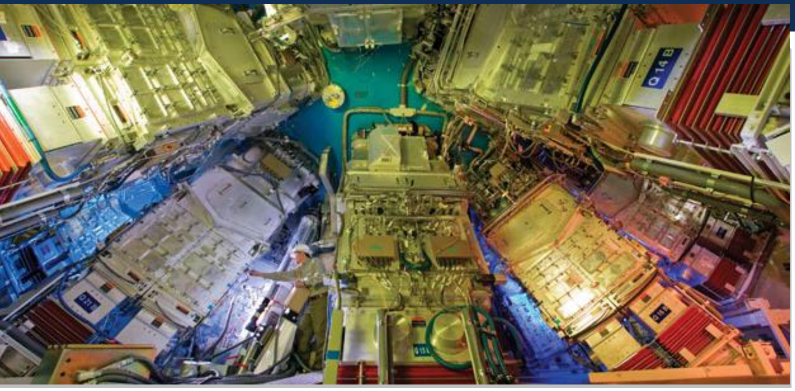
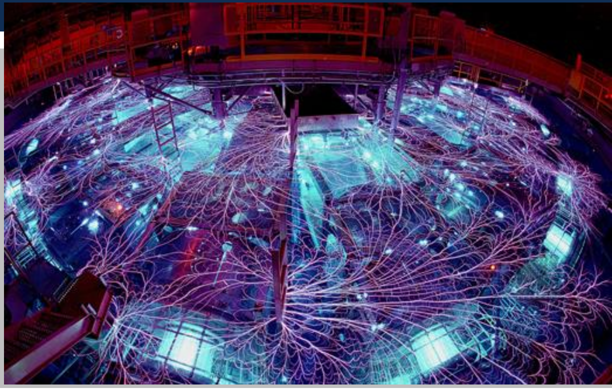
SAND2017-13441PE

Exceptional service in the national interest

Sandia National Laboratories





Diagnostics and Development Efforts on Z

Gregory A. Rochau

Manager – Radiation and Fusion Experiments

National Diagnostics Workshop – December 5-6, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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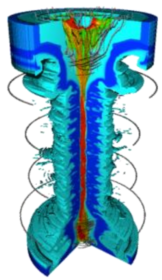
Z Supports a broad portfolio of experiment campaigns with diverse requirements

Dynamic Materials Properties (DMP)



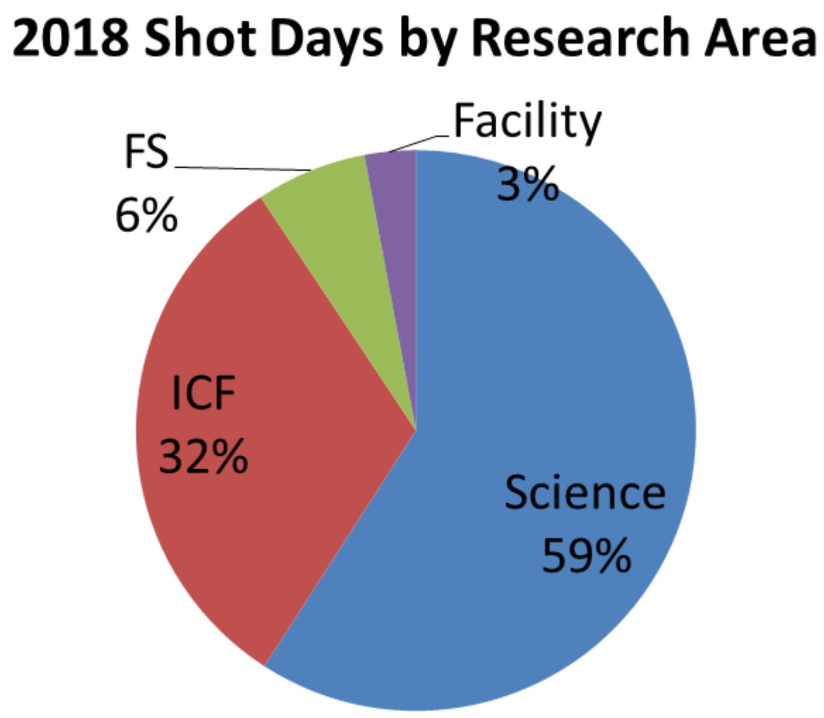
Inertial Confinement Fusion (ICF)

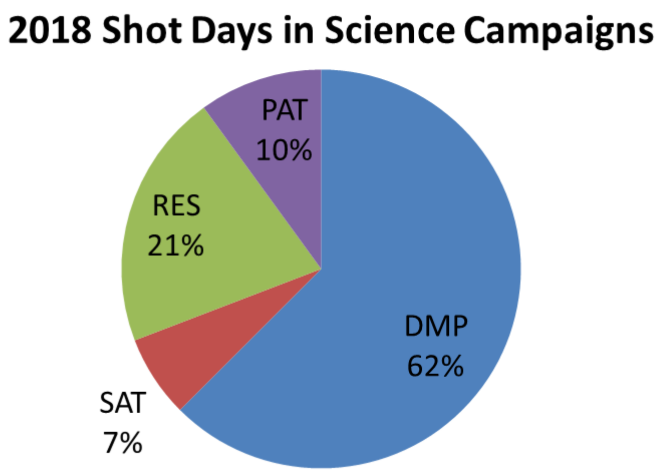
Secondary Assessment Tech (SAT)

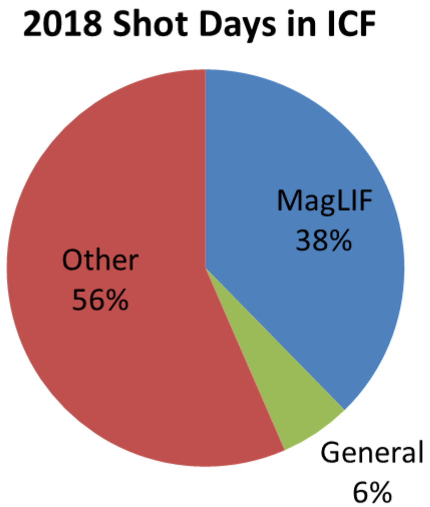
Radiation Effects Sciences (RES)

Fundamental Science (FS)

The CY18 Z shot schedule emphasizes Science Campaigns with ~30% of the shot days in ICF



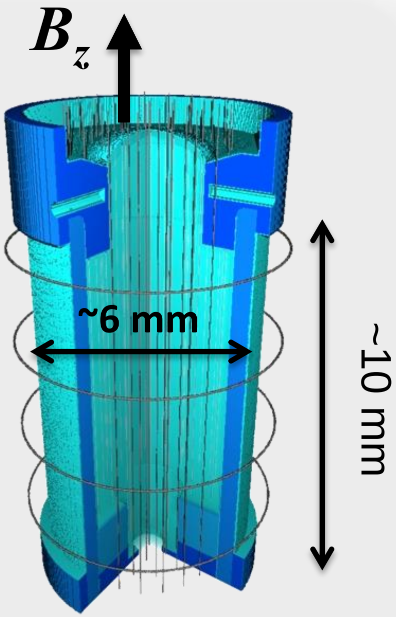




179 planned shots out of 234 shooting days

The US is studying a form of magnetic direct drive called Magnetized Liner Inertial Fusion (MagLIF).

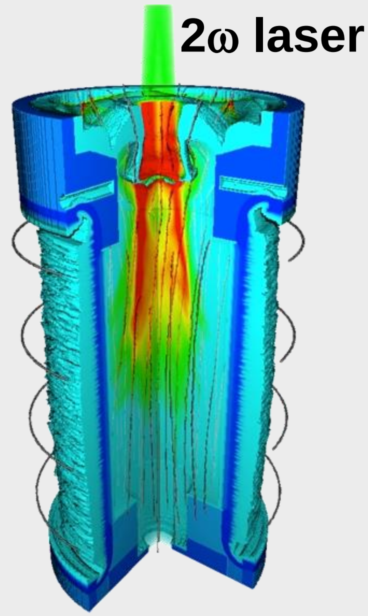
Pre-Magnetize



Beryllium liner

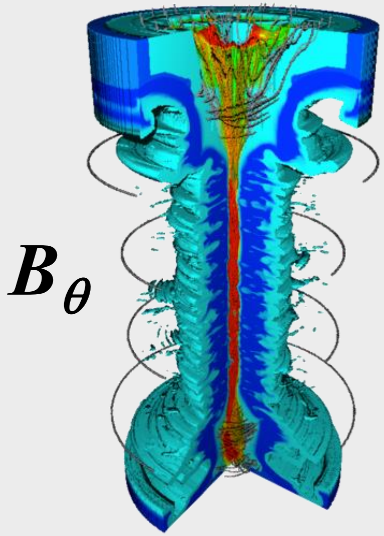
- B_z = 10-30 T
- Inhibit e^- conduction
- Confine α's

Preheat



- Laser Energy = 1-4 kJ
- T_0 ~ 100's eV
- Reduce required implosion velocity

Compress

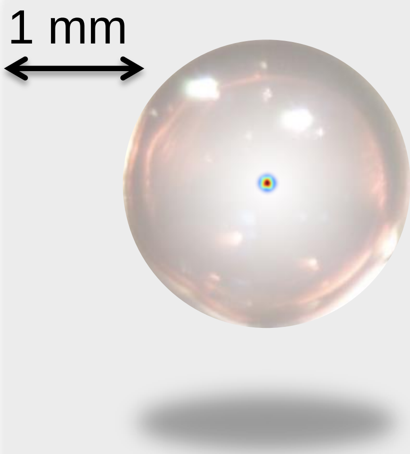


- CR ~ 35
- ρR ~ 0.003 g/cm^2
- P ~ 5 Gbar
- BR ~ 0.5 MG-cm

Slutz et al., POP 17 (2010).

The MagLIF stagnation column is much different in size, pressure, and time-scale than a typical ICF hot spot.

Laser Indirect Drive On NIF



E_{driver}	~ 1.8 MJ
P_{HS}	~ 300 Gbar
R_{HS}	~ 30 um
Y_{DT}	~ 2E16
Δt	< 100 ps

Laser Direct Drive On OMEGA

E_{driver}	~ 26 kJ
P_{HS}	~ 55 Gbar
R_{HS}	~ 20 um
Y_{DT}	~ 5E13
Δt	< 100 ps

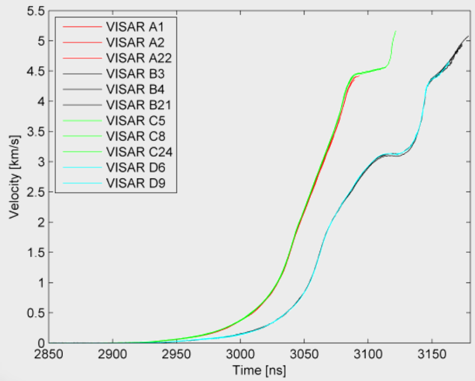
MagLIF On Z

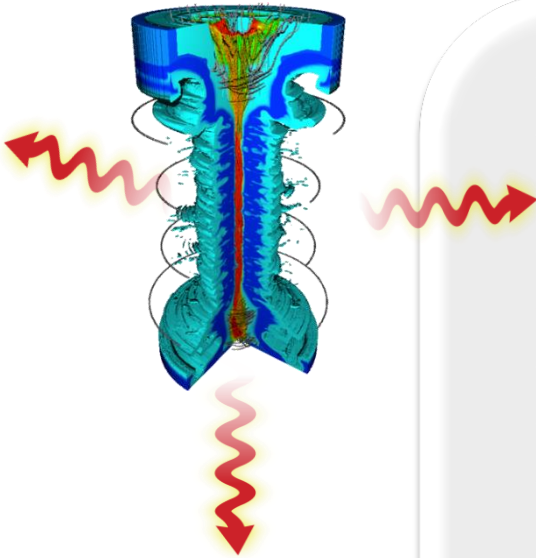
E_{driver}	~ 2 MJ
P_{HS}	~ 1 Gbar
R_{HS}	~ 100 um
L_{HS}	~ 10 mm
Y_{DD}	~ 4E12
Δt	> 1 ns

Multiple diagnostics are used to interpret the Magnetic Direct Drive implosion dynamics and resulting stagnation conditions

