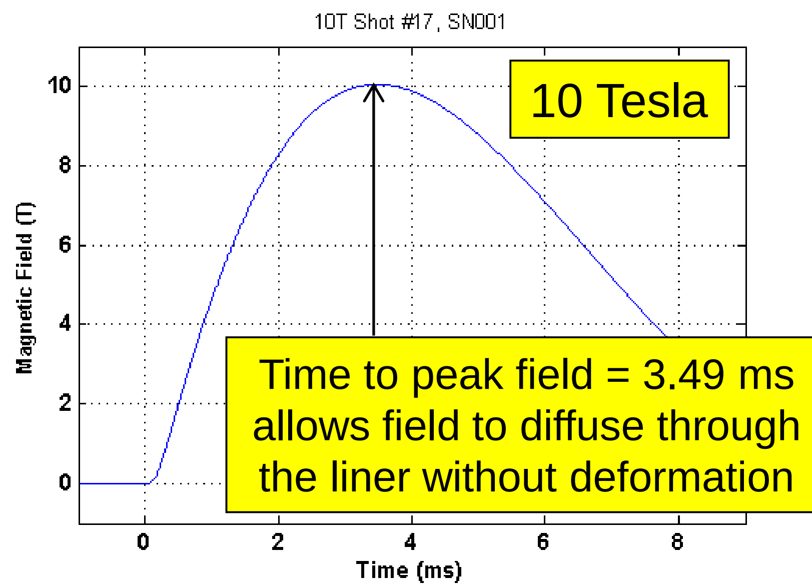
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV (Feb. 2013)

Example MagLIF coil assembly with copper windings visible



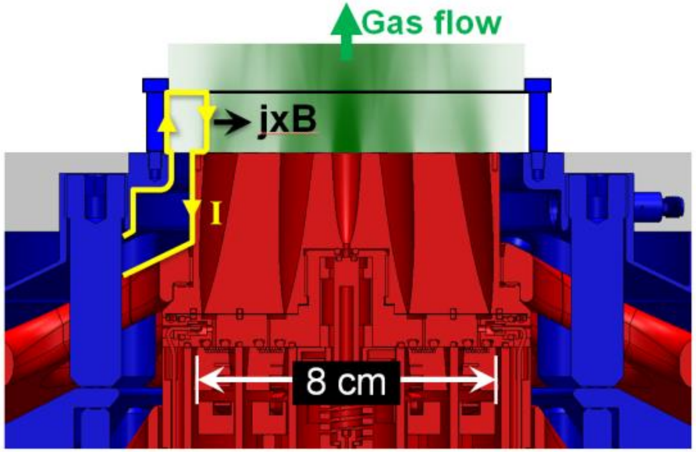
Cross section of coil showing Cu wire, Torlon housing, and Zylon/epoxy reinforcement

