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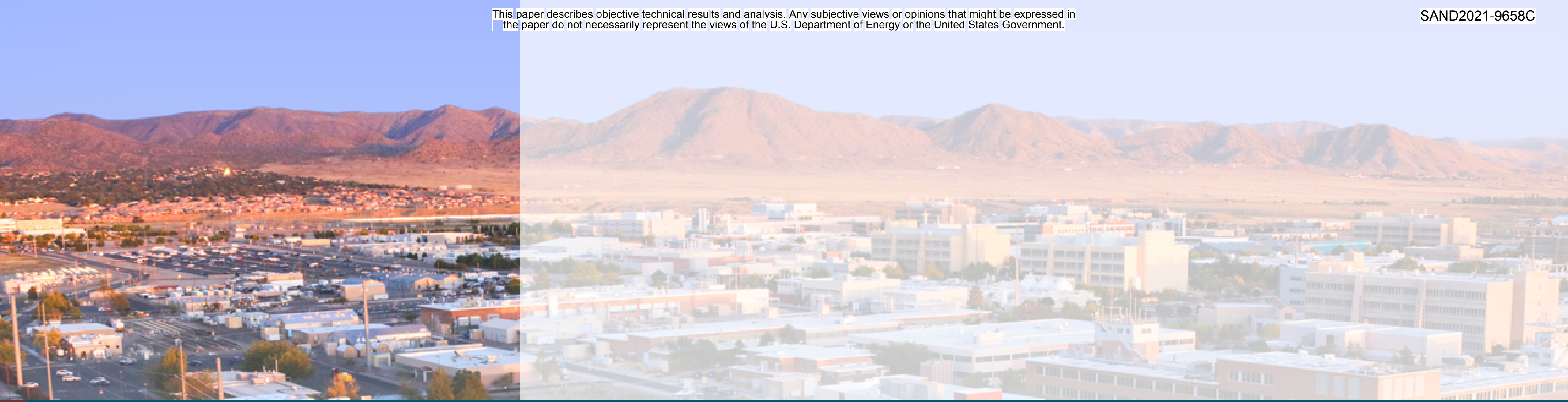

Diagnostic Efforts at Z

SAND2021 xxxxxxxxxx

Z Fundamental Science Workshop

8/9/2021

Michael Jones on behalf of the Z Diagnostic Team

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We have created summary slides for over 60 diagnostics that are currently utilized at Z

Exceptional service in the national interest

Sandia National Laboratories

SUMMARY SLIDES FOR Z DIAGNOSTICS

Contents

- Organizational Structure of Diagnostic
- List of Z Diagnostics by Area
- Summary Slides for each Diagnostic Instrument
- Summary Slides for Enabling Capabilities

SAND2019-7354 O

U.S. DEPARTMENT OF ENERGY NNSA

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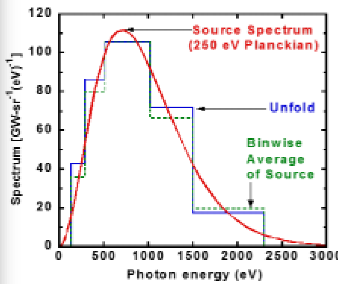
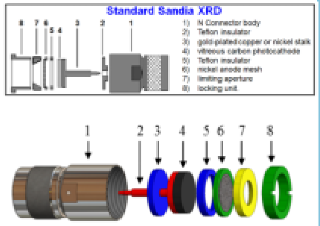
In the process of being updated

FILTERED X-RAY DIODES

Activity	Radiation & Fusion
Diagnostic Scientist	Tim Webb
Primary POC	Tim Webb
Engineering POC	Decker Spencer

Overview:
Five Channel Filtered XRD System that consists of diamond polished vitreous carbon disk and one of the following filters: Kimfol, Vanadium, Zinc, Beryllium Parylene, Beryllium Vanadium.





Specifications:

Spectral band(s)	Used for sub 2.5 keV radiation
Spatial resolution	NA
Temporal resolution	Recorded on 1GHz analog bandwidth digitizers.
Field of view	Can view entire length of emission that is visible through 12deg. Typically an aperture is used to define emission length.
Physical Location(s)	LOS50, 12°, xxx cm from source; LOS170, 0°, xxx cm from source; LOS210, 12°, xxx cm from source
Number of Channels	5 @ LOS50, 2 @ LOS170, 4 @ LOS210
Dynamic Range	

References:

X-ray power and yield measurements at the refurbished Z machine. M. Jones, RSI, 85, 083501
Filtered x-ray diode diagnostics fielded on the Z accelerator for source power Measurements, G. A. Chandler, RSI, 70, 561.

RADIATION & FUSION: X-RAY IMAGING

Diagnostic	Spectral band(s)	Spatial resolution	Temporal resolution	Field of view
High resolution continuum x-ray imager (HRCXI)	1st order = 3.1069 keV (Δ = 2 eV) 2nd order = 6.2137 keV (Δ = 4 eV) 3rd order = 9.3206 keV (Δ = 6 eV) 4th order = 12.4275 keV (Δ = 8 eV)	Mag ~5.8 15 µm x 15 µm	Time-integrated	3 mm wide and >10 mm tall
Time Gated High Energy Radiation pinhole camera (TiGHER PHC)	Minimum filter for debris mitigation 2 mm Kapton with additional filters possible Mag 3: 1 channel Mag 1: 3 channels	Mag 3: 31 µm (20 µm pinhole) Mag 1: 64 µm (20 µm pinhole)	Gen 2 MCP 0.15, 0.25, or 0.8 ns gates 8 frames	Mag 3: ~1 mm wide and ~12 mm tall Mag 1: ~3 mm wide and ~12 mm tall
Time Integrated Pinhole Camera (TIPC)	Minimum filter for debris mitigation 1.5 mm Kapton 5 channels with additional filters	Mag 0.375: 190 µm (50 µm pinhole)	Time-integrated	Several cm in both directions
Multilayer mirror pinhole cameras (MLM)	277 eV or 528 eV Can split frames between the two spectral bands	Mag 0.5: 320 µm (100 µm pinhole)	Two Gen 1 MCP 0.25 or 0.8 ns gates 6+8 = 14 frames	Several cm in both directions Views target at 13 degrees above horizontal
Filtered pinhole camera (MLMC)	Filter options available from 1 µm aluminized-Lexan (> 0.5 keV) to 30 mils Kapton (> 5 keV)	Mag 0.5: 180 µm (50 µm pinhole)	Gen 1 MCP 0.25 or 0.8 ns gates 8 frames	Several cm in both directions Views target at 13 degrees above horizontal
Z beamlet x-ray backlighting	6.151 keV or 7.242 keV or 1.865 keV Can field two different configs	Mag ~6: ~15 µm (limited by image plate)	1 ns long x-ray bursts recorded on image plate (2 separate LOS)	~10 mm wide and ~4 mm tall Frames are at +/- 3 degrees from horizontal
Axial pinhole imager (APE) and Side-on pinhole imager (SOPI)	Minimum filter for debris mitigation 3 mm polycarbonate 12 filtered channels per head SOPI = 2 heads, APE = 3 heads	Mag 10: 10-15 µm (10 µm pinhole)	Time-integrated	< 1 mm Many pinholes in array and need to avoid overlapping images
Final Optics Assembly pinhole camera (FOA PHC)	Soft x-ray, minimum filter 2 µm poly carbonate 3-4 channels with additional filters per head Multiple heads available	Mag 1: ~600 µm (300 µm pinhole)	Multi-frame ultrafast x-ray imager: 2-8 frames, 2 ns gate Image plate: time-integrated	~1 cm Views target at ~7.5 degrees from vertical
Mirrored Imager Plasma emission acquisition systems (MIPs)	Multilayer mirrors at 277 eV or 528 eV Can split frames between the two spectral bands	Mag 1: ~400 µm (200 µm pinhole)	2 Gen 1 MCP 0.15, 0.25, or 0.8 ns gates 8+8 = 16 frames	~8 mm Views target at ~9 degrees from vertical

For a copy of this slide deck please contact Marcus Knudson or Michael Jones: *Summary Slides for Z Diagnostics: SAND2019-7354 O*

Z Diagnostic Workshop

- A multi day workshop is tentatively planned for the fall of 2022

- Would like participation from many institutions: SNL, LLNL, LANL, LLE, NNSS, and our university partners

- The primary focus last time was around our stagnation diagnostics
  - Program leads shared the direction and future measurement needs for their programs
  - Breakout sessions were held focused on: 1) an initiative to time-resolve target diagnostics at Z and 2) developing baseline requirements for DT based neutron diagnostics.