Optical

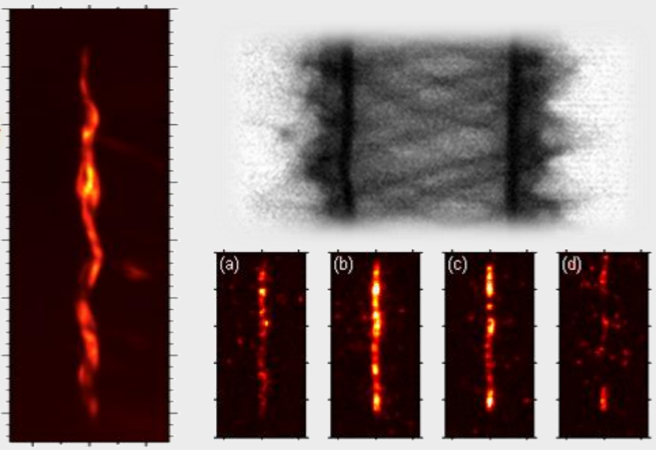
Point VISAR



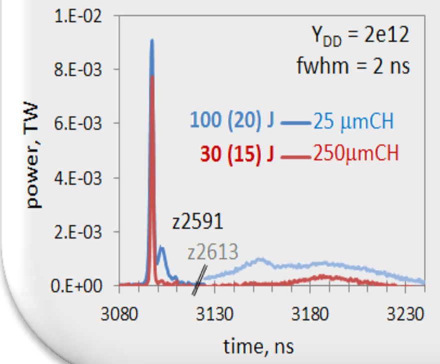


X-rays

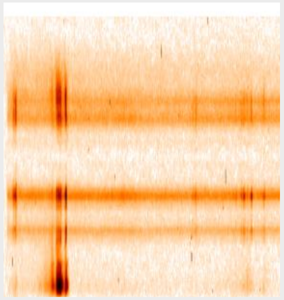
Imaging & Radiography



Power History

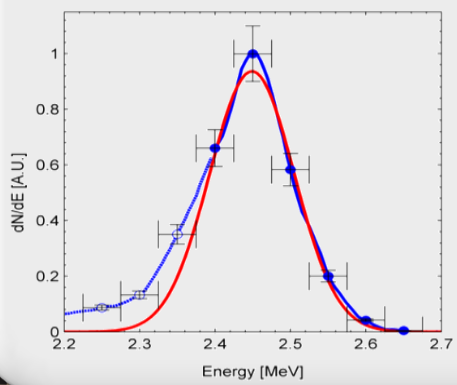


Spectroscopy

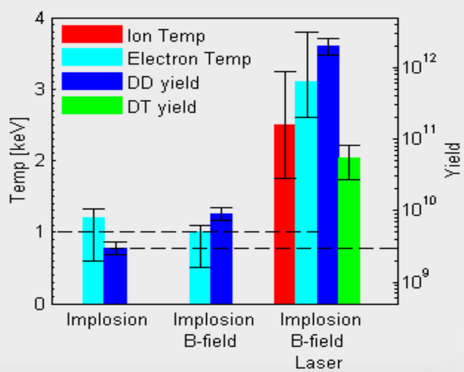


Neutrons

nTOF (side & bottom)

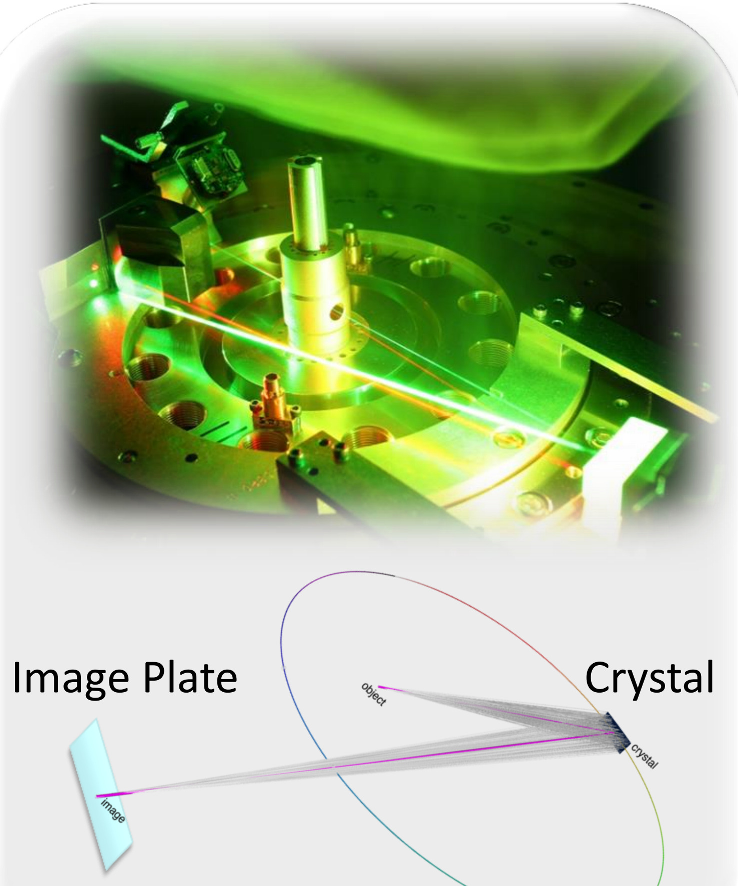


In & Cu Activation

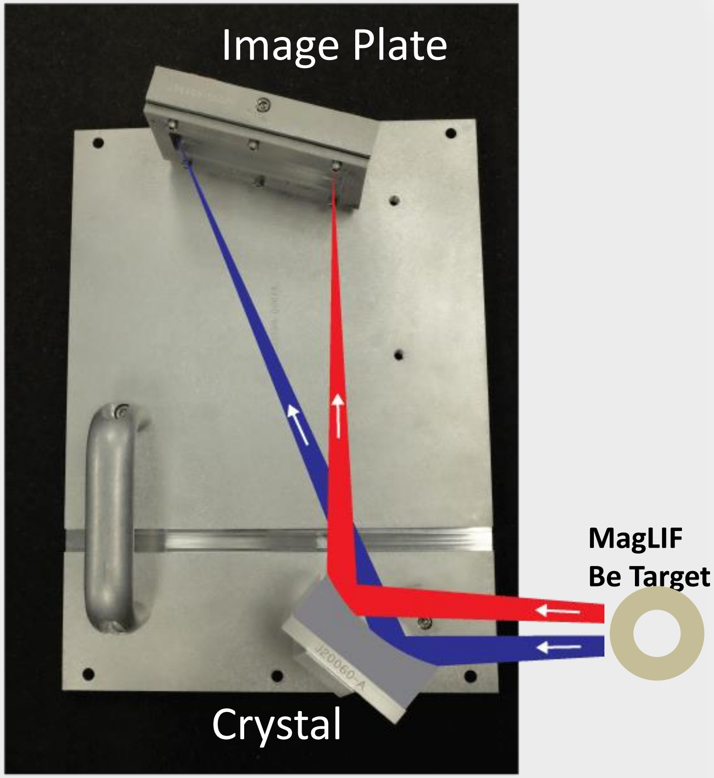


Spherical-crystal diagnostics are a workhorse capability for MagLIF, but all are presently time-integrated

2-D Backlighting and Self-Emission



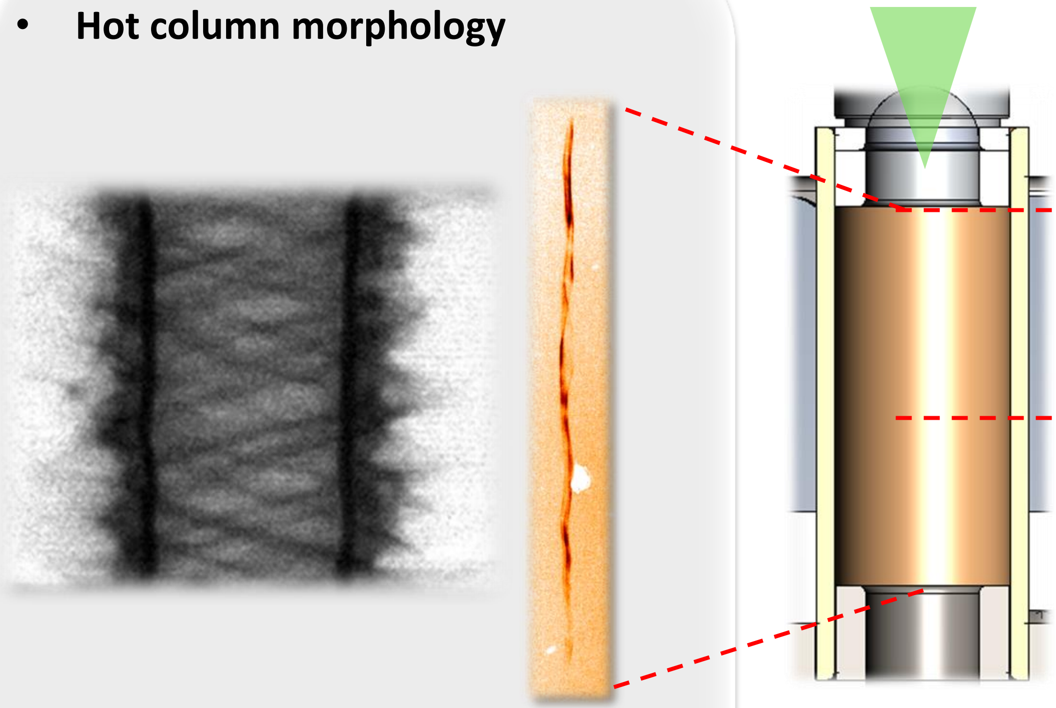
1-D Space Resolved Spectra



Spherical-crystal diagnostics are a workhorse capability for MagLIF, but all are presently time-integrated

2-D Backlighting and Self-Emission

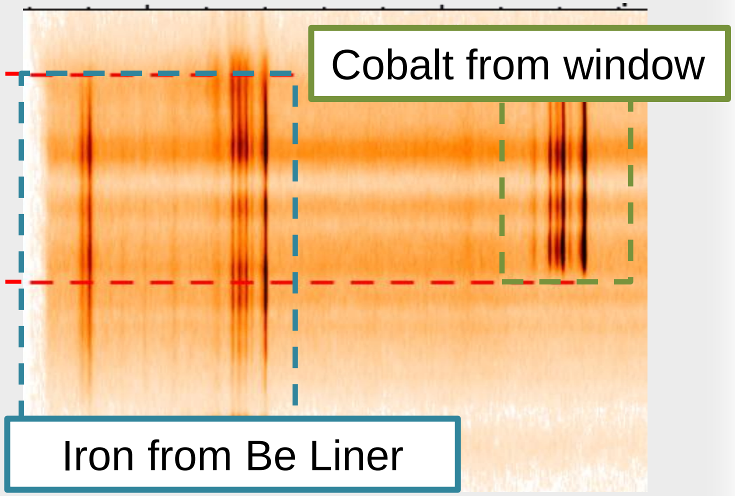
- Liner morphology (2-frames/shot)
- Hot column morphology



- How does this morphology evolve?

1-D Space Resolved Spectra

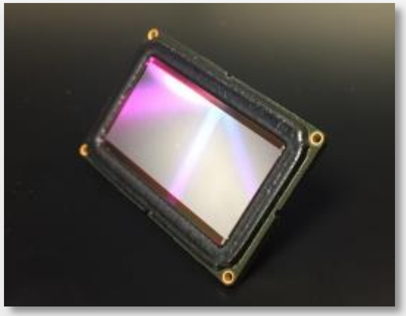
- Plasma Conditions
- Mix



- When does the Fe come?
- How does the window mix propagate?
- What is the radial mix distribution?

