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FUSION-NEUTRON MEASUREMENTS FOR MAGNETIZED LINER INERTIAL FUSION EXPERIMENTS ON THE Z ACCELERATOR*

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The work presented here involves a large group of collaborators.

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Presentation Highlights

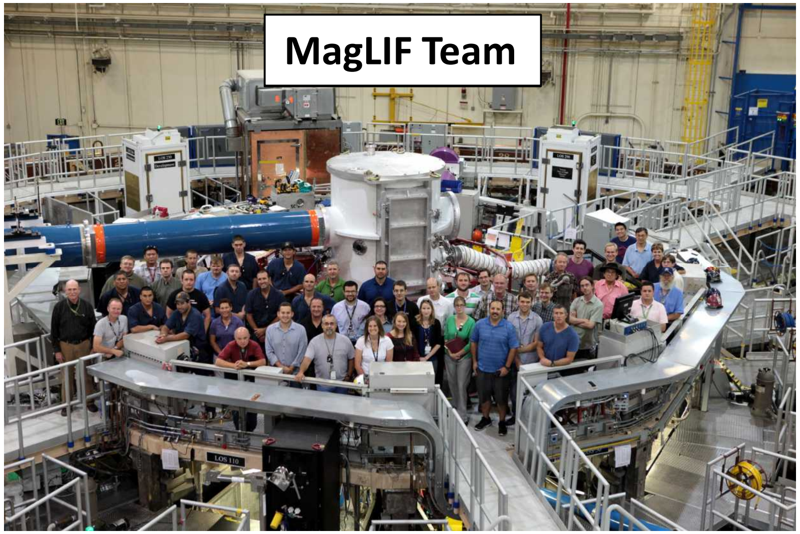
- Several magnetized liner inertial fusion (MagLIF) experiments[1-2] have been conducted on the Z accelerator[3] at Sandia National Laboratories since late 2013.
- Measurements of primary DD neutrons for these experiments suggest that the neutron production is thermonuclear.[4-5]
- Primary DD yields up to 3e12 with ion temperatures ~2-3 keV have been achieved.
- Measurements of secondary DT neutrons indicate that the fuel is strongly magnetized.[6-7]

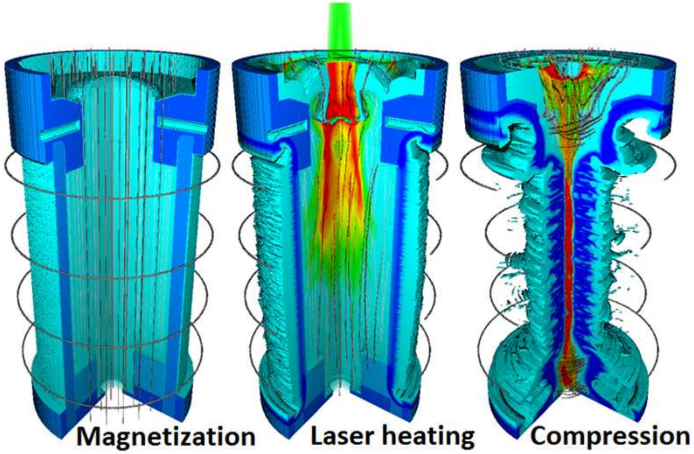
Presentation Highlights

- Measurements of down-scattered neutrons from the beryllium liner suggest ρR_{liner} ~ 1 g/cm^2.
- Neutron bang times, estimated from neutron time-of-flight measurements, coincide with peak x-ray production.
- We plan to improve and expand the Z neutron diagnostic suite to allow us to measure the following:
  - Neutron burn history.
  - Neutron time-of-flight spectra with increased sensitivity and higher precision.
  - Neutron recoil-based yield and spectra.

Outline

I. **Introduction**
II. **MagLIF experiments on Z**
III. **Neutron diagnostics on Z**
IV. **Diagnostic results**
   A. Yields
   B. Ion temperatures
   C. Fuel magnetization
   D. Liner areal density
   E. Burn and bang times
V. **Comparisons to simulations**
VI. **Proposed DT fuel experiments**
VII. **Collaborations and future work**
VIII. **Summary**





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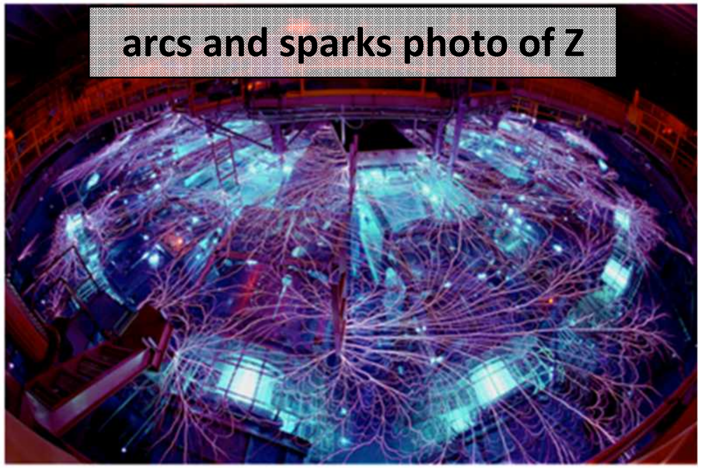
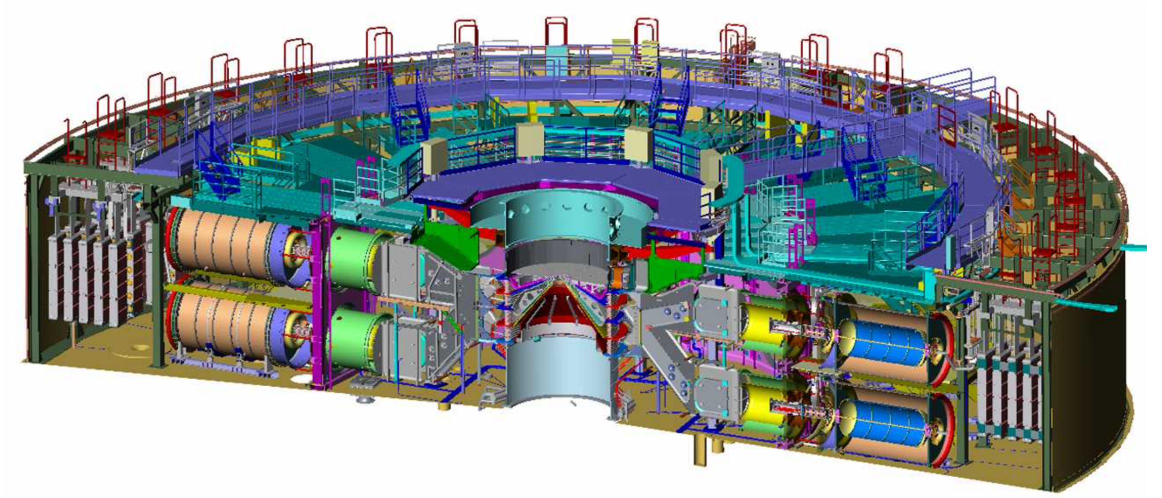
Diagnosing the neutron production from ICF experiments is essential for assessing the plasma conditions of the target.

- The Z Accelerator at Sandia National Laboratories is the world's largest and most powerful pulsed-power accelerator.[3]



- We are conducting magnetized liner inertial fusion[1-2] (MagLIF) experiments on Z.

- On such experiments, we deliver 17-18 MA to the MagLIF target in 100 ns.



Cross-section of Z accelerator

We are characterizing the primary DD and secondary DT neutrons on MagLIF experiments.