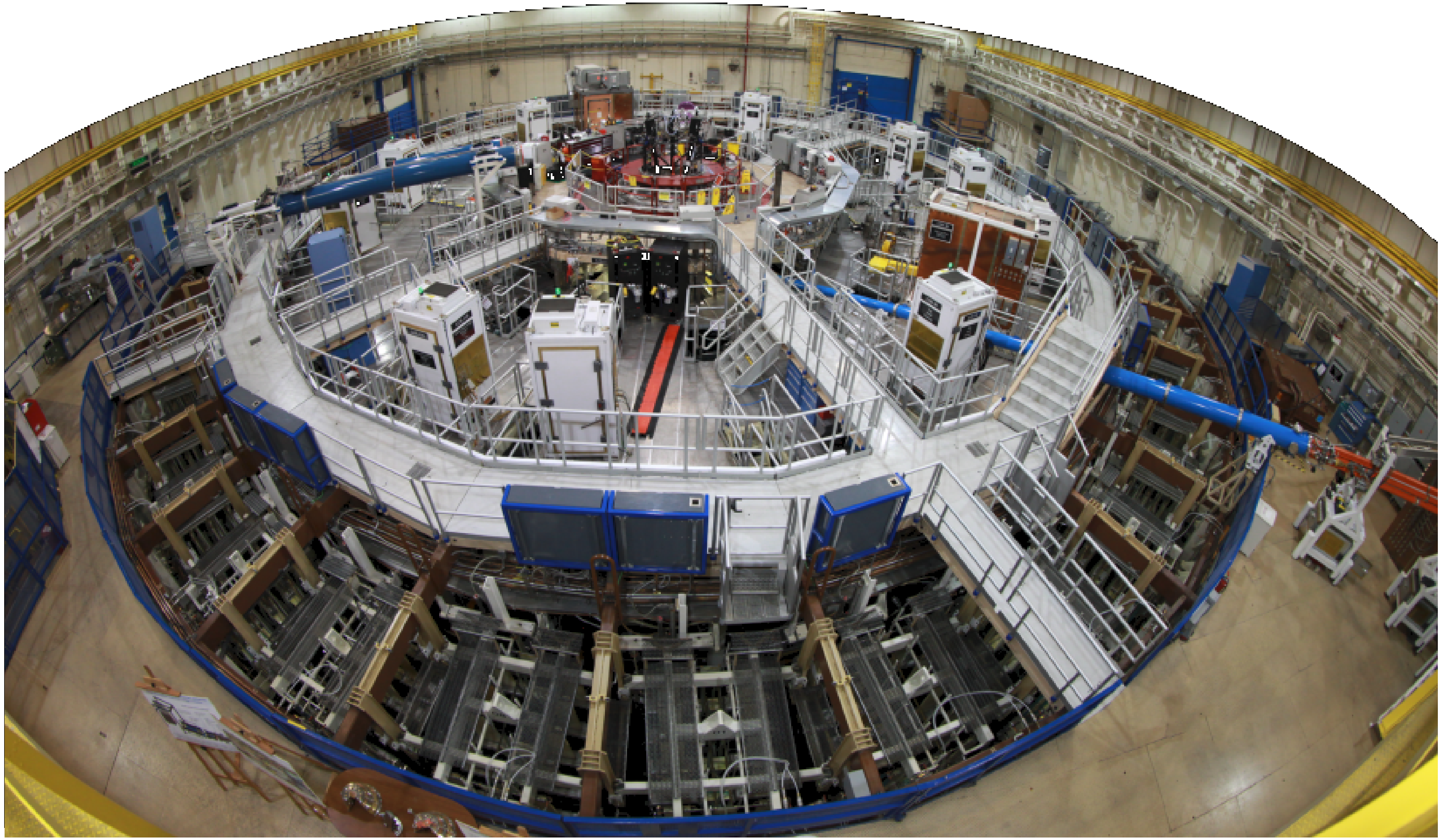
- The focus of the next workshop is still under discussion.
  - Potential Topics – high resolution X-ray imaging & spectroscopy, future uses of the hCMOS / UXI in Z measurements, alternative methods to measure nuclear burn history & T_{ion}, expanding university collaborations on novel diagnostic development.

  - If you have ideas or suggestions please send them to me

National Diagnostics Working Group Update

- The National Diagnostics Working Group (NDWG) is an active and productive community focused on transformational diagnostics for Z, NIF, and LLE.
- Workshops have attendees from each site and are used to share ideas, identify solutions, and develop action plans.
- In 2019 the 14th National Diagnostics Working Group Meeting Occurred at LLNL. There were breakout sessions focused on:
  - >15 keV GHz photon detection
  - High Resolution Imaging
  - Passive detectors
  - Burn Widths
  - Hot spot velocity
  - Magnetic field characterization
- The 2021 meeting is being planned for mid December at Los Alamos.
- Please let me know if you want further details

Several engineering challenges need to be addressed in the development and operation of diagnostic systems on Z



- **Shock**
- **EMP/EMI**
- **High Energy Gammas**
- **Accessibility**
- **Installation & Alignment**
- **Open Oil tanks**

Engineering Challenges: Mechanical Shock

Challenge: Mechanical shocks >20G's are measured within the Z highbay. Primary source is from the water switches.

Understand the challenge: Mechanical shock measurements yield the mechanical response of Z during a shot. These data are generally recorded as acceleration time histories, which are the basis for analysis such as, Shock Response Spectra (SRS), Pseudo-Velocity Response Spectra (PVRS), and frequency-based methods

Best Practice: Shaker table, design to a minimum 8G of acceleration, mechanical isolation.

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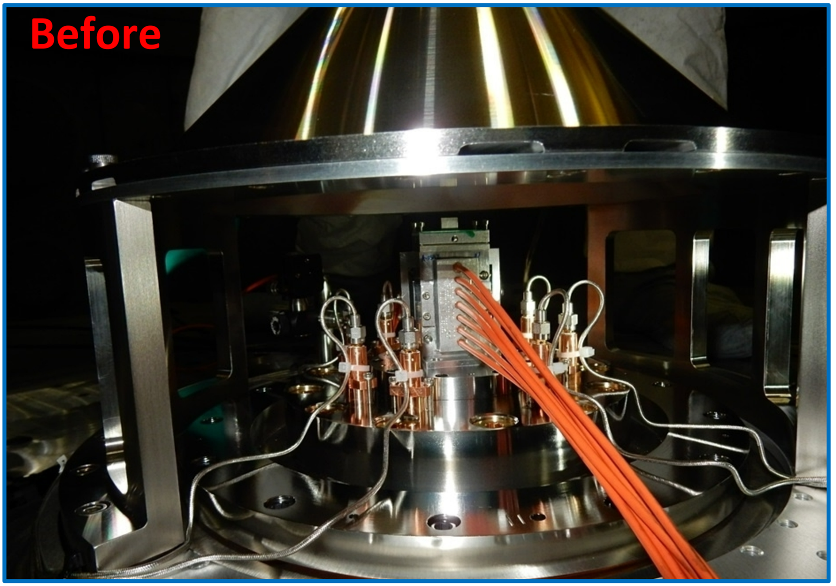
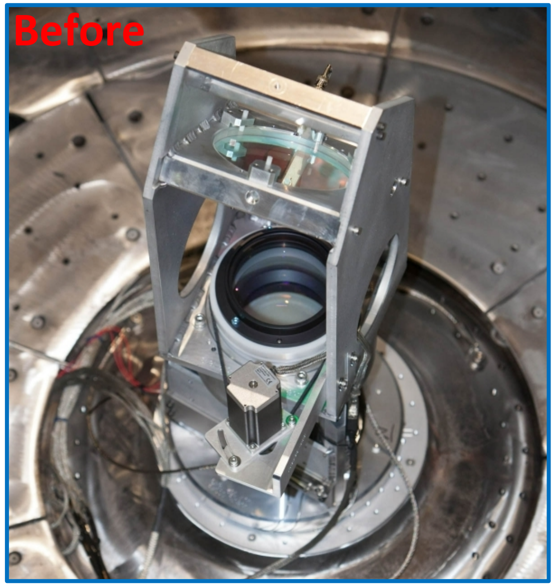
Best Practice: Shaker table, design to a minimum 8G of acceleration, mechanical isolation.

Engineering Challenges: Debris

<u>Challenge</u>: On every Z shot, the equivalent of several sticks of dynamite explodes at the center of the vacuum chamber. This in turn produces debris able to penetrate ~2cm of stainless steel and everything within a 2’ radius is destroyed. This debris has damaged detectors, filters, crystals, vacuum integrity and has to be carefully evaluated.

<u>Why</u>: There is 5MJ of energy that becomes “trapped” in the vacuum section after the insulator stack flashes. The energy is dissipated into kg’s of mass at small radius over several microsecnods.





<u>Understand the challenge</u>: Have developed diagnostics to measure the “debris wind” and impact magnitude of the species, which is proportional to momentum.

<u>Best Practice</u>: Sacrificial filters and baffles, crystal optics to move detector out of direct line of sight, implementation of limiting apertures.