Fast-gated single line-of-sight hCMOS sensors are a key part of the strategy to time-resolve the MagLIF stagnation

hybrid CMOS Focal Plane Array

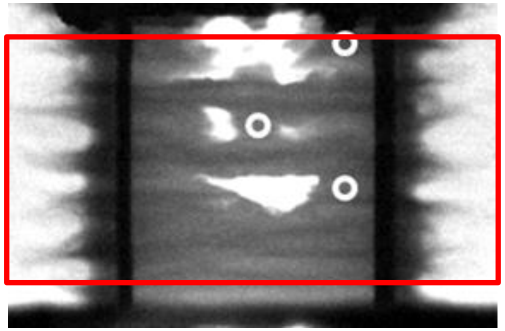


Pixelated 25 μm thick Si diode layer on top of a burst-mode CMOS circuit

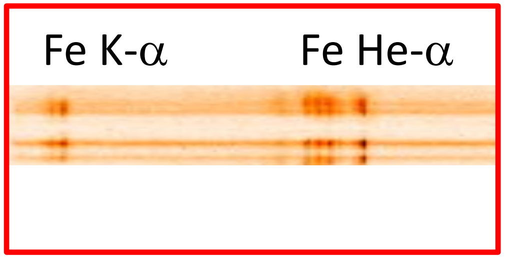
Daedalus Specifications (Late FY18)

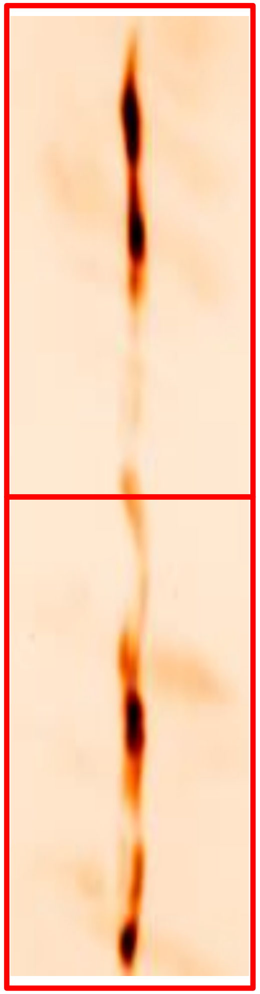
- 512x1024 25 μm pixels
- 12.8 x 25.6 mm active area
- 1 side abutable (12.8 mm x 51.2 mm)
- 3 frames per pixel
- Interlacing for more frames
- 1 ns per frame
- Sense 1-500 photons/pixel at 10 keV

6.2 keV Radiograph at Mag = 6



>6 keV Spectrum at Mag = 1/3





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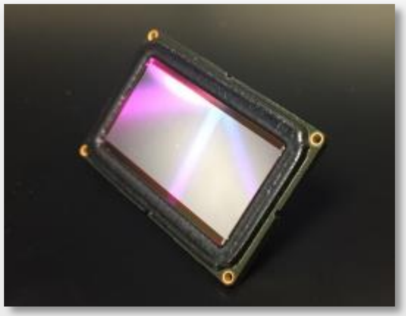

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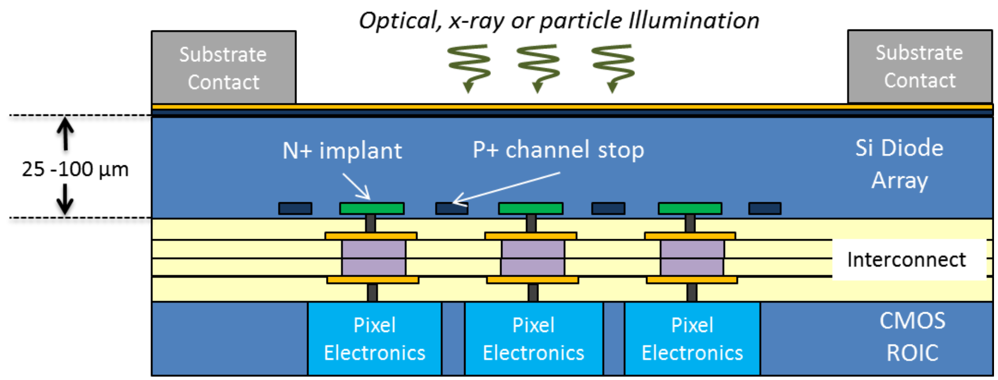

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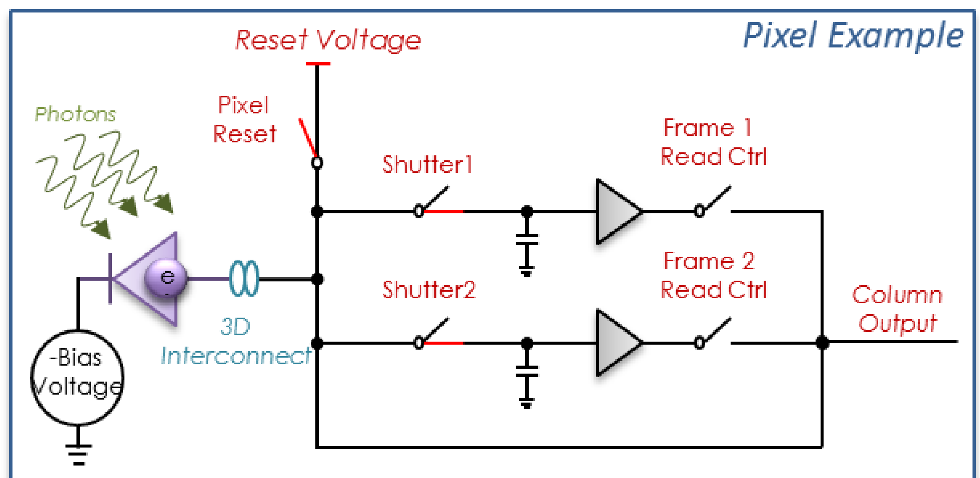
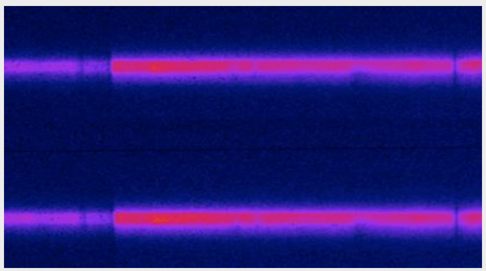


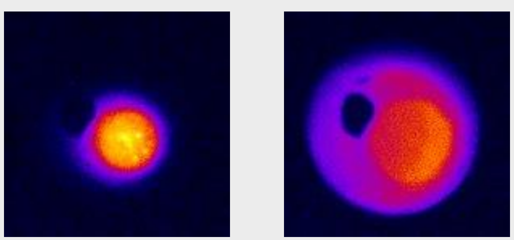
hCMOS cameras are now taking data on all three US ICF facilities: Z, NIF, and Omega

Z

Opacity Spectrometer

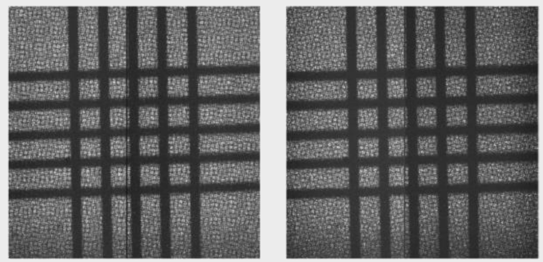


Axial Pinhole Imager

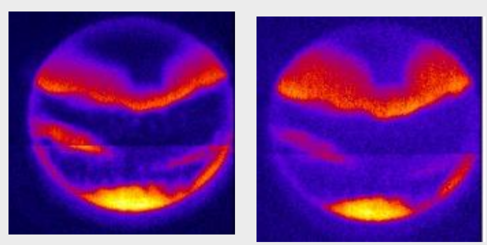


NIF

Gated Crystal Backlighting (Pulse Dilation SLOS)

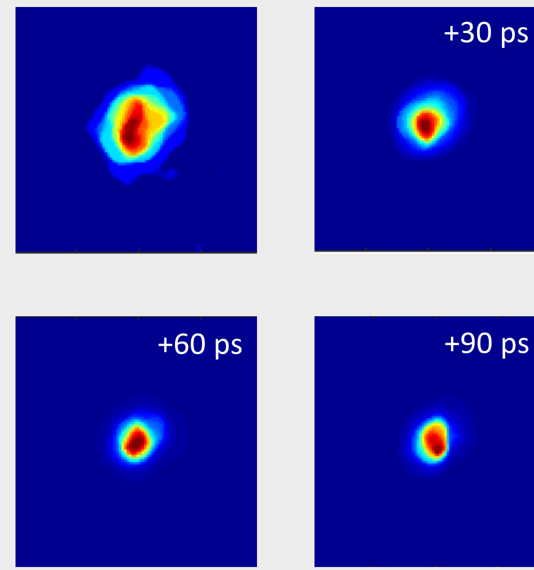


Gated LEH Pinhole Imager

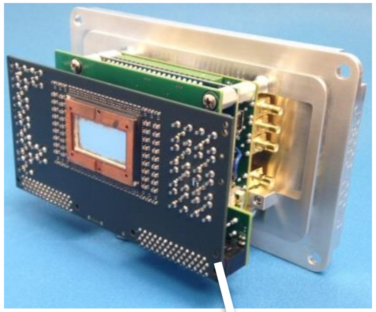


OMEGA

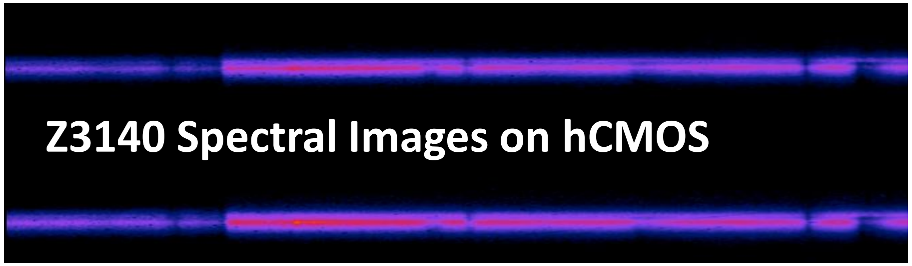
Gated Pinhole Imager (Pulse Dilation SLOS)

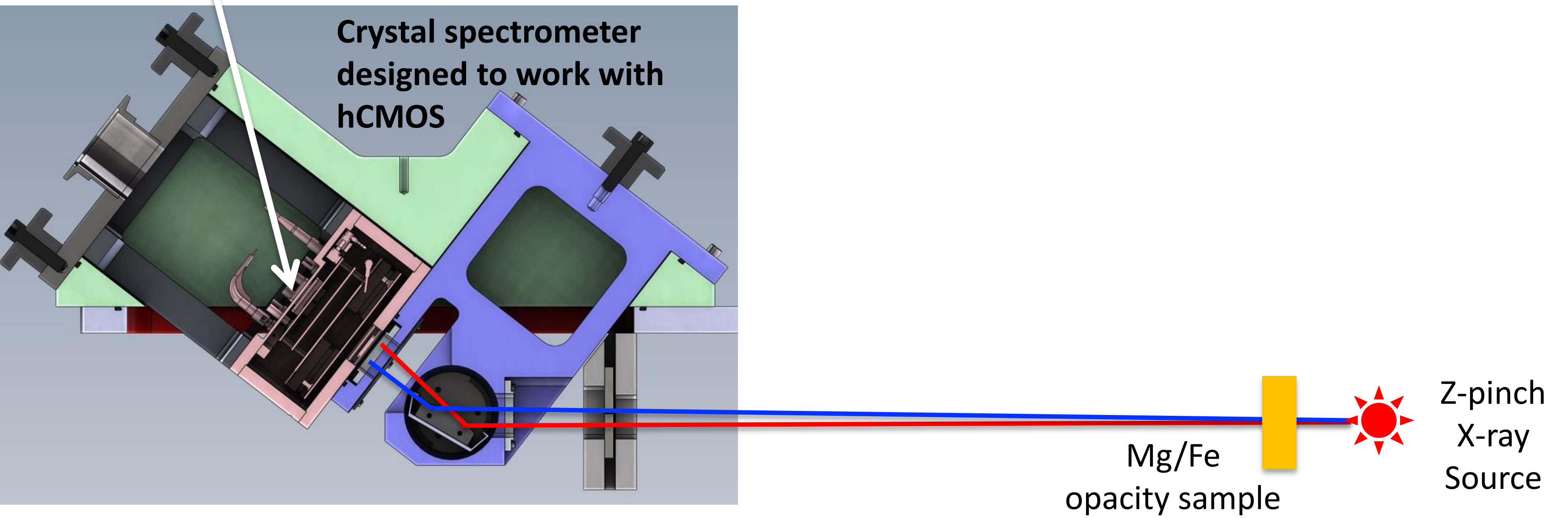


A new capability for time-resolved opacity measurements gave first data on Z in September.



