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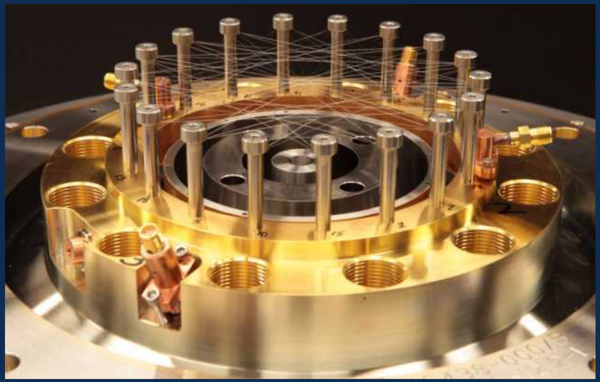
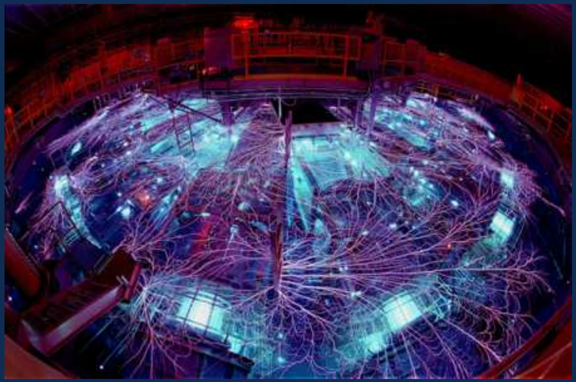
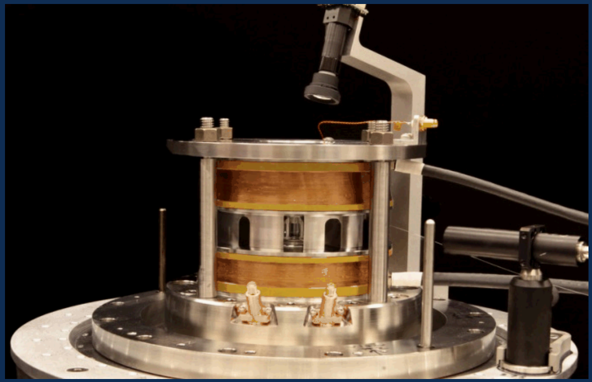






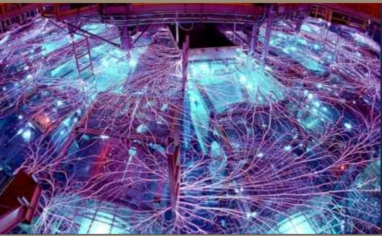
Capability Advances at the Sandia Z Machine

Presented By: Chris Ball.

Slides By: Joel Lash

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration



Z Overview 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

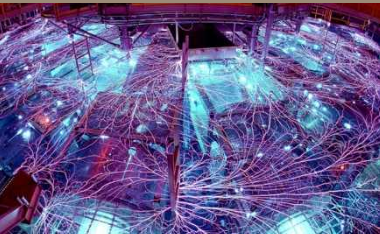
- Backlighter
- Cryogenics
- External Magnetic Fields
- Gas Fills
- Explosive Containment for High Z Materials

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



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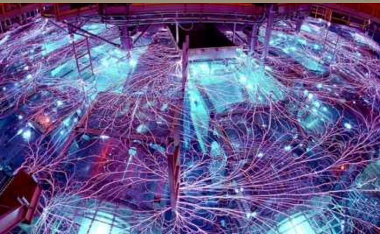
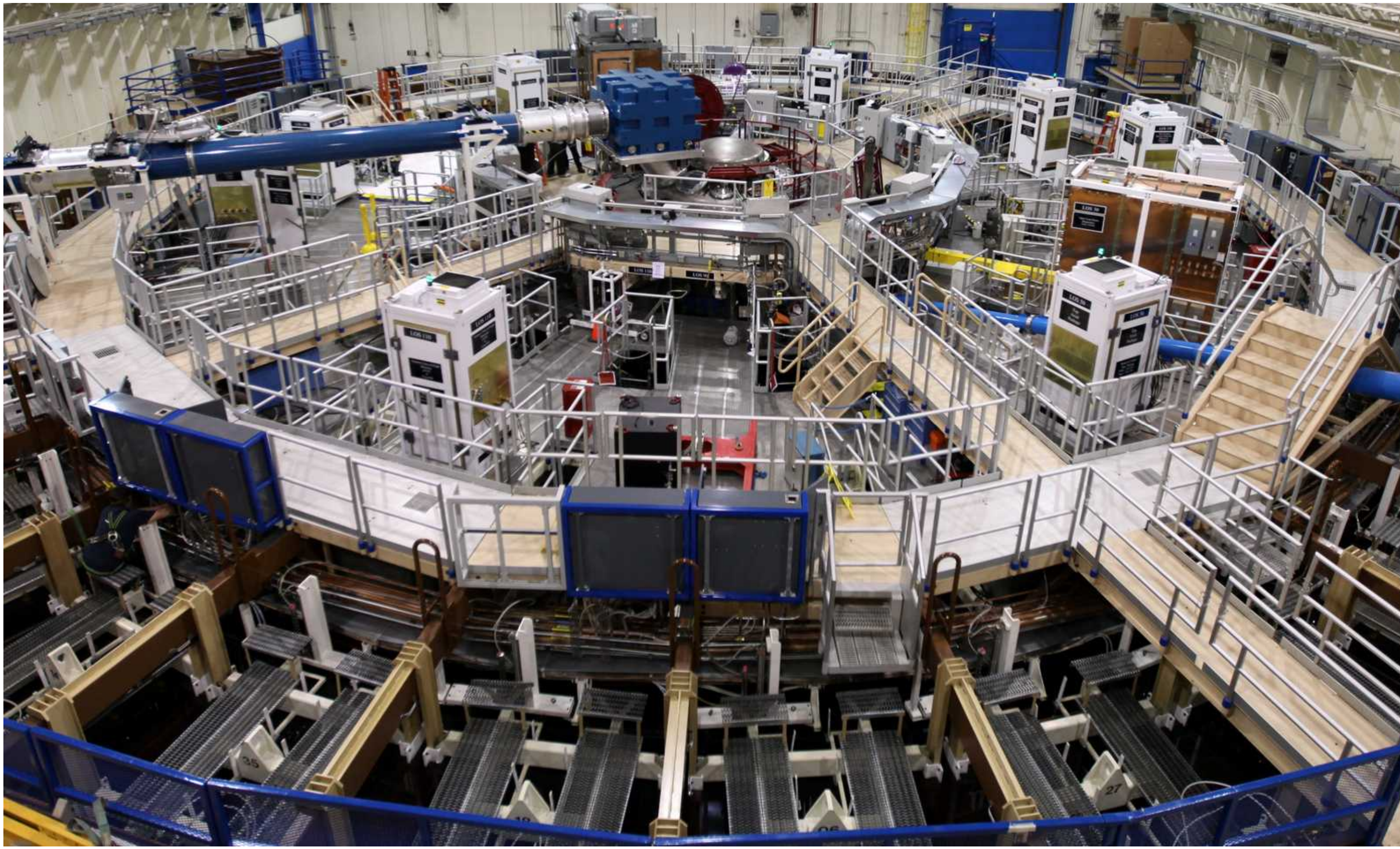


