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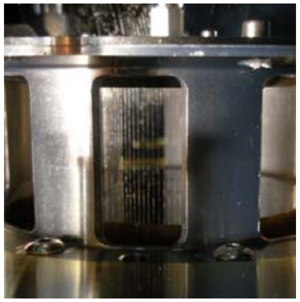

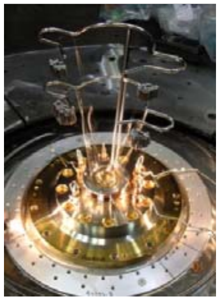

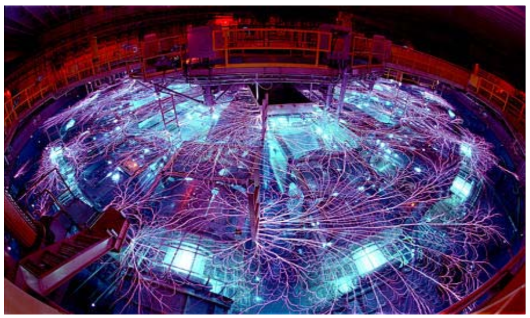

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Neutron Diagnostics on the Z machine

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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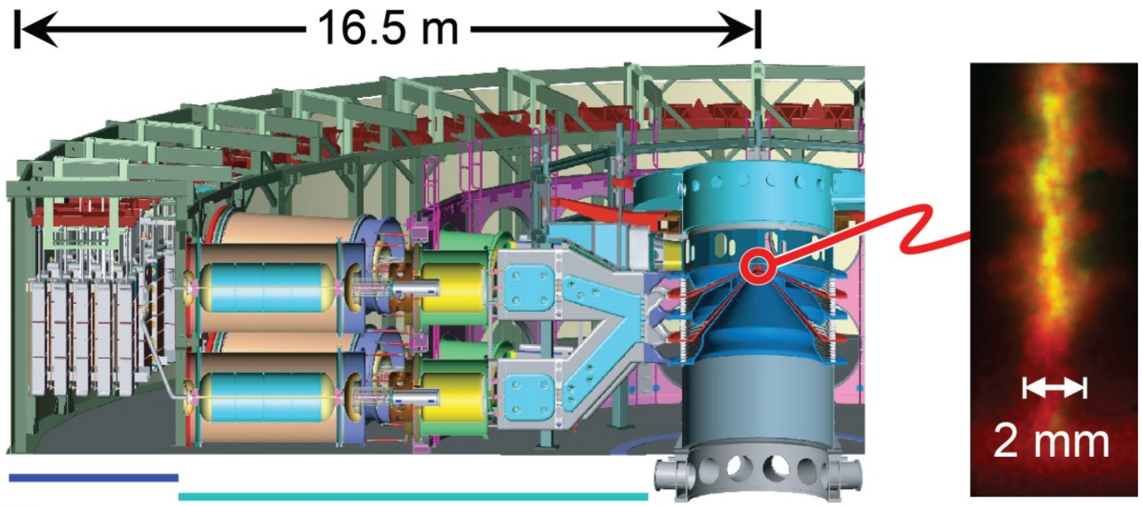
Overview

- **The Z machine and pulsed power ICF neutron sources**
- **Summary of the Z neutron diagnostic suite**
- **Sandia IBL neutron calibration source**
- **Interesting physical effects in nTOF data on Z**
- **Challenges in fielding nTOF and other neutron diagnostics at Z**

Pulsed power on Z provides extremely efficient coupling of energy to targets to generate high energy densities

20 MJ stored electrical energy



Energy Storage Section

Pulse Forming Section

Vacuum Section

Z-Pinch Radiation Source

1-2 MJ total radiated x-rays

10s-100s kJ K-shell x-rays

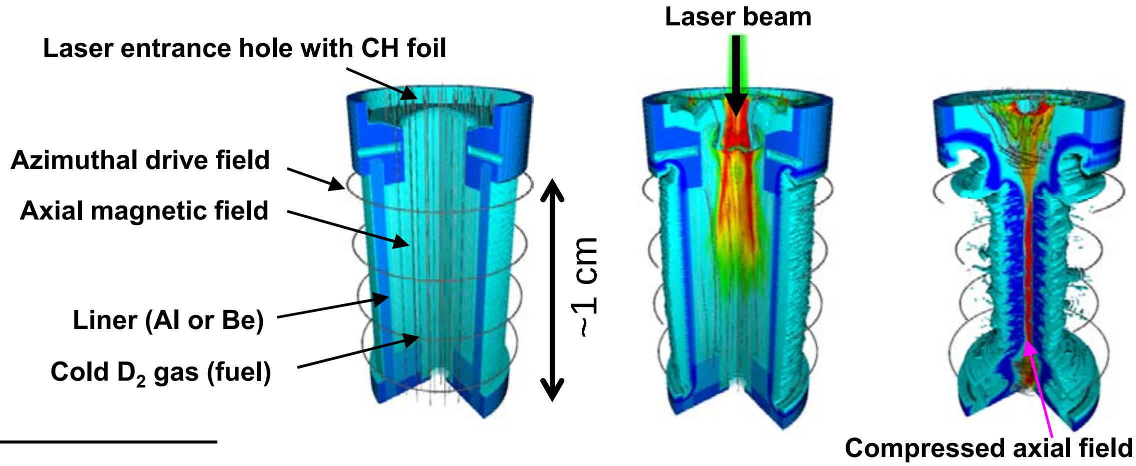
Up to 4 x 10^{13} DD neutrons

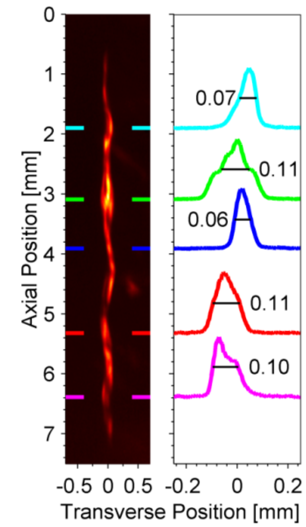
- 15% conversion of wall-plug electrical energy to radiated x-ray energy is demonstrated in wire array implosions
- Total energy of several MJ is coupled to the load region

M. C. Jones *et al.*, RSI **85**, 083501 (2014).

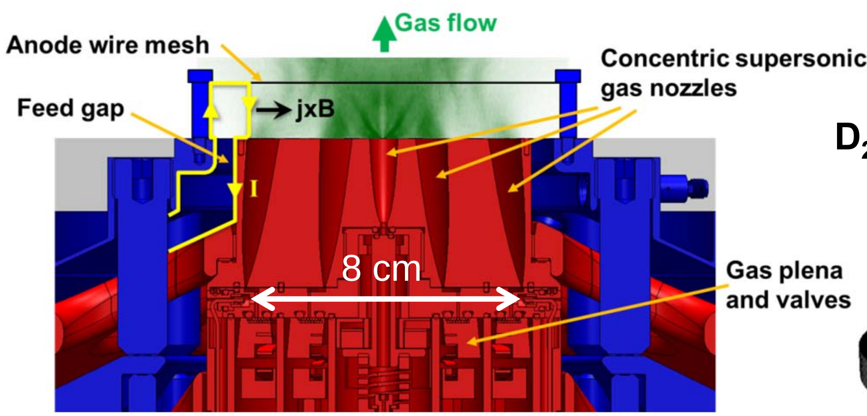
ICF neutron sources at Z can have very different implosion dynamics and plasma conditions