- **Presently, we only use deuterium fuel on Z experiments:**

Primary DD reactions	$D + D \rightarrow$	T (1.01 MeV) + p (3.02 MeV)	~50%
	$\rightarrow$	He^3 (0.8 MeV) + n (2.45 MeV)	~50%
Secondary DT reaction	$D + T$(1.01 MeV) $\rightarrow$	He^4 (1.4-6.7 MeV) + n (11.8-17.1 MeV)	

- **We have observed the following:**
  - Thermonuclear neutron production.[3-4]
  - DD yields as high as ~ 3e12 with ion temperatures as high as 2-3 keV.
  - $\omega_c >> \nu_{coll}$ (based on secondary DT yield and spectral measurements[5-6]).
  - Liner areal densities ~ 1 g/cm^2 (based on spectral measurements of down-scattered neutrons).

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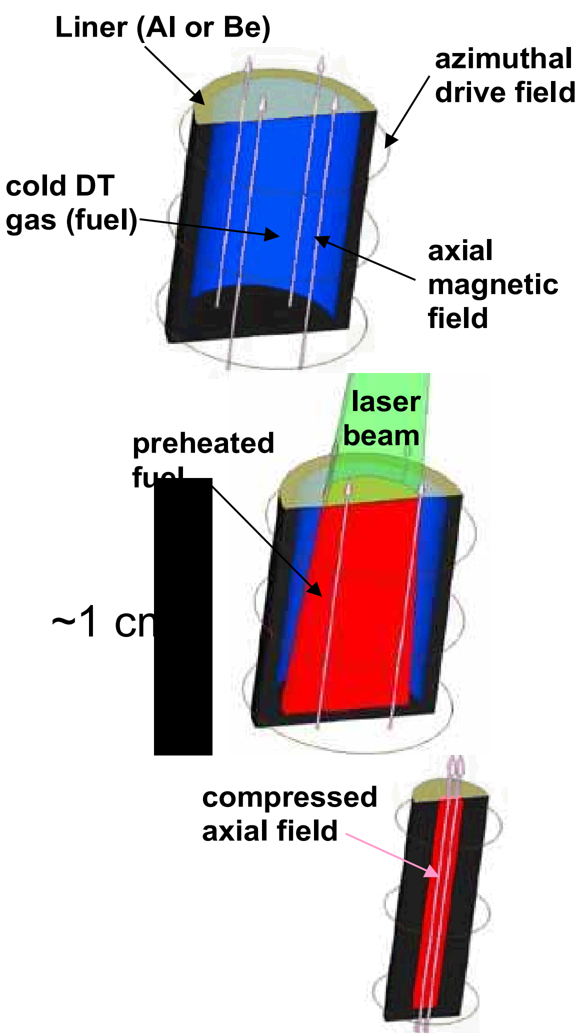
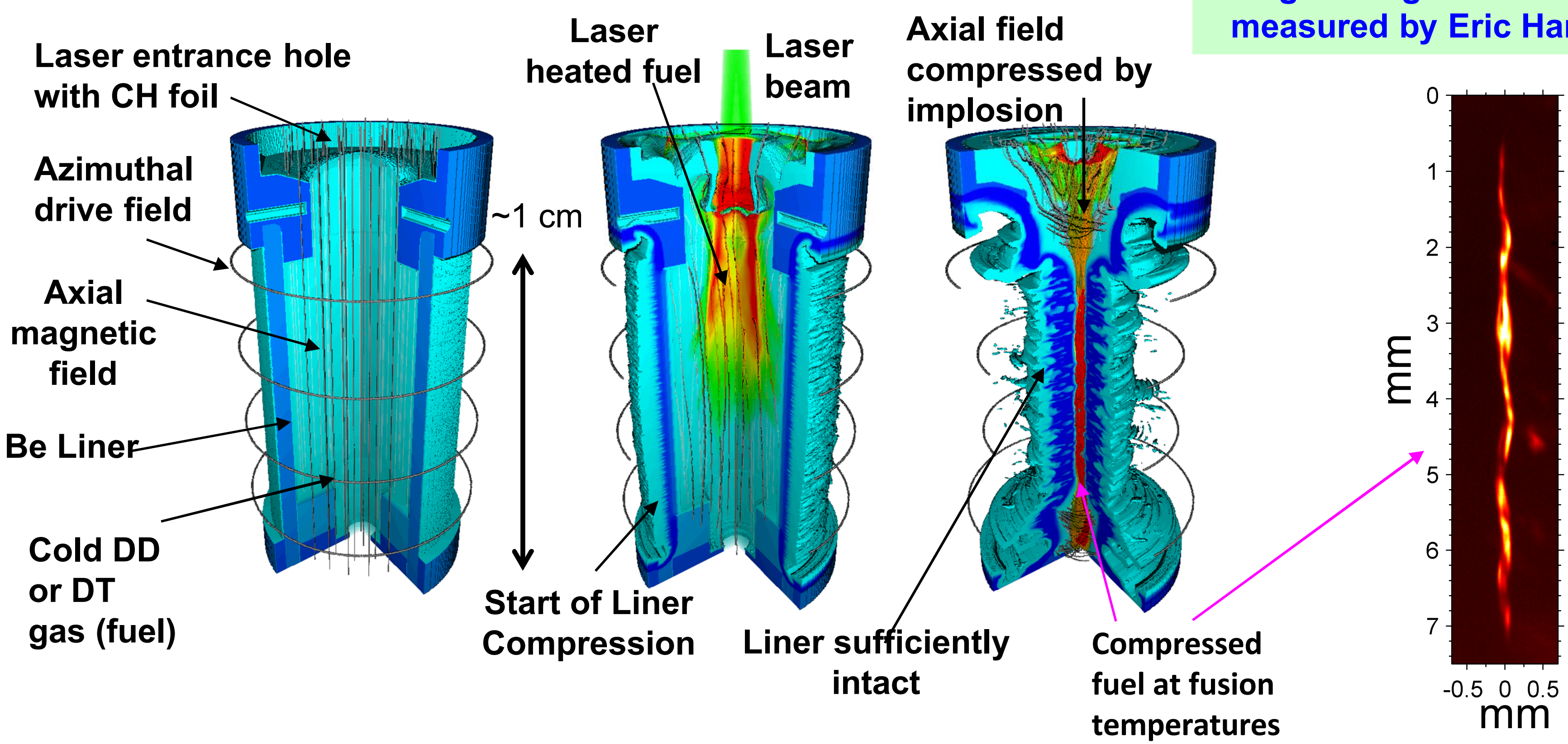
In principle, the MagLIF concept can achieve 100 kJ yield on Z (i.e., Fuel Gain = 1) using DT fuel.



- **This will require the following:**
  - **30-T applied axial magnetic field, which does the following:**
    - Inhibits thermal conduction losses.
    - Enhances alpha particle energy deposition.
    - May help stabilize implosion at late times.
  - **6 kJ Z Beamlet laser, which does the following:**
    - Preheats the DT fuel.
    - Reduces the convergence ratio needed to obtain ignition temperatures to R_o/R_f ~ 25.
    - Reduces the required implosion velocity to ~ 100 km/s.
    - Allows the use of a thick, more robust liner.
  - **26-MA, 100-ns current pulse from Z, which compresses the liner.**

Experiments have confirmed the expectation that fuel magnetization and preheat can help reduce fusion requirements (i.e., compression).

