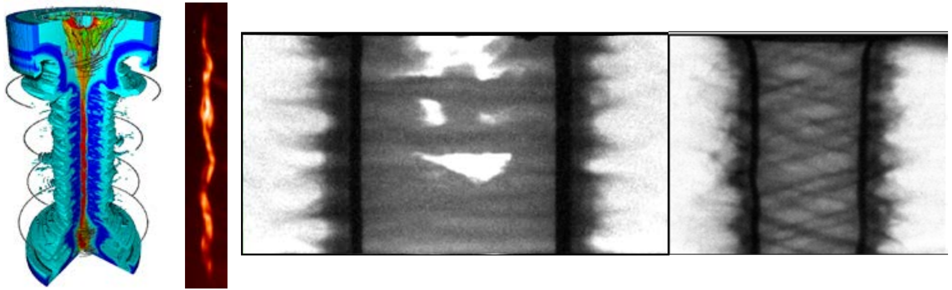
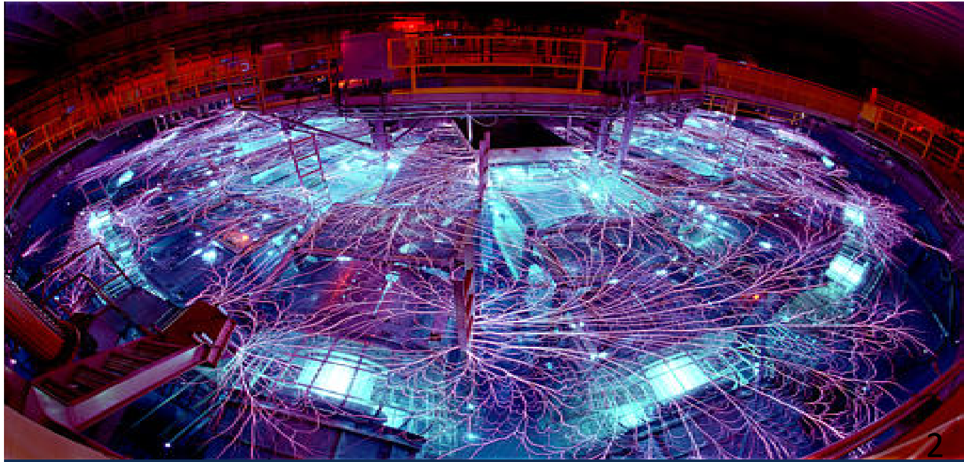
# nTOF (and other) measurements at Z:

## Assessing the impacts of flows, spatial variations, and Magnetic Fields

*Exceptional service in the national interest*

Sandia National Laboratories





**Patrick Knapp**
**NISP Working Group**
**LLNL, Livermore CA**
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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

# As always, many people contributed to this talk….

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… And many many more

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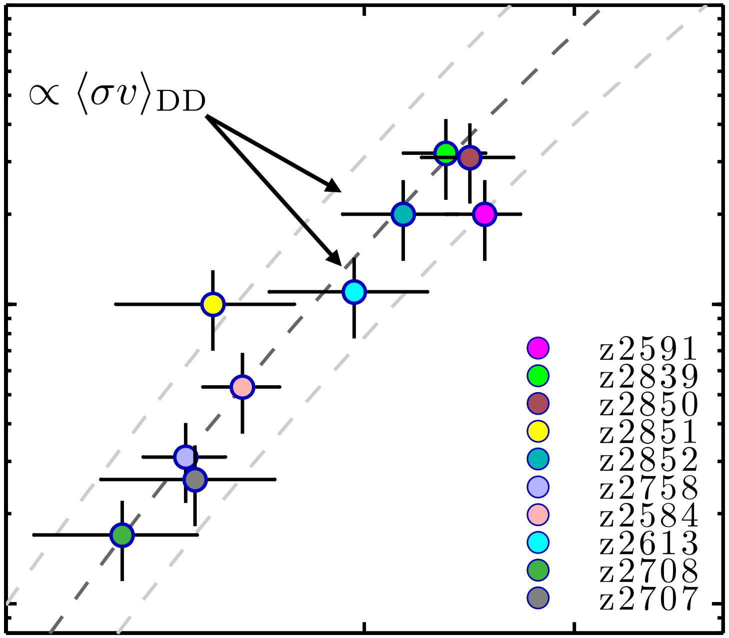
[6] *MIT, Cambridge Massachussettes*

# We are continually improving target performance and understanding of the MagLIF concept



- DD neutron yield scales with ion temperature as expected for a thermonuclear neutron production
- Measurement errors are large due primarily to uncertainties in scattering environment and instrument responses
- Nominally identical shots are reproducible within measurement uncertainties