MagLIF

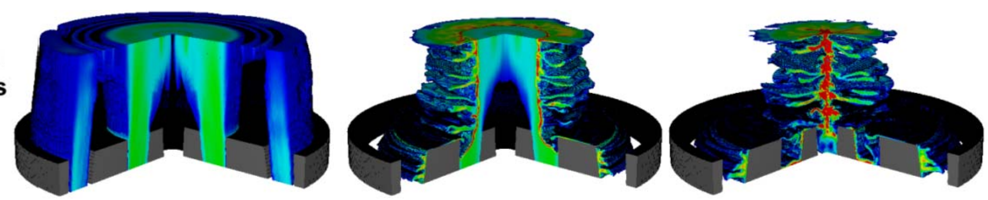




D_2 gas puff

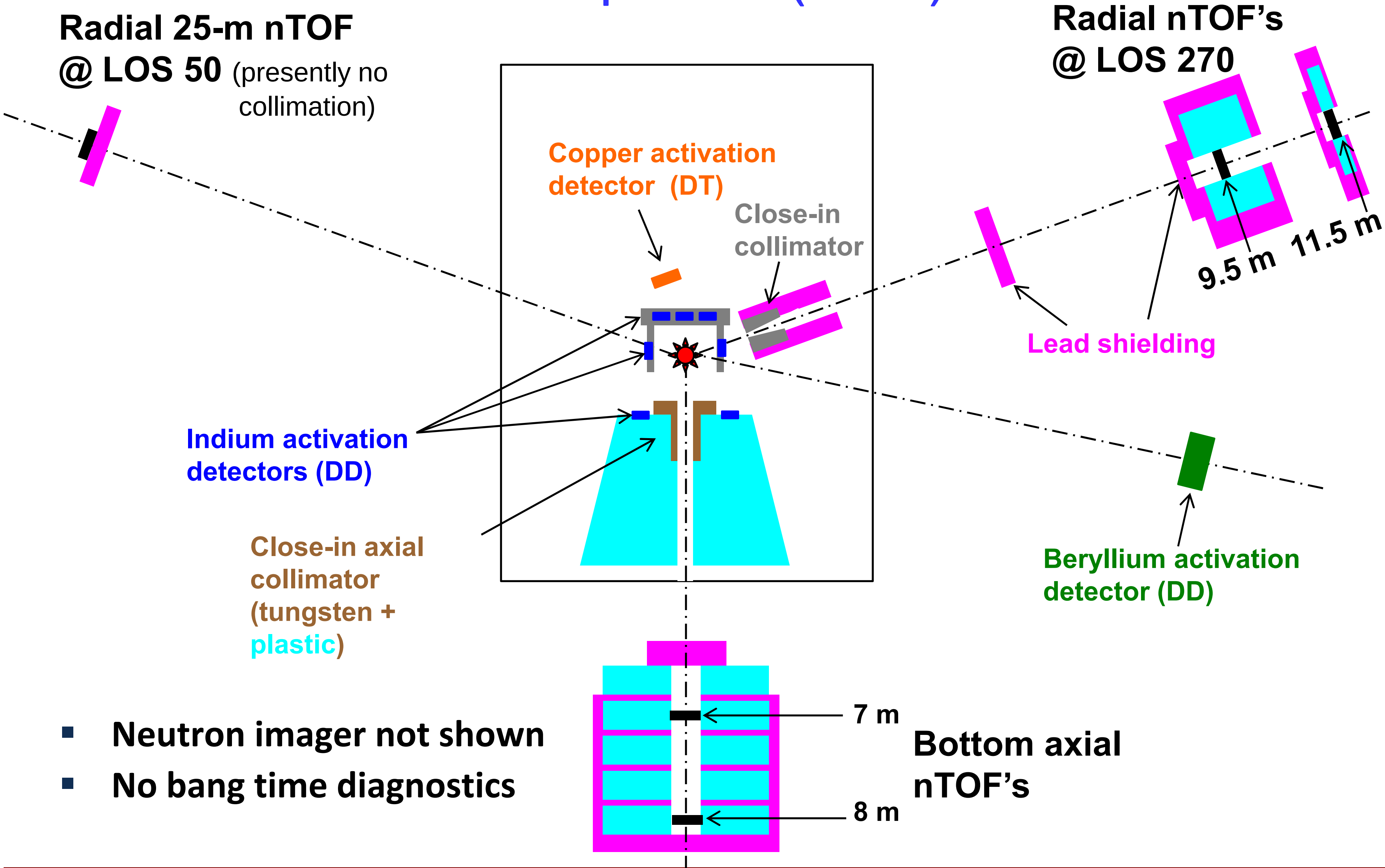


MagLIF: M. R. Gomez *et al.*, accepted to PRL (2014).
D_2 gas puff: C. A. Coverdale *et al.*, PoP **14**, 022706 (2007).



	Y_n(DD)	Y_n(DT)	T_e (keV)	T_i (keV)	n_i (cm^{-3})	Δt (ns)	Diameter
MagLIF	2×10^{12}	5×10^{10}	~3	2.5	~ 10^{23}	< 2	~50 μm
D_2 gas puff	4×10^{13}	<4×10^{9}	2.2	~10	2×10^{20}	~30	6 mm

The Z neutron diagnostic suite characterizes yield (activation) and spectrum (nTOF)



- Neutron imager not shown
- No bang time diagnostics

For deuterium fuel experiments on Z, neutron yields are measured based on neutron activation of select materials

- **Primary DD yield**
  - **Indium***

    $^{115}In(n,n')^{115m}In$
    336-keV threshold
    4.5-hr half-life

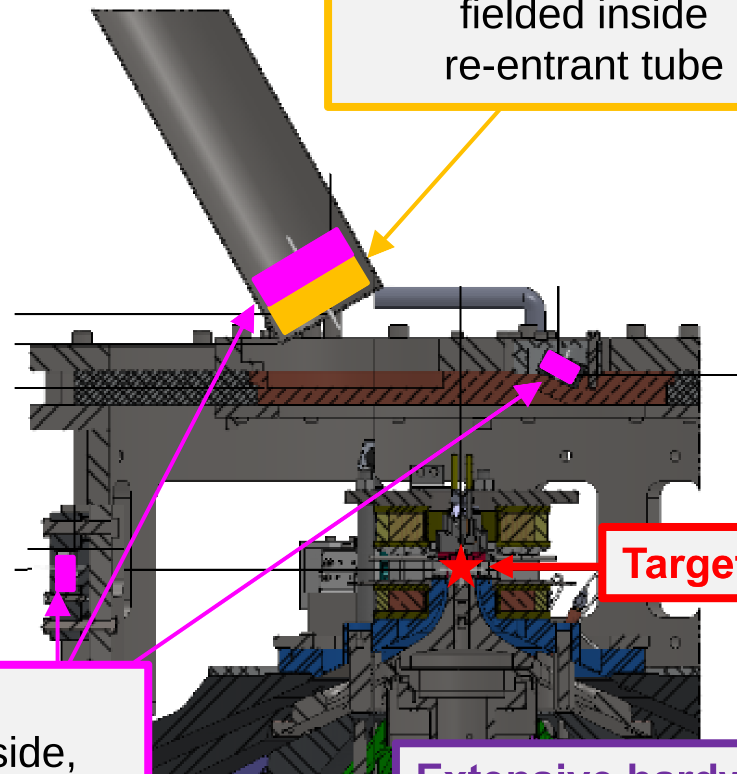
  - **Beryllium detector***

    $^{9}Be(n,\alpha)^{6}He(\beta-)$
    670-keV threshold
    0.8-sec half-life

- **Secondary DT yield**
  - **Copper***

    $^{63}Cu(n,2n)^{62}Cu(\beta+)$
    11-MeV threshold
    9.7-min half-life

Copper and indium fielded inside re-entrant tube



Target

Extensive hardware surrounds target.