Hybrid CMOS (hCMOS) X-ray camera provides 4 time-gated frames of absorption spectra





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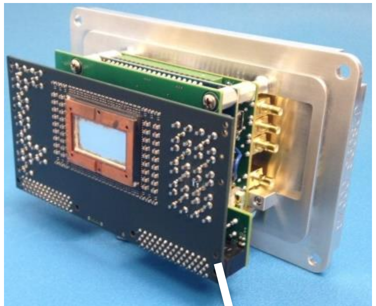

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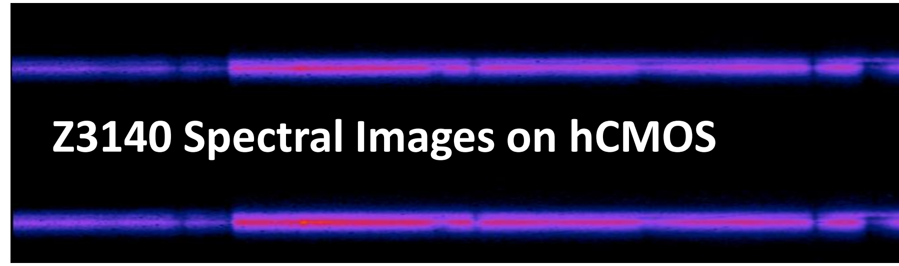
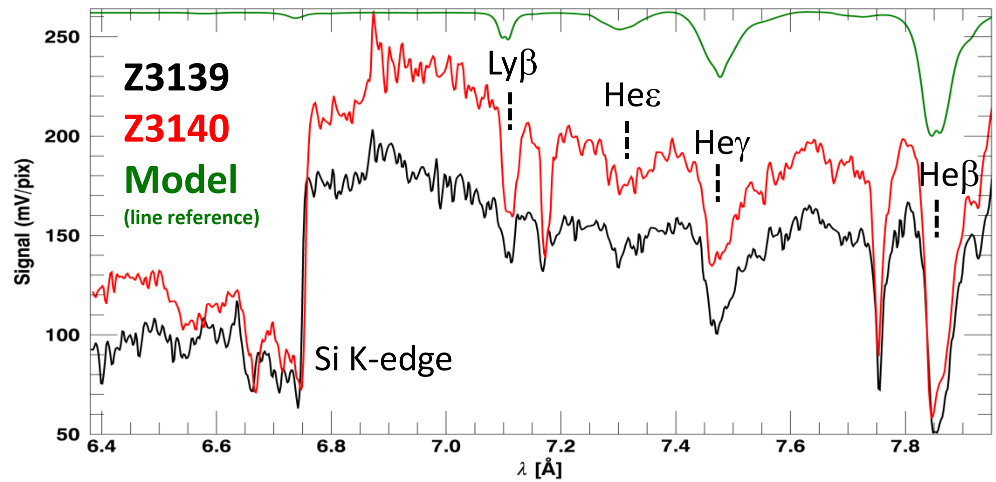
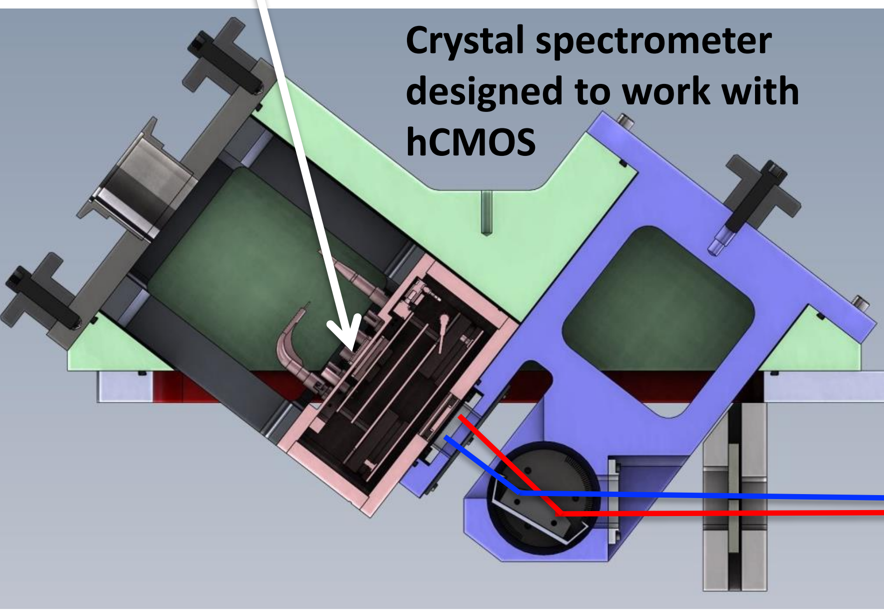
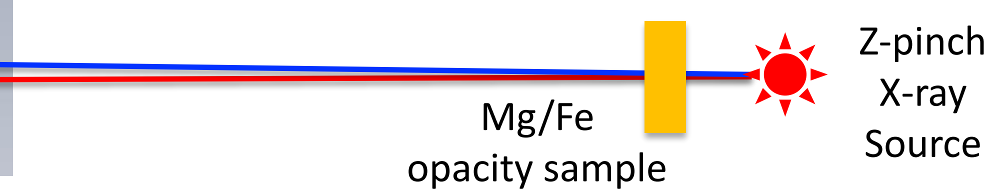


Magnesium K-shell spectra are observed







hCMOS is entering a production phase, but supply chain issues have caused some delay in delivery for key applications

We need dozens of sensors

Z

Opacity Spectrometer
Axial Imager
Gated Crystal Backlighting
Gated Crystal Spectra
Gated Crystal Imaging
Blast Wave Shadowgraphy

NIF

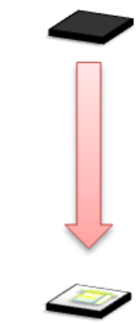
SLOS1-CBI
SLOS2-KBO
Gated LEH
TARDIS-t
DMX Imager (LMJ-CEA)

OMEGA

SLOS-TRIXI
SLOS-TRIXI-2

- We have fabricated enough ROIC and diode wafers to produce hundreds of sensors.

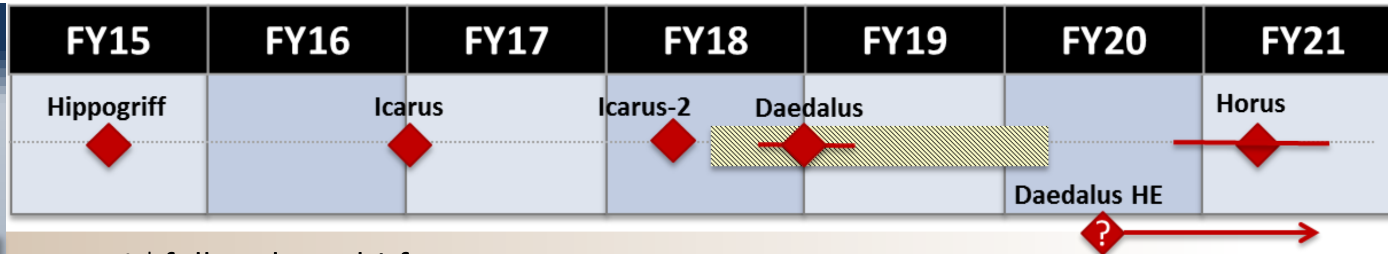
- Hybridization has become the key risk



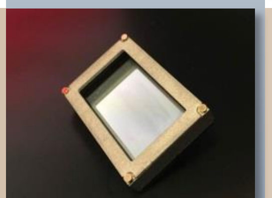
- ➢ Preferred method is wafer-to-wafer direct bond interconnect (DBI)
- ➢ Previous DBI supplier quit supporting this size wafer in April causing a delay in delivery
- ➢ New supplier under evaluation.
- ➢ Die-to-die indium bump bonding has been demonstrated at Sandia this summer and expected to provide ~10 sensors this year

We are continuing to develop new hCMOS sensor technology with an emphasis on more, faster frames

Timeline

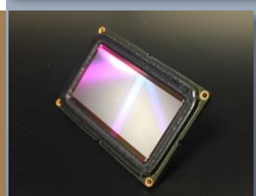


Furi / Hippogriff



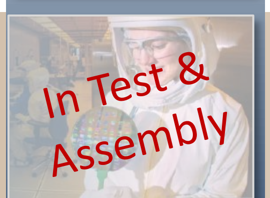
- 1st full-scale multi-frame sensors
- 1.5-2ns minimum shutter
- Optimized for 1-10 keV x-ray detection

Icarus



- 1st cameras compatible with pulse-dilation
- 1 ns min. shutter with 2 or 4 (Icarus-2) frames per hemisphere
- Optimized for soft x-ray, visible, and e- detection

Daedalus



- 3 frames per hemisphere (≥6 frames with interlacing)
- 1-side abuttment for spectroscopy and z-pinch imaging applications
- Large well for high energy x-rays while maintaining low end sensitivity

Horus

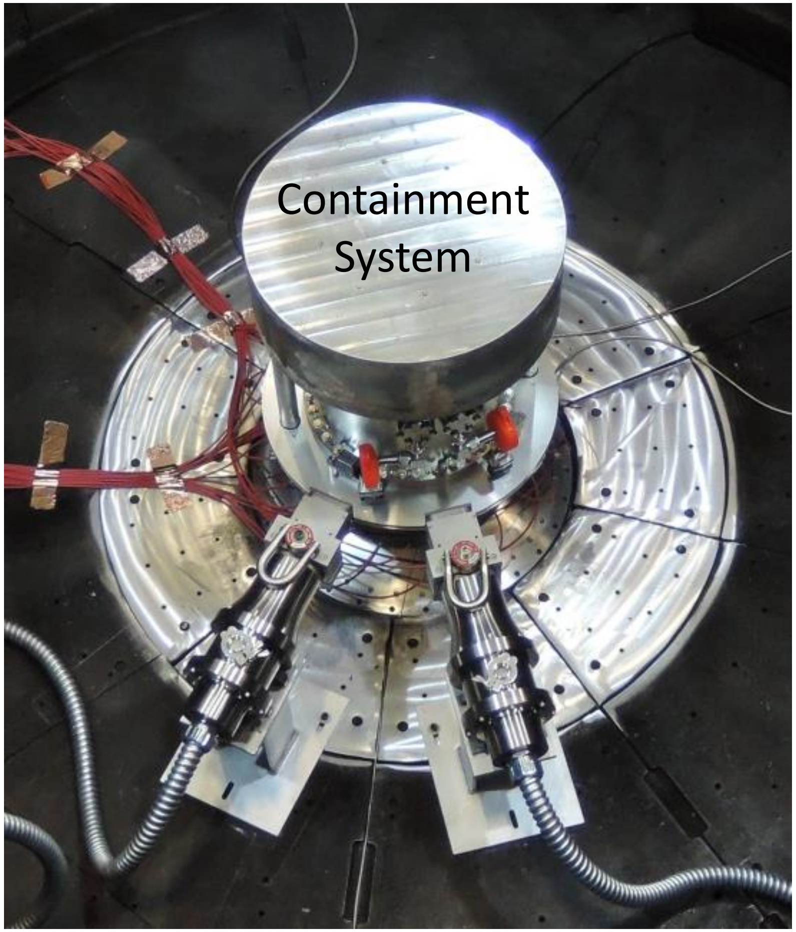
- 1st 180 nm sensor in Sandia's new CMOS-8 architecture

  Design goals include
  - 6 frames per pixel w/ independent quadrants (≥12 frames with interlacing)
  - 0.5 ns minimum shutter

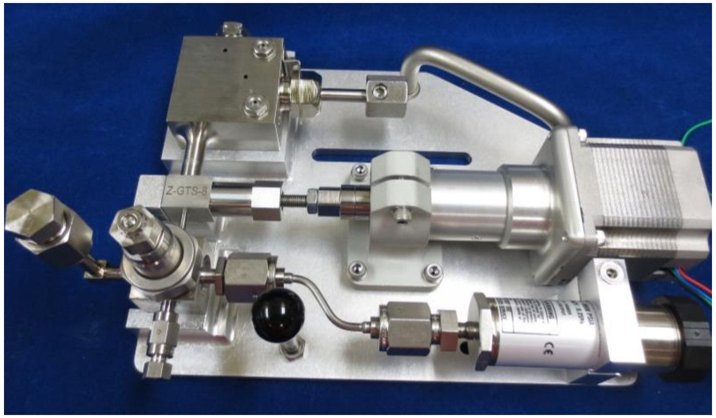
UXI Sensors

The tritium era on Z has begun, with contained (and uncontained!) capability tested at 0.1% DT