Z is a unique world class pulsed power facility at Sandia National Laboratories



36 Marx generators
2160 capacitors

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

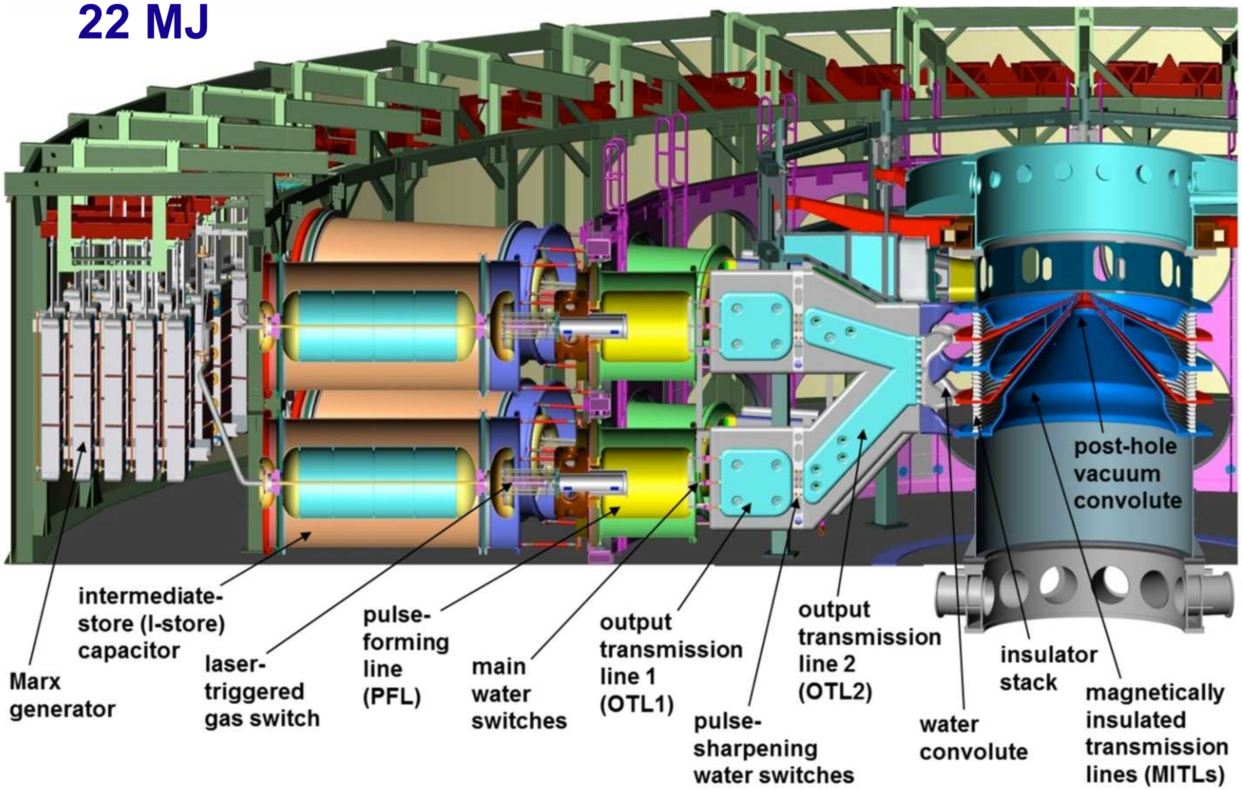
100,000 liter vacuum vessel

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

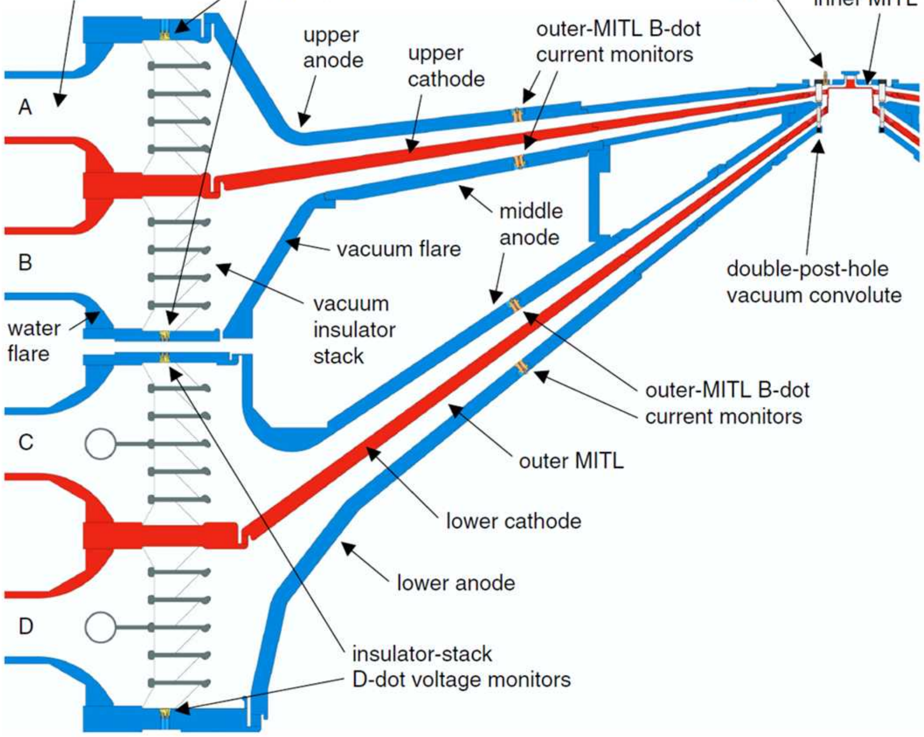


330 TWs & 2.5 MJ of x-ray output in a few ns

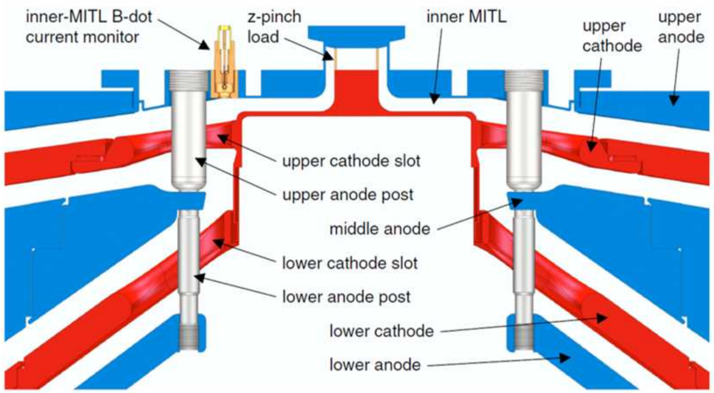
. . . and literally shakes the earth almost every day!

A complex series of conductors combine currents for the load

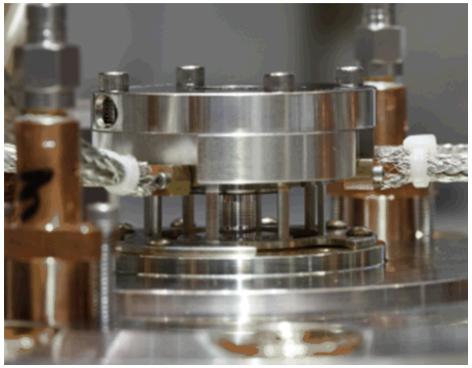
Z vacuum insulator stack and MITLs



Post hole convolute system and load



ICF liner load



DMP load

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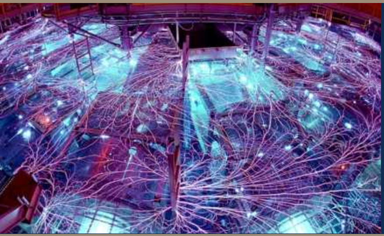
Daily Z Activities: Unload and Refurbishment

- 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

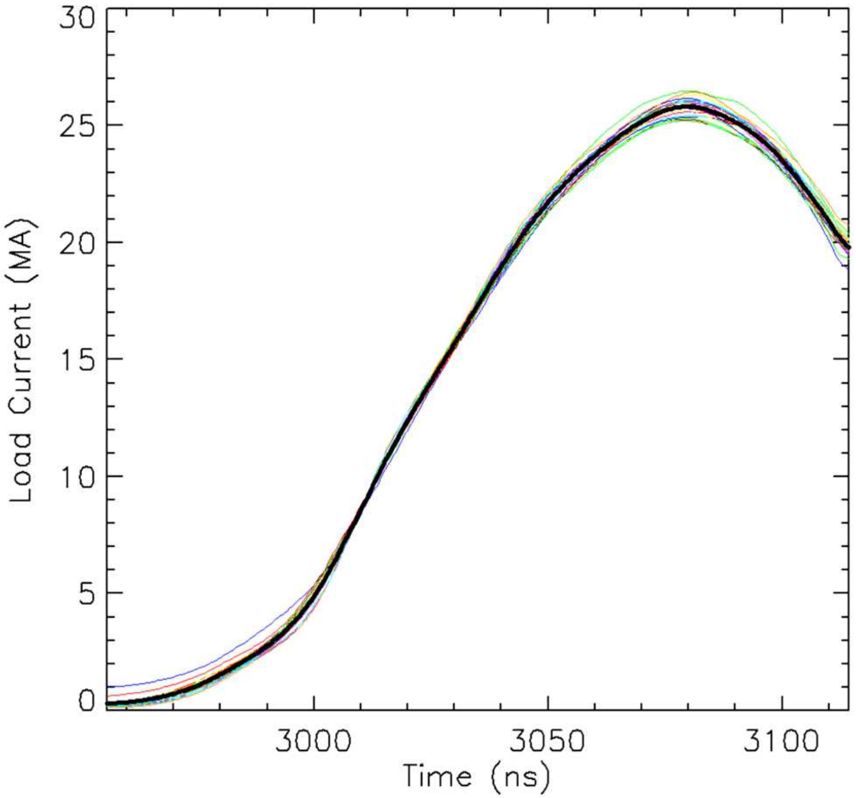
Wire array transport

Target and diagnostic loading

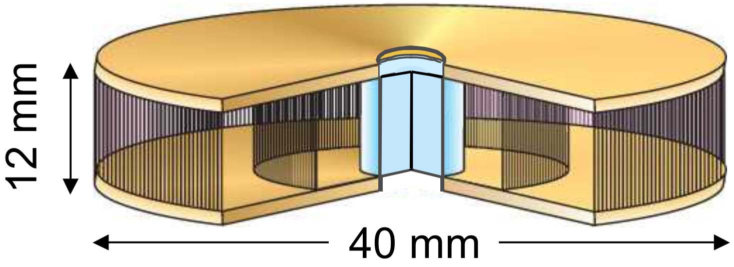
- Install Load Hardware
- Install Diagnostics
- Install FOA, Align Diagnostics
- Pump down vacuum chamber
- Checklists and fire Z!

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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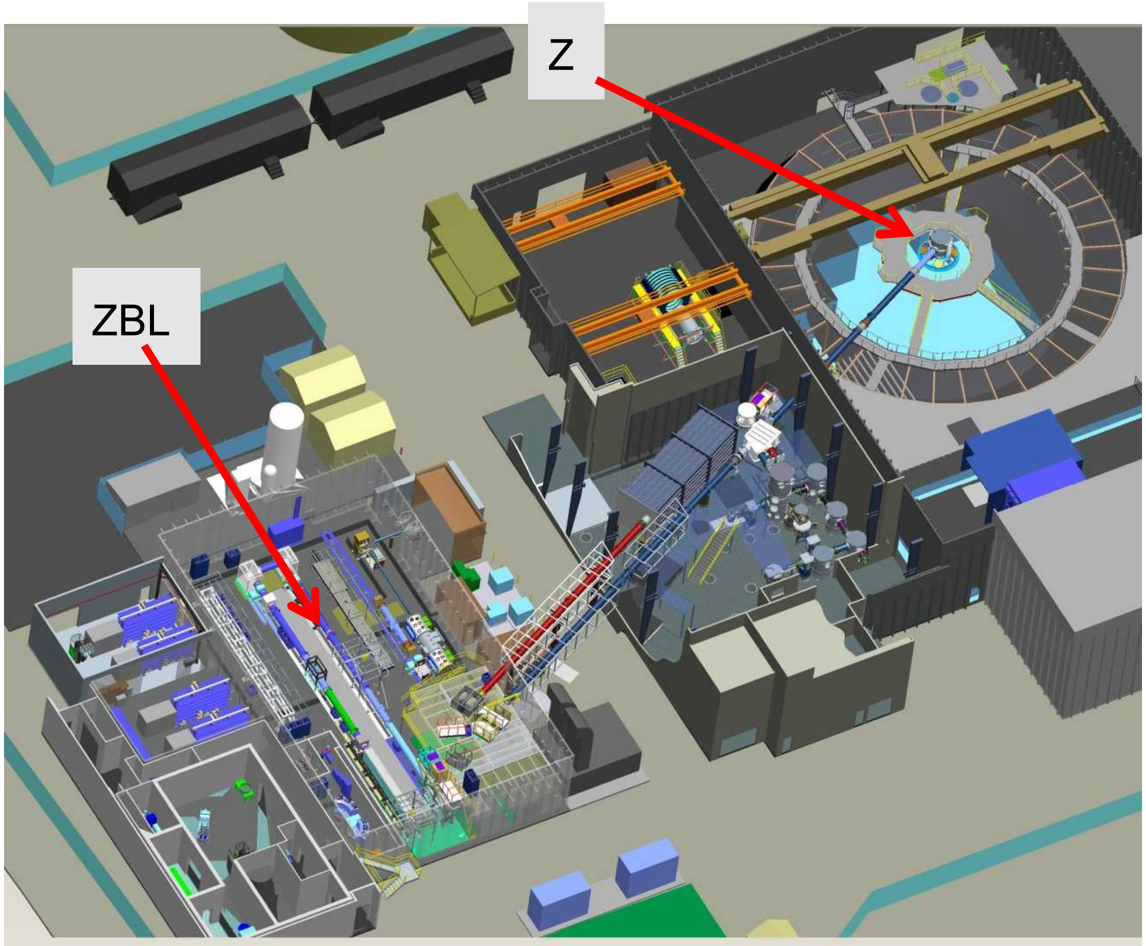
Z Core Capabilities: ZBL

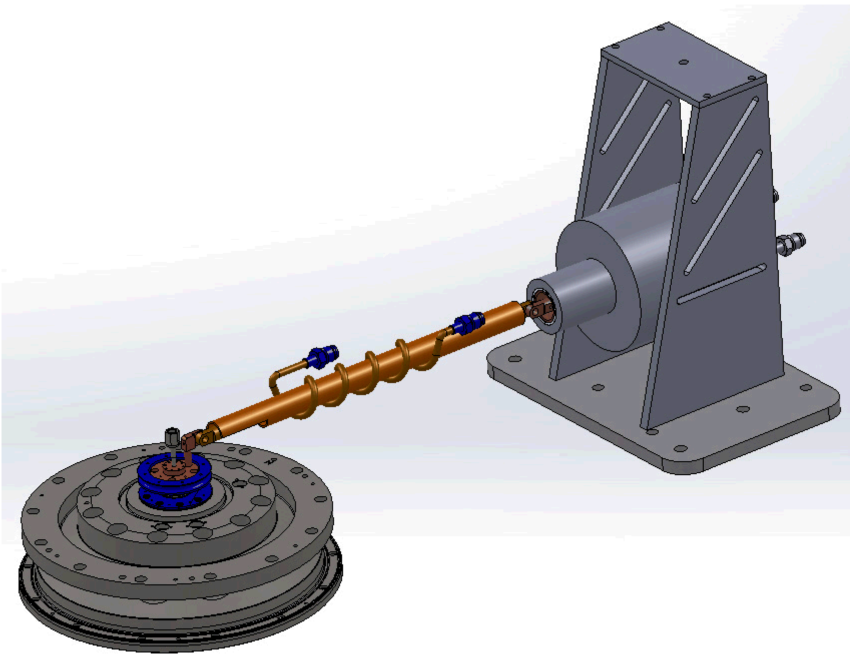
Z-Beamlet Basics



- 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

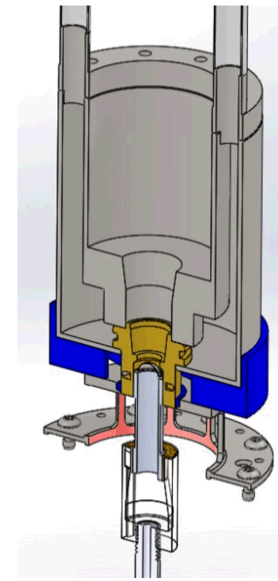
Standard Configuration (Mini Cryostat)