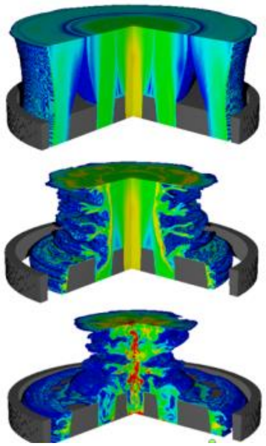




Z Core Capabilities: Gas Puffs

- 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

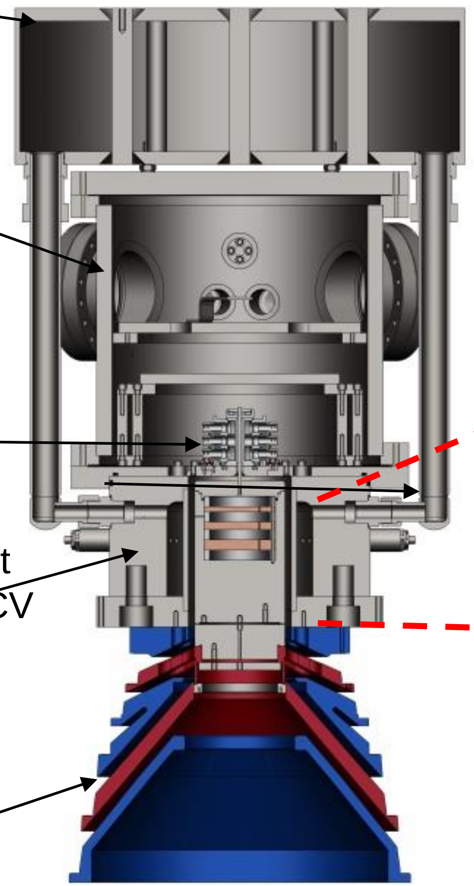




- The use of deuterium gas creates a neutron source producing ~4e13 DD neutrons
- A gas puff neutron source enables studying stagnation physics for comparison with MagLIF
- Robust yields also support diagnostic development