Image of compressed MagLIF target from z2613, measured by Eric Harding

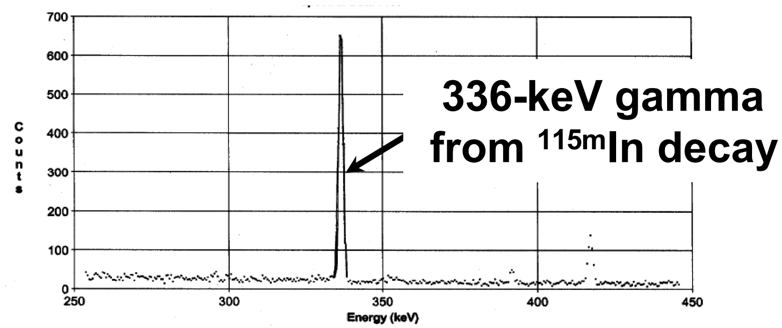


3-D Gorgon simulations by Chris Jennings.

Our primary fusion-yield diagnostics are based on neutron activation. [8-12]

- **We use the following three reactions:**
  - **$^{115}In(n,n')^{115m}In(\gamma)$**
    - For primary DD yield
  - **$^{9}Be(n,\alpha)^{6}He(\beta-)$**
    - For primary DD yield
  - **$^{63}Cu(n,2n)^{63}Cu(\beta+)$**
    - For secondary DT yield

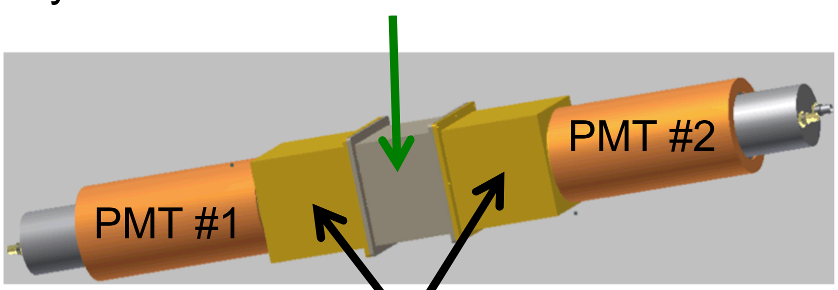
Indium Activation



The indium activation spectrum is measured using high-purity germanium detectors.

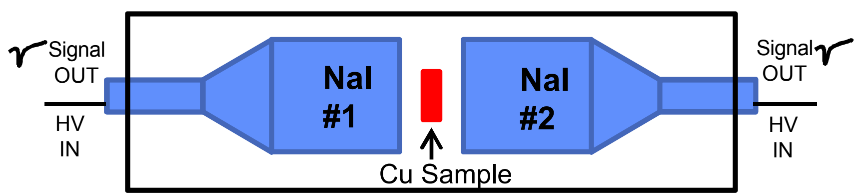
Beryllium Detector

Layers of Be and scintillator inside shield



Betas from ^{6}He decay deposit energy in scintillator, emitting light collected by two separate PMTs.

Copper Coincidence Counting System



Two NaI detectors detect the oppositely opposed 511-keV annihilation gammas (in coincidence) from positrons associated with ^{62}Cu decay.

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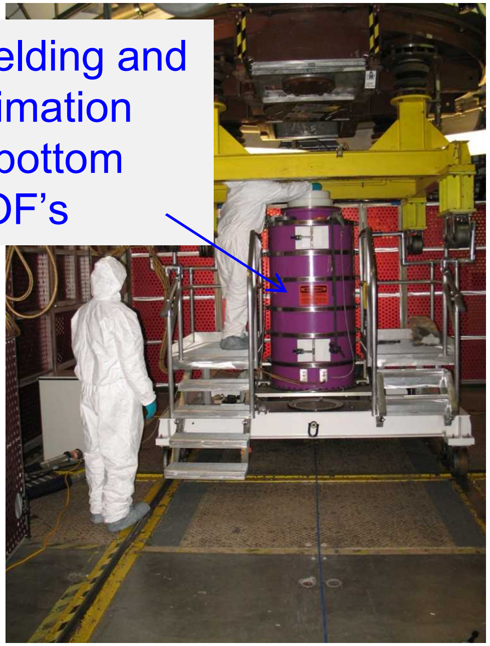
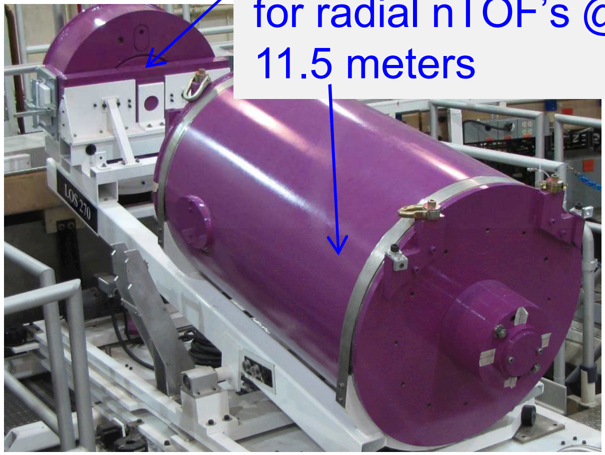
Neutron time-of-flight (nTOF) detectors[12-14] measure the neutron spectrum.

- **Six nTOF detectors are fielded on Z**
  - Two axial detectors are fielded at 7 and 8 meters, below the target.
  - Three radial detectors are fielded at 9.5, 10, and 11.5 meters.
  - One radial detector is fielded at 25 meters.

- **Detectors require extensive collimation and shielding to limit effects of neutron scattering.**
  - Most detectors also utilize a collimator fielded close to the target in addition to collimation and shielding around the detectors.

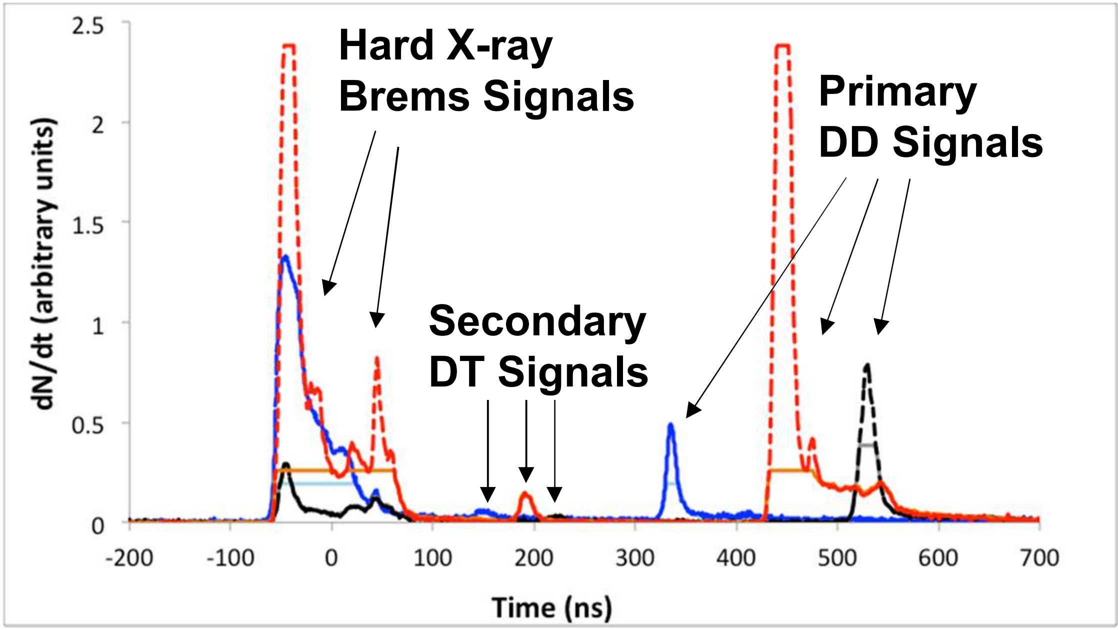




Most nTOF detectors (and others) are developed and characterized in collaboration with NSTec.