- 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

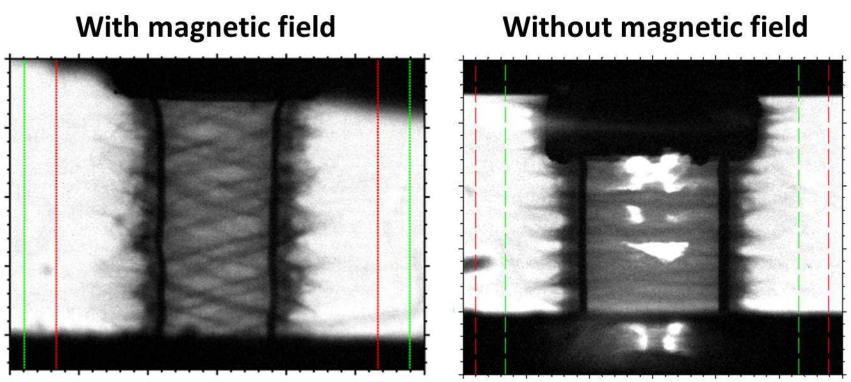


Liquid Helium Reservoir Cryostat

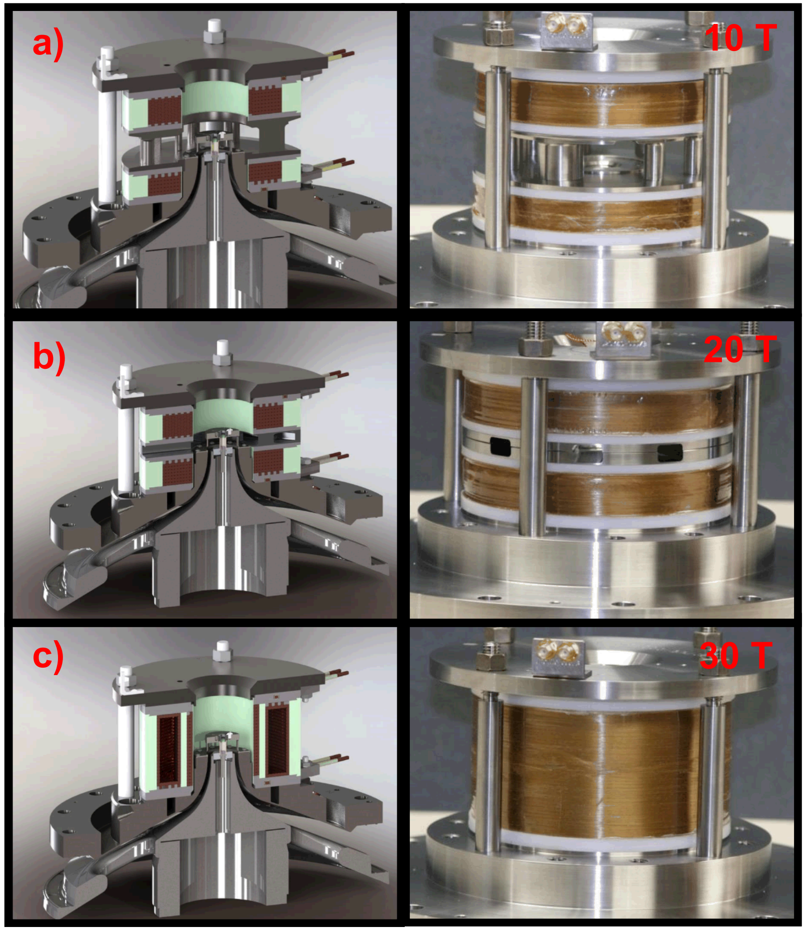
- Achievable temperature range 4.2K to 2.17K
- Cooling time 60 – 90 min
- Cryostat must have vacuum applied at 4.2K to achieve lower temperatures

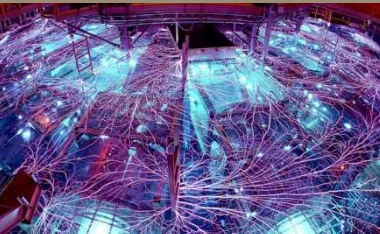
Z Core Capabilities: Applied B-Field

- 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



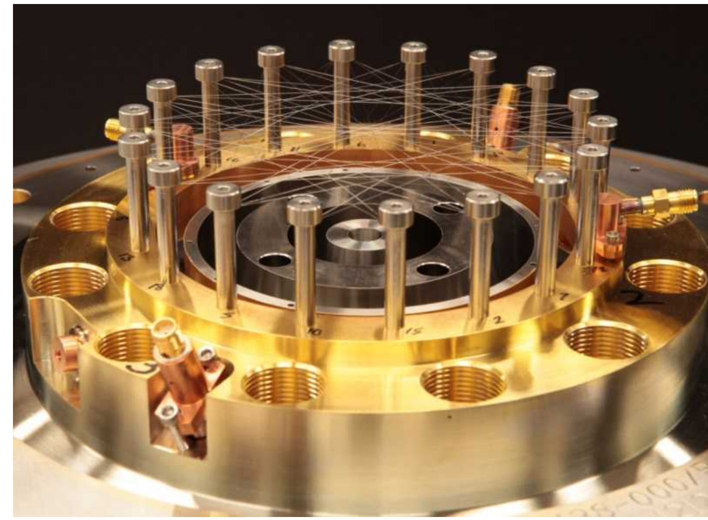
ABZ Field Coil Configurations

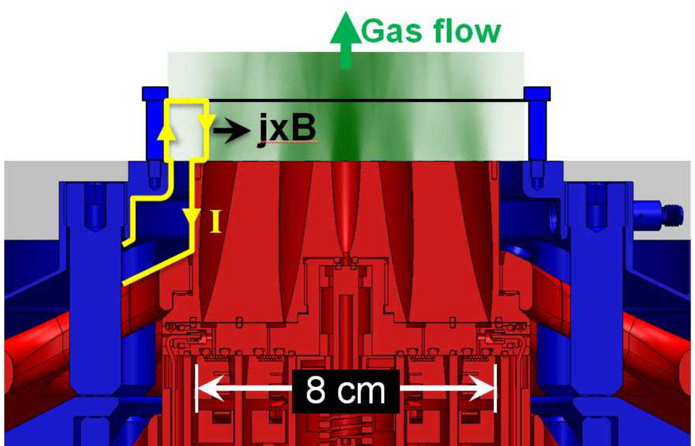


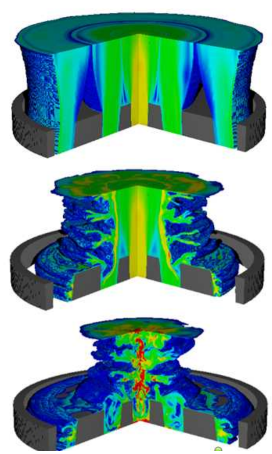


Z Core Capabilities: Gas Puffs

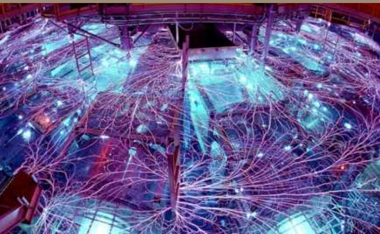
- Gas Puffs provide unique loads for tailoring x-ray outputs through judicious choice of gases
- Nozzle design and characterization is critical with development being done at the Sandia Systems Integration Test Facility
- Record K-shell x-ray outputs are robustly generated on Z







- 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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- Neutron
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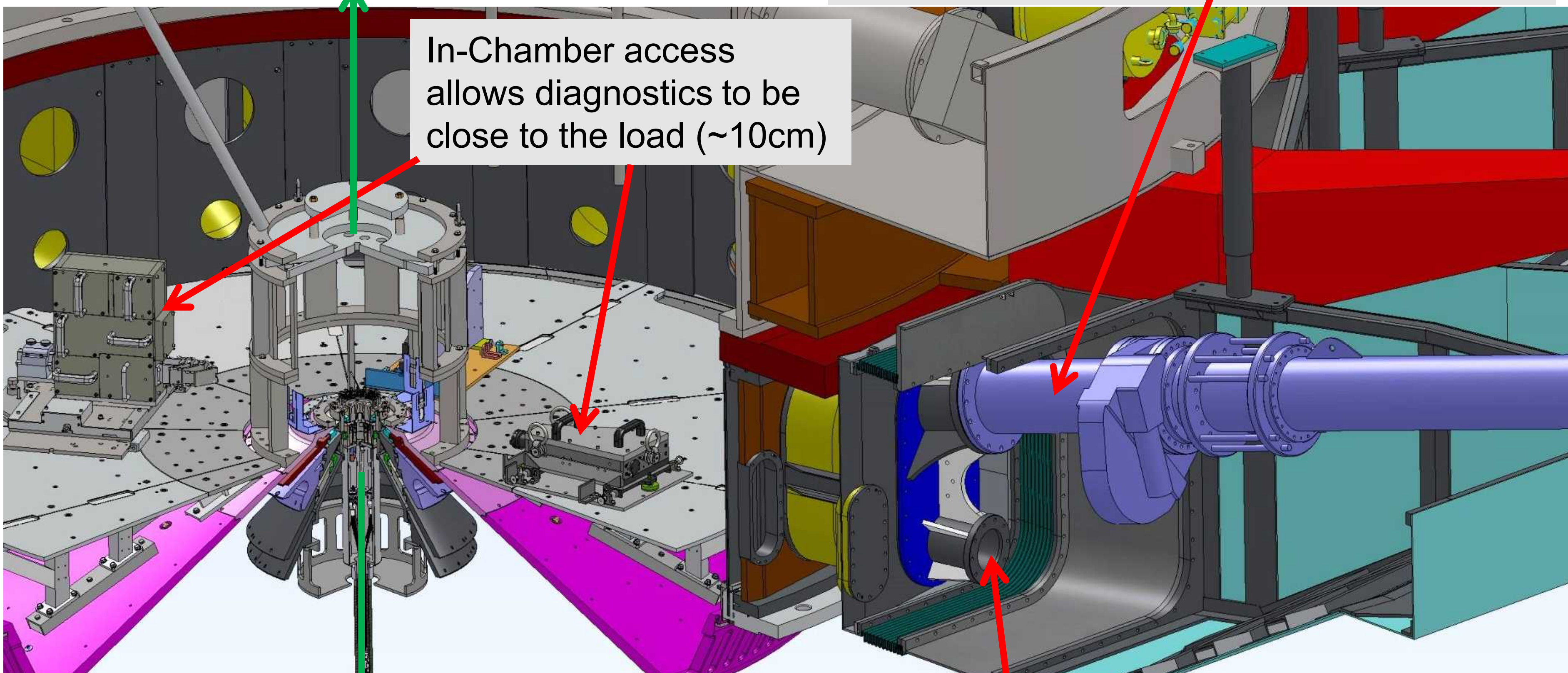
Diagnostics: Overview



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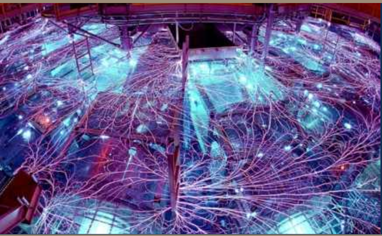