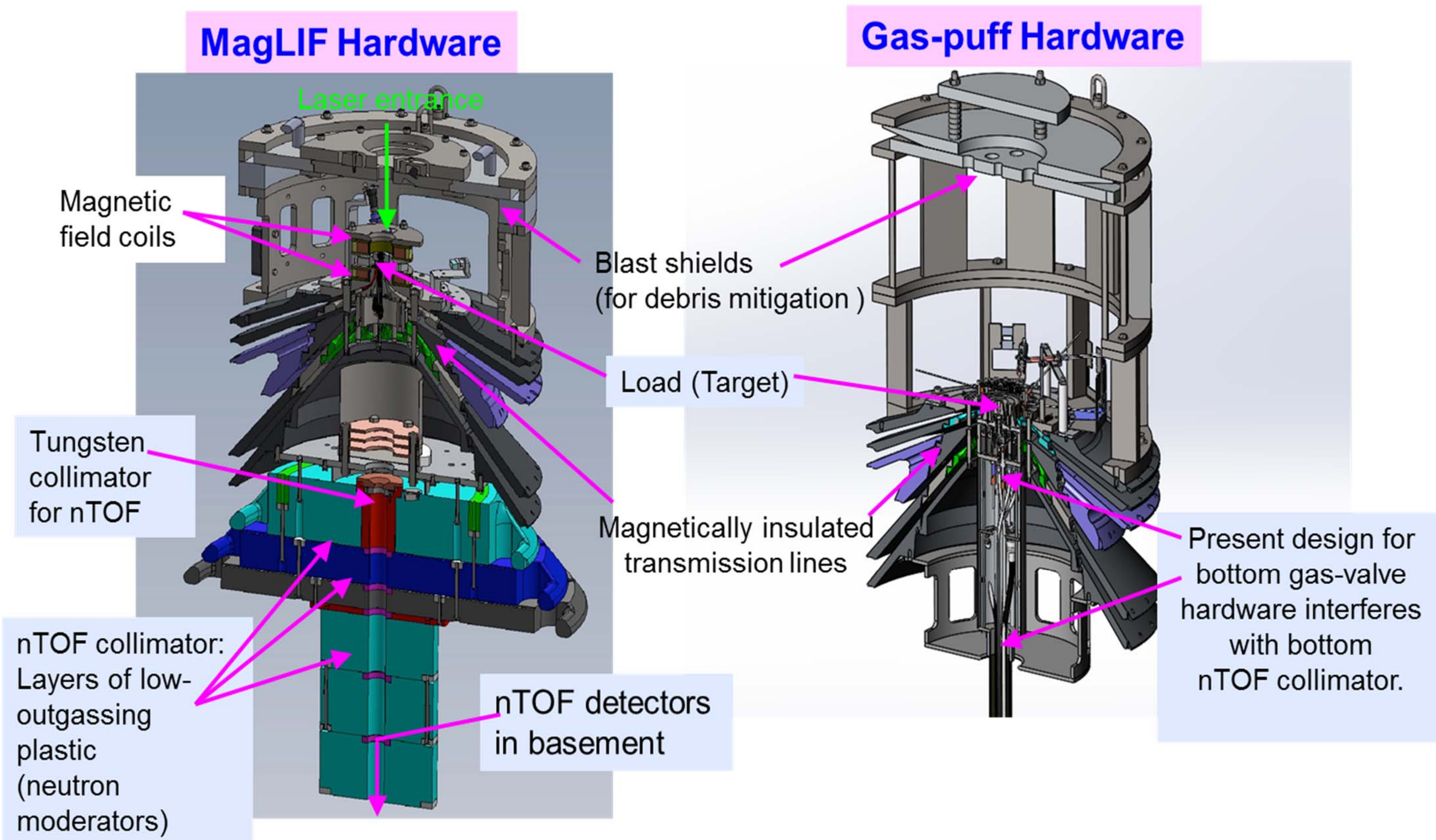
Brems can produce ~10^{10}-range equivalent yield; must corroborate activation yields with nTOF data

Indium
fielded on top, side, & bottom (not shown)

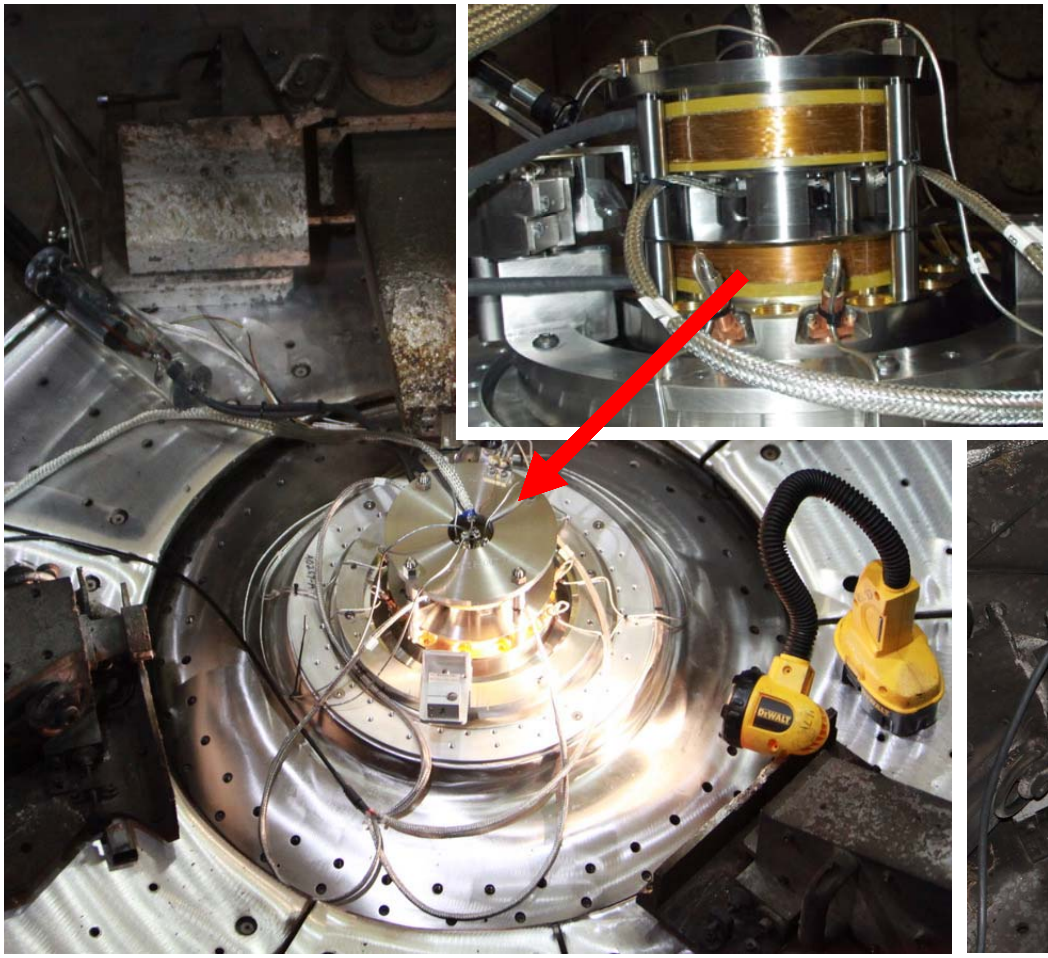
Neutron scattering from extensive hardware near target contributes > 30% to induced activity for most activation diagnostics on Z.