First Z shot with 0.1% DT (August, 2016)



Z Gas Transfer System



Neutron time of flight diagnostics measured a primary DT neutron signal for the first time on Z

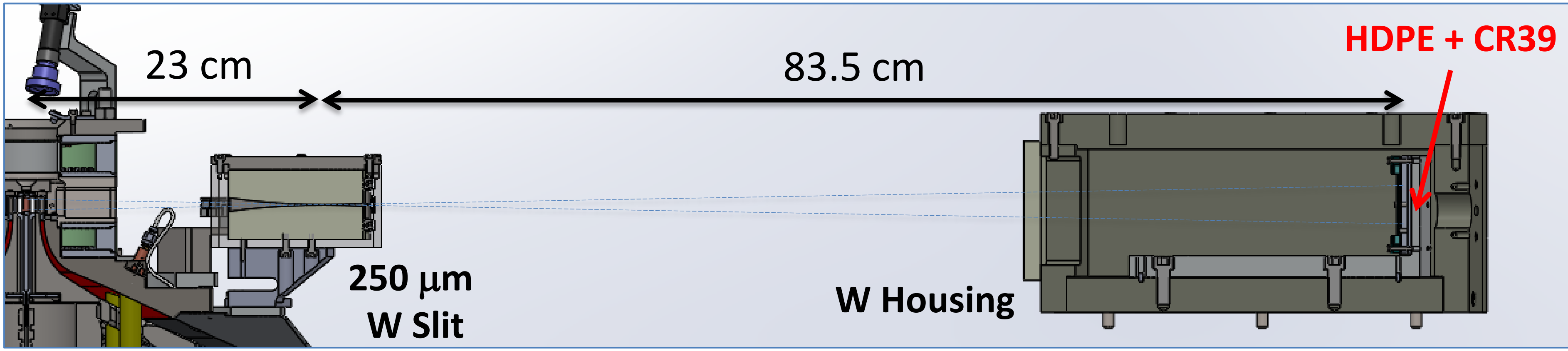
Vacuum chamber post-shot characterization found tritium contamination levels were indistinguishable from background

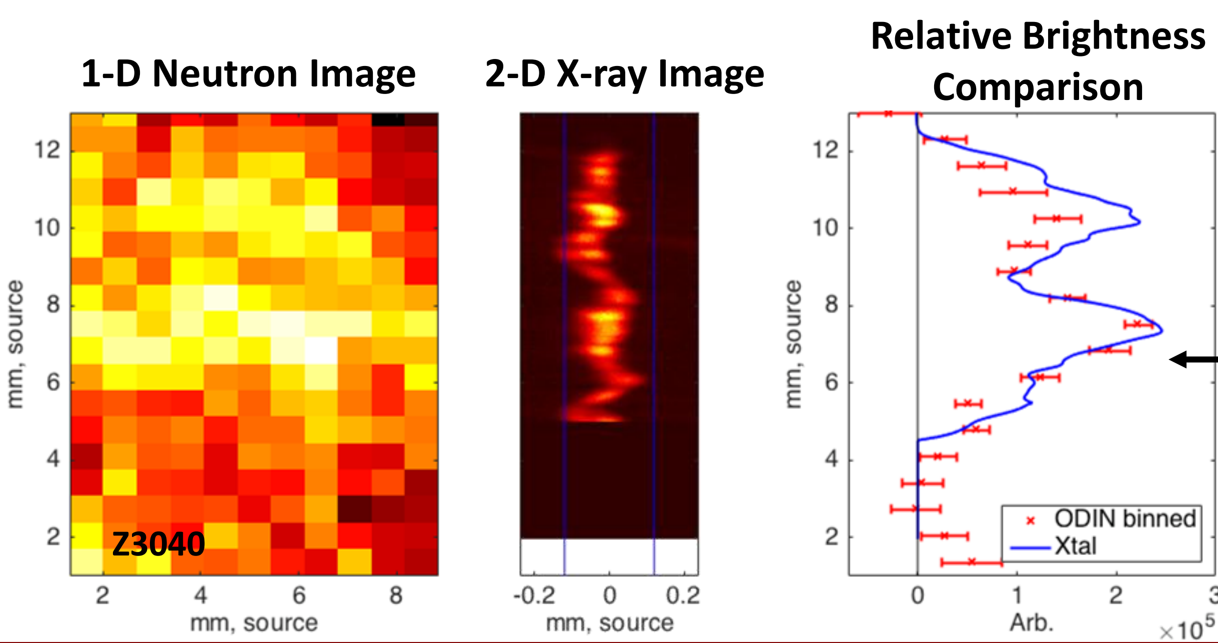
DT on Z will enable more precise diagnosis of the thermonuclear processes occurring during stagnation

	2015	2016	2017	2018	2019	2020
Contained	D_2, ^3He	0.1% T	--	--	3% T	3% T
Uncontained	D_2, ^3He	D_2, ^3He	0.1% T	1% T	1% T	3% T

		T Fill %	
Physics	**Measurement**	**0.1%**	**1-3%**
Behavior of tritium in the Z pulsed power environment	Sampling of tritium contamination, migration		
Thermonuclear scaling (DD vs. DT)	DT yield		
Ion temperature and non-thermal population	Precision nTOF and DT/DD yield ratio		
Liner/fuel mix	DT yield with tritiated gas fill and deuterated liner		
Fuel morphology	Neutron imaging		
Thermonuclear reaction history	Gamma Reaction History, Thompson parabola		
Liner/fuel density, non-thermal effects (peak shifts)	Compact Recoil Spectrometer (CRS), MRS, precision nTOF		

Neutron imaging is finally becoming a reality on Z (at least in 1-D)





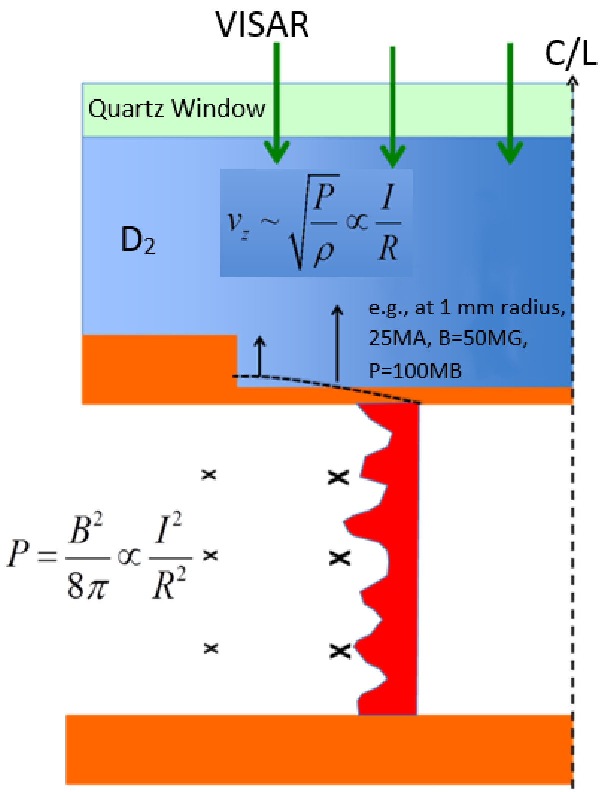
- Designed for Y_{DD} > 3E12
- Analysis w/ 900 μm binning

X-ray and neutron images aligned to best fit

- need to develop absolute co-alignment

Line VISAR is being developed on Z as a collaboration between LLNL and SNL for assessing current delivery to MDD targets

- Z-pinch exerts pressure on a D2 gas cell
- Line VISAR resolves pressure vs. radius



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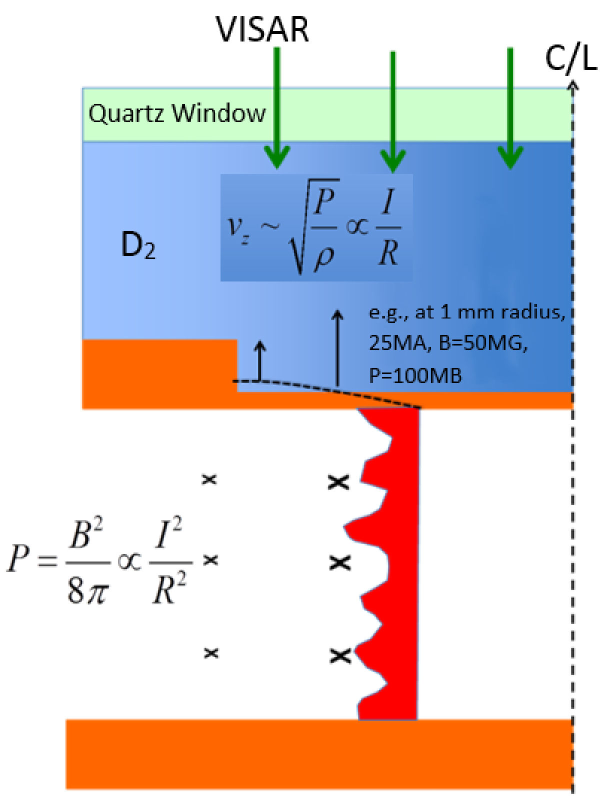


- Optics and back-end electronics developed and supplied by LLNL
- Beam path, facility mods, and operations provided by SNL

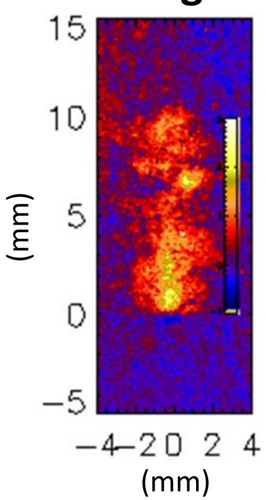
The initial Z Wolter design is complete and we are preparing for commissioning to begin in January

- Wolter optic with coating optimized to image Mo K-α emission region from a z pinch (Ag He-α region in FY18)
- 5 mm x 5 mm x 5 mm Field-of-view (FOV)
- < 100 micron resolution over majority of FOV
- Complex instrument response function will require additional analysis method development

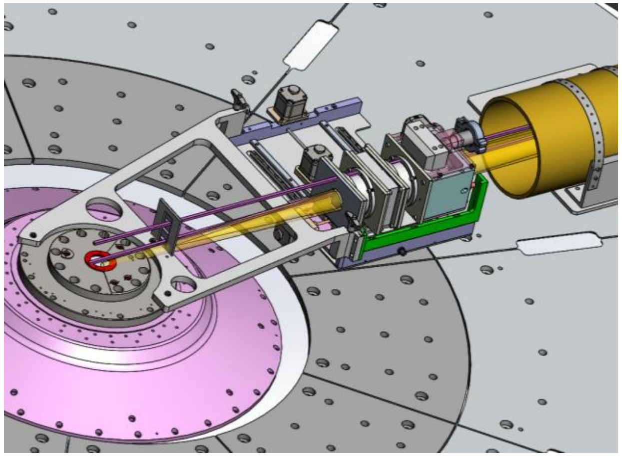
Four-way Collaboration

- Optic designed by LLNL
- Mandrel Fabricated by NASA
- Coatings applied by Harvard
- Z integration by SNL