Diagnostics: Overview

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

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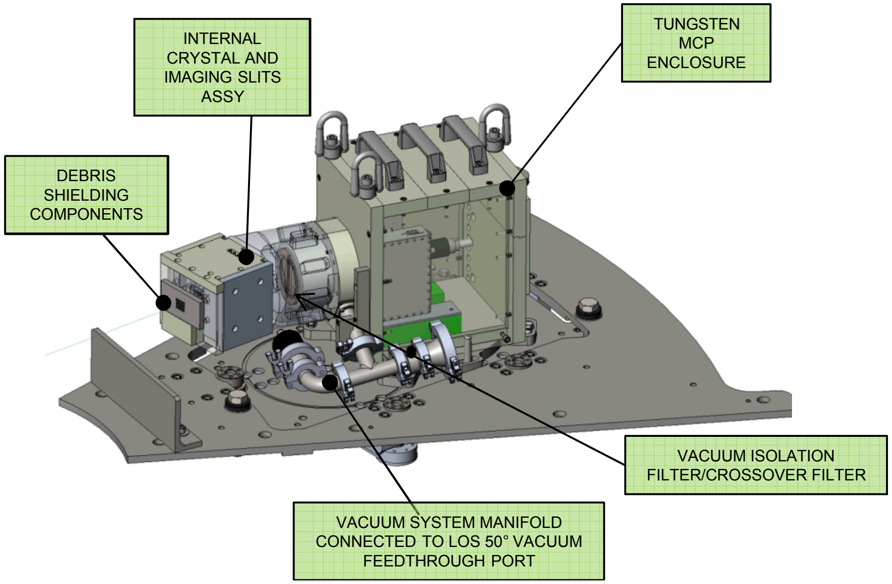
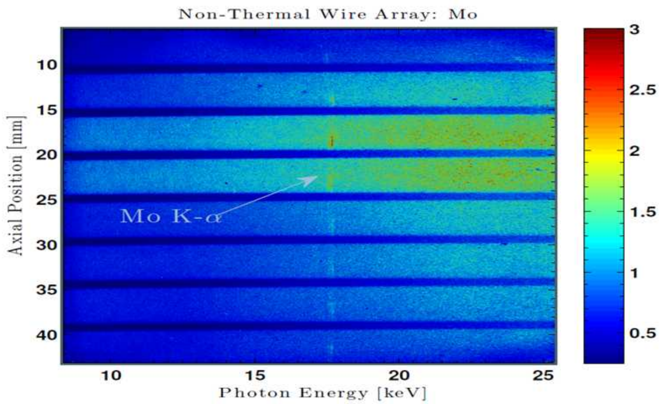
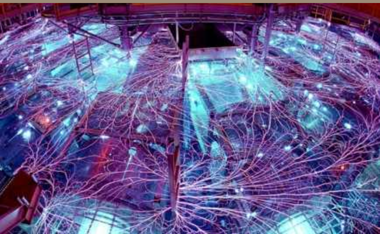
Diagnostics: New Deployments

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)

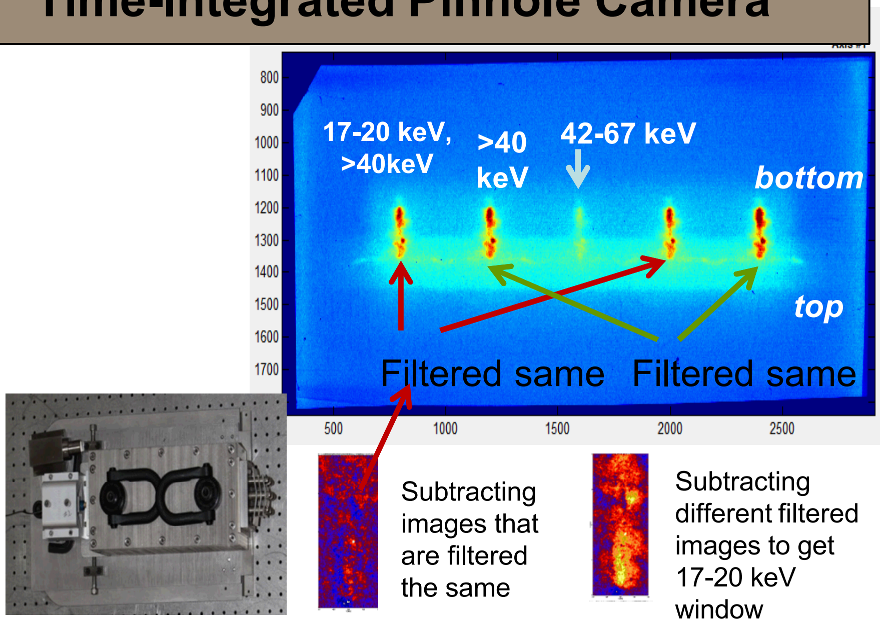






Diagnostics: New Deployments

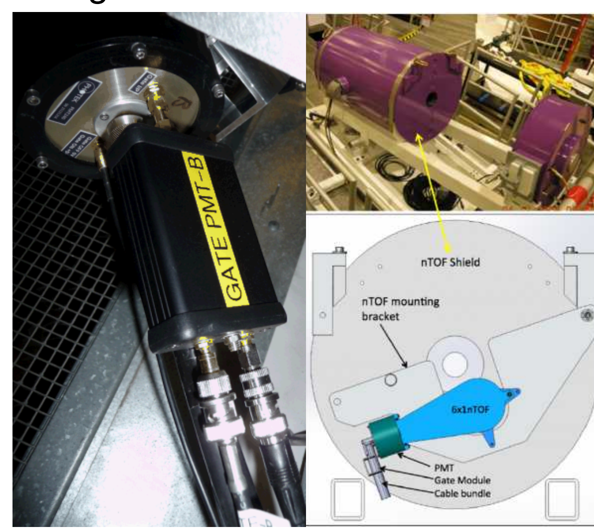
Time-Integrated Pinhole Camera

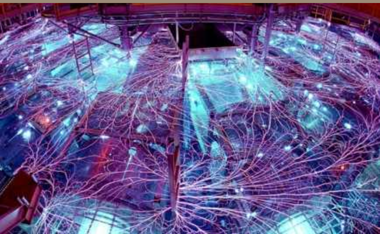


- In-chamber pinhole camera designed for imaging warm x-rays (15 -100 keV)
- 5 filtered pinhole images per experiment
- Developed under hostile environments LDRD to identify where in the source warm x-rays are produced
- Currently used broadly in ICF and RES programs

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





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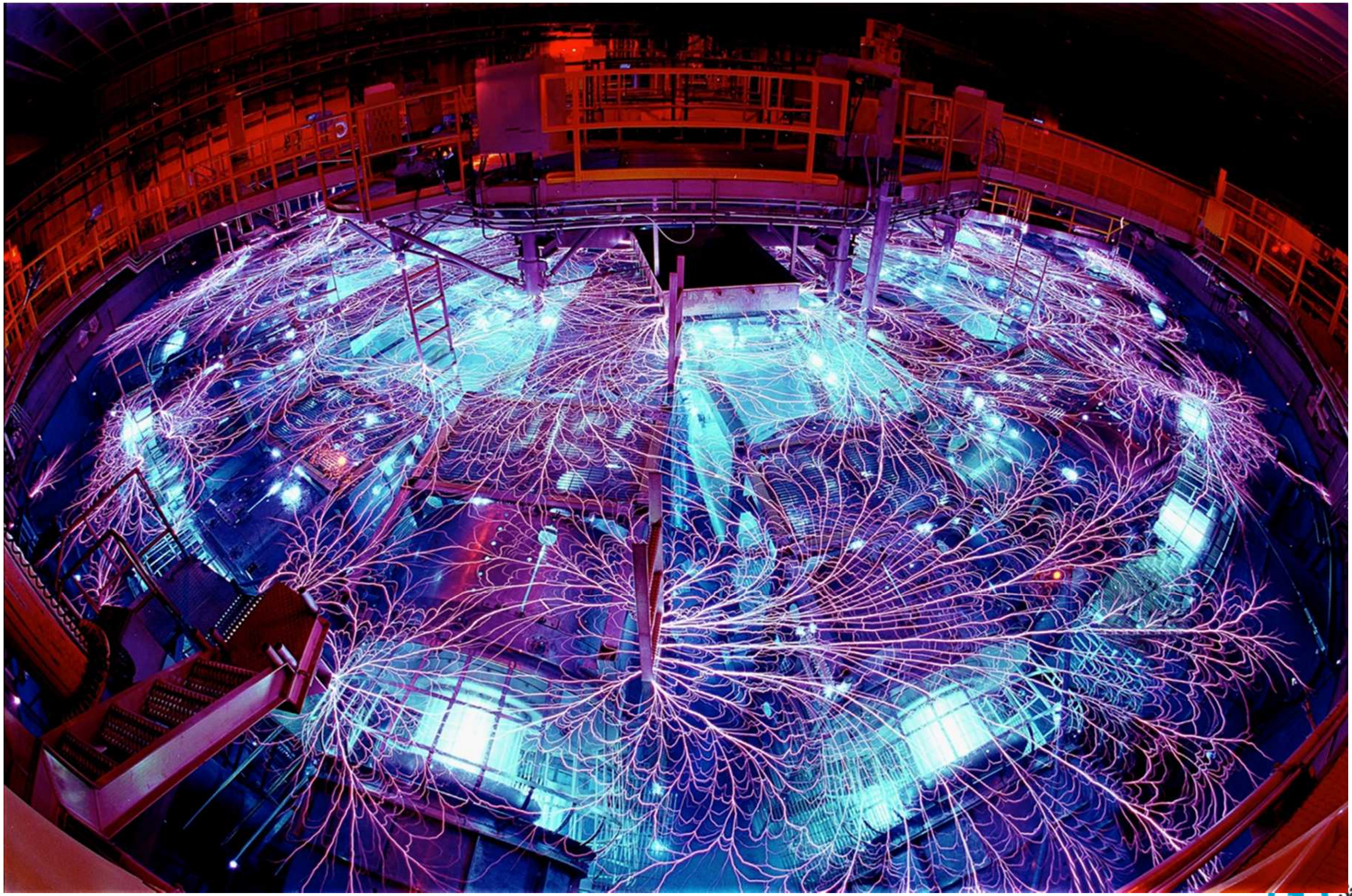
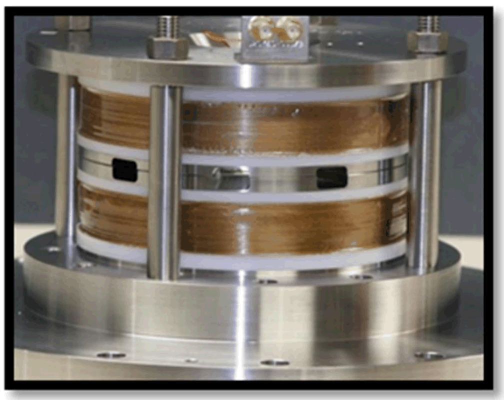
Questions?

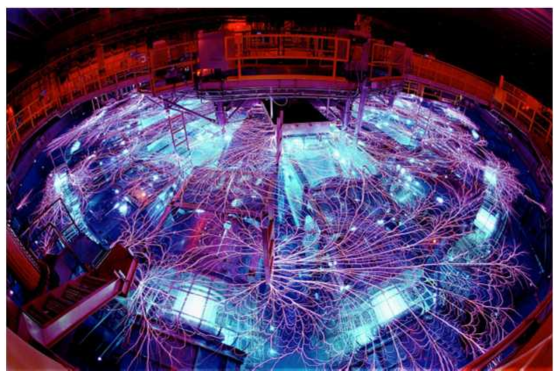


Z Debris



Custom Physics Hardware

+



330 TWs & 2.5 MJ

=

Lots of Debris and Shrapnel

Outline

Debris Taxonomy

- Soot
- Spray
- Particulate
- Bullets

Debris Analysis

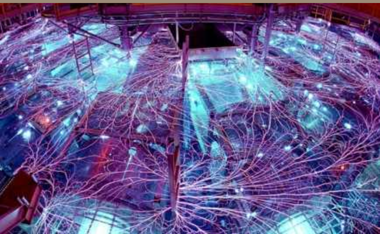
- Debris Time History Hypothosis
- FOA Window Analysis
- NASA Methodology
- Multiphysics???