*Absolutely calibrated at Sandia's Ion Beam Laboratory.

Necessity of pulsed power transmission lines and blast shields leads to >30% scattering corrections



Z produces significant debris, which makes fielding diagnostics at less than ~25 cm a challenge



Pre-shot photo of coils & target hardware

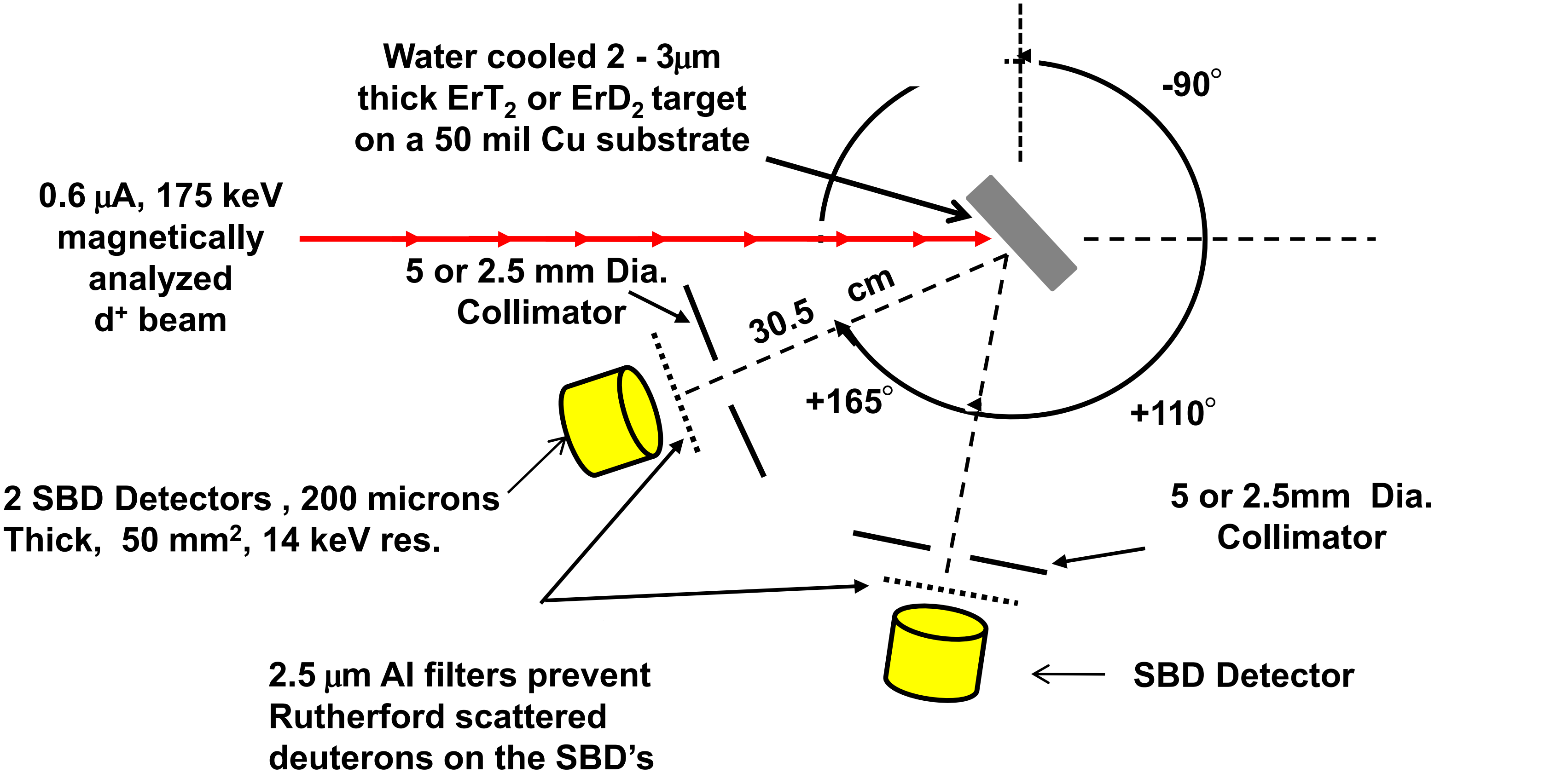
Post-shot photo

- **Debris from MagLIF experiments must be carefully managed (several MJ energy release equivalent to few sticks of dynamite)**

Sandia's Ion Beam Laboratory provides a valuable DD and DT calibration source for Z neutron diagnostics

Associated-particle technique employs the measurement of the ^{4}He (or p^+) particle emission from the dT (or dD) reaction

d + T → n (14.1 MeV) + ^{4}He(3.23 - 2.77 MeV) Q=17.6 MeV
d + D → T (1.01 MeV) + p (3.02 MeV) Q=4.04 MeV
→ ^{3}He (0.8 MeV) + n (2.45 MeV) Q=3.27 MeV



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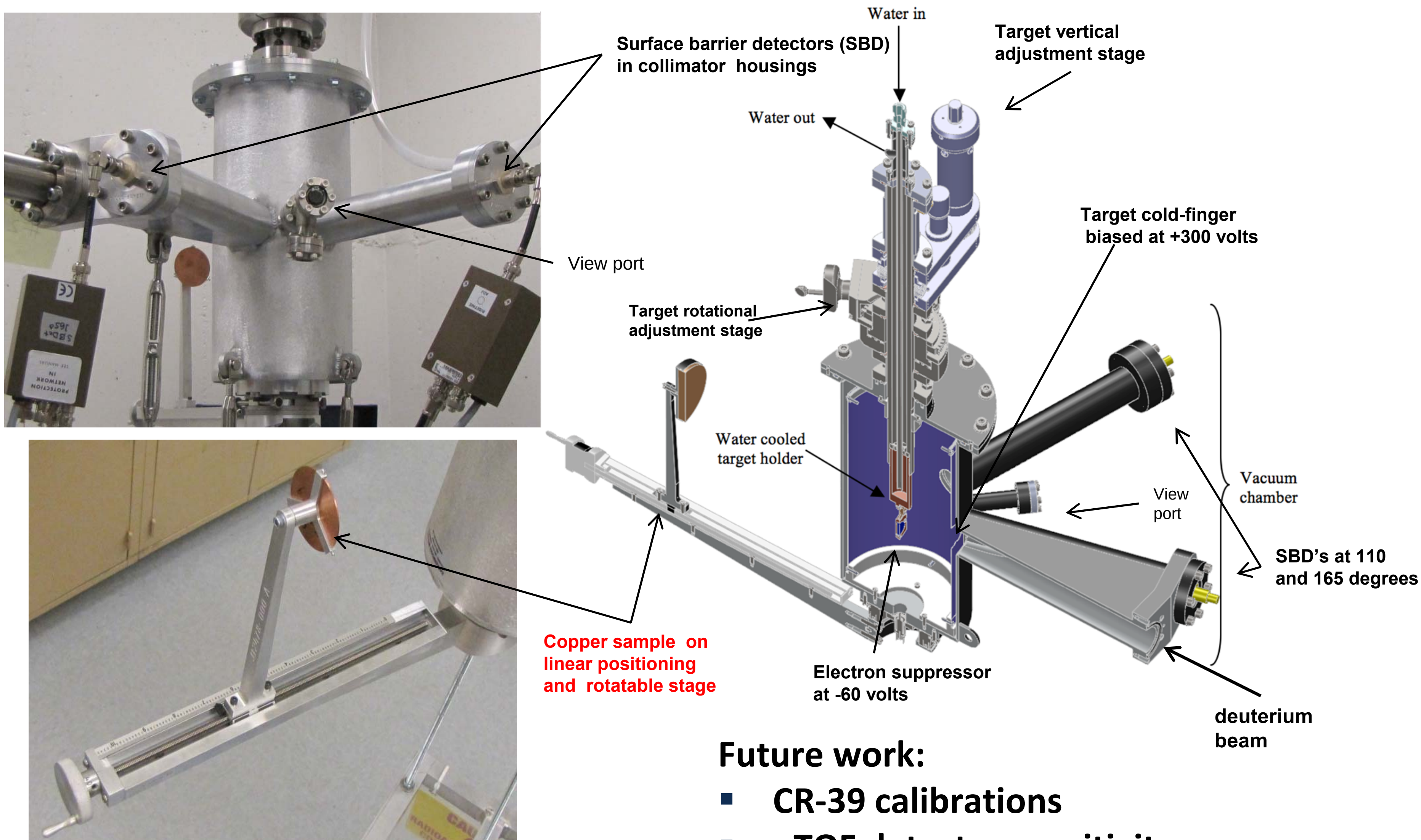