Pinhole Image

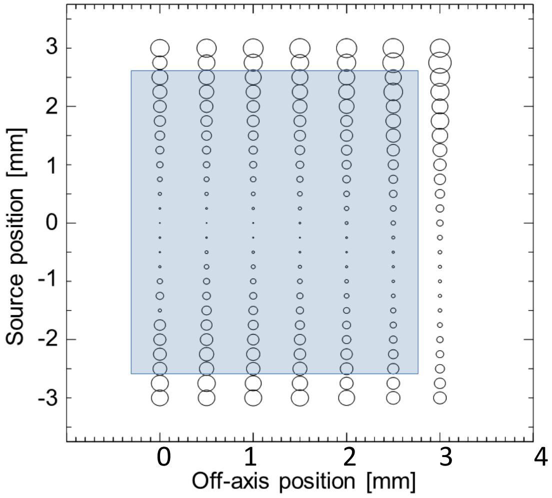


In-chamber Optics mount



Prototype Optic

Modeled PSF

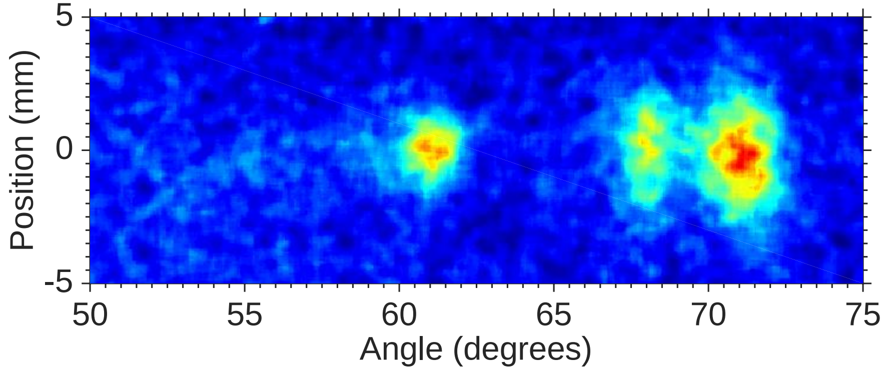


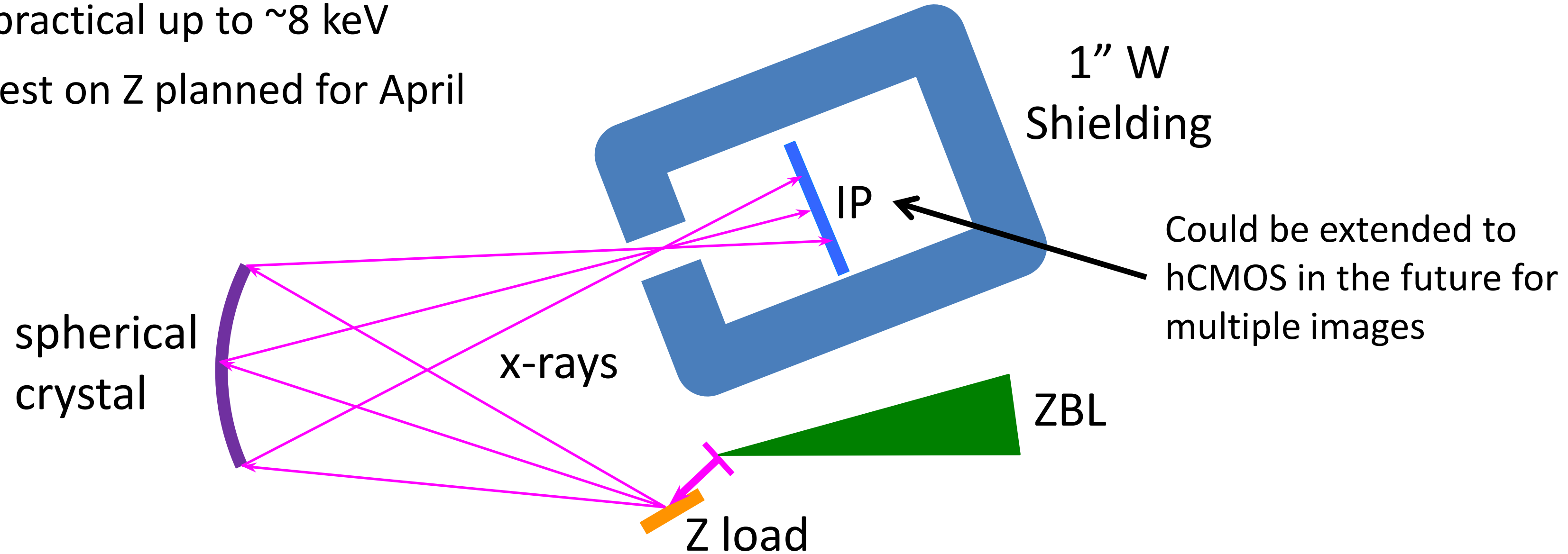
A novel approach to diffraction is under development using crystal optics to capture and relay the diffracted x-rays

- X-ray diffraction is a key capability needed to determine the phase and compression of a sample under high pressure.
- Debris and background pose problems on Z for typical diffraction schemes
- Spherical crystal optics provide a way to relay the signal to a protected detector
- Only practical up to ~8 keV
- First test on Z planned for April

Proof of concept on ZBL

Be sample, Mn target (6.2 keV), HOPG crystal



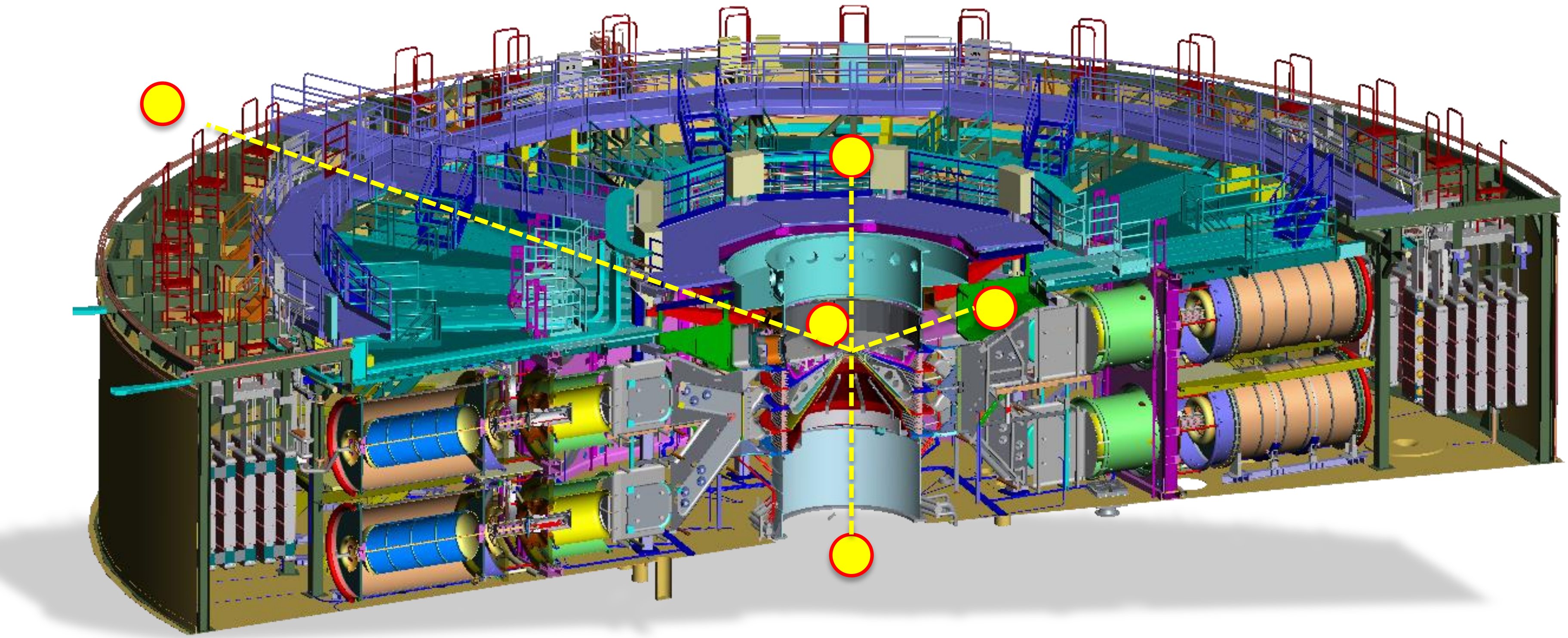


New diagnostic capability development on Z is phased through FY20

Diagnostic		Status	FY18 Q1	FY18 Q2	FY18 Q3	FY18 Q4	FY19 Q1	FY19 Q2	FY19 Q3	FY19 Q4	FY20 Q1	FY20 Q2	FY20 Q3	FY20 Q4
Opacity Spectrometer		Commissioning												
In-chamber MCP PHC		Test & Iteration												
Axial PHC		Test & Iteration												
Neutron Imager		Test & Iteration												
Wolter	*	Final Design & Assembly												
Line VISAR	*	Final Design & Assembly												
Gated Xtal Backlighting	*	Final Design												
Diffraction	*	Final Design												
Compact Recoil Spectra		Conceptual Design												
Gated Xtal Spectra		Conceptual Design												
Gated Wolter		Not Started												
Z SLOS		Not Started												
Gamma Reaction History		Not Started												
DT-nImager		Not Started												

Extra

Diagnostic access on Z is limited by the geometry of the pulsed power components



Radial 12°, 0°;   Top Axial;   Bottom Axial;   Chamber

In-chamber diagnostics provide opportunities for improved access and sensitivity

<u>Fiber-Based Diagnostics</u>

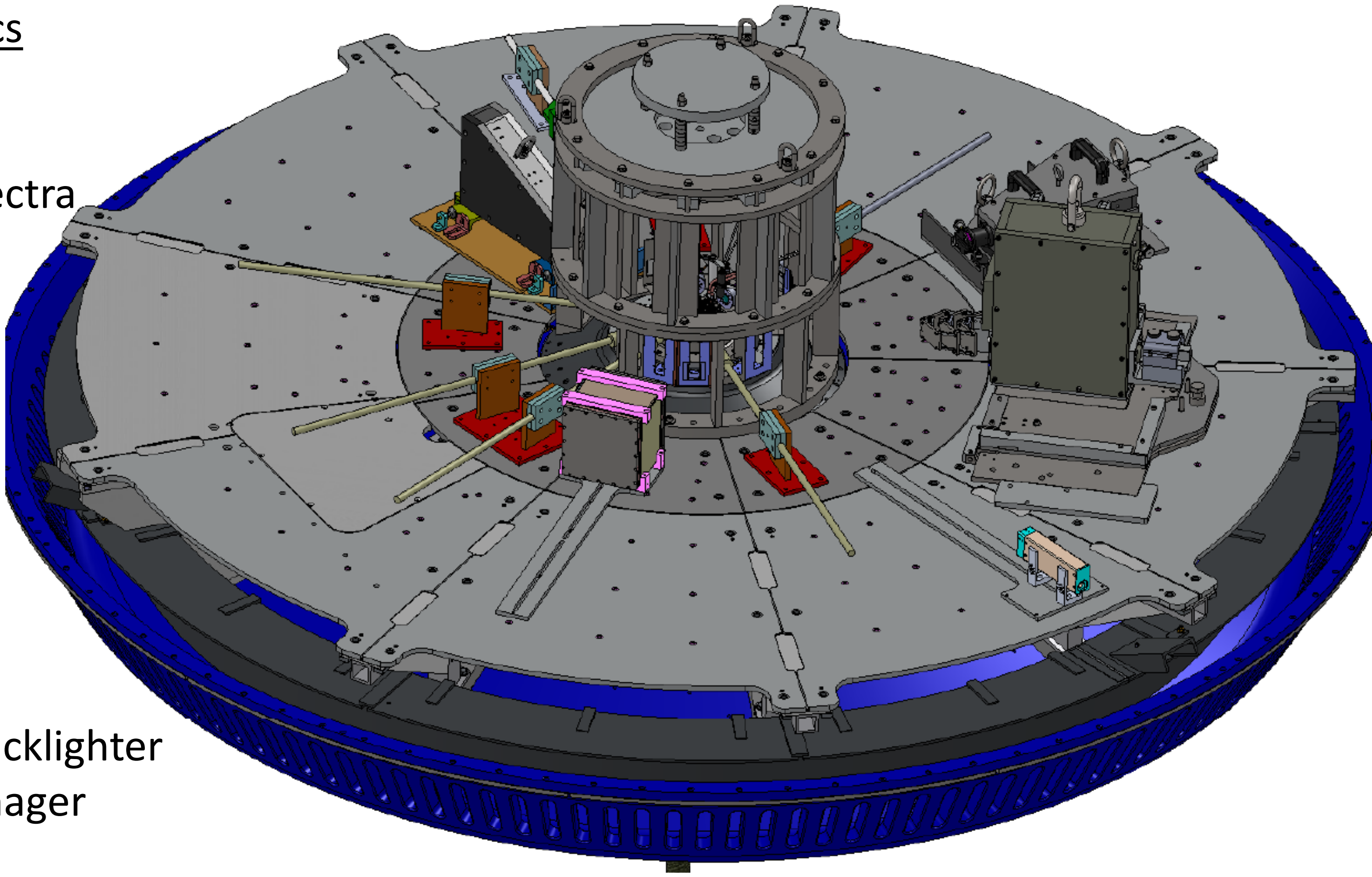
- VISAR
- PDV
- Streaked visible spectra