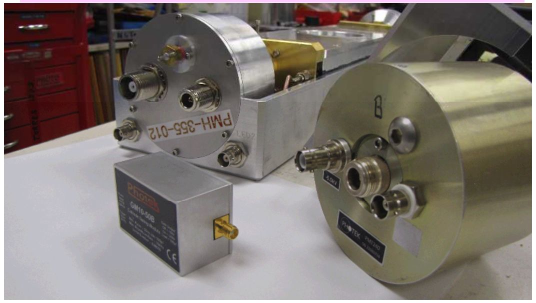
The intense bremstrahlung x rays produced during Z shots affect all of our neutron diagnostics.

- **The x rays have a hard spectrum with energies > 1 MeV, which have the following consequences:**
  - Produce large x-ray signals on the nTOF scintillators, which may saturate detectors.
  - Require several inches of Pb or W attenuation in front of the nTOF's.
  - Can contribute to indium activation (> 1 MeV) and even copper activation (> 11 MeV).



- **A gated Photek detector is being tested at Z to suppress the large x-ray signals in order to enhance the smaller DT and DD signals.[15]**
  - This work is in collaboration with LLE Omega's Vladimir Glebov.

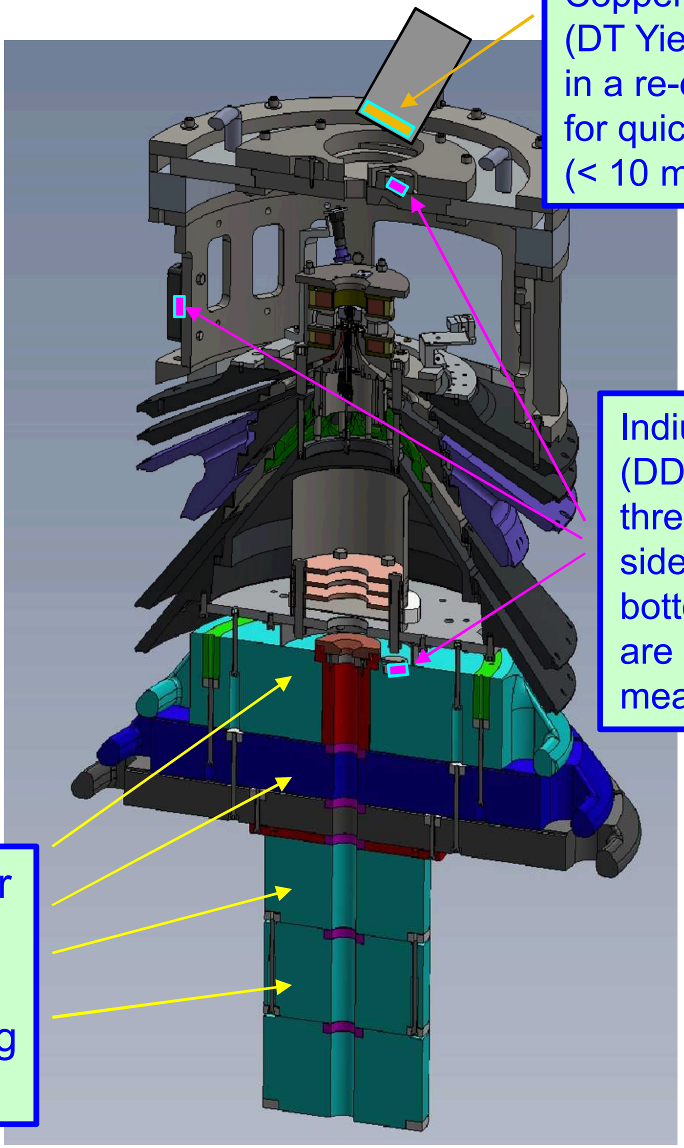
Gated Photek detector



[15] V. Yu. Glebov, *et al.* Rev. Sci. Instrum., **81**, 10D325 (2010).

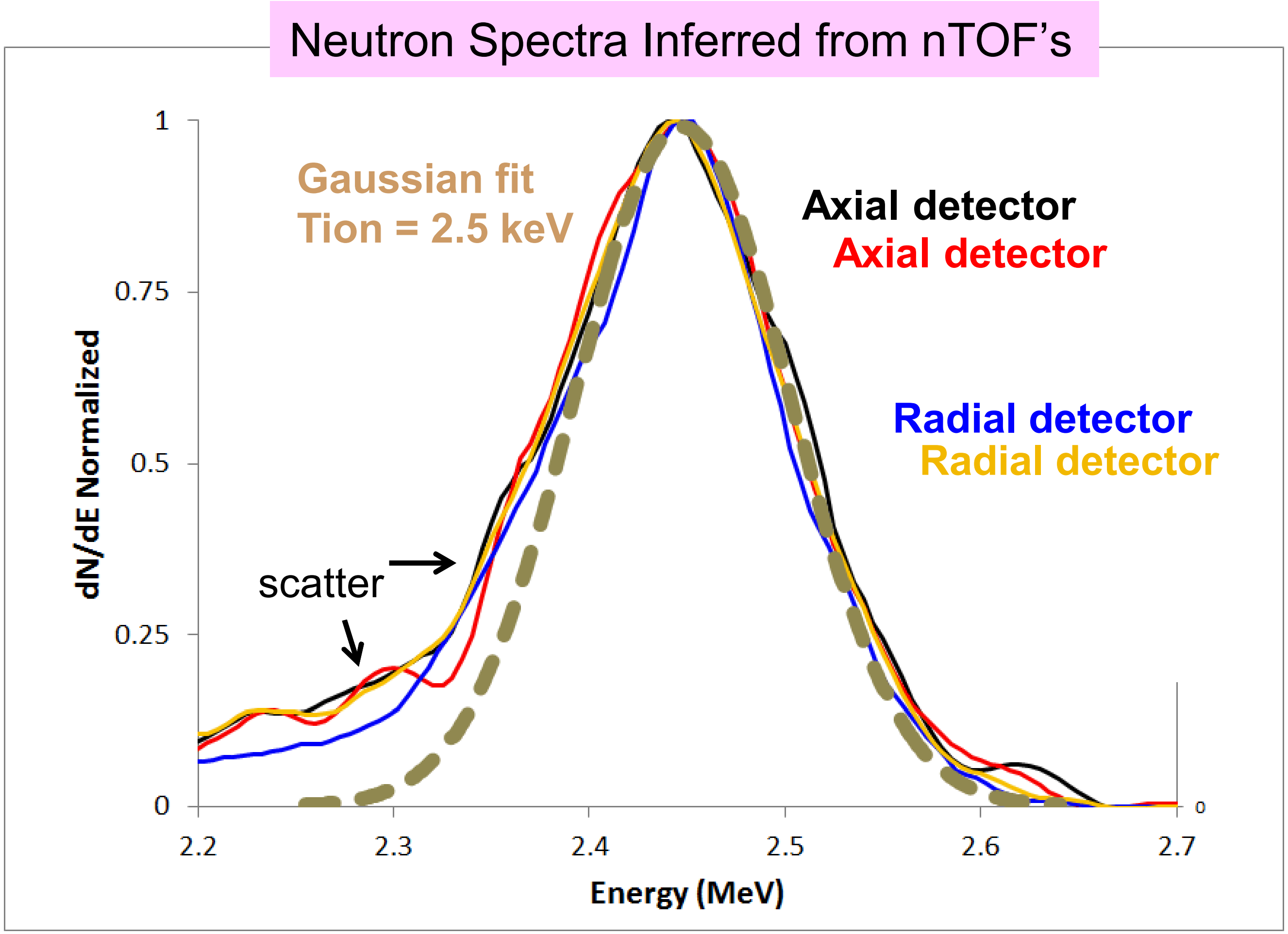
Extensive hardware near the target and other locations affect neutron measurements.