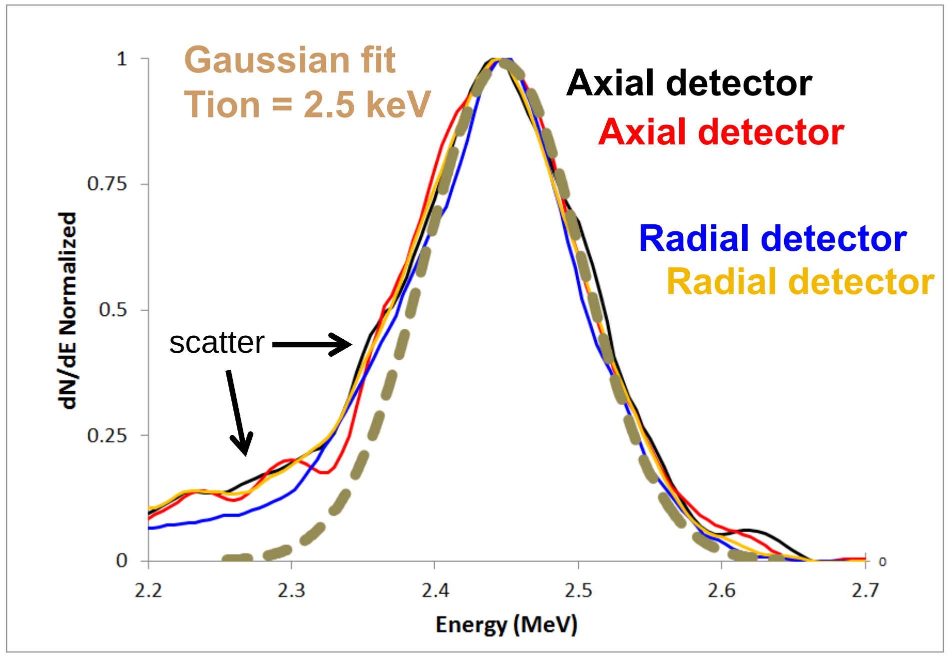
Future work:

- CR-39 calibrations
- nTOF detector sensitivity

The first set of integrated MagLIF experiments on Z have produced 2 x 10^{12} primary DD neutrons

2 kJ laser preheat
10 T applied axial B field
19 MA drive current
5×10^{11}-2×10^{12} primary DD yields
1-5×10^{10} secondary DT yields
Peak neutron energy ~2.45 MeV
2-3 keV ion temperatures
X-ray signal FWHM ~ 2 ns (implies burn time < 2 ns)
Near term improvements (increased laser coupling) may increase DD neutron yield

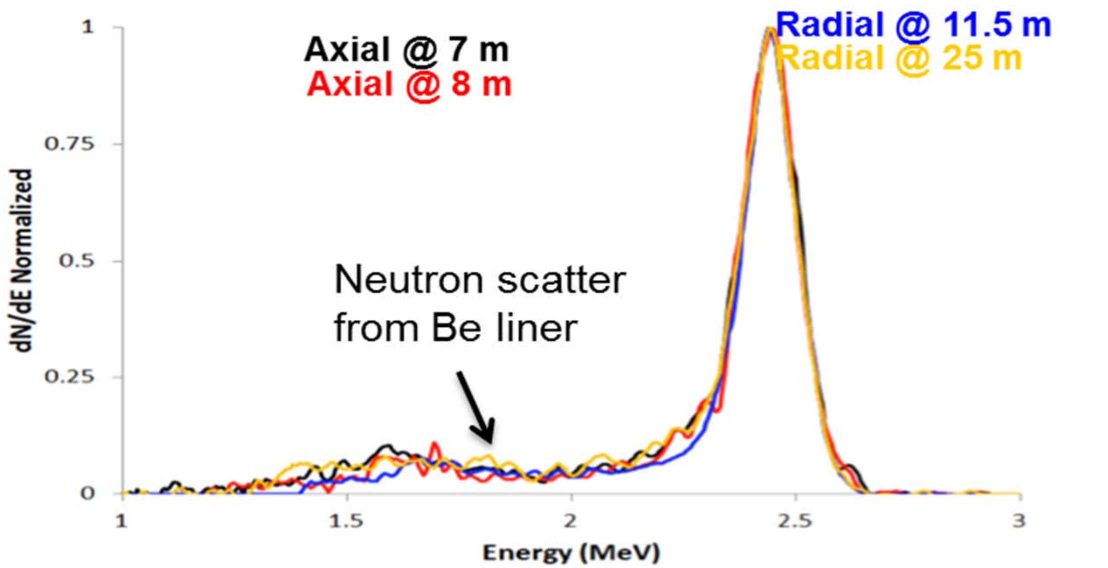
DD Neutron Spectra Inferred from nTOF

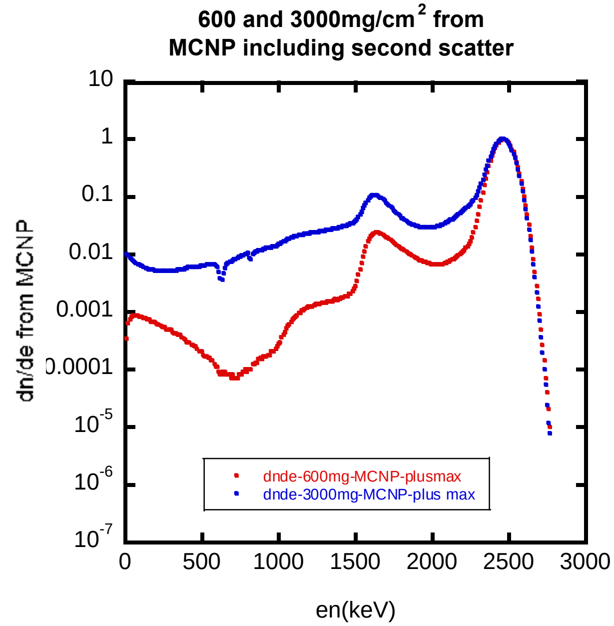


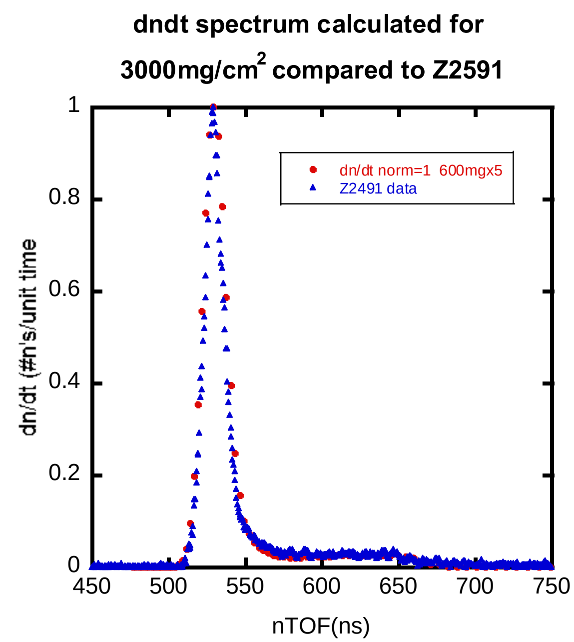
M. R. Gomez *et al.*, accepted to PRL (2014).
K. D. Hahn *et al.*, HTPD 2014.