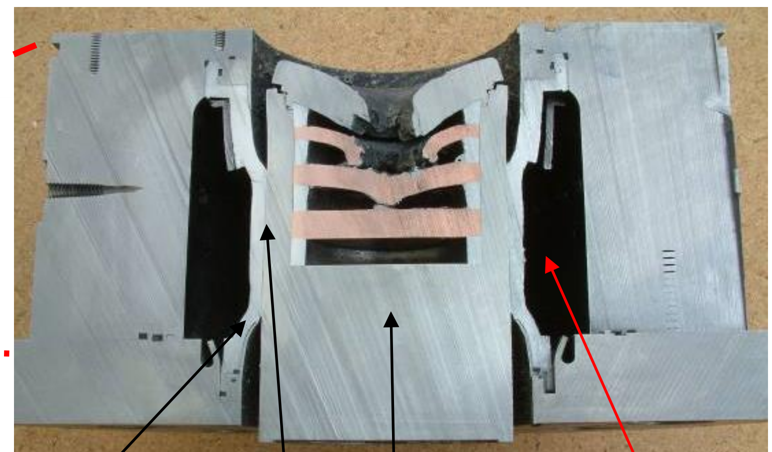
Z Core Capabilities: High Z

Primary containment system



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

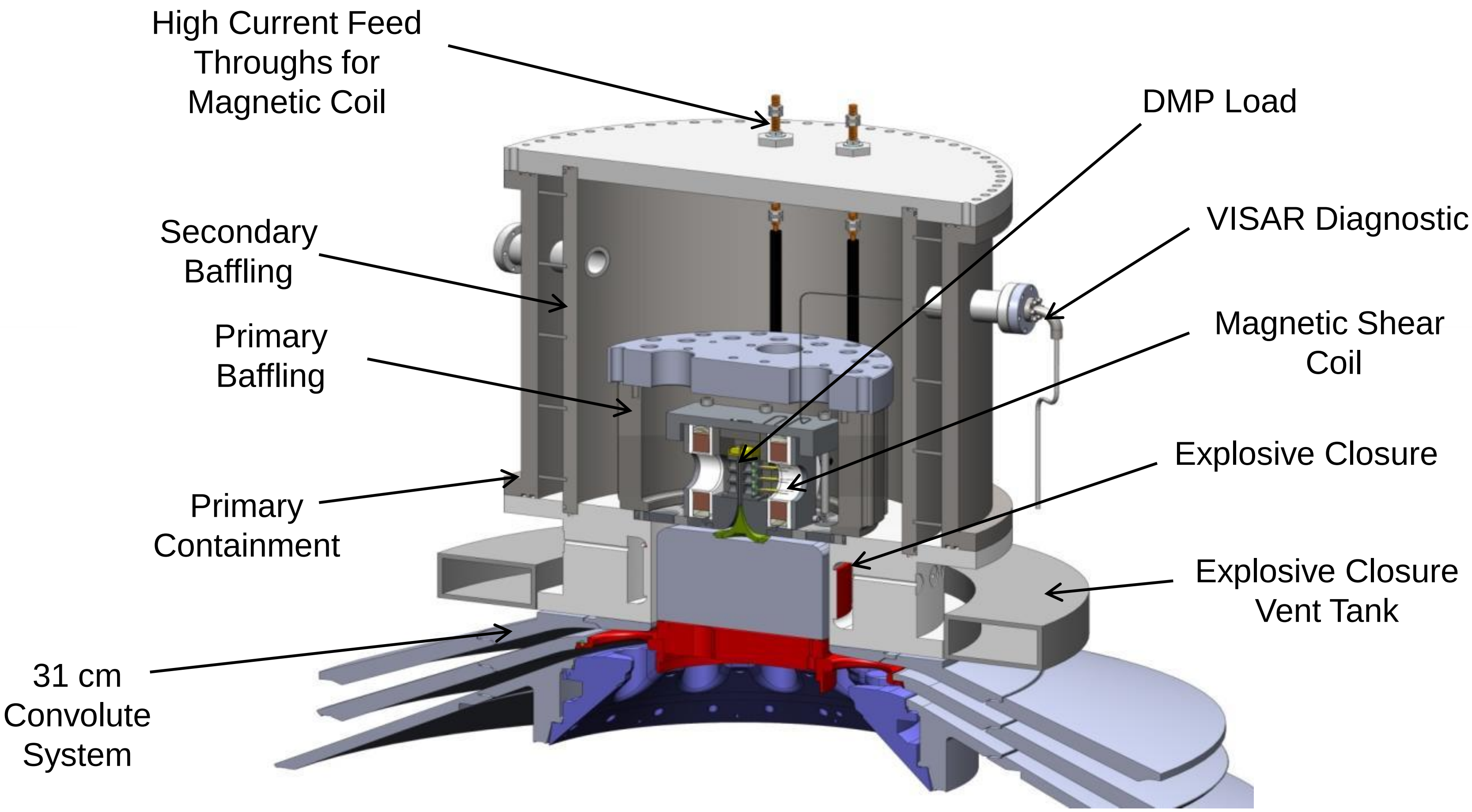
- Valve closes in ~ 40 μs
- Leak spec is < 1e-5 atm-cc/sec
- Typical leak rates are 1e-8 atm-cc/sec



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

Upcoming Capabilities: NGC

Conceptual design using the 31 cm convolute system.



DMP Load with Magnetic Shear

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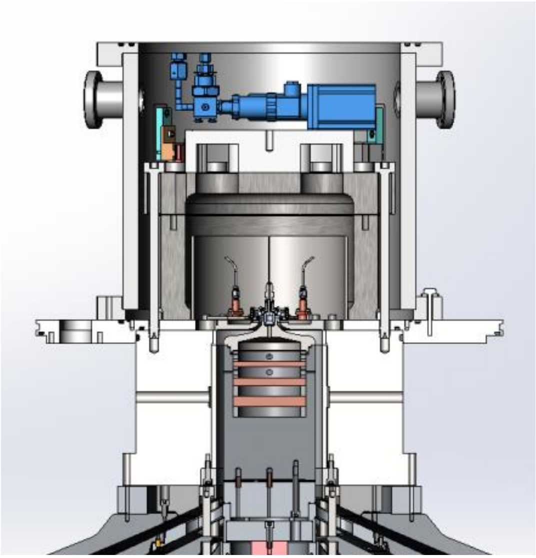
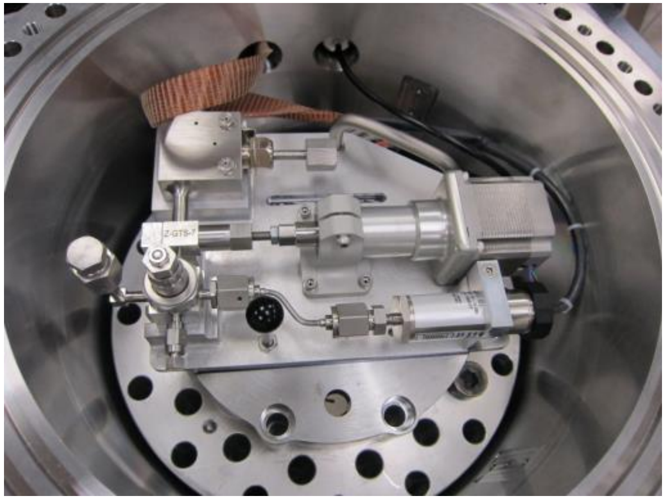
Upcoming Capabilities: Tritium