- **Detailed Monte Carlo[16] (MCNP) simulations are used to model neutron scattering.**
  - Scattering effects are ~20-50+% for most diagnostics.
  - Models are required to apply corrections to activation measurements for neutron yields.
  - nTOF models are also being developed to improve collimation and shielding designs and to infer yields.



MagLIF experiments show that neutron production is thermonuclear.

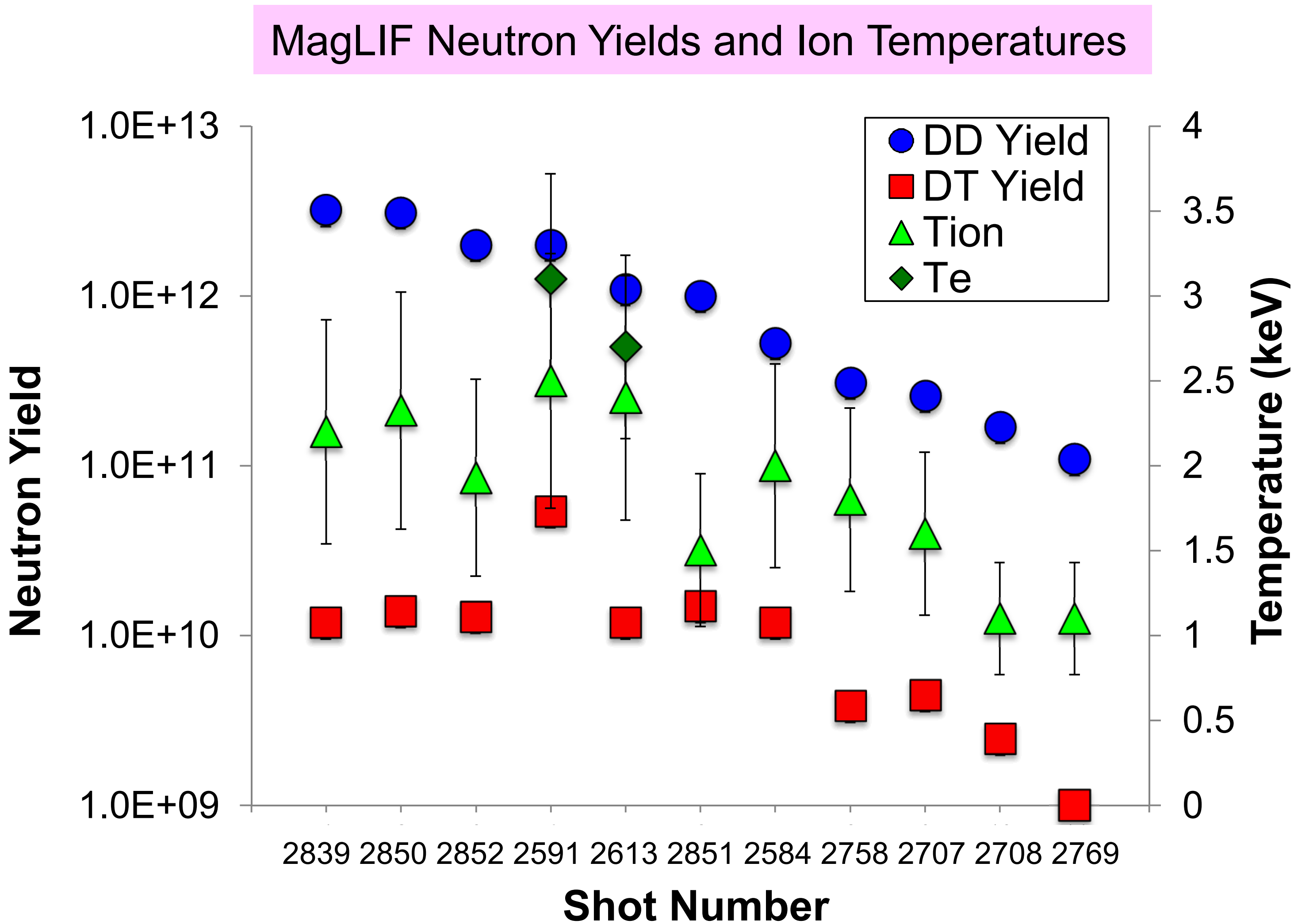
- **Primary DD yields are isotropic based on indium activation measurements.[4]**



[4] M. Gomez *et al.* Phys. Rev. Lett. **113**, 155003 (2014).

Neutron diagnostics provide a wealth of information about fusion plasmas.

Variations in target performance appear to be dominated by current delivery, laser energy deposition, and/or mix.



Detailed simulations[17] of Shot 2591 are in good agreement with measured neutron yields, ion and electron temperatures[18], and other parameters.

For MagLIF experiments, secondary DT measurements reveal information about magnetization.

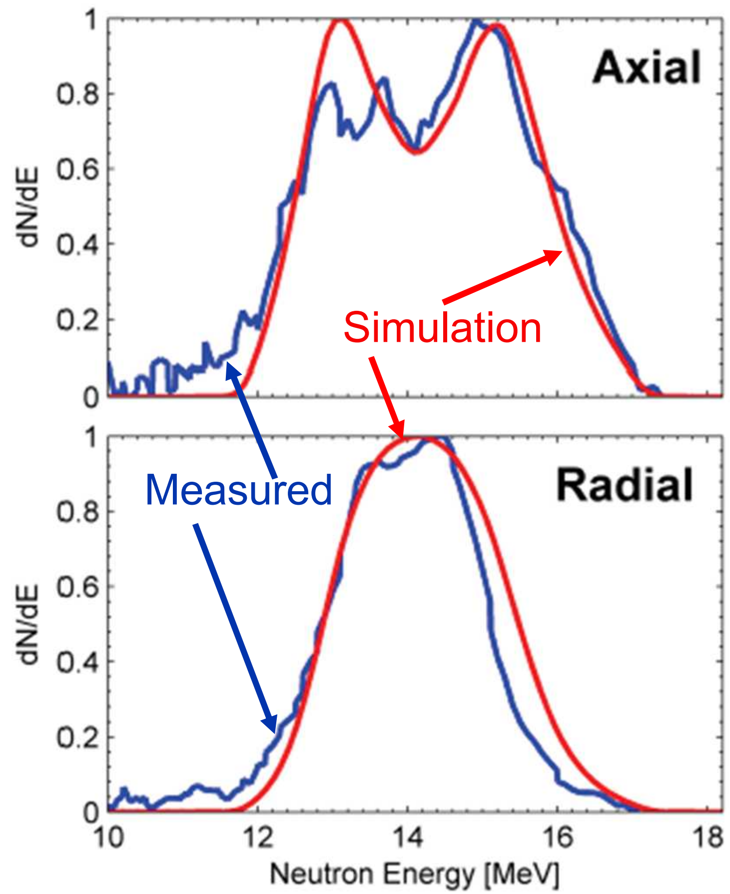
- **Measured secondary DT spectra (from nTOF's) and DT/DD ratios are used to infer degree of fuel magnetization.**

- **Based on simulated (red curves) fit to measured data (blue curves), $BR = 0.34$ MG-cm.[6-7]**
  - This follows from: $\frac{R_{fuel}}{R_\alpha} \cong 4BR$