<u>X-ray Spectrometers</u>

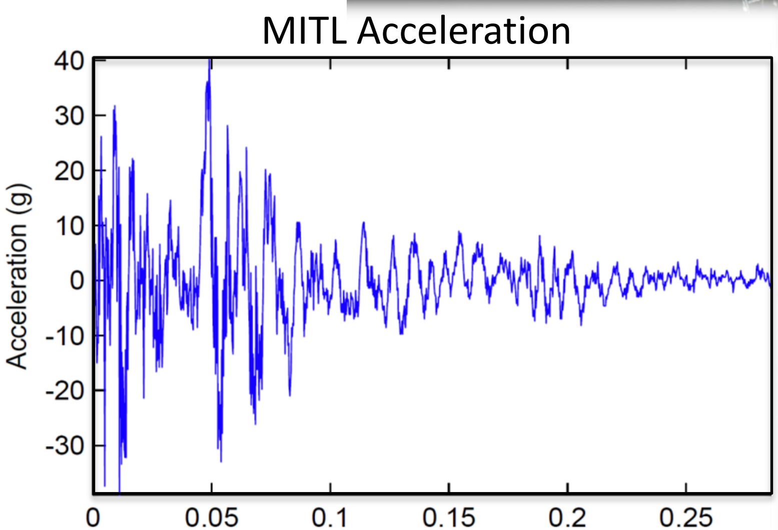
- High Energy
  ~7-70 keV @ E/ΔE ~500
- High Resolution
  ~5-10 keV @ E/ΔE ~ 4000
- MCP-gated
  ~10-22 keV

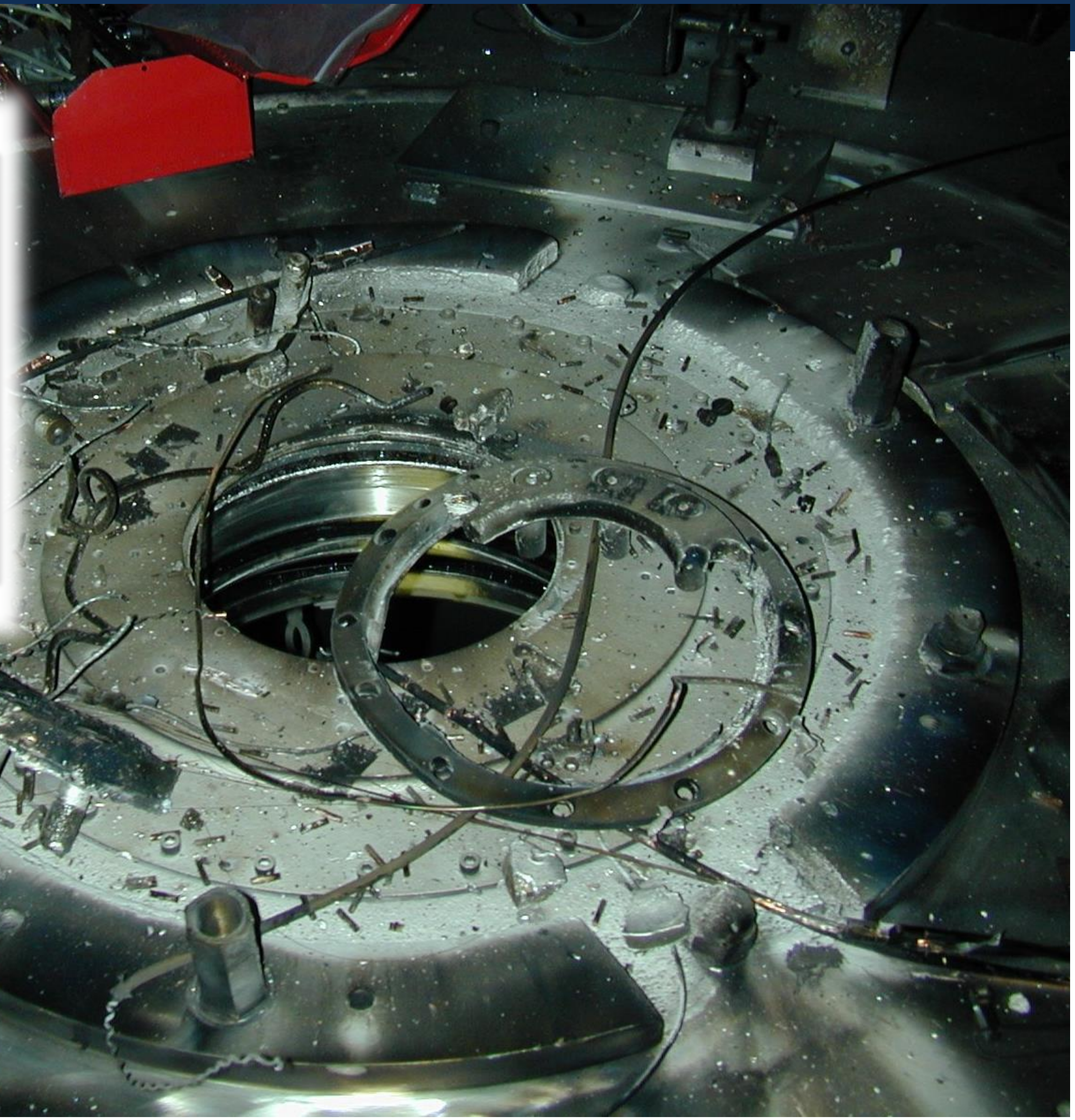
<u>X-ray Imagers</u>

- Spherical Crystal Backlighter
- Spherical Crystal Imager



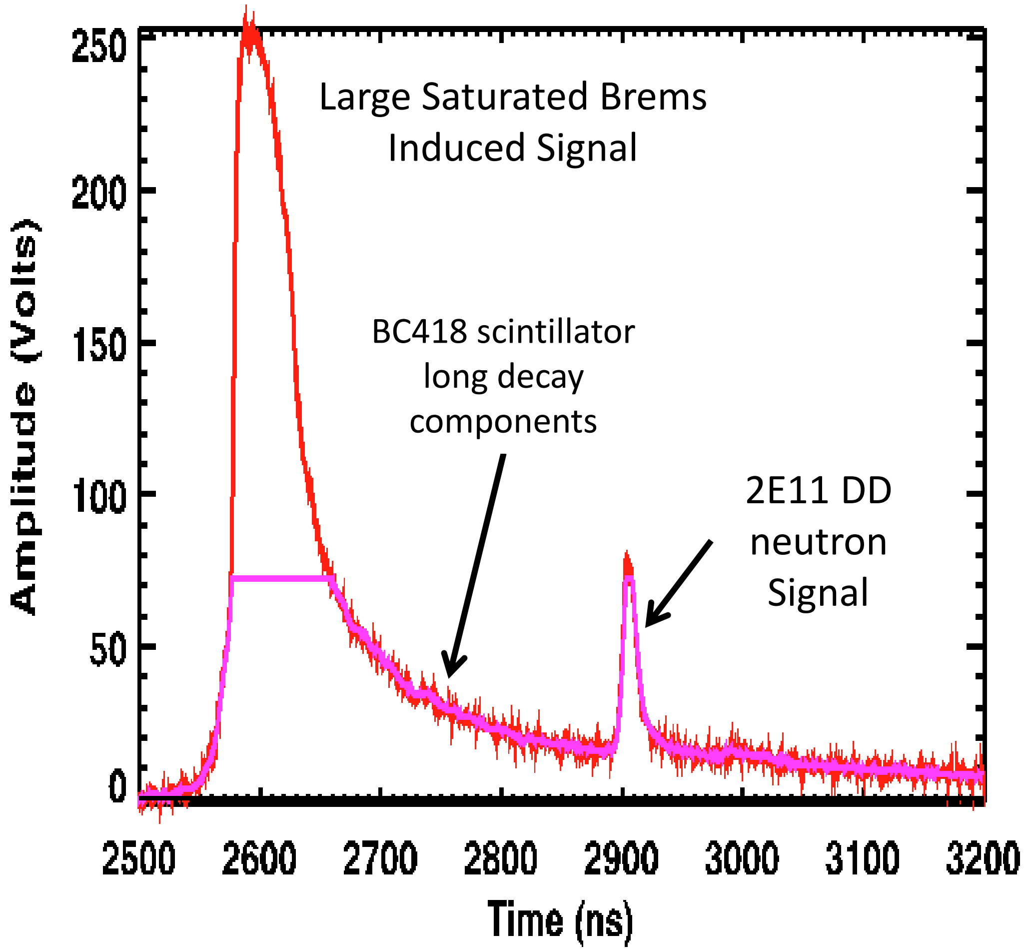
Shock and debris pose major challenges





The Bremsstrahlung background forces long fielding distances and significant line-of-sight shielding for nTOF.

Example nTOF data on Z



Bremsstrahlung background source:

- Originates from power-flow and late-time z-pinch instabilities
- End-point energy > 10 MeV
- Highly variable depending on electrical load design

To mitigate background effects:

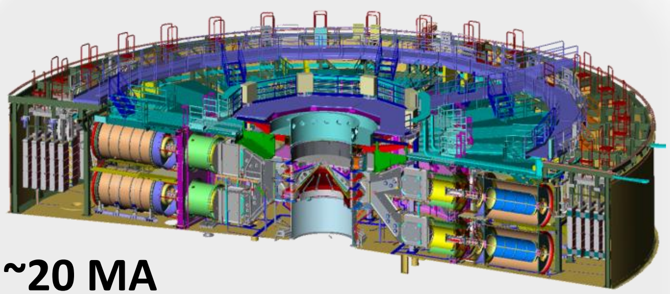
- 4” lead shielding
- Collimation
- Fast Mesh PMT’s (NSTec) with a large linear current and fast recovery

Diagnostic Operation on Z is heavily influenced by the unique Z environment

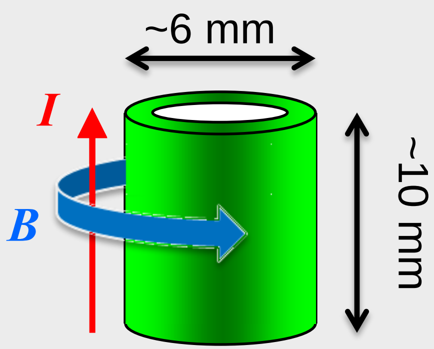
- Target chamber must be vented in-between every shot
  - ➢ Removal of all in-chamber and axial diagnostics every shot
- Debris environment requires inspection of diagnostic components between each shot
  - ➢ Venting of most fixed diagnostics every shot
- Shock environment and replacement of load hardware requires re-alignment of diagnostics every shot
- X-ray Background requires heavy, 4-pi shielding (Typically 1” Tungsten)
- EMP environment requires carefully shielded cables and RF enclosures for all active electronics
  - ➢ CCD cameras are challenging to properly shield and operate