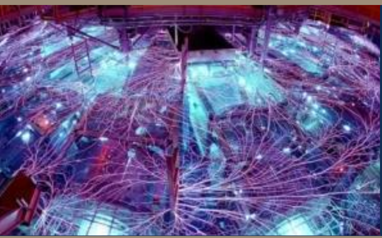
A Sandia Grand Challenge LDRD project demonstrated the feasibility of using an explosive containment system for trapping tritium

- 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)
- Conducted successful trace tritium (0.1%) experiment in August using the ZGTS in a containment system



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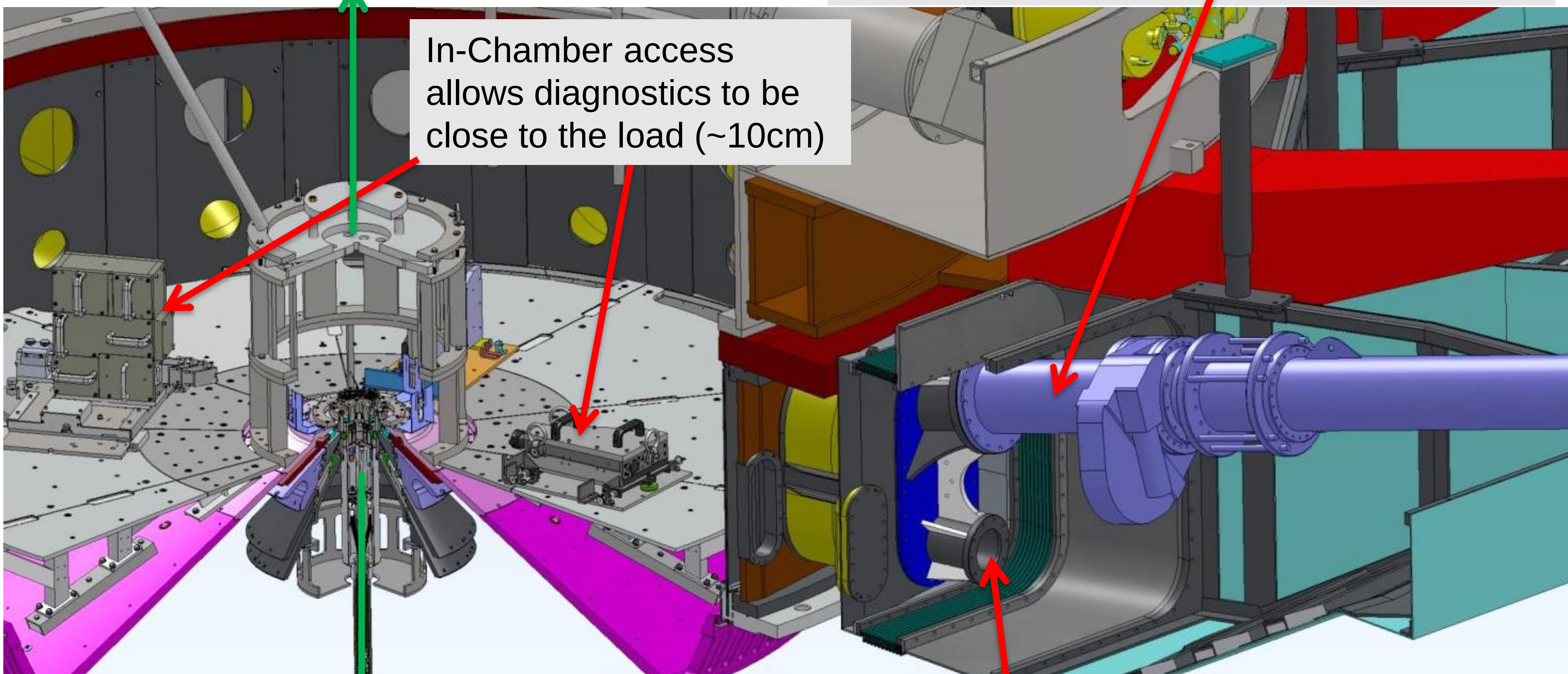
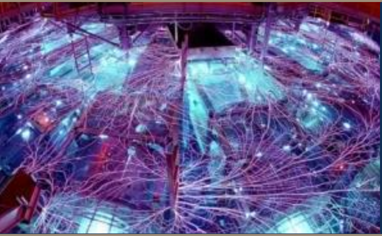
- Short Circuits – Material Sciences