    $R_\alpha \sim R_{triton}$

    $\omega_{c-triton}\tau_{triton-e} \sim \omega_{ce}\tau_{ee}$

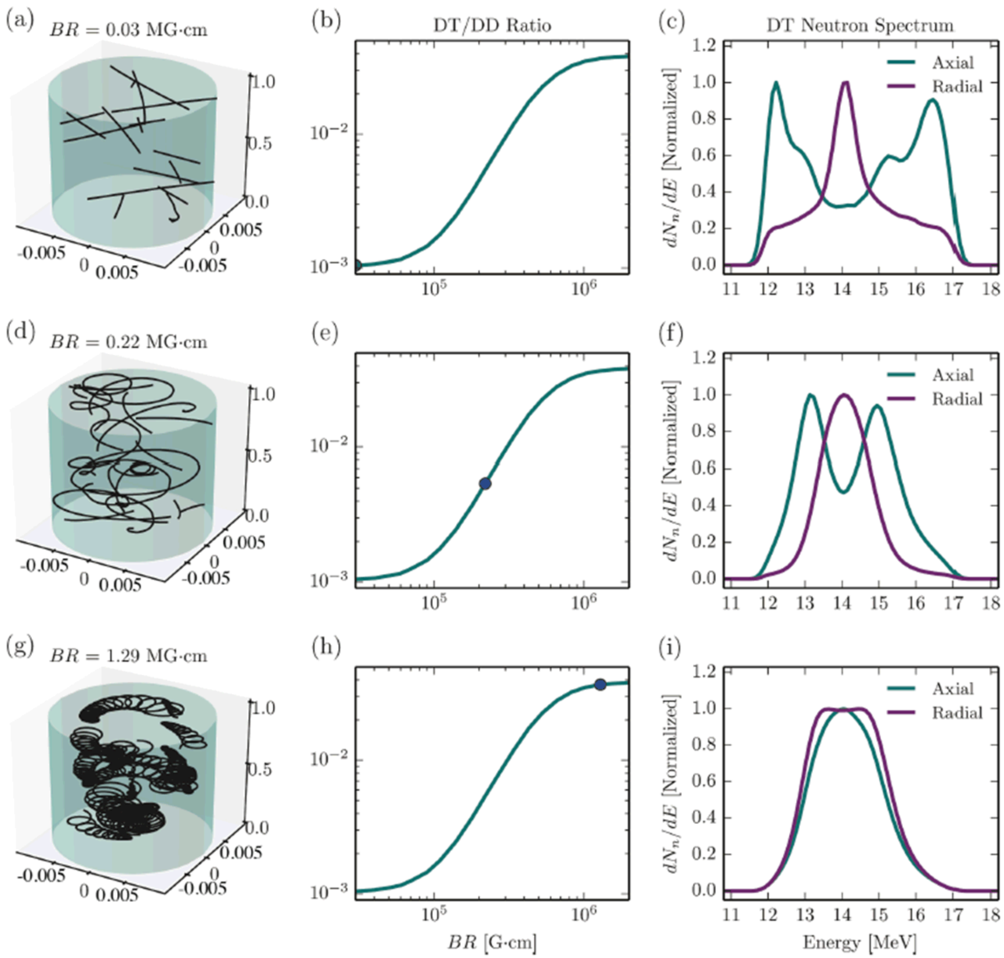
- **Asymmetry in axial and radial DT spectra is due to high-aspect ratio cylindrical geometry.**



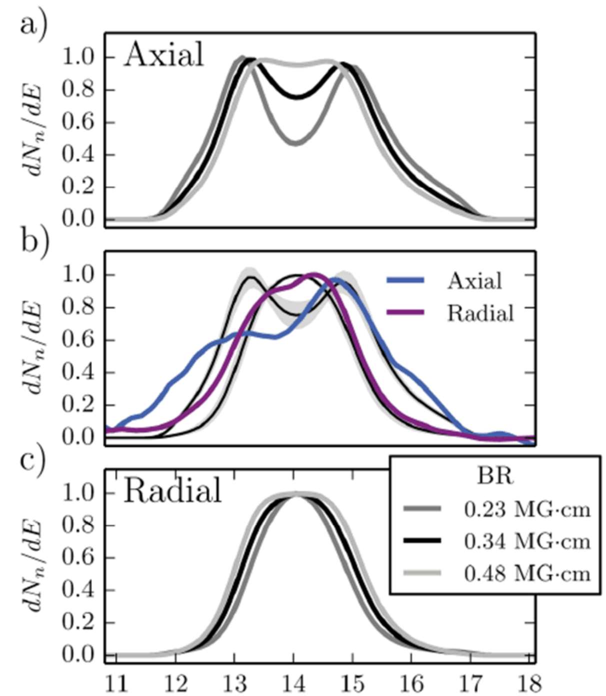
P. Schmit *et al.* Phys. Rev. Lett. **113**, 155004 (2014).
P. F. Knapp *et al.* Phys. Plasmas, **22**, 056312 (2015).

The parameter BR, not ρR, is the primary confinement parameter for magnetized ICF experiments.

Secondary DT spectral shapes are sensitive to the degree of magnetization.



$$\frac{R}{r_\alpha} = \frac{BR\,[T \cdot \mathrm{cm}]}{26.5} \approx 4BR\,[MG \cdot \mathrm{cm}]$$

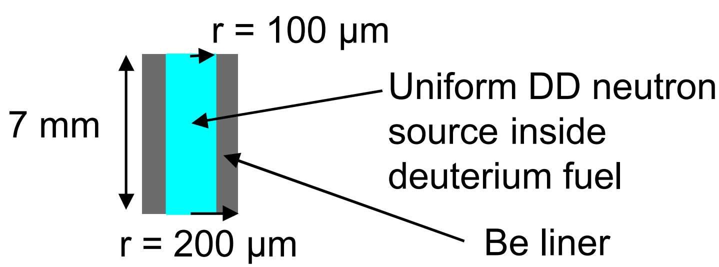


P. Schmit *et al.* Phys. Rev. Lett. **113**, 155004 (2014).
P. F. Knapp *et al.* Phys. Plasmas, **22**, 056312 (2015).

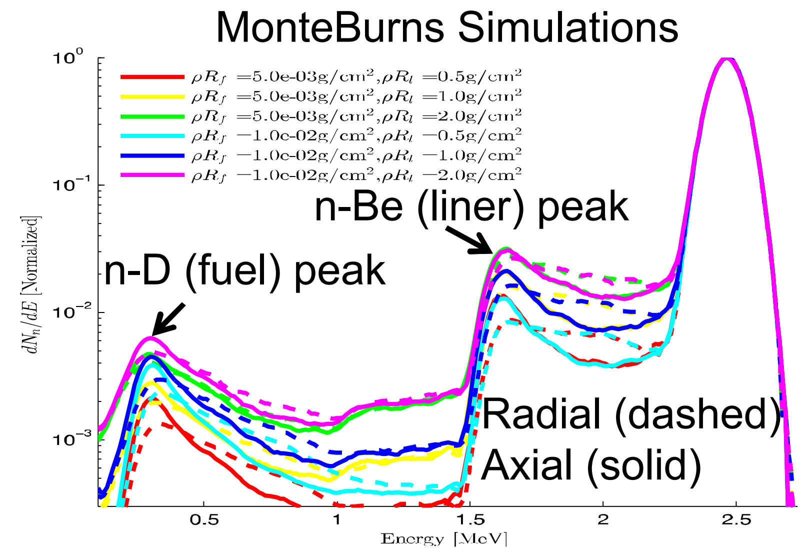
Based on DT measurements, we infer that tritons have deposited ~30% of their birth energy.