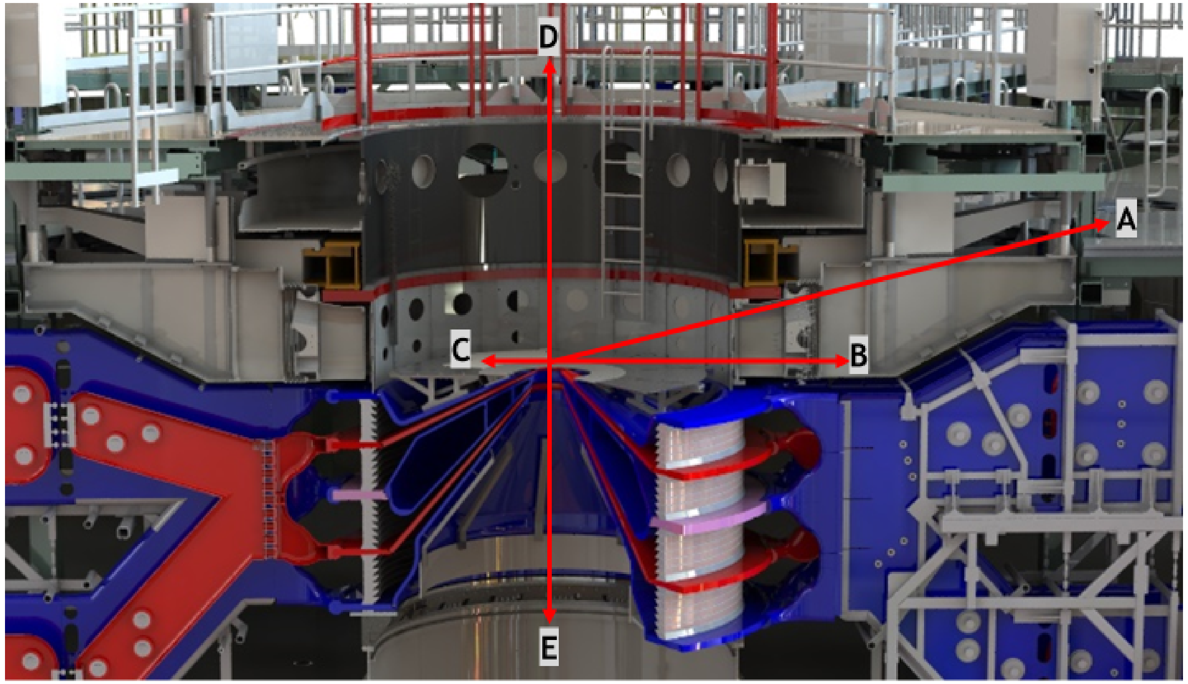
Engineering Challenges: Installation & Alignment

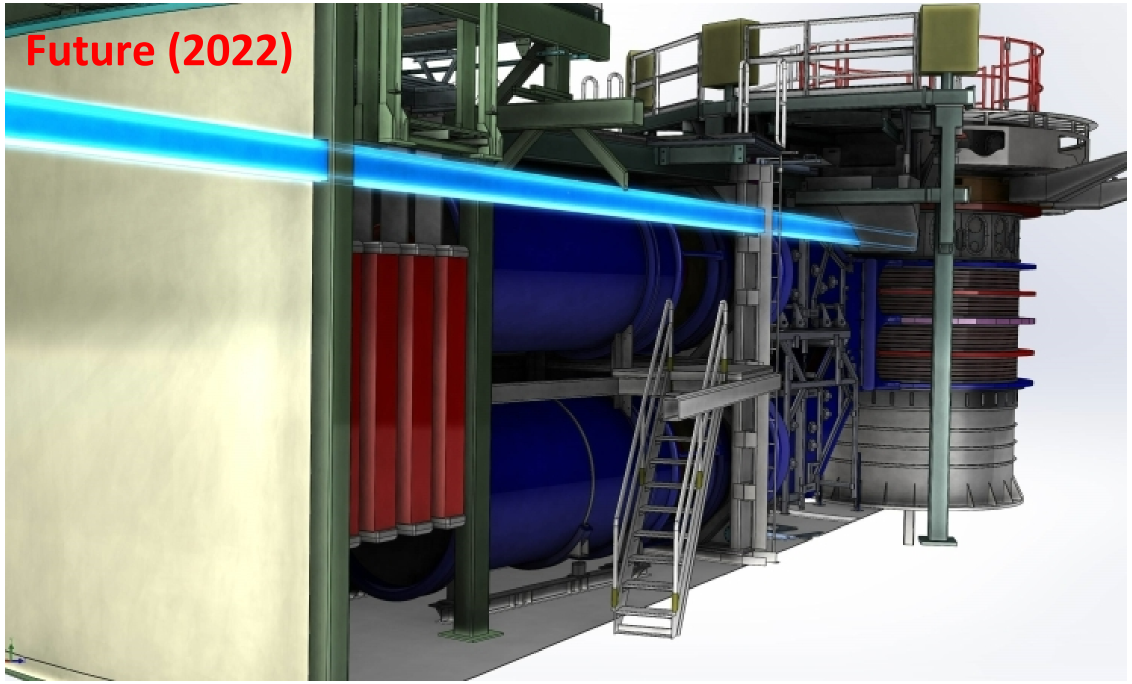
Challenge: The central 10' diameter (40,000lbs) of Z has to be removed between every shot.

- All in-chamber diagnostics need to be removed using the 20-ton overhead crane.
- These diagnostics must be removed, refurbished, re-installed, and re-aligned on every experiment.
- Alignments are accomplished by a combination of Brunson / K&E telescopes, lasers, rangefinders, and retroreflectors depending on the accuracy needed.
  - Alignment accuracy ranges from 1cm down to 50um
- Alignment times vary from 5 minutes to 1 hour.

Engineering Challenges: Accessibility

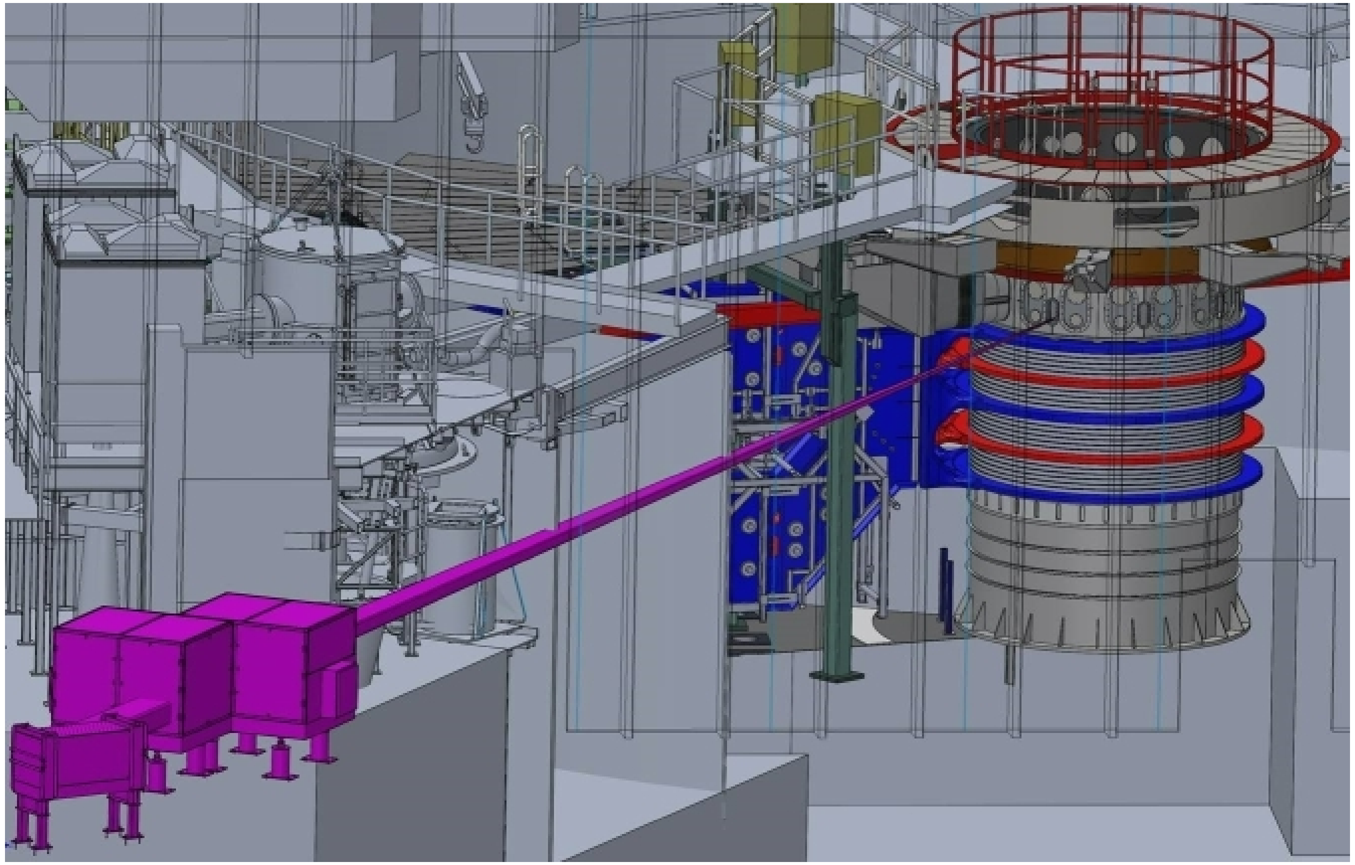
Challenge: Diagnostic placement is limited by the pulsed power geometry. The furthest location near the horizontal [B&C] (equatorial) is only 3m. At 12°[A], there is no visual (x-ray) access to some target designs.





Future: To enable a new class of measurements a new equatorial line of sight capability is being engineered that will allow detectors to be placed 4m to over 20m from the target.

Implementing a Horizontal Line of Sight



➢Up to nine locations are available for future diagnostic implementation. Distances can vary from 3m to >20m

➢Precision nToF will use LOS20, LOS140, and LOS260.

➢High resolution 2D neutron imaging is being planned.