Current Debris Mitigation Strategies

- Aperturing
- Shielding
- Sacrificing
- Accepting

Debris Diagnostics

- DTOF



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Soot

- Soot ranges from small particulate dust, to fibrous, soft particulate ~1-3mm in length (often in the shape of tendrils or dendrites).
- The origin of soot is thought to be a combination of condensed gaseous material, and low-mass ablated material.
- The constituents of soot have not been characterized; however it is suspected to have a significant metallic fraction (i.e., not completely hydrocarbon based), since thin film deposits have measurable attenuating effects on x-ray measurements.
- Soot damages vacuum equipment, clogs apertures, coats crystals and mirrors, and fouls detectors.

Spray

- Spray is molten particulate, probably <1mm in dia.
- Some spray probably originates from ablation by hot, high velocity gas/plasma
- Some spray may originate from components liquefied by the load physics (x-ray, infra-red, etc.) and propelled by electromagnetic forces
- Spray damages apertures, crystals, mirrors, filters, detectors, and hardware.

Particulate

- Particulate is small grained, solid, material generated by the load.
- Particulate may be condensed spay, or may be resultant of thin coatings ablating (without melting).
- Unlike spray, particulate is solid, and doesn't coat the impacting surface.
- Particulate damages apertures, crystals, mirrors, filters, detectors, and hardware.

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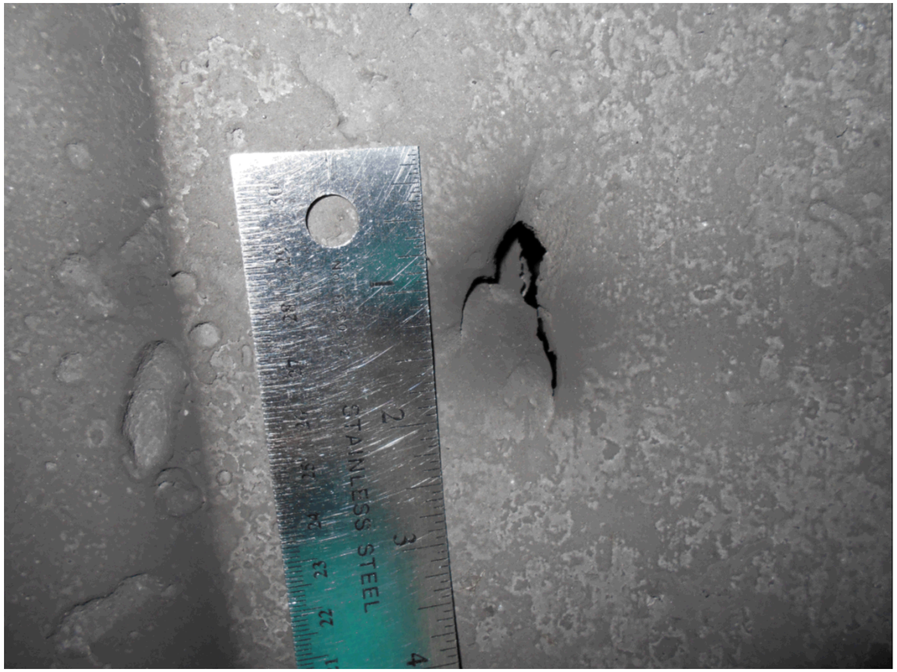
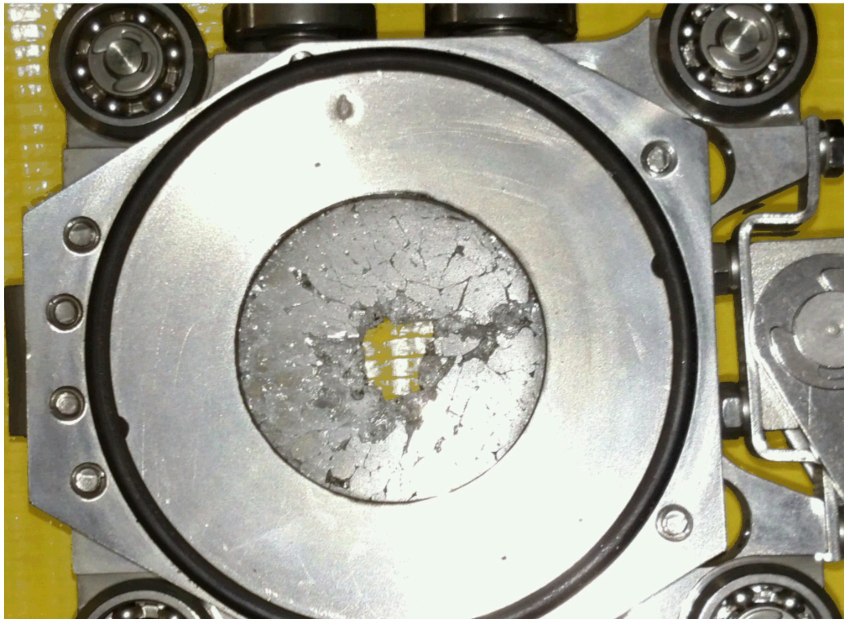
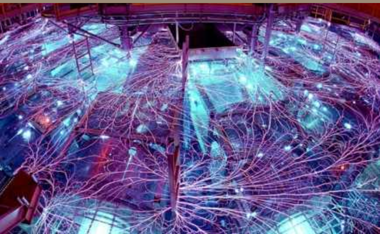
Bullets

- Bullets are large (>1mm), solid particles ejected from the load area.
- Bullets can penetrate through 0.25” or more of stainless
- Some bullets appear to be fragments of the fasteners used in the load







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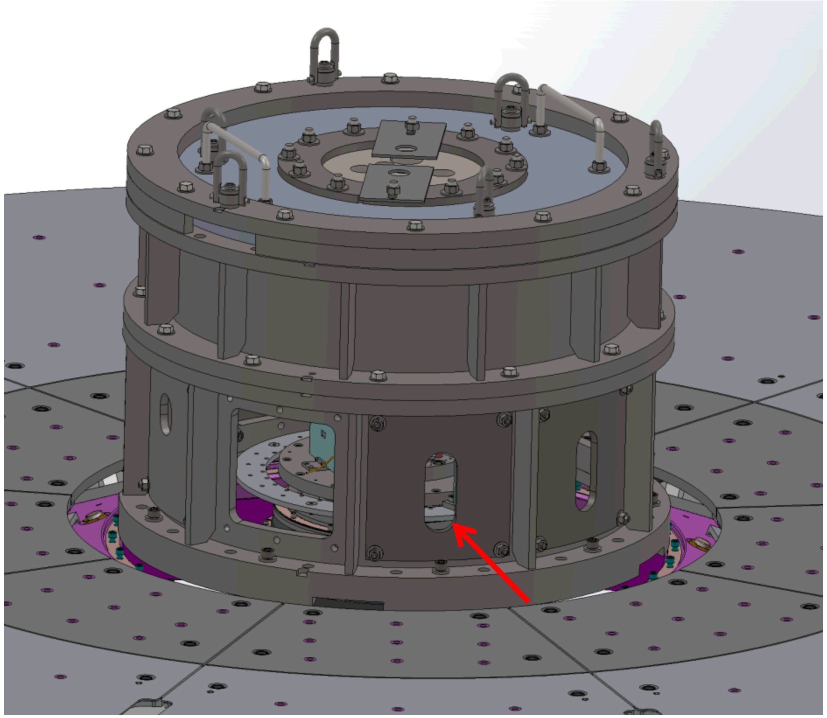
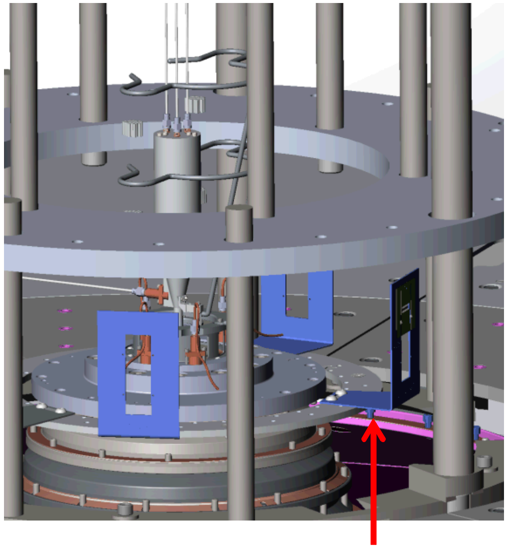
Debris Diagnostics

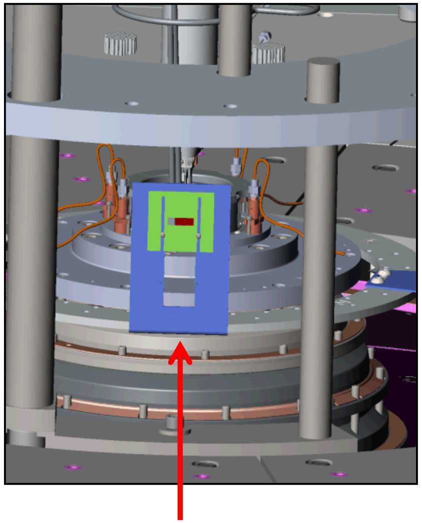
- DTOF

Aperturing

- **Aperturing simply reduces the solid angle of the diagnostic that is exposed to the load.**
- **Most blast shields have apertures to reduce debris**
- **Additional aperture brackets may be used.**