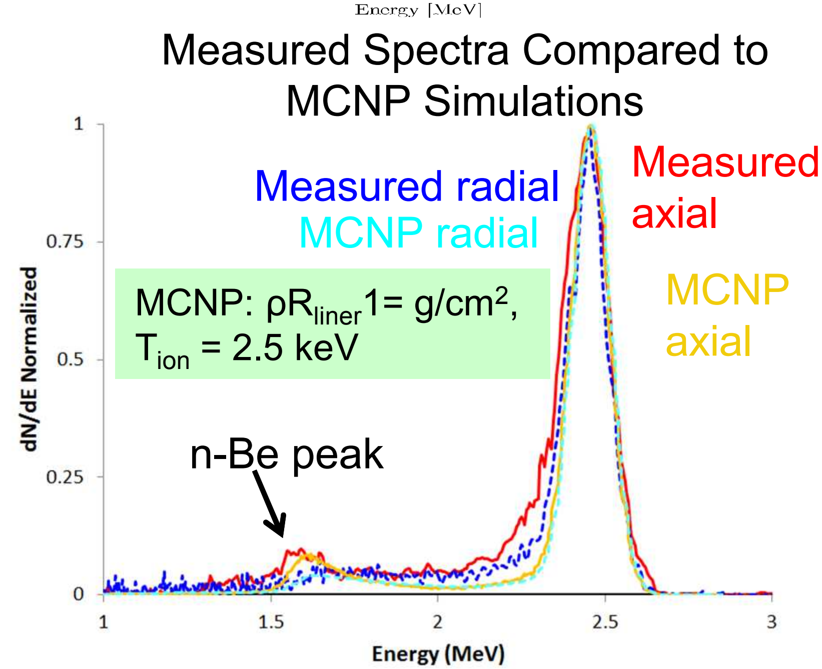
Down-scattered neutrons from Be liner reveal information about *liner* areal density.

- **Neutron down-scattering simulations (MCNP, MonteBurns[18]) show how fuel and liner areal densities affect neutron spectra.**



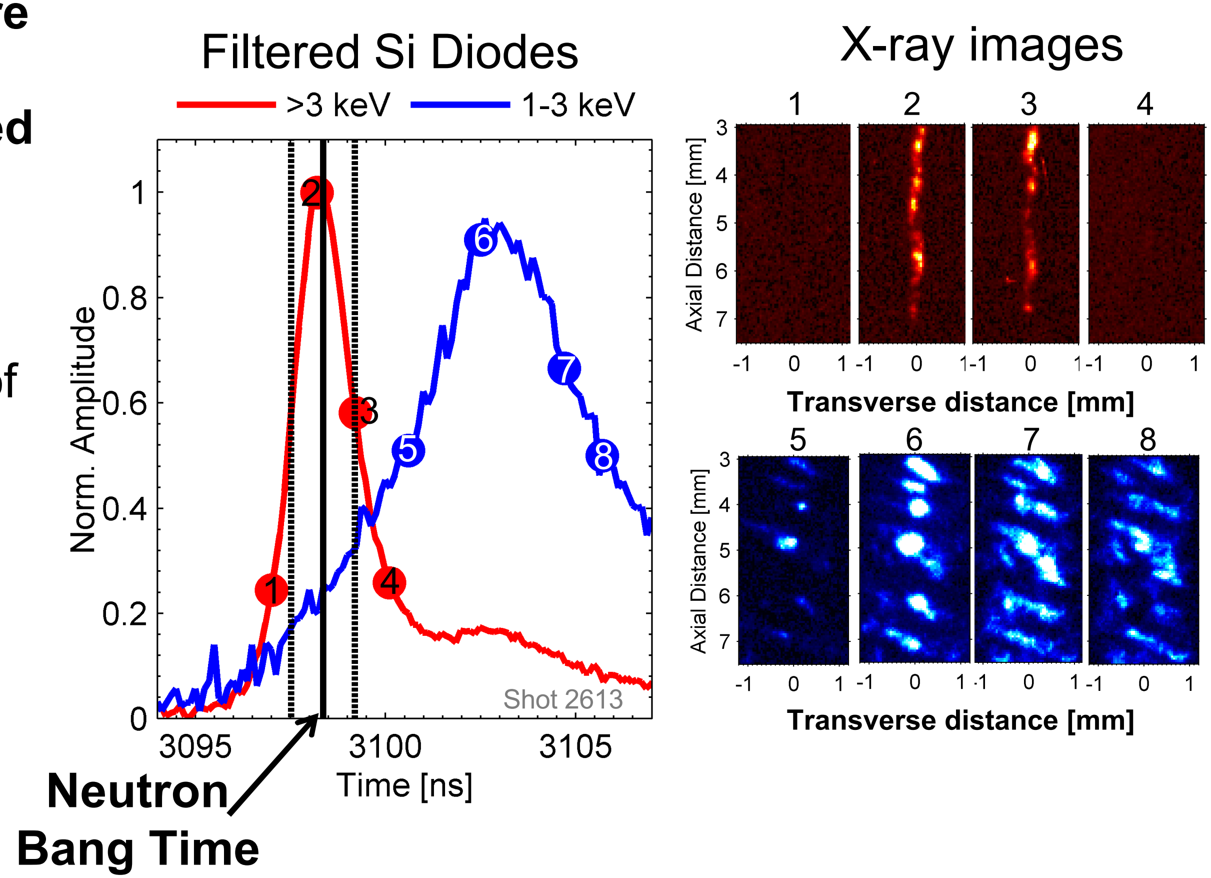
- **Measured ~1.6 MeV peaks associated with n-Be down-scatter from liner suggest ρR_{liner} ~ 1 g/cm^2.**
  - Differences between measured and simulated scattering tails are likely due to additional scattering in surrounding hardware.
  - Agrees with x-ray spectroscopy measurements[17] and simulations[18].





Peak neutron emission and burn times occur near time of peak x-ray emission.

- **Bang time and E_{peak} are determined from five nTOF detectors (fielded 7-25 meters from source).**
  - Uncertainties are ±1 ns for this type of measurement.
- **Neutron burn time is estimated from x-ray signals (> 3 keV) and x-ray imaging.[5]**
  - Burn ~ 2 ns (or less).



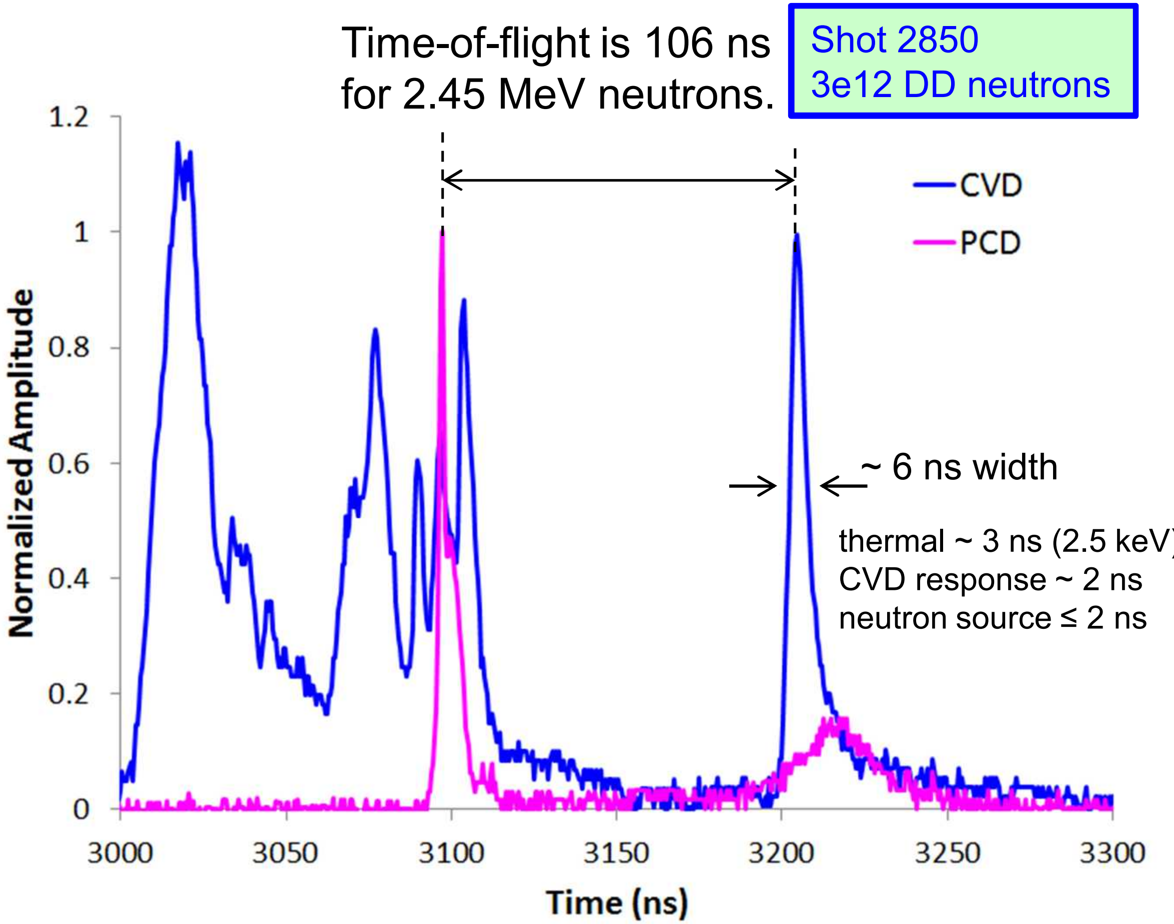
[5] M. Gomez *et al.* Phys. Plasmas **22**, 056306 (2015).