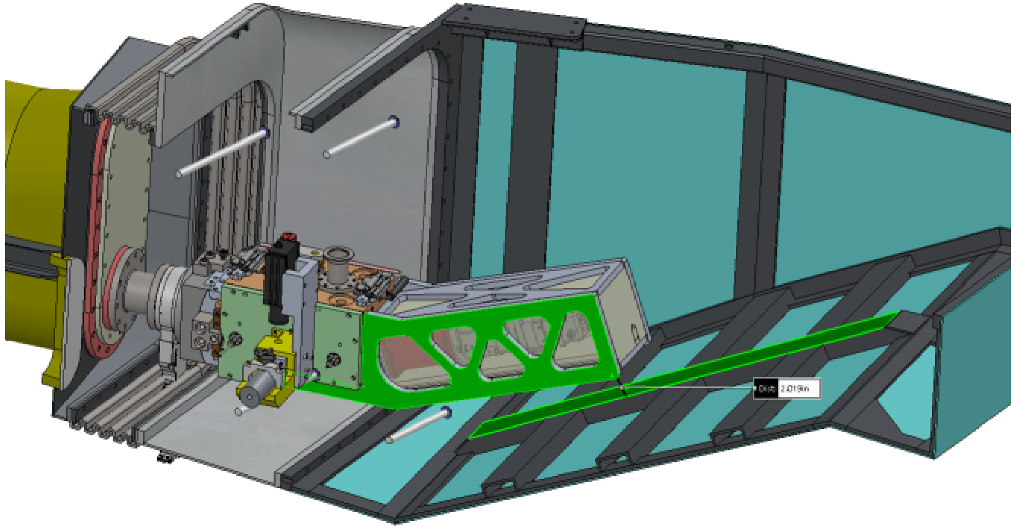
A line of sight that extends through the water and oil sections will also place the detectors in a cleaner neutron environment. (less scattering & more collimation)

A multitude of diagnostic systems are deployed at Z to measure key parameters

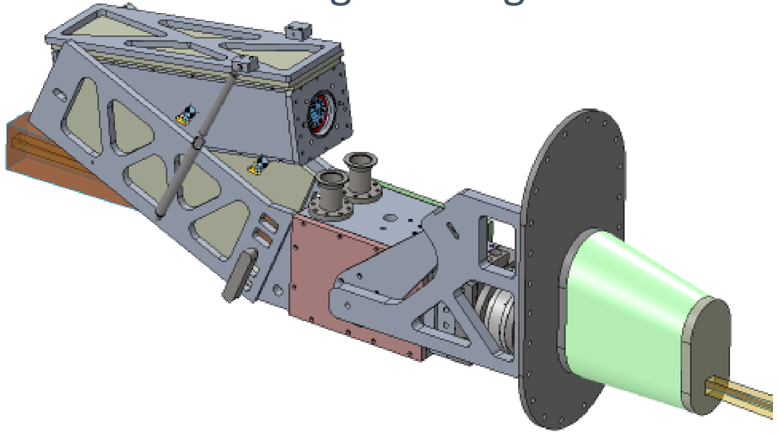
X-Ray	Time integrated & resolved x-ray fluence, yields, imaging, and spectroscopy from 200eV to 500keV
Nuclear	Area is focused on measuring key stagnation metrics. Neutron yields, T_{ion}, Burn History.
Velocimetry & Materials	Area is focused on velocimetry-based diagnostics: VISAR, PDV. Primarily to measure / infer equation of state in materials.
Environmental	Area is focused on the understanding of Shock, Debris, EMI, Vibration, Tritium Contamination, ..
Power Flow & Electrical	Area focused on the measurements of current delivery to small radius and the overall health of the pulsed power delivery.

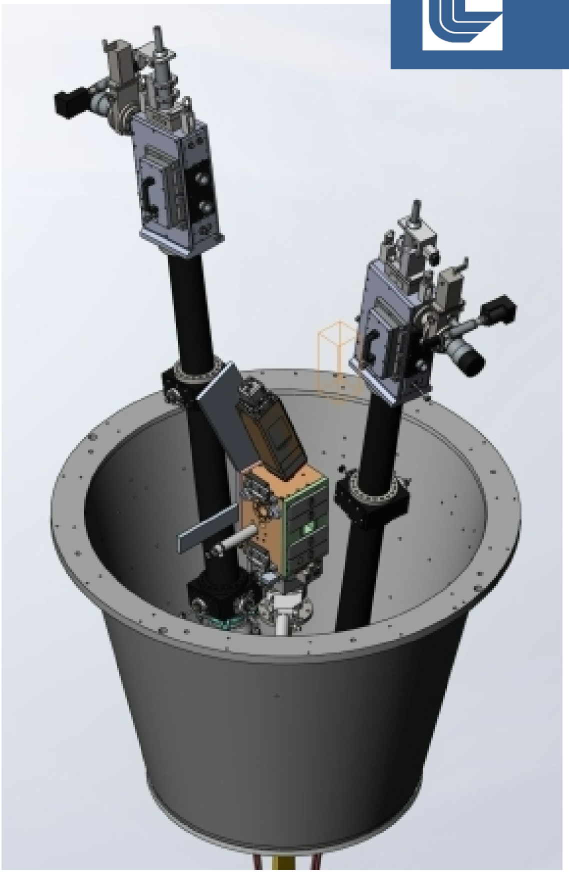
In collaboration with LLNL we are developing a radial and axial streak camera capability for Z

- The SCORPIONZ (**S**treak **C**amera **O**bservatory with **R**adial and **P**olar **I**mplementation **ON Z**) shall record the time-resolved X-ray emission from Z experiments. Similar to SPIDER on NIF.
- Key Expectations for SCORPIONZ:
  - Record X-ray emissions in the energy range of 1-15keV in a radial location and a polar location on the Z machine, and additionally be able to record emissions at 0.2-2keV in the polar location
  - Have a spatial record and temporal record of 200 elements each
  - At temporal windows of 2, 5, 10, 20, 50 & 100ns
  - At a temporal resolution of at least 25ps



Phase 1a – at 0deg in a diagnostic boat





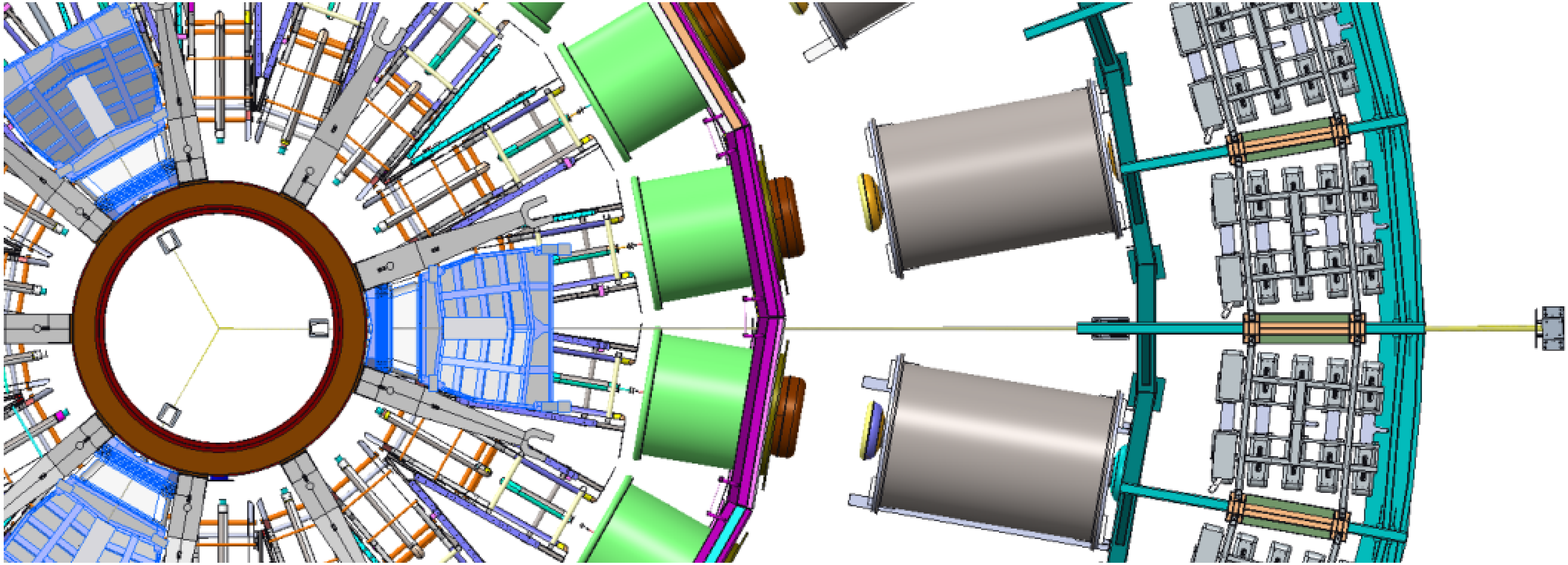
Phase 1b – axially

Phase 2 – Streaked 1-D imaging
Phase 3 – Streaked Spectroscopy

LLNL: Shannon Frick, SNL: Greg Dunham et al.