Diagnostics

- X-Ray
- Neutron
- Optical
- ZBL Backlighter Laser

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

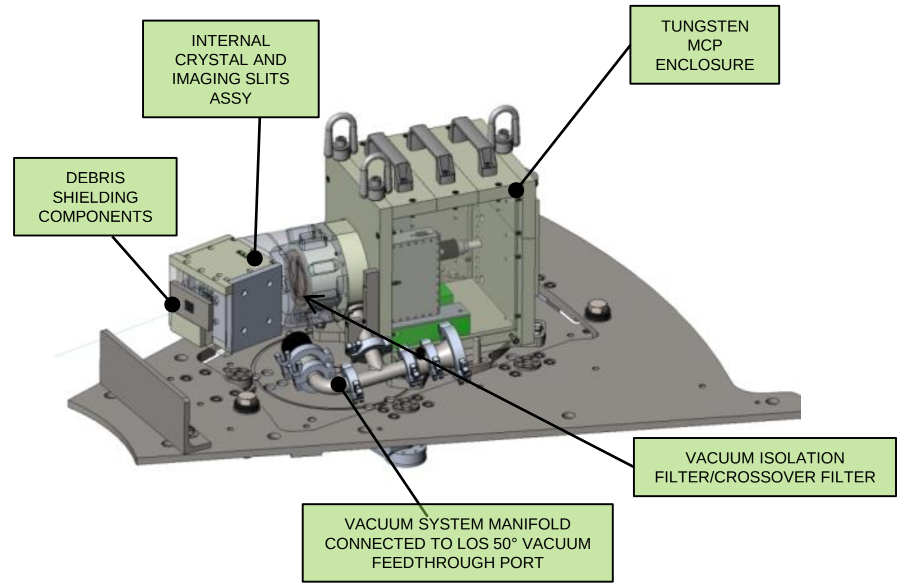
Z-Beamlet Laser

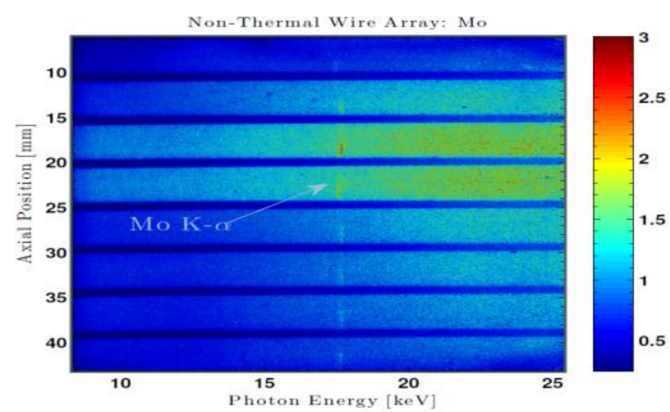
- Monochromatic Crystal Backlighting
  - Typically 6.151 or 1.865 keV
- X-Ray Thomson Scattering
- Diffraction under study