Initial MagLIF experiments show that neutron production appears to be dominated by a thermonuclear process.

Neutron scattering from Be liner provides a measurement of MagLIF liner ρR

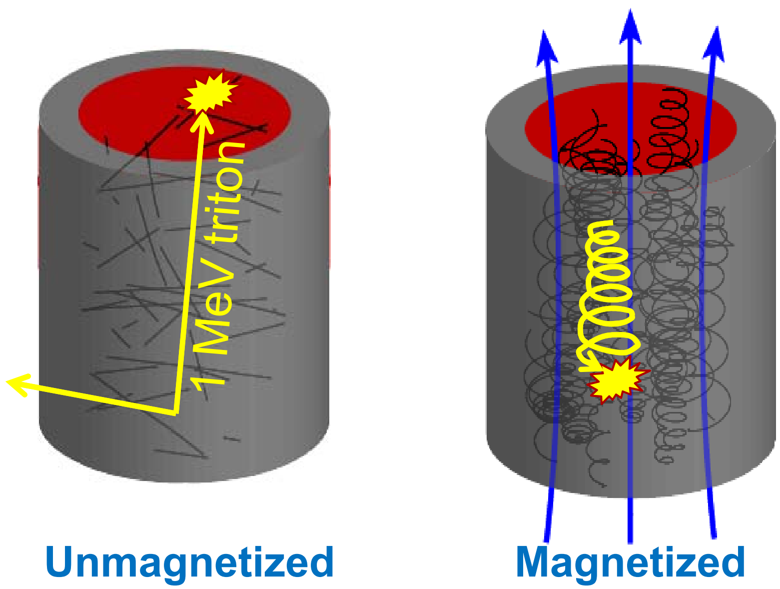


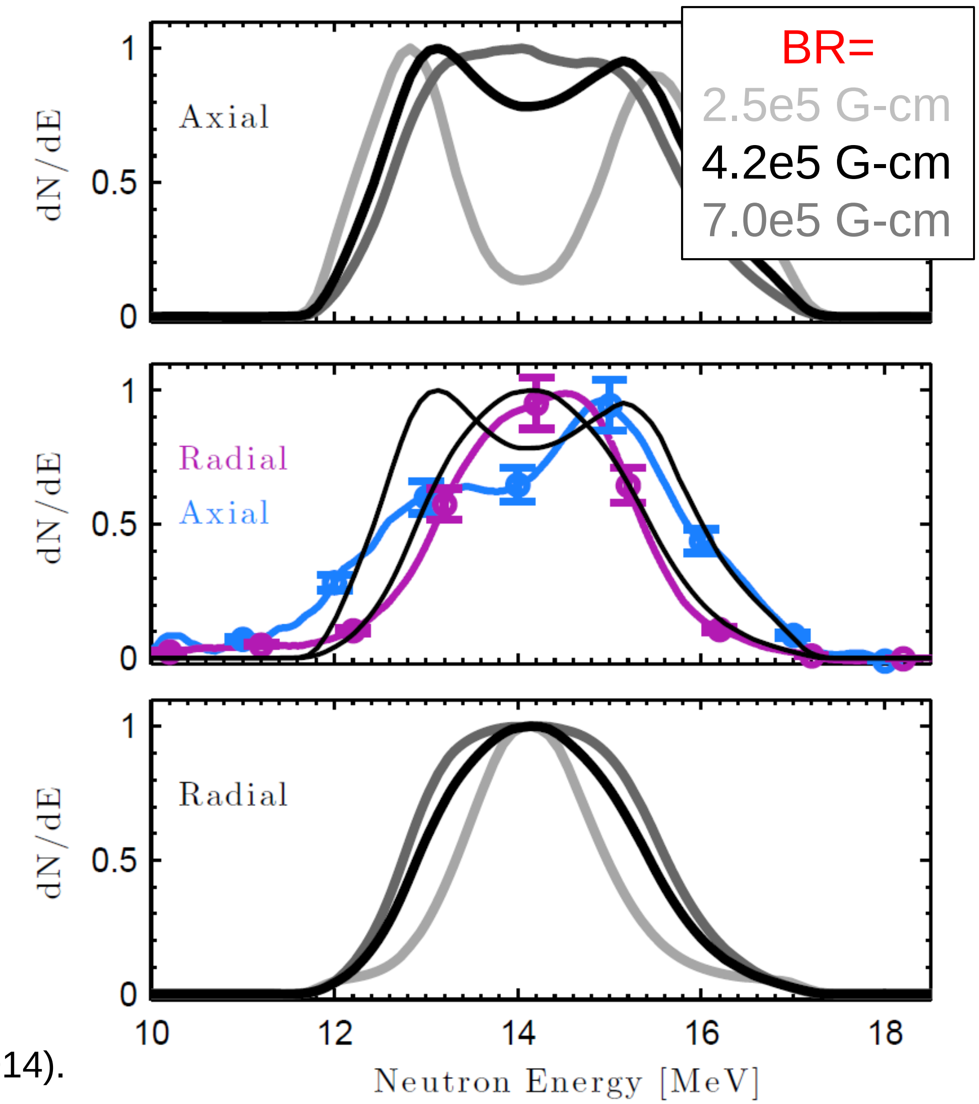




- Downscattered signal cannot be explained as nD scattering—requires too much fuel to reproduce the observed signal
- Peak near 1.5 MeV as expected from nBe scattering kinematics
- Inferred 3000 mg/cm^2 Be areal density can help to validate MagLIF implosion models

A comparison of side-on versus axial DT spectrum from MagLIF nTOF data is consistent with high magnetization