In collaboration with LLNL we are developing a precision nToF system that will utilize three equatorial lines of sight

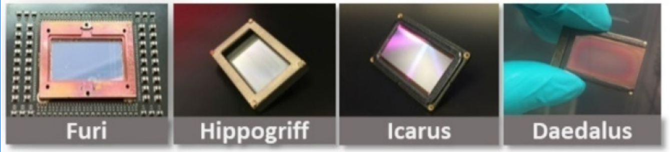
- Will improve fidelity of burn weighted ion temperatures
- Enable quantification of Residual Kinetic Energy
- Larger dynamic range



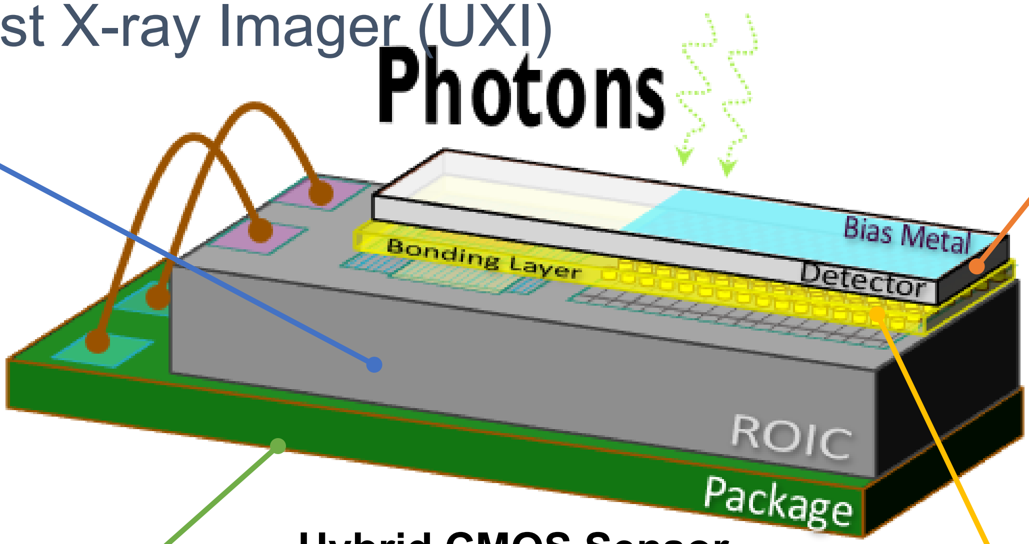
LLNL: Jorge Carrera, Alastair Moore, SNL: Gordon Chandler et al.

Over the last decade significant advances have been made in the development of a hybrid CMOS camera systems for HED Applications. At Z we package the hCMOS into the Ultrafast X-ray Imager (UXI)

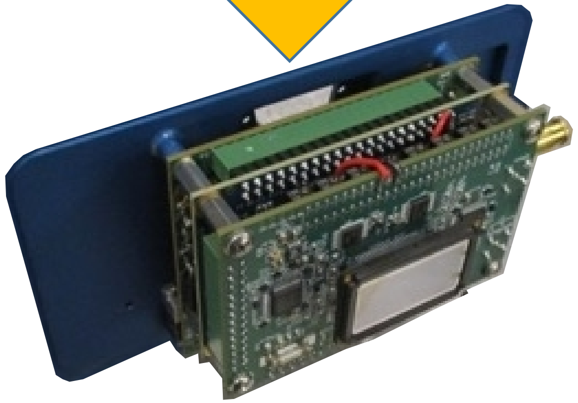
Readout Integrated Circuit



- Fabricated in SNL's 6" 350-nm CMOS
- 1-2 ns minimum shutter time, 2-8 frames
- 1024x512 array of 25 μm x 25 μm pixels
- Adjustable shutter timing

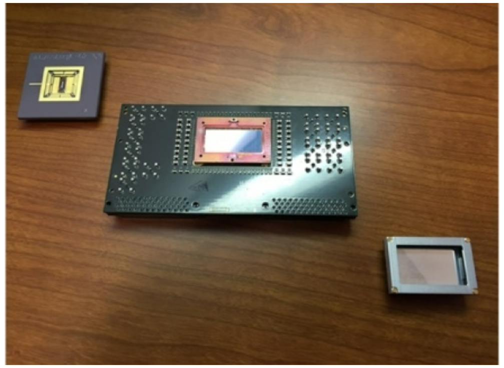


Hybrid CMOS Sensor

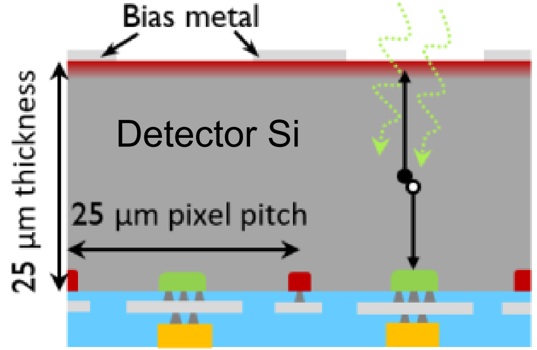


UXI Camera System Development for Application-Specific Needs

Package

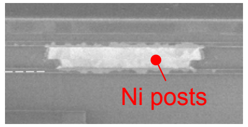


Detector Array



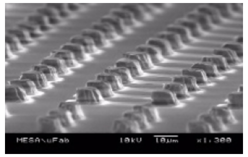
Integration

Direct Bond Interconnect (DBI)



- External supplier
- Wafer-to-wafer bond

Indium bump



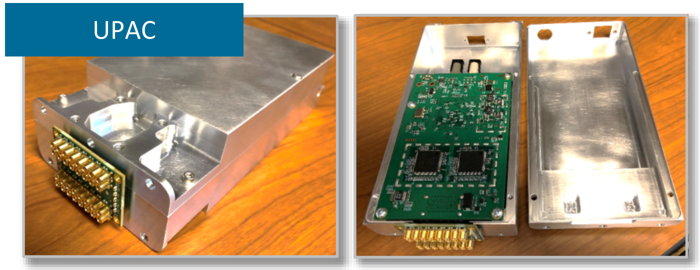
- Processing at Sandia
- Die-level processing

*Porter et al., in The 20th Topical Conference on High Temperature Plasma Diagnostics, (2014). L. Claus et al., Proc. SPIE **9591**, 95910P (2015), T. Colombo et al., HTPD 2018. Q. Looker et al.*

Update on hCMOS, ASIC, & Detector Development

hCMOS Sensor Realization and Delivery

Specification	Icarus V2 (Currently deployed)	Daedalus V2 (Available FY22)	Tantalus (In Fabrication)
Array size	1024x512	1024x512	1024x512
Number of frames	4	3 (6+ with row interlacing)	4
Full well	0.5 M e^-	1.5 M e^-	0.5 M e^-
Shutter Speed	1.5 ns	~1 ns	~500ps
Abutment	No	1-side	No

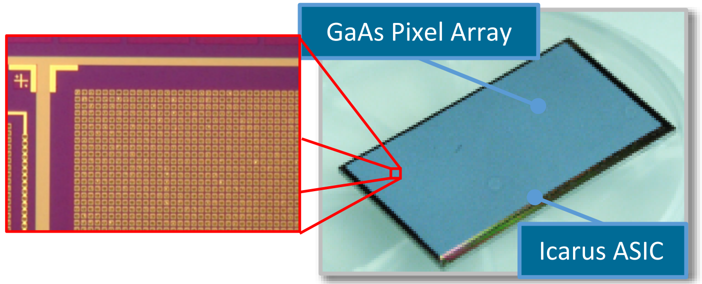


ASIC Development

The UPAC system has been developed in collaboration with Nalu Scientific and University of Chicago to create a compact, continuous-time small pixel array. A 32-channel digitizer prototype has been developed and serves as a complementary technology to hCMOS, with more temporal coverage at the cost of spatial resolution.

Detector Development

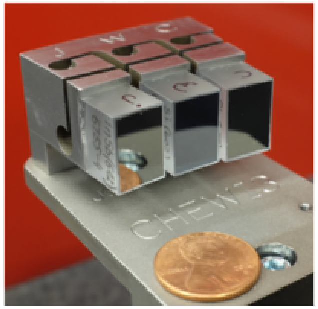
Faster silicon detectors are being developed to keep up with improved ASIC performance. Test structures that enable higher breakdown voltages and new electrode designs have been fabricated and will be tested Q4 FY21. Pixelated GaAs photo-diodes have been created and are being bonded to Icarus ROICs. These detectors will improve temporal performance and extend the sensors use beyond 10 keV and will be available for use in Q4.