Magnetic direct drive (MDD) ICF is studied on the Z Facility

Z Facility



~20 MA

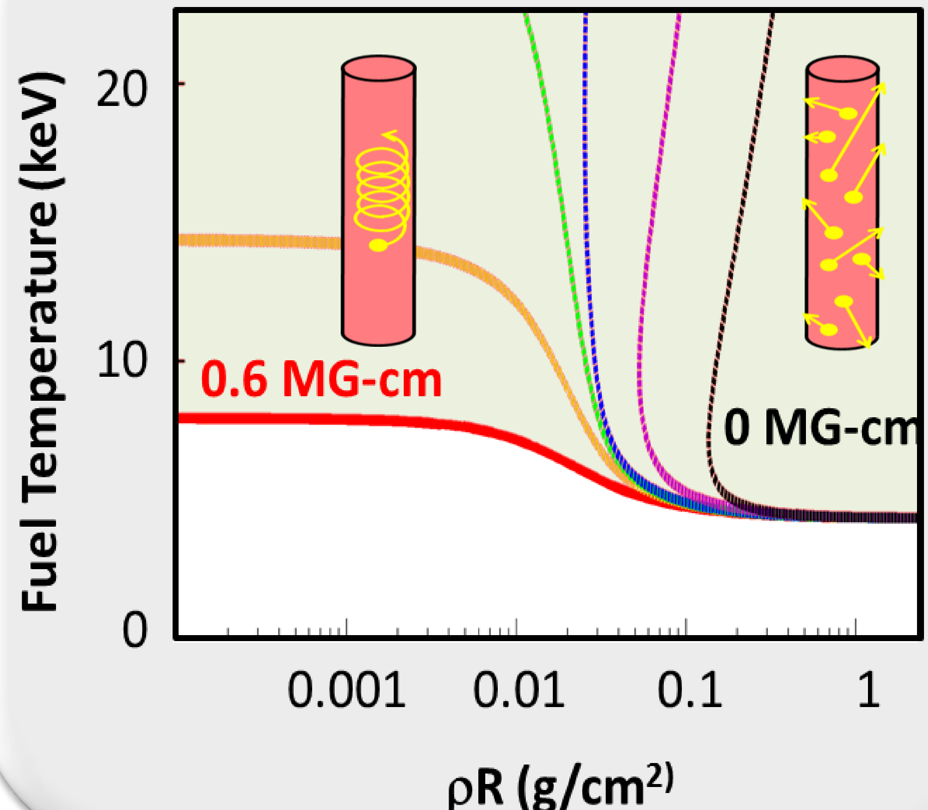


Drive Pressure

$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ Mbar}$$

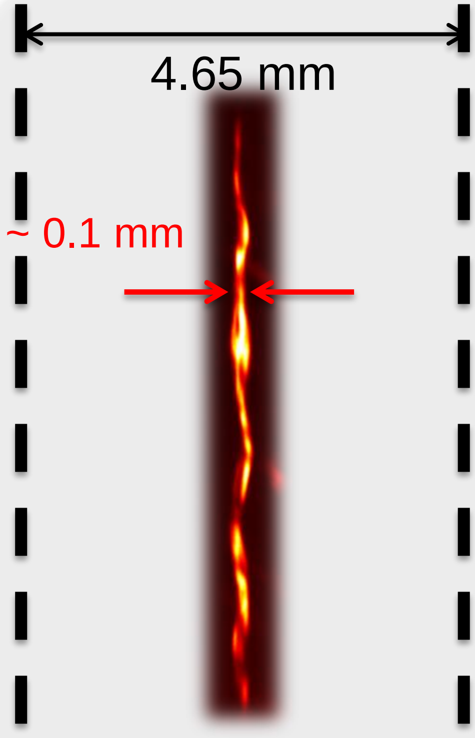
Imposed B-fields relax ρr requirements

Contours of positive energy gain at various values of BR



MagLIF experiments on Z have demonstrated the key features of magnetized inertial fusion.

High Convergence Implosion



6+9 keV Emission Image

CR > 40

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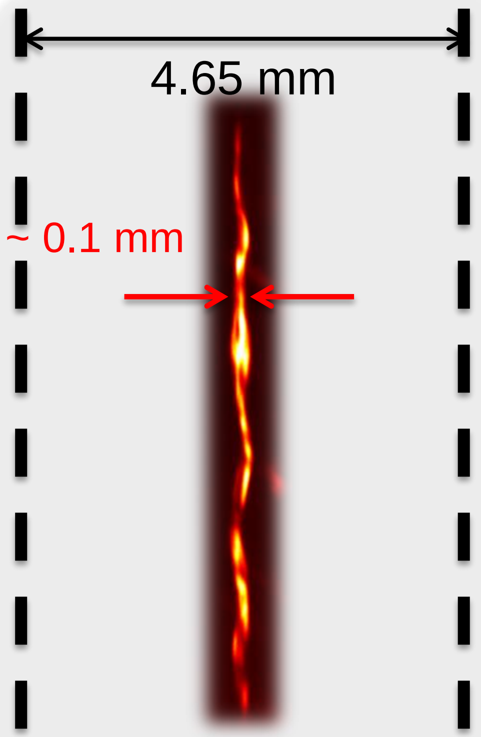

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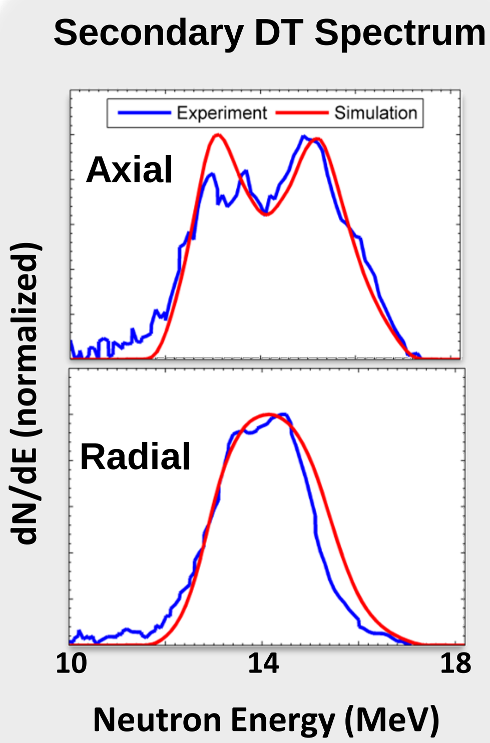
B-field Flux Compression



DT Secondary Spectra

BR > 0.35 MG-cm

Gomez et al., PRL 113 (2014); Schmit et al., PRL 113 (2014); Hahn et al., RSI 85 (2014)

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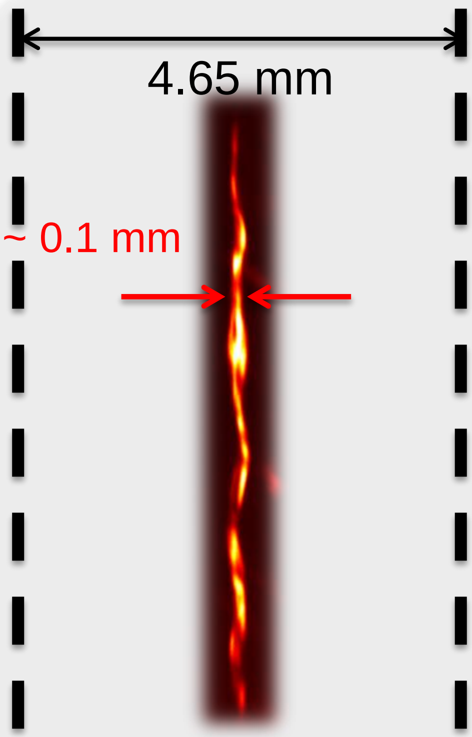

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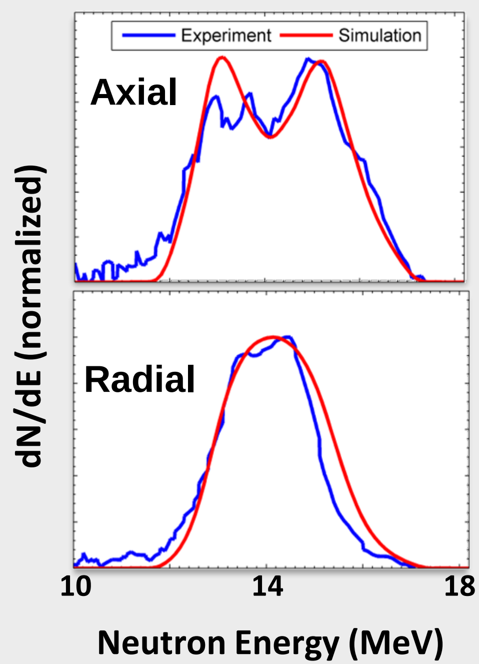

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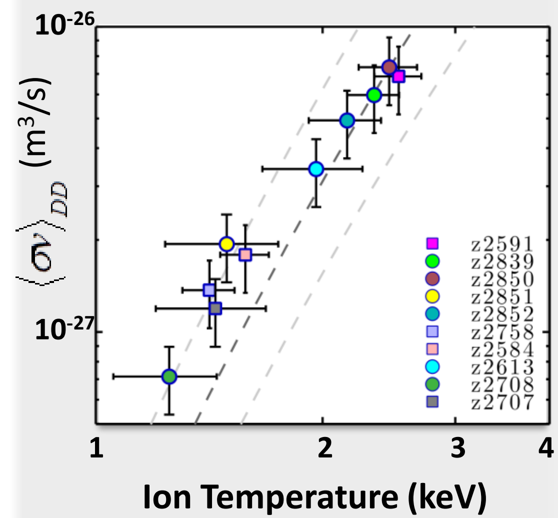
Thermonuclear Neutrons

Reactivity Scaling vs. T_i

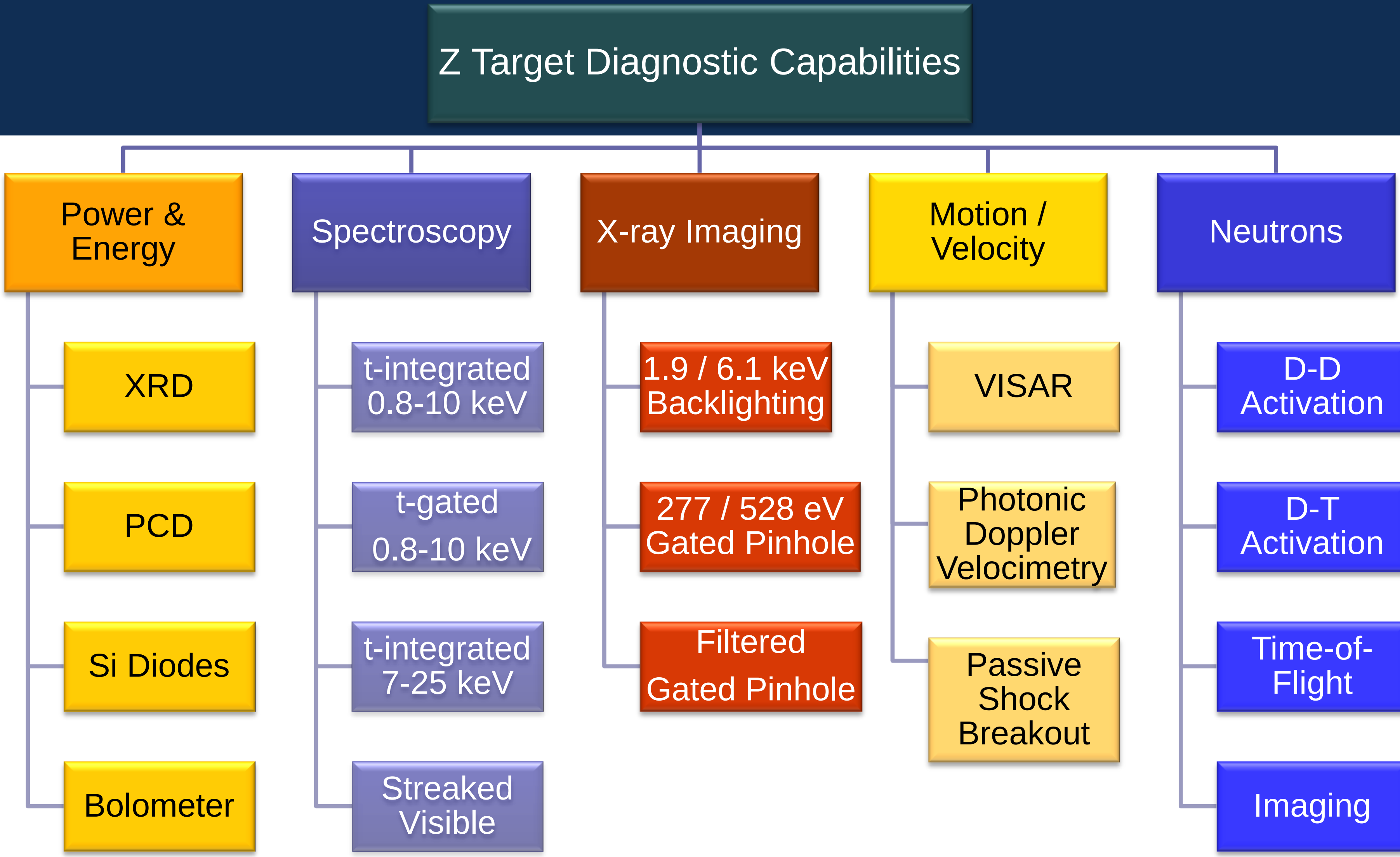


$$Y_{DD} = \frac{1}{2} n_D^2 \langle \sigma v \rangle_{DD} V \tau$$

Yield, Volume, Duration

Consistent with DD reactivity

Gomez et al., PRL 113 (2014); Schmit et al., PRL 113 (2014); Hahn et al., RSI 85 (2014)



These broad categories represent hundreds of different diagnostic configurations and fielding locations