Actual *neutron* burn history measurements are being developed for present and future experiments with higher DD yields or DT fuel.

Initial measurements of bang times and burn widths using CVD diamonds are promising.

- **Presently, several CVD diamond detectors are fielded 2.3 m from the source.**
  - Results are shown for 16mm x 1mm detector.

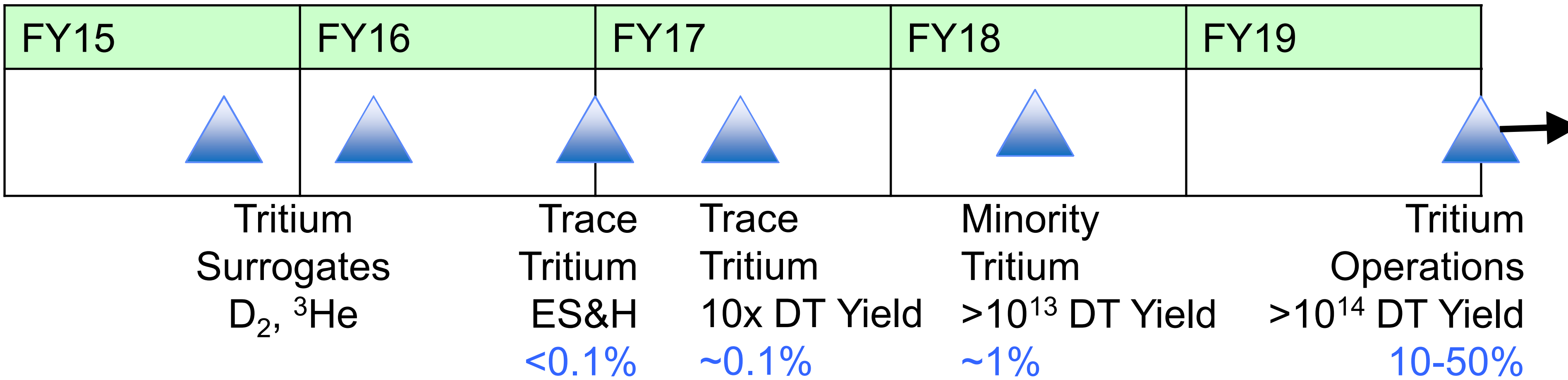
CVD Diamond Detectors



Plans are underway to implement closer-in, higher-resolution detectors with improved shielding.

During the next few years, we intend to gradually increase the use of tritium fuel on Z.

Proposed Z Timeline

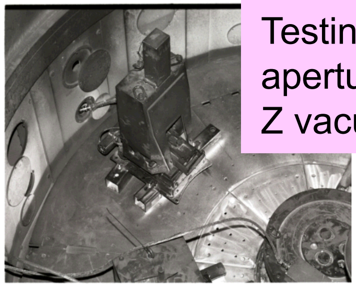


- **Presently, with deuterium fuel, our highest yields are:**
  - Gas puff ~4e13 DD
  - MagLIF ~3e12 DD

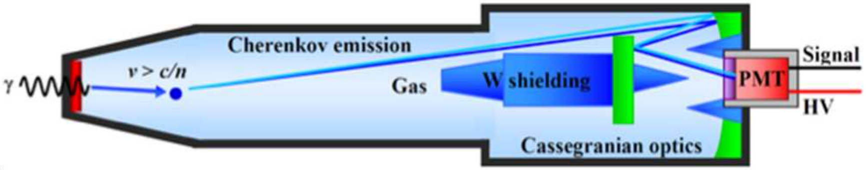
Incorporating tritium fuel on Z experiments will create opportunities for improved neutron measurements and new physics understanding.

We are collaborating with many colleagues to improve Z's neutron diagnostic suite.

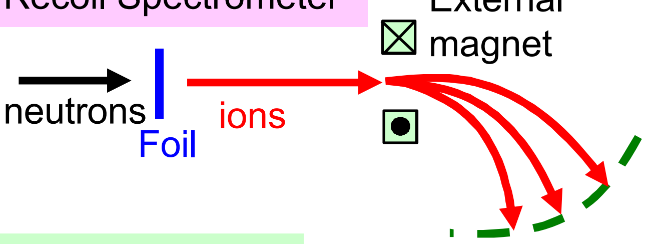
- **LLNL:** D. Fittinghoff, M. May
  - Neutron imager[20]
  - CVD diamonds (also with LLE and NSTec)
- **LANL:** H. Herrmann, R. Leeper
  - Gas Cherenkov Detectors[21]
- **LLE:** V. Yu. Glebov
  - Gated and alternative nTOF detectors[15]
- **MIT:** R. Petrasso, J. Frenje, F. Seguin, M. Gatu-Johnson, H. Han, B. Lahmann
  - Neutron recoil spectrometers[22-26]
- **NSTec:** K. Moy, R. Buckles, I. Garza, J. Tinsley
  - nTOF detectors, CVD diamonds, CR-39 processing
- **UNM:** G. Cooper and J. Styron
  - Time-resolved Thomson Parabola (burn history)


Testing neutron imager aperture hardware installed in Z vacuum chamber

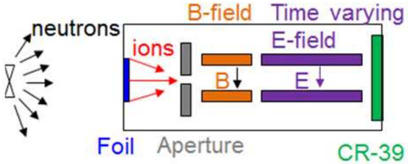
Gas Cherenkov Detector



Magnetic Recoil Spectrometer



Thomson Parabola



Summary and Future Work

- **Important physics information about MagLIF experiments can be inferred from neutron diagnostics:**
  - Plasma (thermonuclear) conditions → Isotropic ~ 3e12 DD yields
  - Ion Temperatures ~ 2-3 keV
  - Fuel magnetization: BR = 0.34 MG-cm ($R_{\alpha} \sim R_{triton}$)
  - Liner areal densities ~ 1 g/cm^2
  - Neutron bang time within ± 1 ns of peak x-ray emission

- **With our collaborators (LLNL, LANL, NSTec, UNM, LLE, MIT) we are exploring improvements and additions to our neutron diagnostic suite for present and future (DT) experiments:**
  - Improved neutron imager
  - CVD diamonds
  - GCD gamma-reaction history
  - Thomson parabola
  - Gated nTOF's
  - Recoil neutron spectrometers

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