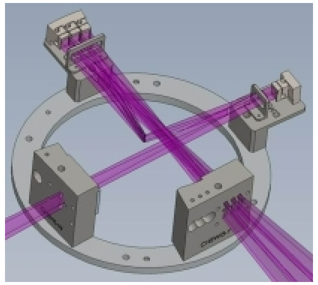


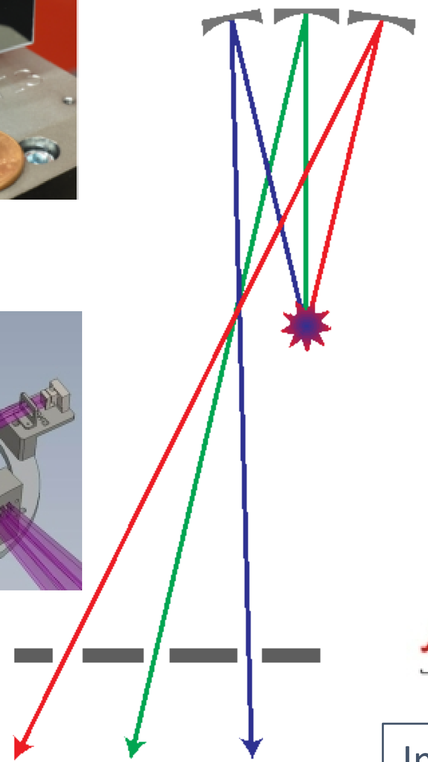
*Porter et al., in The 20th Topical Conference on High Temperature Plasma Diagnostics, (2014). L. Claus et al., Proc. SPIE **9591**, 95910P (2015), T. Colombo et al., HTPD 2018. Q. Looker et al.*

A new three-crystal imager is being developed to measure temperature gradients in MagLIF targets with a 20 μm spatial resolution

Three-crystal imager (a.k.a., CHEWI3)







3-channel crystal imager generates spectral images in 3 narrow bands.

Co K-shell spectra from z3078

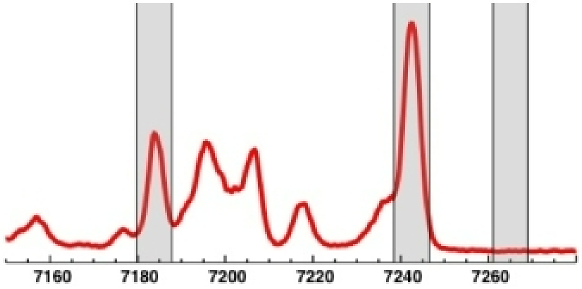
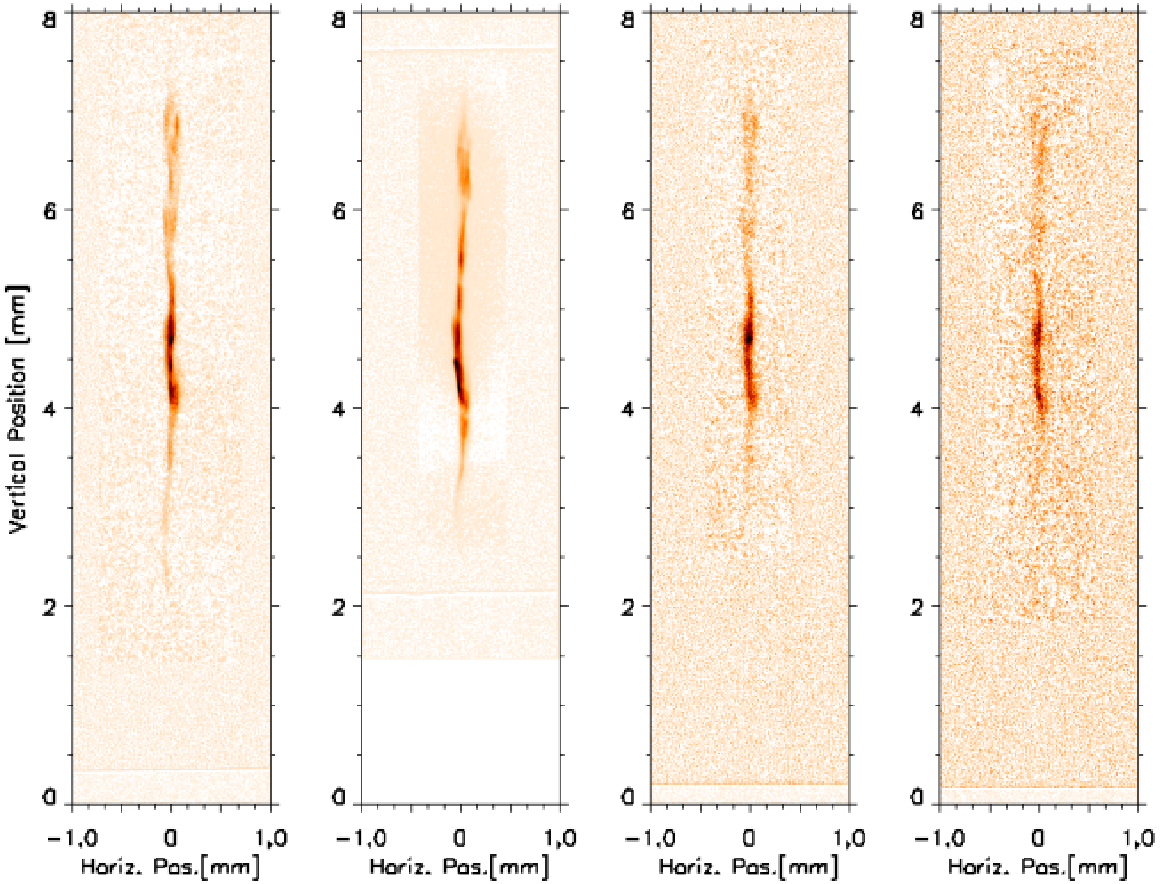


Image ratios can reveal variations in T_e or n_e depending on spectral lines.

Recent Data from MagLIF Mix19 (z3479)



E. Harding et al.

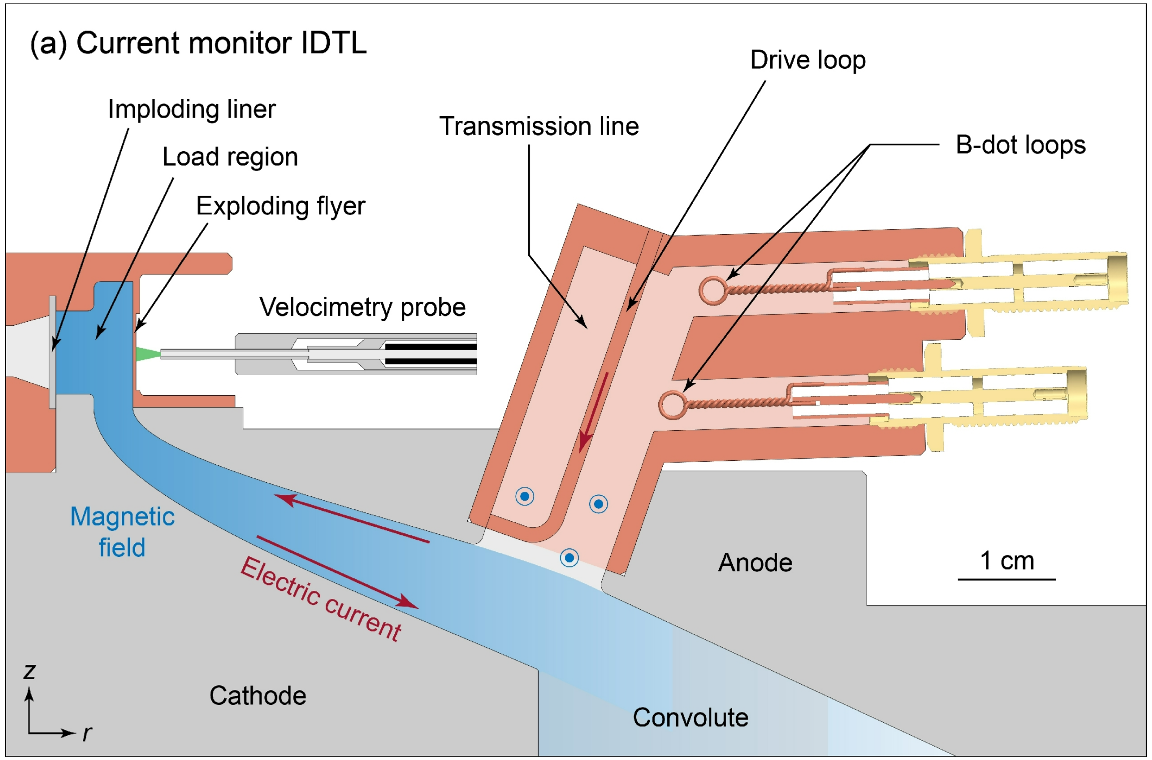
Inductively Driven Transmission Lines (IDTLs)

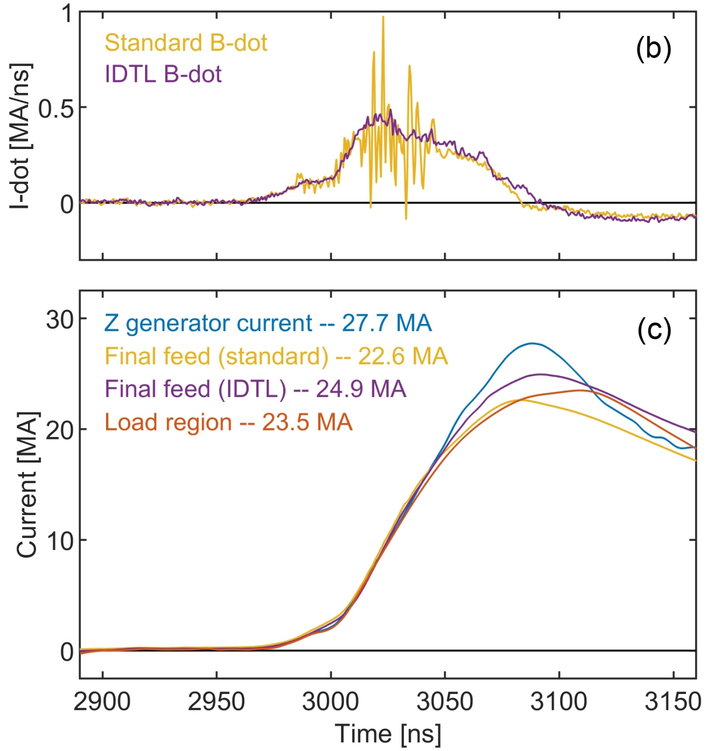
Passively redirect a small amount of Z's magnetic energy along a secondary path to ground.