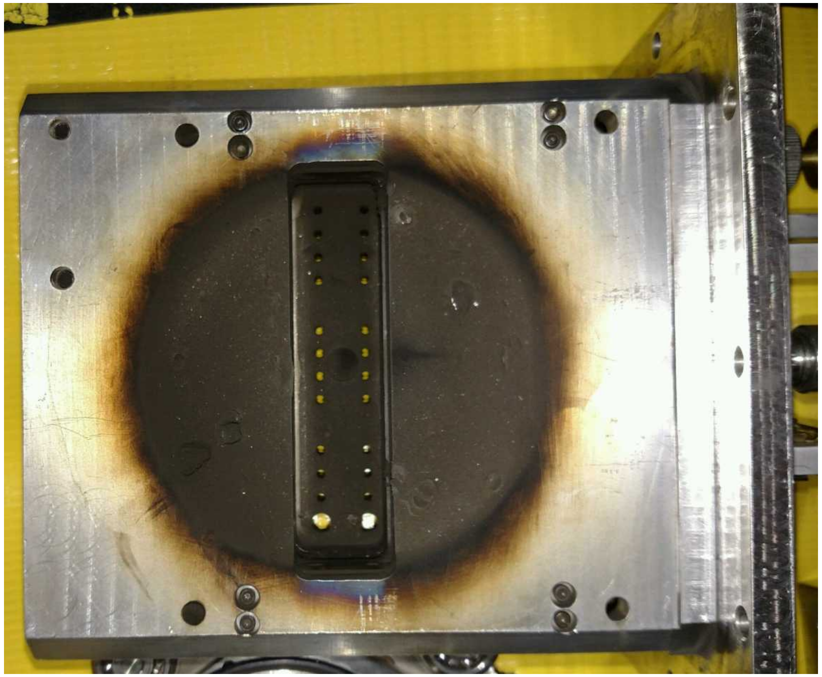


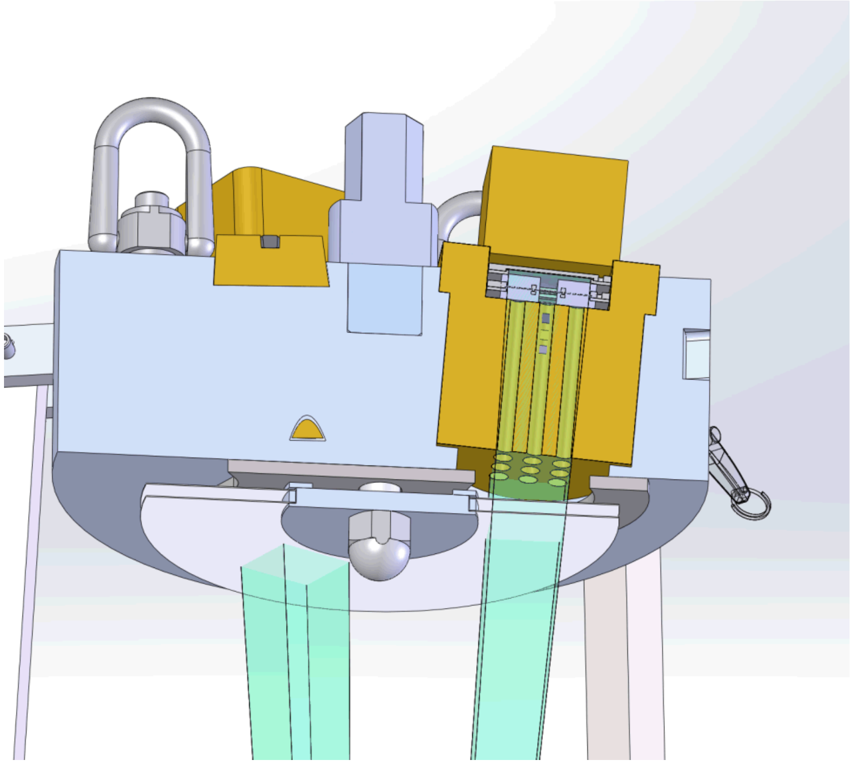




Shielding

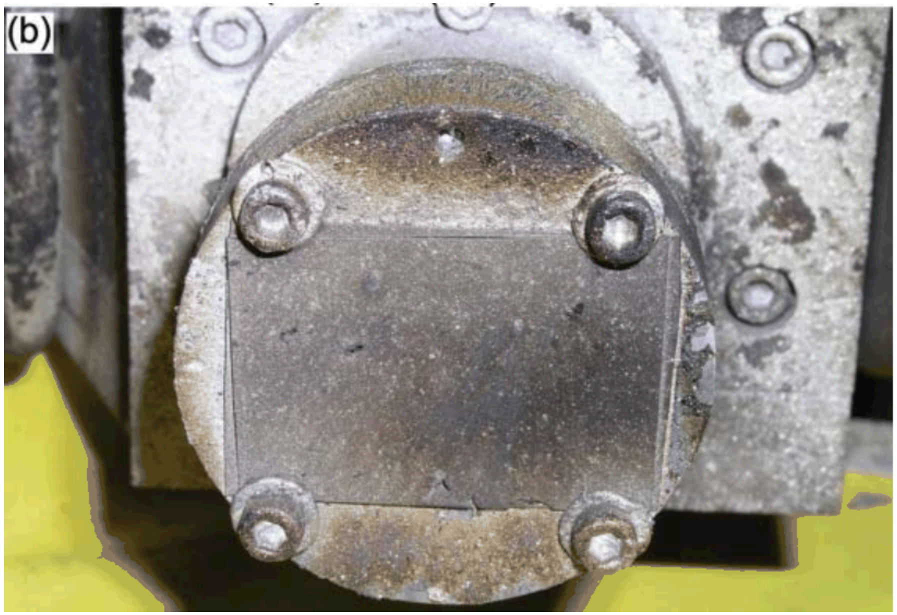
- Most diagnostics have a debris baffle system to reduce, or eliminate a debris path from the load to the detector.
- Most diagnostics incorporate some form of polymer (usually Kapton) debris shielding.





Sacrificing

- In-chamber diagnostics are exposed to lots of debris
- Most incorporate sacrificial shielding (usually Kapton), that must be replaced after every shot.
- 1.5mm of Kapton is usually adequate to protect in-chamber diagnostics from spray and particulate debris.



Accepting

- It's impractical (impossible?) to design a soft x-ray diagnostic that is invulnerable to debris.
- We inspect and refurbish our diagnostics to address to continual damage and fouling caused by debris.
- We often lose expensive components, such as crystals, mirrors and detectors. (Our annual budget for crystals is $1M.)
- We employ redundant strategies to maximize the likelihood of data return, even if the diagnostic sustains local damage.

Outline

Debris Taxonomy

- Soot
- Spray
- Particulate
- Bullets

Debris Analysis

- Debris Time History Hypothesis
- FOA Window Analysis
- Multiphysics???

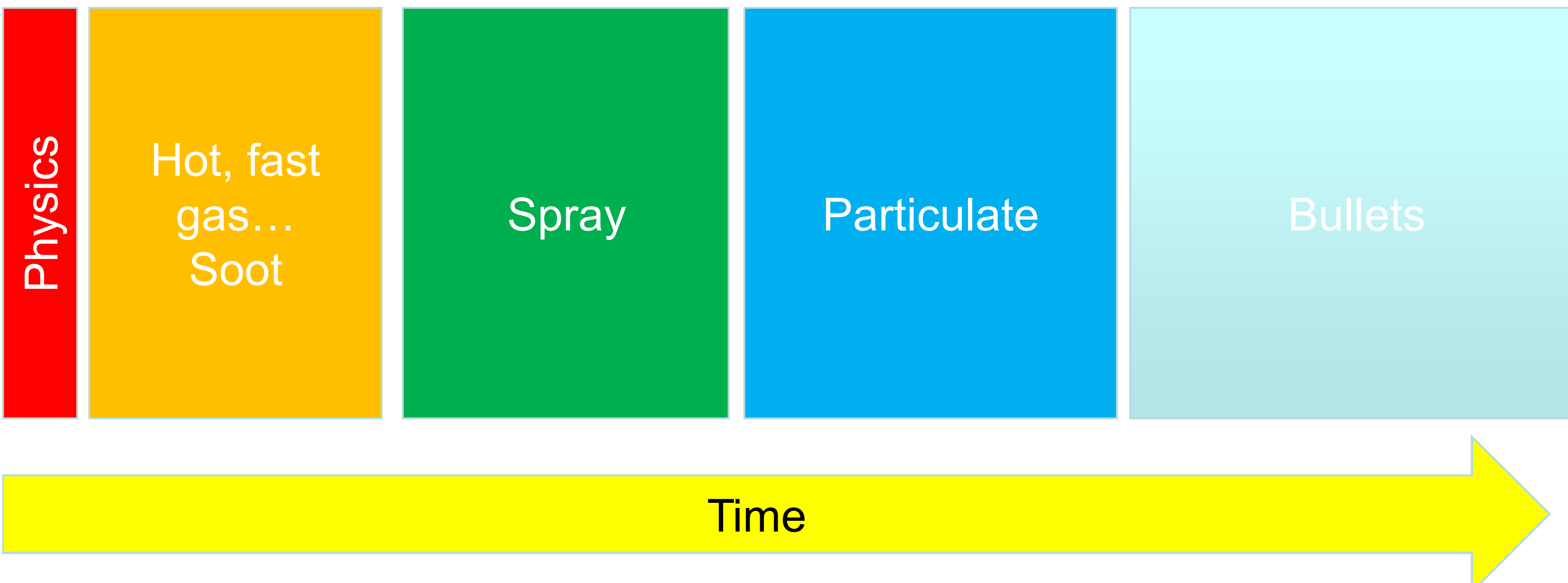
Current Debris Mitigation Strategies

- Aperturing
- Shielding
- Sacrificing
- Accepting

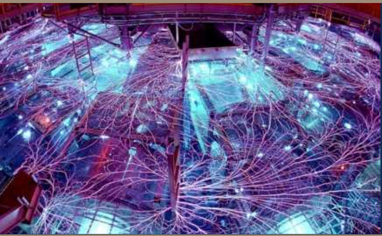
Debris Diagnostics

- DTOF

Debris Time History Hypothosis



Opportunities may exist to target specific types of debris with tailored mitigation strategies.



Predicting Ballistic Performance

“Ballistic Limit Equation”
for fused silica

$$P = 0.53{\rho_P}^{0.5}{d_P}^{19/18}{V_N}^{2/3}$$

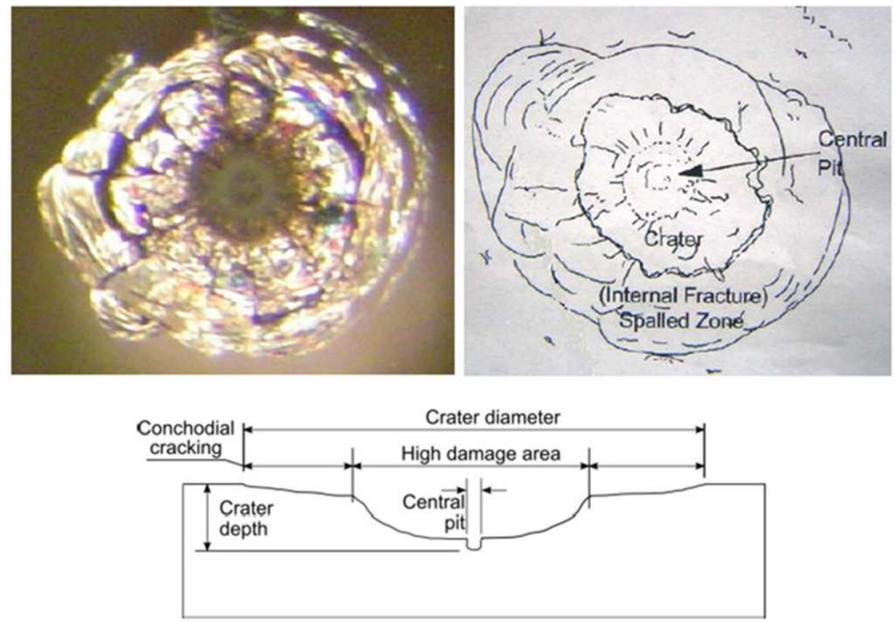


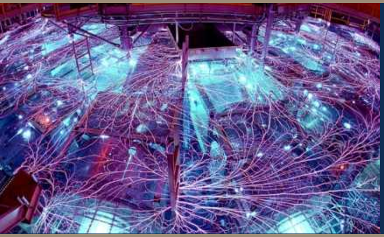
Figure 9: Damage characteristics and measurements in glass targets. Top: front view (photograph and schematic); bottom: damage measurement schematic (side view).