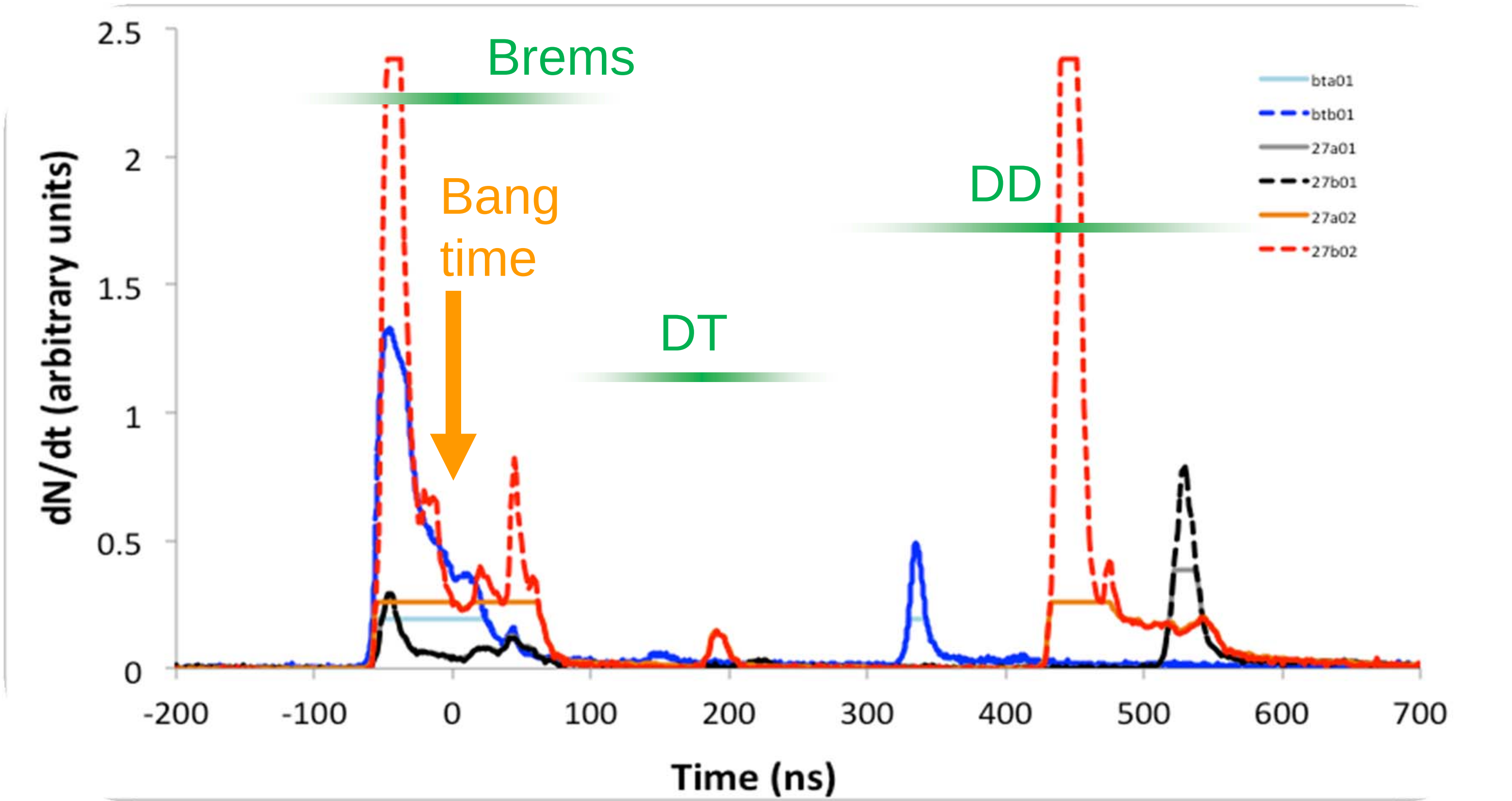




- **Cylindrical geometry leads to split nTOF peak from axial view, sensitive to BR**
- **ρZ replaces ρR as the effective areal density for secondary particle confinement**

P. F. Schmit, P. F. Knapp *et al.*, accepted to PRL (2014).
A. B. Sefkow *et al.*, PoP **21**, 072711 (2014).

Large hard x-ray/brems signals on Z are a challenge for capturing smaller DD and very small DT signals on nTOF

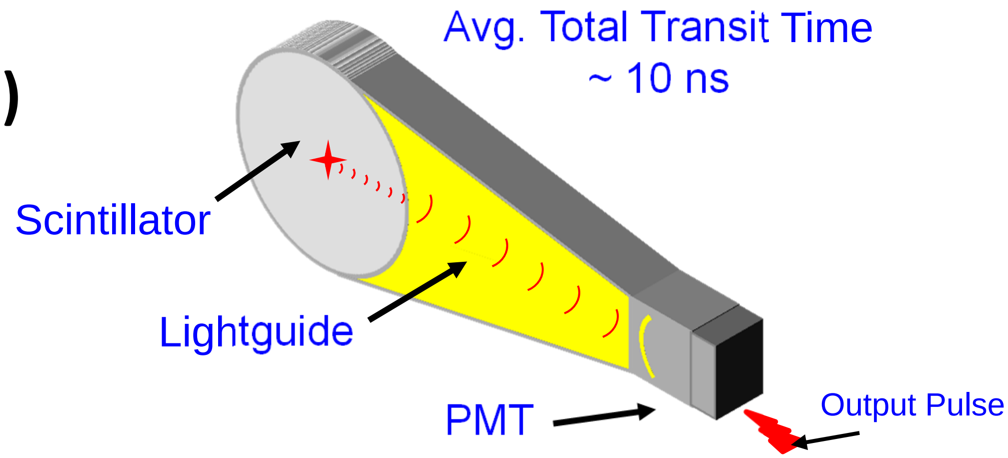


- Brems overdrives PMTs and scopes, which may not recover
- ~100 ns brems makes it difficult to field close-in detectors
- DT signal overlaps with scintillator recovery decay
- Dynamic range needed to record both DT and DD peaks

Neutron time-of-flight instruments on Z are developed in collaboration with NSTec

- **Present detectors use BC-422Q scintillators coupled to Hamamatsu R5946 (mod4) photomultiplier tubes (PMTs)**
  - High linear current
  - Recover quickly
  - Prior experience

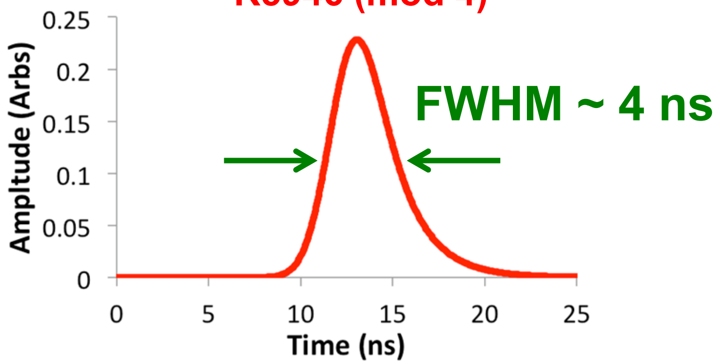
nToF Detector System



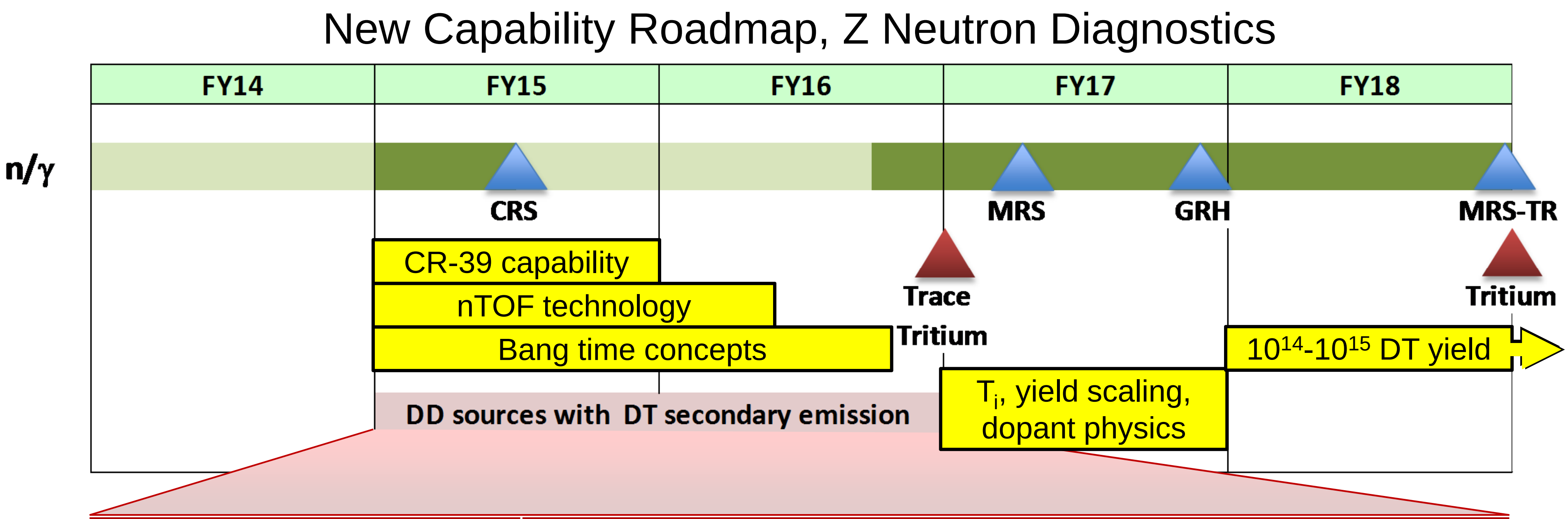
- **We are interested in advancing Z nTOF technology**
  - Low-afterglow scintillators
  - Gated PMTs
  - Photek and other vendors