Generate 10–150 kA of secondary current that is in-phase with Z's primary current pulse.

Diagnostic applications:

- X-pinch backlighter for radiography or diffraction.
- Improved B-dot-based current monitors.





IDTLs better protect the B-dot loops and generate cleaner signals and causal current waveforms.

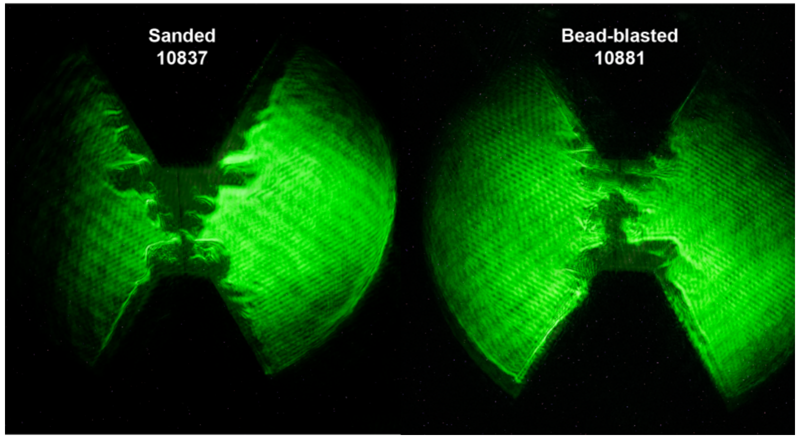
Myers et al. Rev. Sci. Instrum. **92**, 033501 (2021)

Inductively Driven X-Pinches (IDXPs)

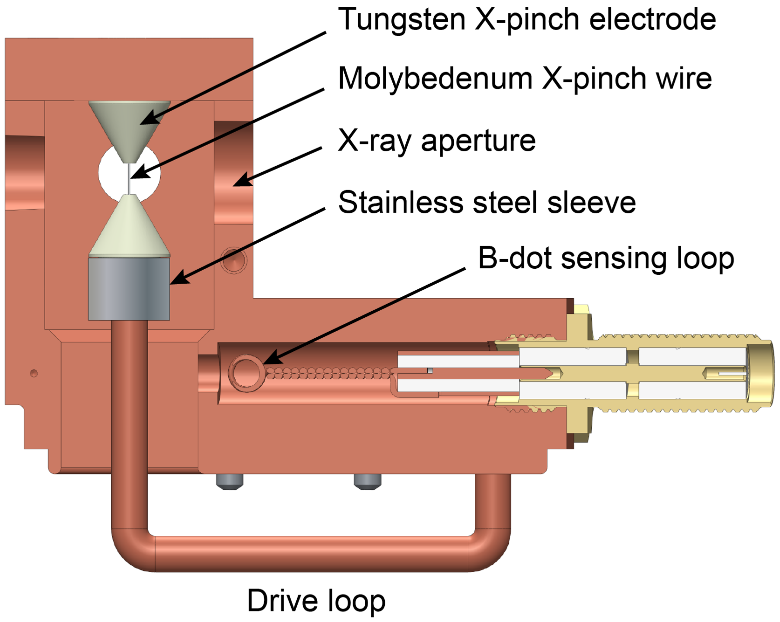
Increase the size of the IDTL drive loop to generate higher secondary currents (~150 kA).

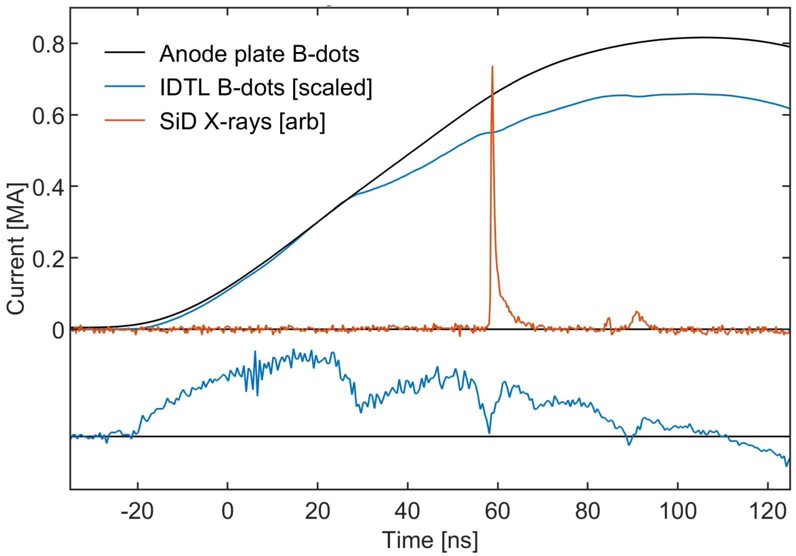
Hybrid X-pinch formed by two conical tungsten electrodes spanned by a single Mo wire.

Compact IDXP X-pinch sources demonstrated both on Mykonos (~1 MA) and on Z (>20 MA).

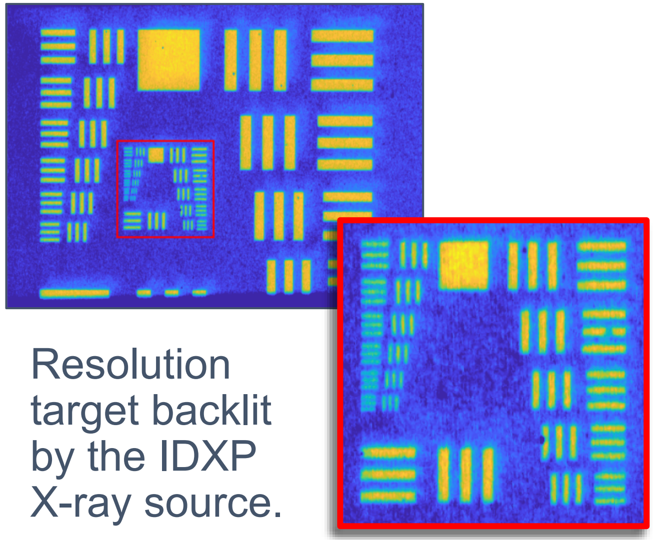


Visible shadowgraphy used to understand the effect of electrode conditioning on IDXP source performance.





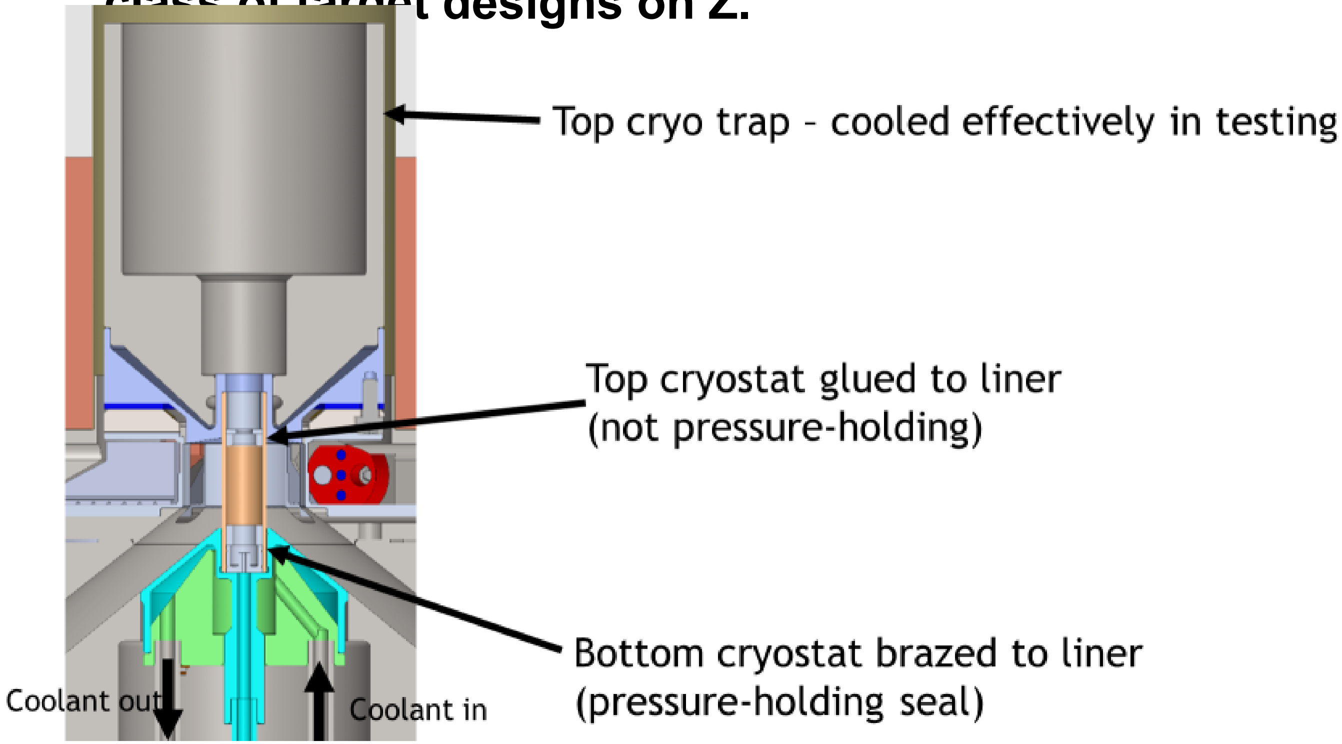
X-ray pulse with inductive dip.