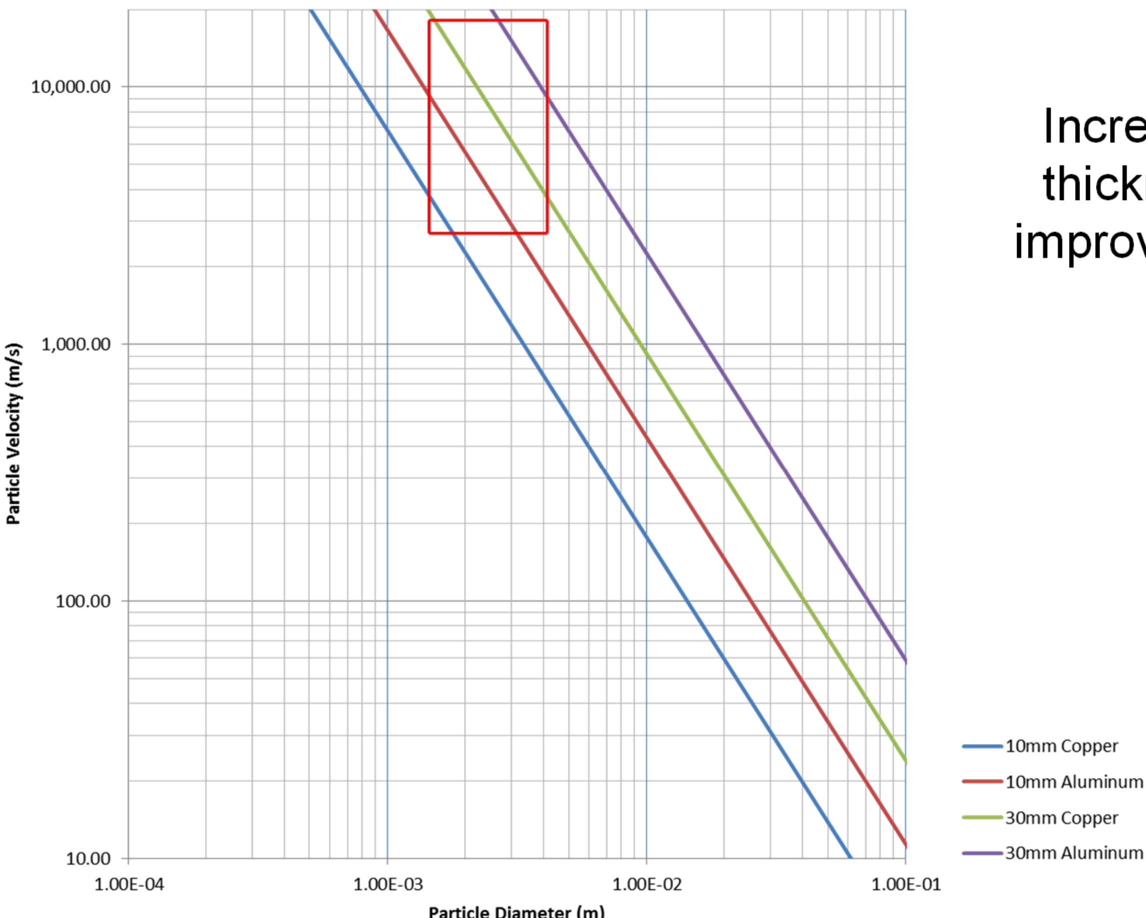
B.G. Cour-Palais. “Hypervelocity Impact Investigations and Meteoroid Shielding Experience Related to Apollo and Skylab.” Orbital Debris Workshop, NASA CP-2360 (pp.247-275), Houston, August 27–29, 1982.

cited in:

S. Ryan, E.L. Christiansen “Micrometeoroid and Orbital Debris (MMOD) Shield Ballistic Limit Analysis Program” NASA/TM-2009-214789

(J.Reneker, SNL)



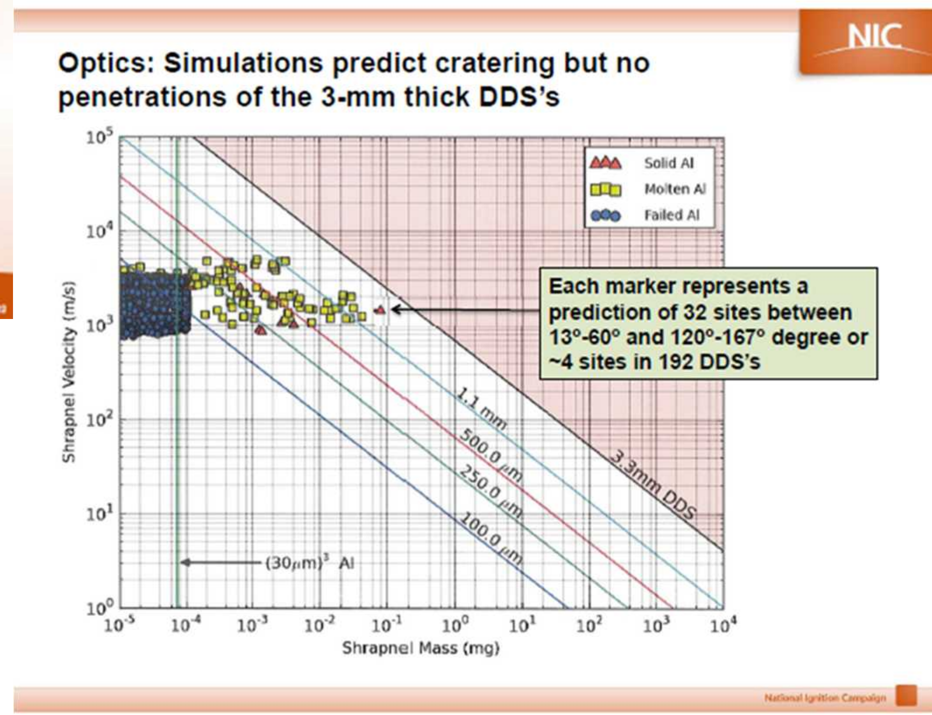


(J.Reneker, SNL)

Increasing debris shield thickness to 30mm may improve model confidence

$$P = 2t_s = 0.53{\rho_P}^{0.5}{d_P}^{19/18}{V_N}^{2/3}$$

Sandia D&S Analysis Basis



(J.Reneker, SNL)

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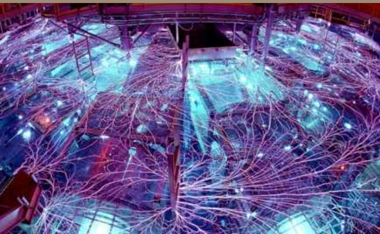
Multiphysics Approach

- Neither Sandia/DOE multiphysics codes, nor commercial multiphysics codes have routinely been applied to Z debris and shrapnel modeling.
- Our DMP codes may be a good starting point.
- Comsol may be a good tool.
- If the environment is nicely segregated, different codes may be used to model different types of debris.



Outline

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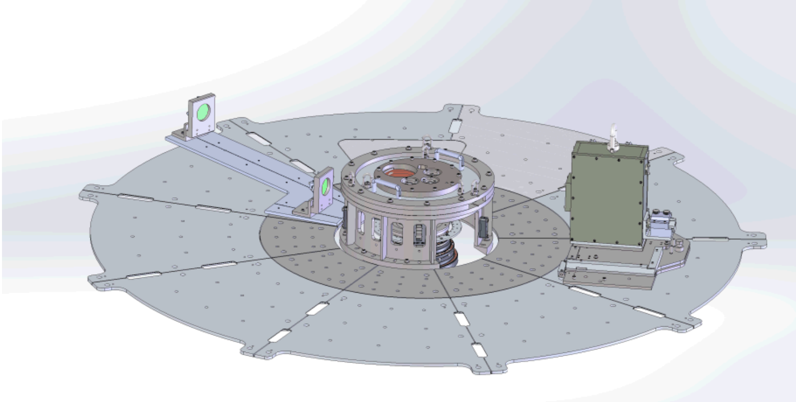
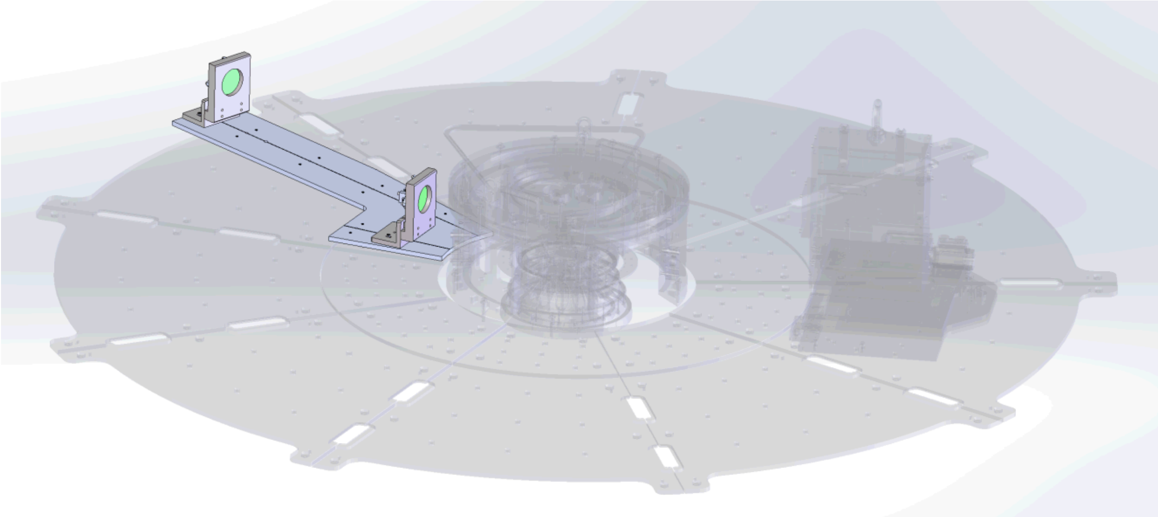
Debris Diagnostics

- DTOF overview
- DTOF basis
- DTOF measurements
- DTOF limitations/next steps

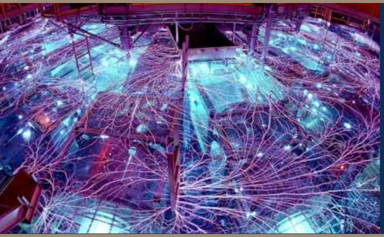
DTOF overview



Debris Time Of Flight

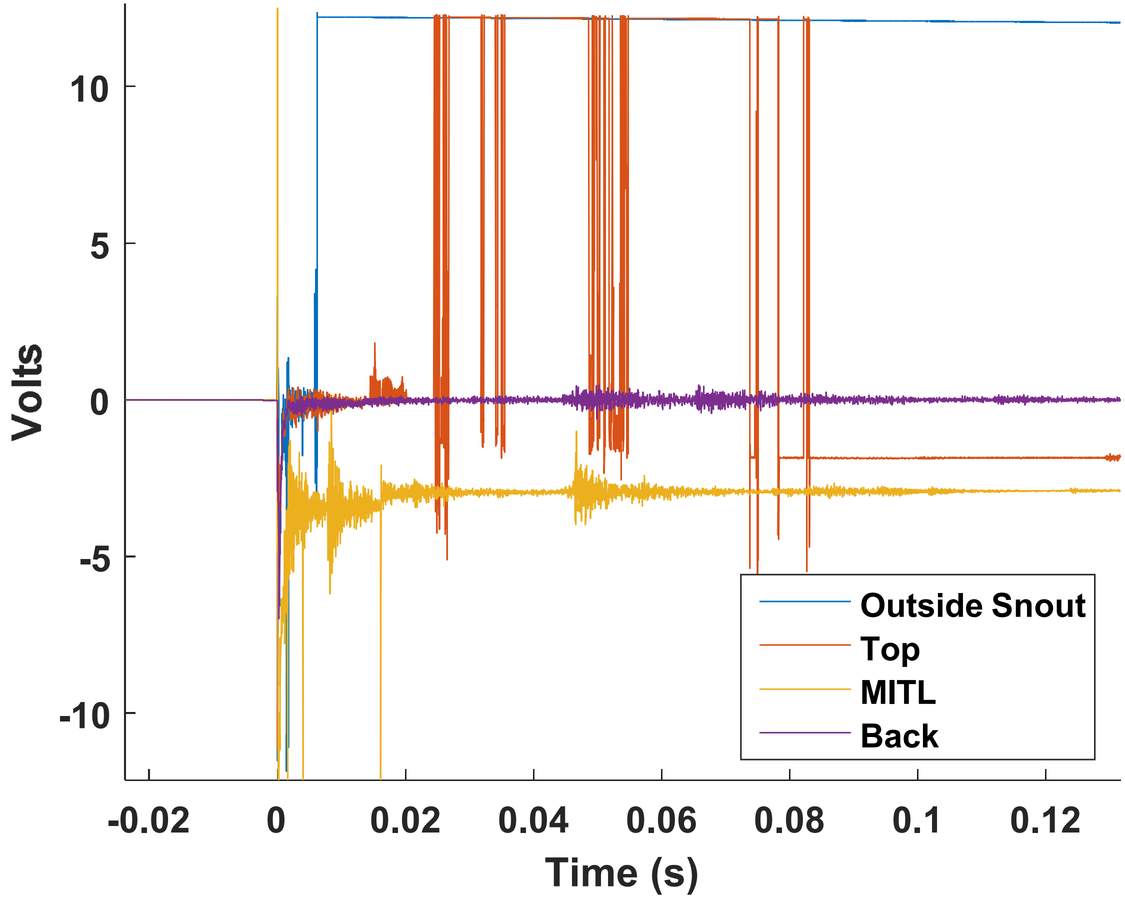


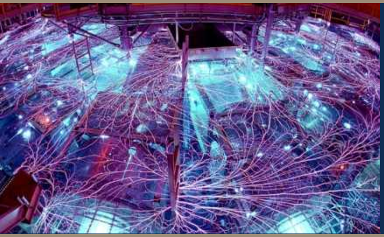
- Measures debris impacts at two radial distances
- Should yield quantitative temporal data
- Debris magnitude will be qualitative