PMT Instrument Response (IR)

R5946 (mod 4)



Until Z is capable of fielding tritium, we need to improve diagnosis of DD output with small DT component



Capability need	Notional starting requirement for impact
Spectroscopy	Mitigation of brems on nTOF detectors for DD/DT CR-39 capability for DD spectroscopy
Bang time/burn width	< 1 ns resolution of bang time, 1 ns res. burn history
Imaging	1D, < 250 μm resolution, 2 cm field of view, sensitive to < 1×10^{12} DD yield, time-integrated (CR-39?)

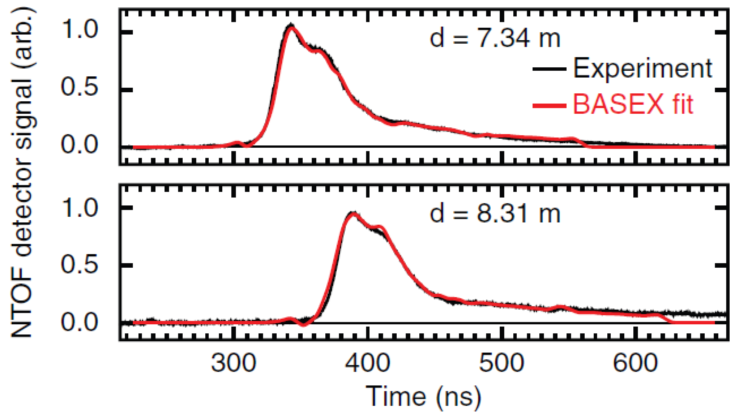
Summary

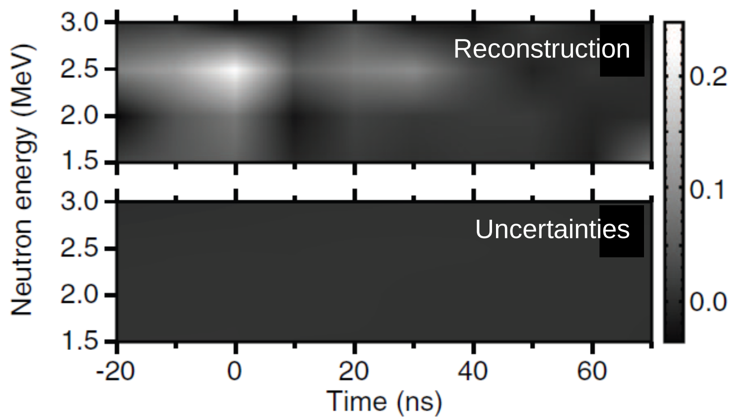
- **Pulsed power ICF experiments produce interesting plasma conditions and unique physical phenomena**
  - Neutron signatures of liner ρR and axial B field in MagLIF nTOF data
  - High-velocity, high-T_i plasmas in shock-heated gas puffs

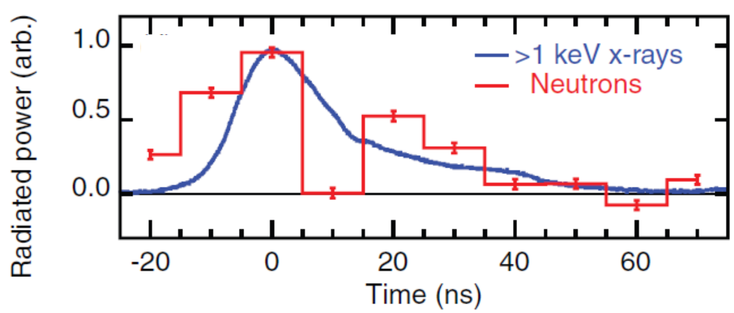
- **Neutron diagnostics on Z encounter challenging environments**
  - Present emphasis on DD spectrum, sensitivity challenges
  - Intense brems/hard x-ray pulses accompany neutrons
  - Significant debris requires mitigation

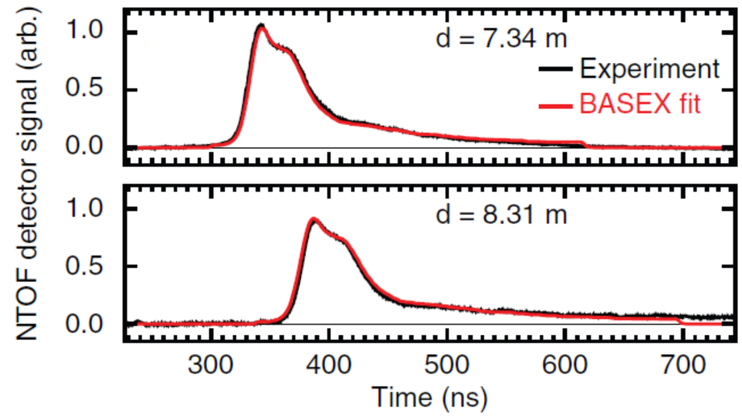
- **Advancing neutron diagnostic capability will help us to understand and optimize these ICF targets**
  - Gated MCP-PMTs and dual PMTs for improved dynamic range
  - Top axial nTOF to study beams and axial B field sensitivity
  - Closer (further) nTOFs for improved temporal (spectral) information
  - Burn history: CVD diamonds, Thomson parabola, gas Cherenkov
  - CR-39 processing capability, enabling future CRS/MRS diagnostics

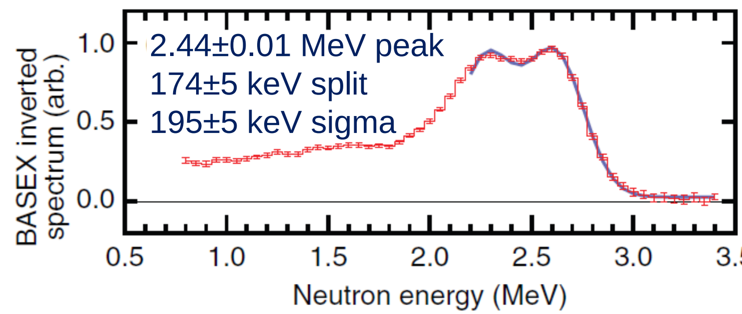
Broad nTOF pulses from gas puffs could indicate high T_i or time-dependent neutron emission











- **Basis set reconstruction can match nTOF data with time dependence or with complex spectral shape**
- **Both show downscattering, likely from surrounding hardware**
- **More nTOF locations and advanced analysis are required**