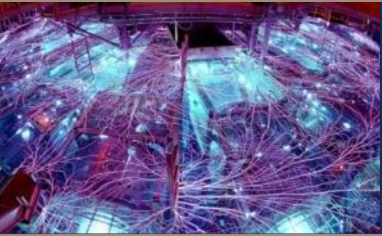
Diagnostics: New Deployments

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)

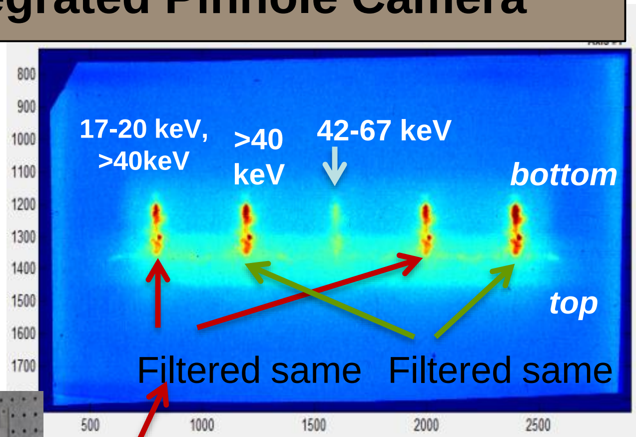


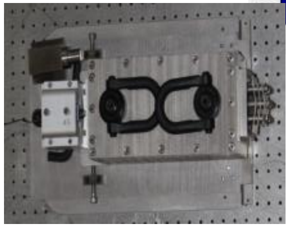


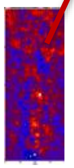


Diagnostics: New Deployments

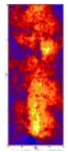
Time-Integrated Pinhole Camera







Subtracting images that are filtered the same

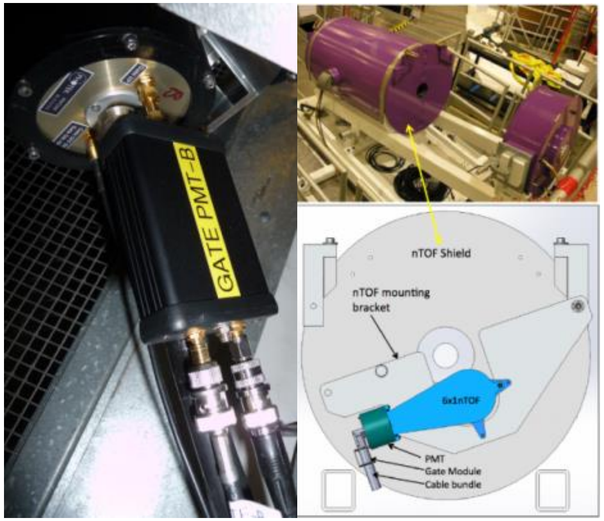


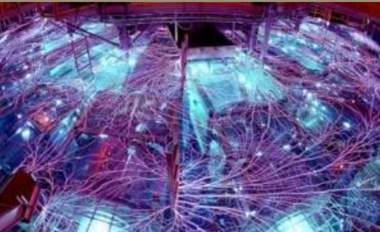
Subtracting different filtered images to get 17-20 keV window