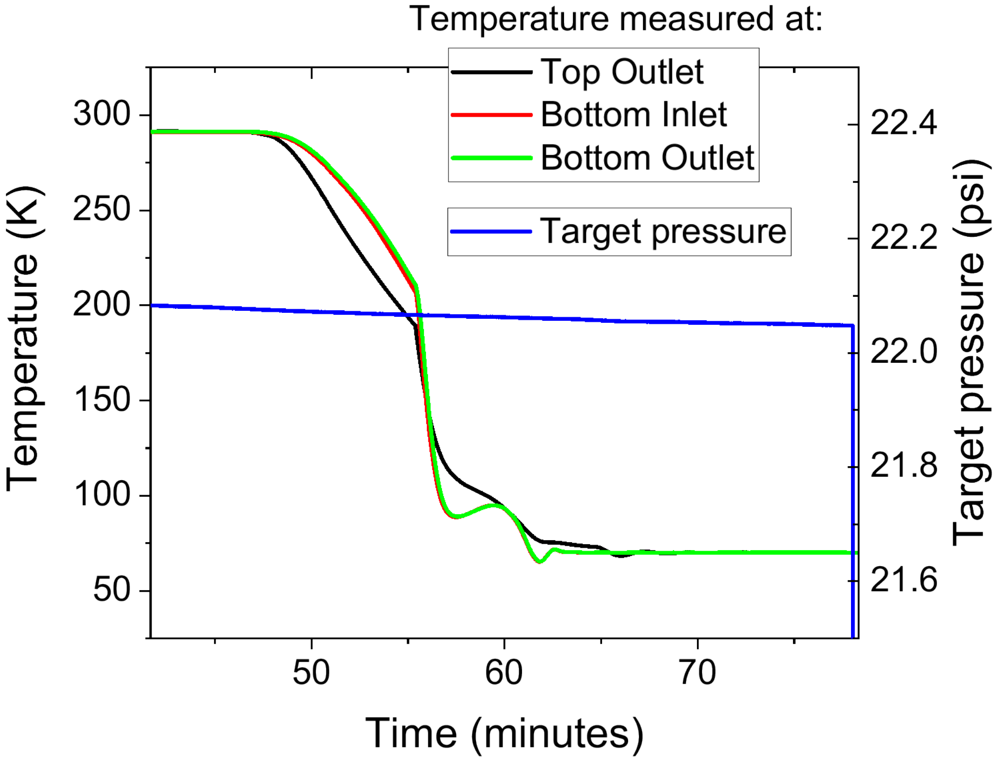


Resolution target backlit by the IDXP X-ray source.

Commissioned a new symmetric cryogenic target cooling capability

- **Several new capabilities were commissioned in support of a symmetric cooling capability on Z.**
  - **Implemented infrastructure to allow cooling for the first time from the bottom of Z's target.**
  - **To improve the reliability of seals in the beryllium liner a new brazing technique was developed and implemented successfully.**
  - **A new bypass cooling system was implemented to reduce the time that the target / LEH (Laser Entrance Hole) window could accumulate ice.**
- **This capability greatly improves the understanding of the initial fuel conditions and will enable a new class of target designs on Z.**





Final pressure: 22.05 psi. Final temperature: 70.05+/-0.07 K. Final density: 1.045+/-0.001 mg/cc

Allen Crabtree

Tritium experiments are underway at Z which are opening up new diagnostic and experimental platforms

Tritium Multi-Year Capabilities

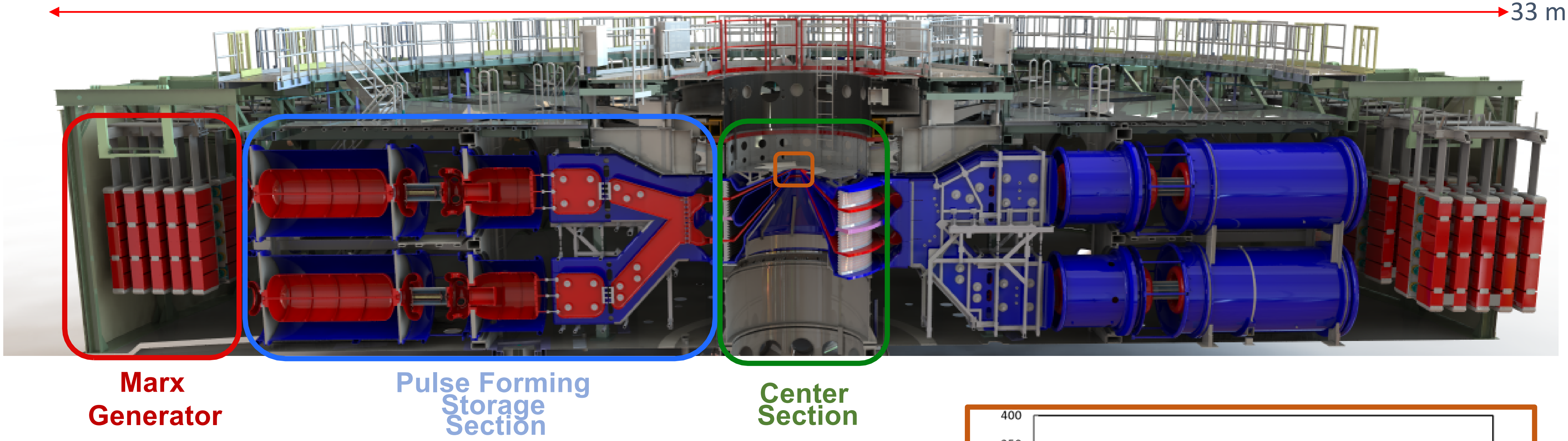
	1-3 Year Outlook	3-5 Year Outlook	5-10 Year
Target Inventory (Chamber)	100 mCi	200 mCi	500 mCi
Target Inventory (UCV)	0.5 - 2 Ci	2 - 5 Ci	10 Ci
Facility Yield	< 1E15	<1E16	<1E17
Experiments / year	1-3	2-5	10-12

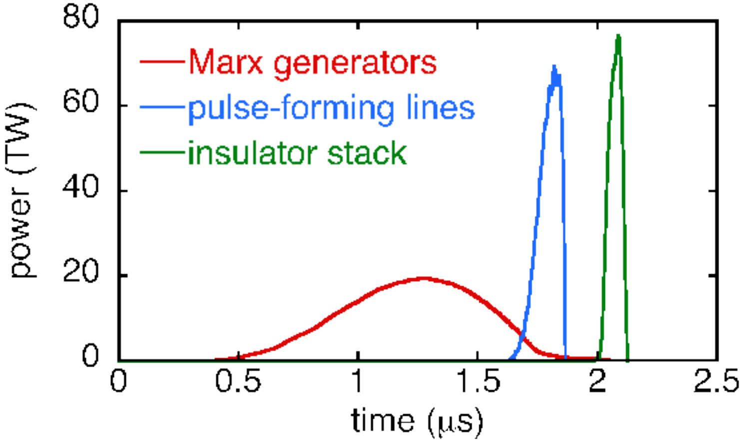
➢Currently authorized up to 300 mCi of Tritium in the target

M. Jones → Kevin Yates

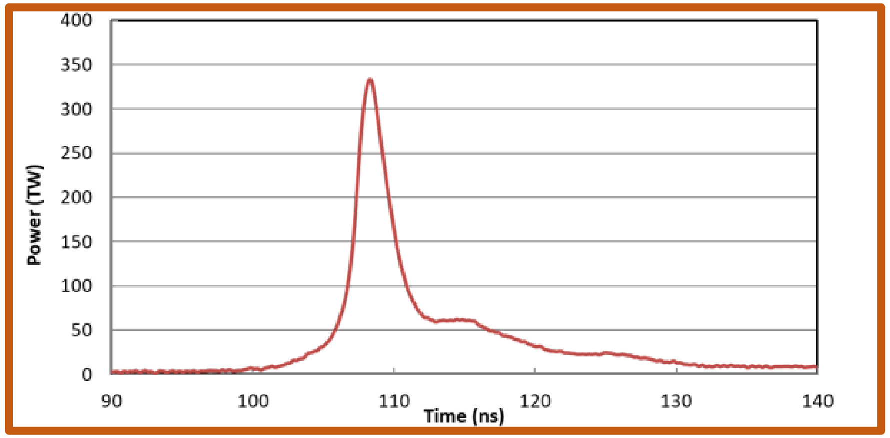
Thanks

Z Compresses Energy in Space and Time to Create Extreme States of Matter





Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.



Capable of outputting >300TW and 2MJ of x-ray output*