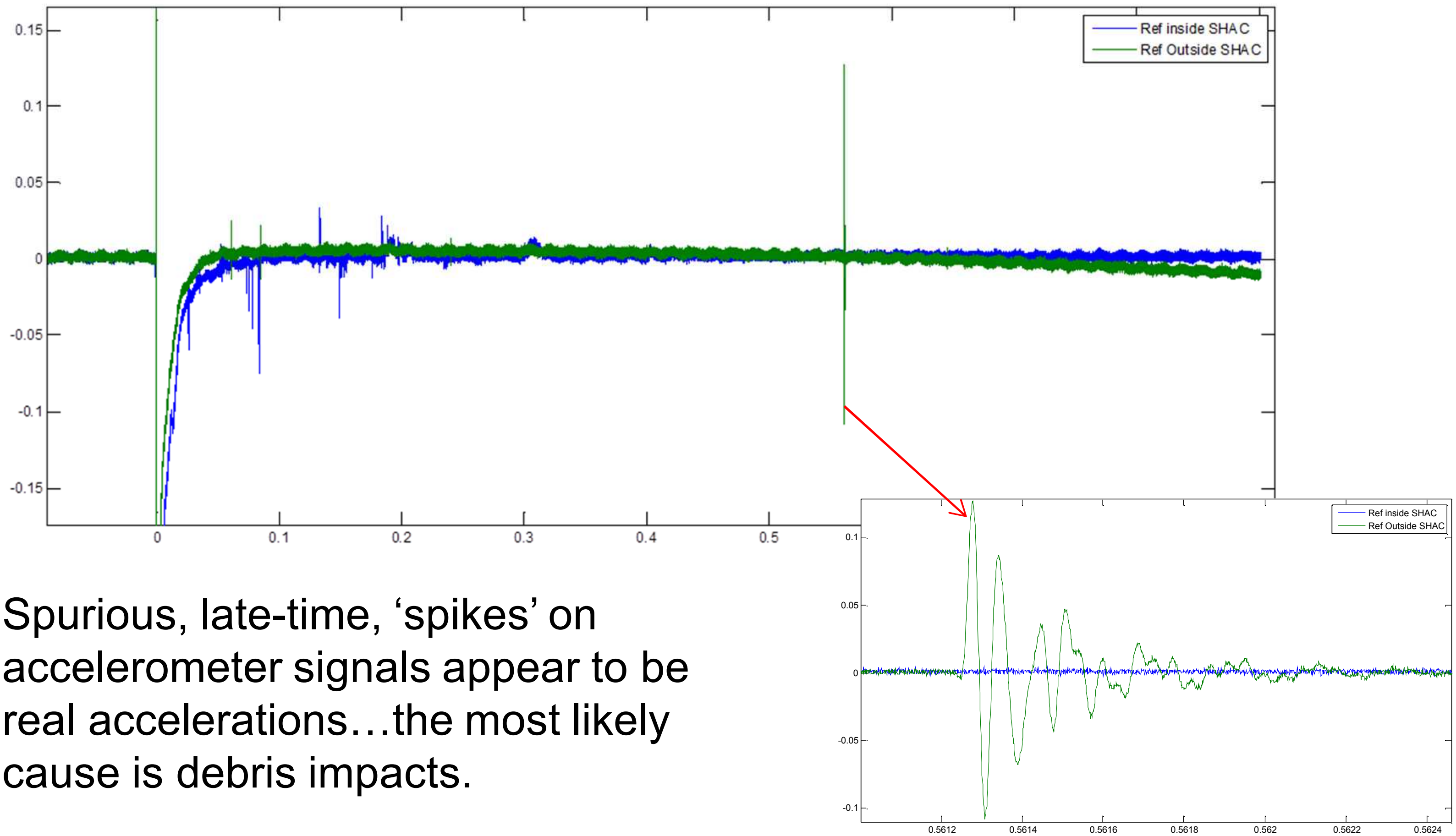
DTOF Basis

Suspected debris impacts observed on in-chamber accelerometers.





DTOF Basis



Spurious, late-time, ‘spikes’ on accelerometer signals appear to be real accelerations…the most likely cause is debris impacts.

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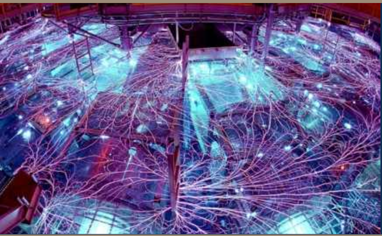
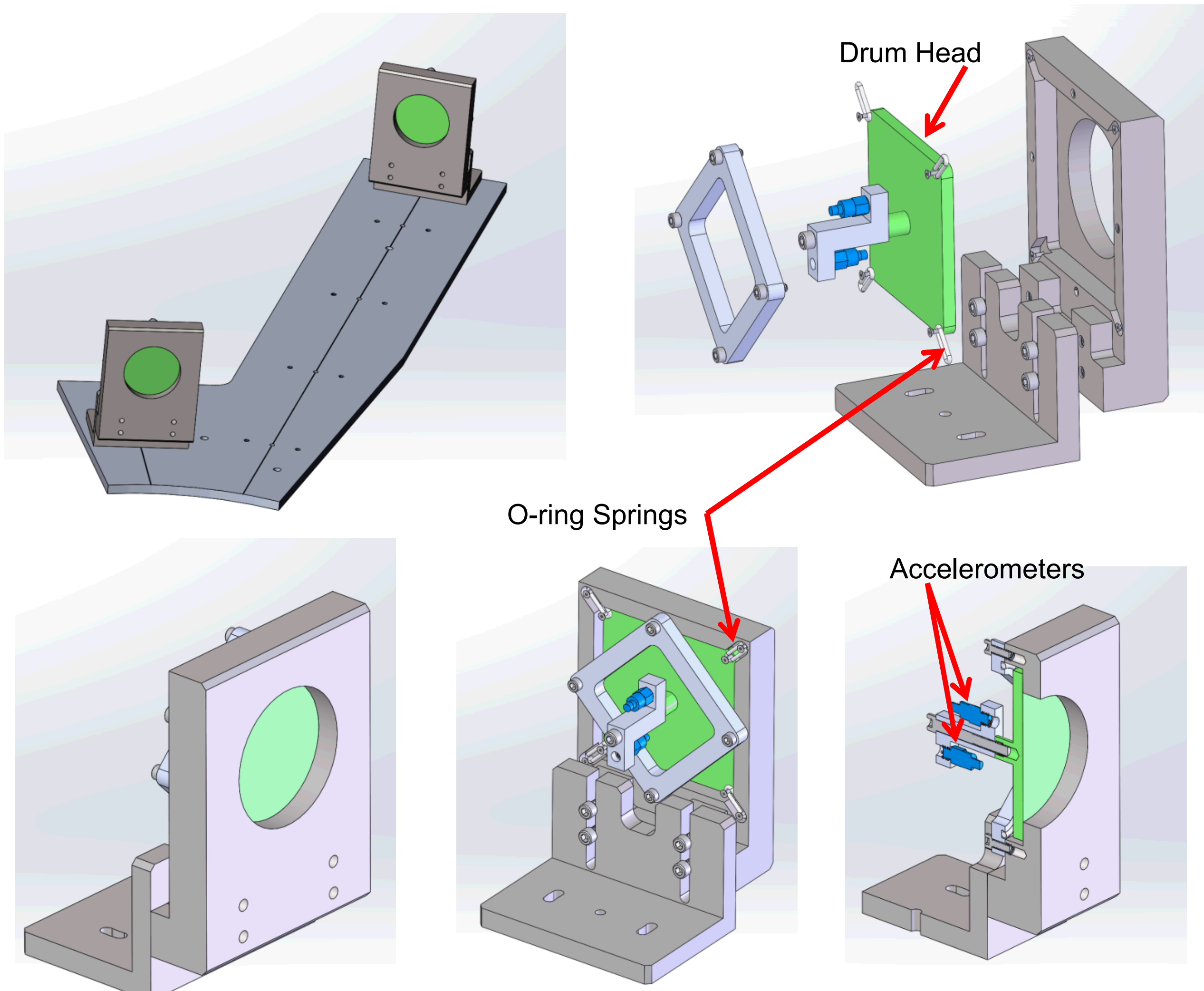


DTOF Measurements



- Debris impacts the drum head.
- Drum head isolated on O-ring springs.
- Accelerometers sense the impacts as accelerations.
- Opposing the accelerometers allows for easy EMI/EMP/X-ray noise removal.
- Two DTOFs, radially spaced, should provide good velocity measurements of uniform field debris such as spray and particulate.
- May be sensitive enough to measure the 'push' from the hot gas wave.
- Will certainly detect bullets, but won't provide velocity measurements.
- Easily adaptable for side-on and axial measurements.

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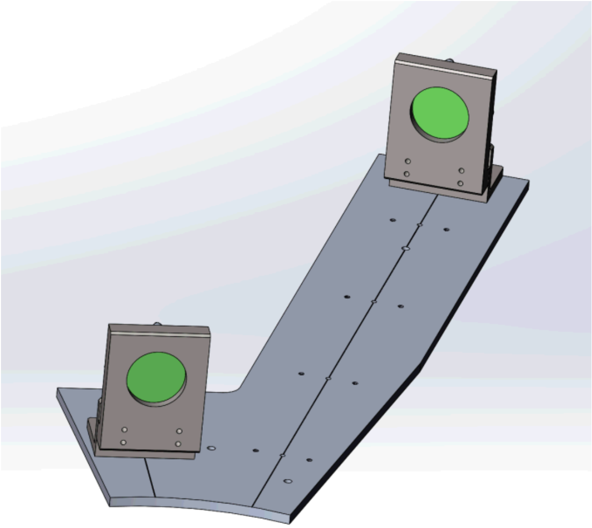
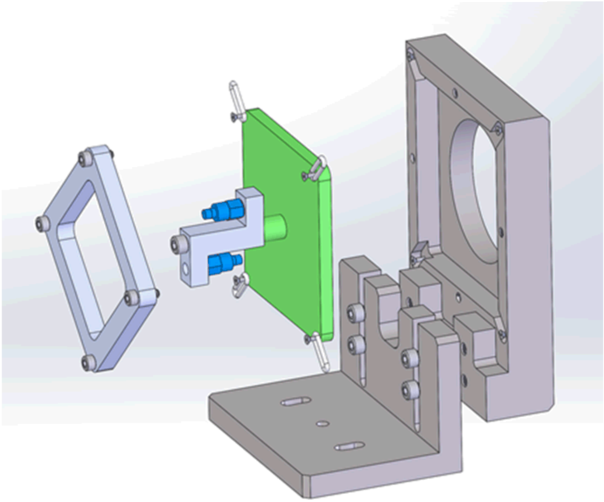
DTOF Limitations/Next Steps



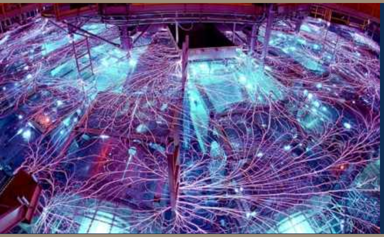


Limitations

- Relatively small sample area (7in²)
  - Limited sensitivity to low-mass debris such as gas or soot
  - Won't measure velocities of sparse stochastic debris, such as bullets.
- Won't differentiate molten from solid debris

Next Steps

- Develop an axial version.
- Optimize for low-mass debris measurements.
- Collect a statistically meaningful library of measurements



Questions?