- 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

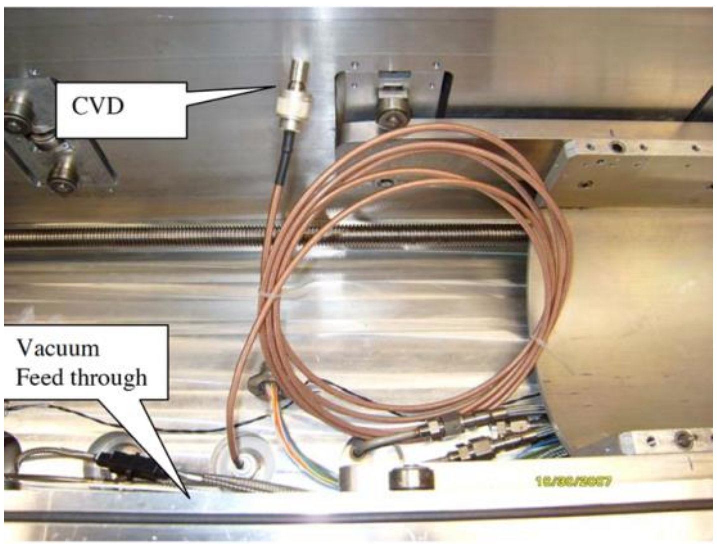




Diagnostics: New Deployments

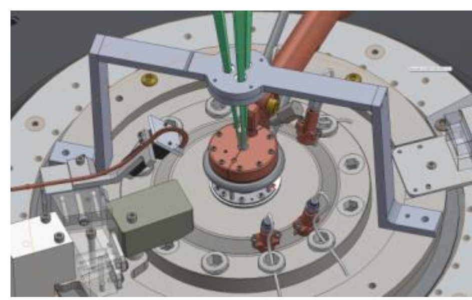
Diamond CVD for Sierra

- Rapid response in fielding LLNL provided Diamond CVD x-ray detector with high temporal resolution beyond current Z PCD detectors

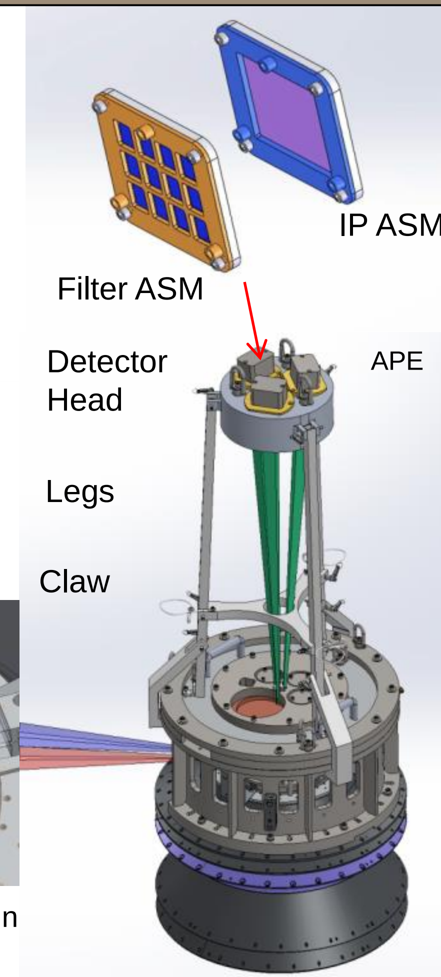


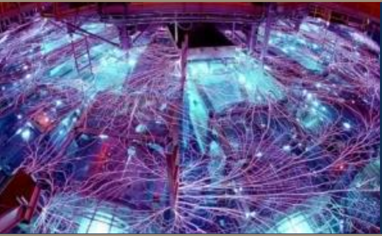
Axial Pinhole Imager (APE)

- Employs LANL-designed 1-micron pinhole arrays installed 10 cm from load
- 3 sets of 12 differentially-filtered data packets collected at head
- Time-integrated, resolution of ~12 μm, magnification ~10
- Initially fielded in July 2015



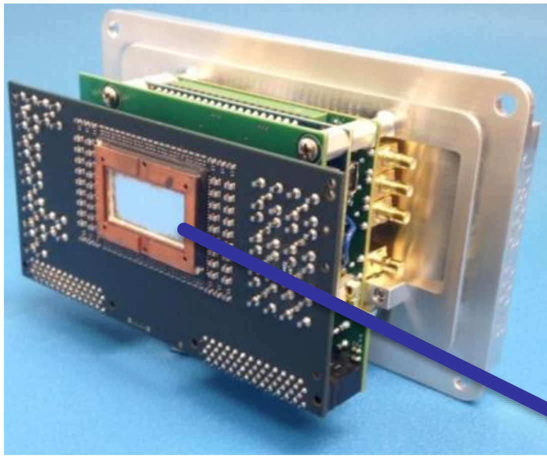
APE pinhole arrays: 3 arrays held in bridge 10 cm above load, inside of blast shield





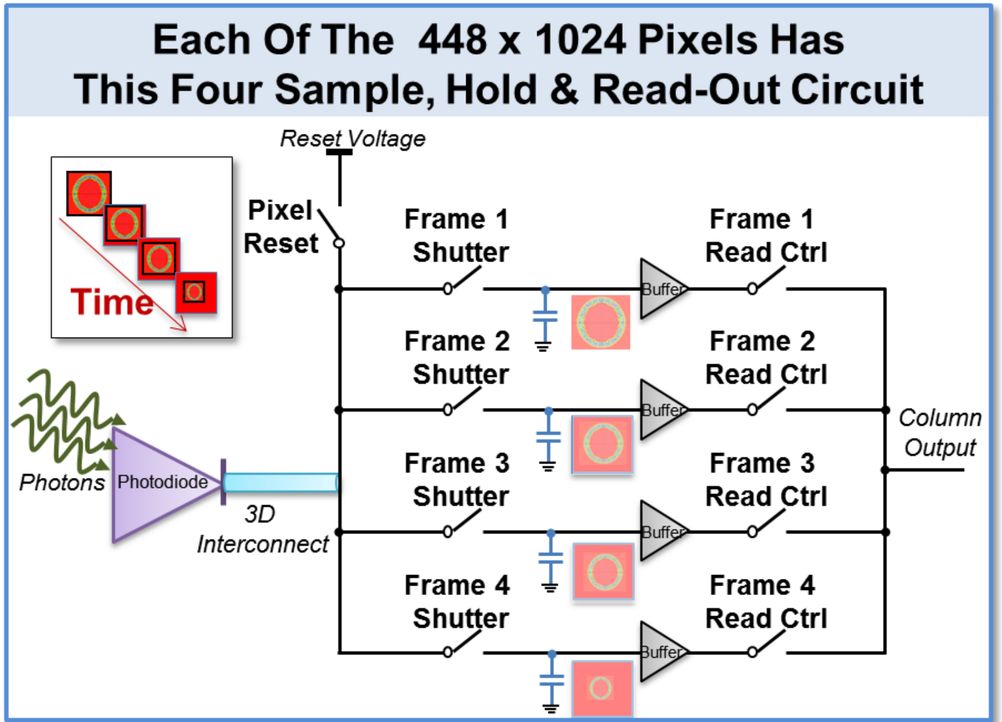
Diagnostics: CMOS imaging

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



We have a diagnostics and capability roadmap to guide our investments

We're working on a plan to 2025 . . .

Spectroscopy and Imaging Diagnostics
Neutron Diagnostics
95 kV Operation
200 shots/year
Oil and Water System Automation
Gas House Upgrade
Tritium
HVAC
Beryllium Safety
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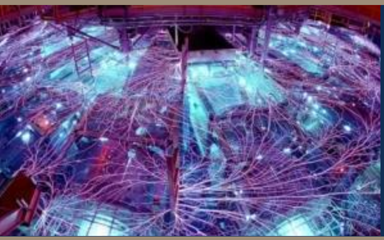

Outline

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 Matl's

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 Laser

Questions?