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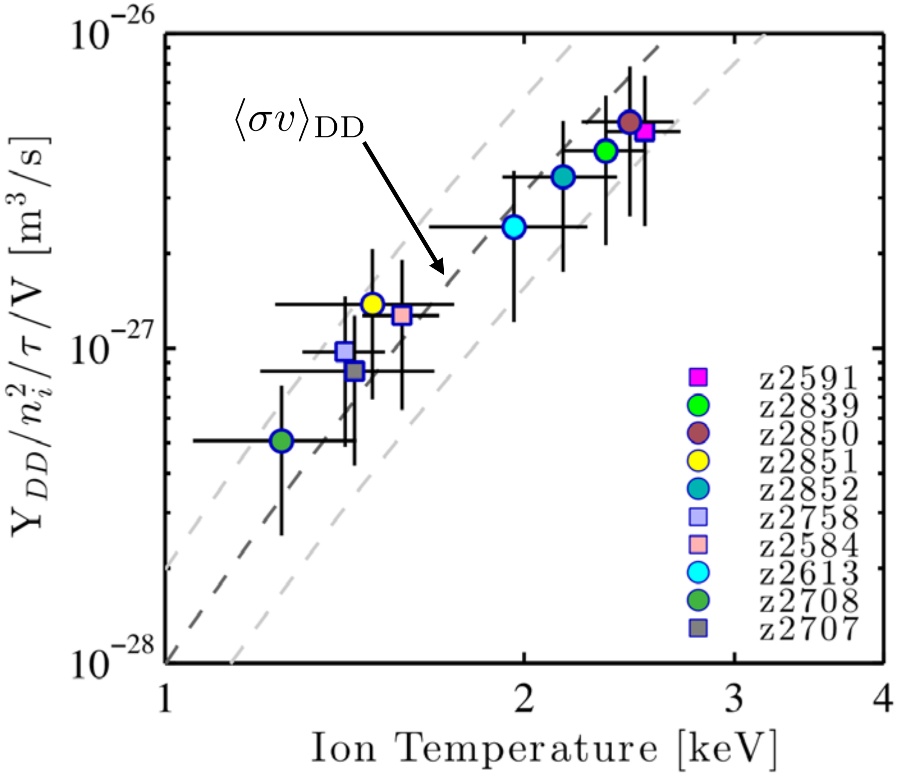

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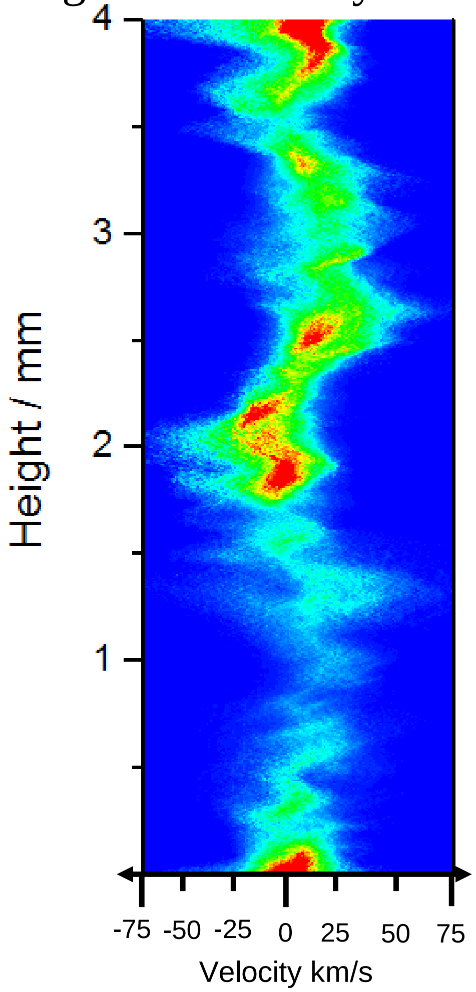
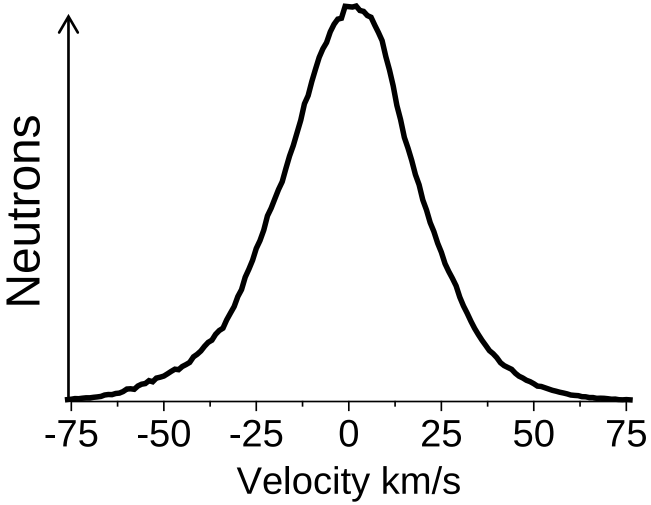
Normalizing the neutron yields to produce burn averaged reactivity shows a clear trend similar to theory

# Broadening of neutron spectra due to residual kinetic energy is *expected* to be small

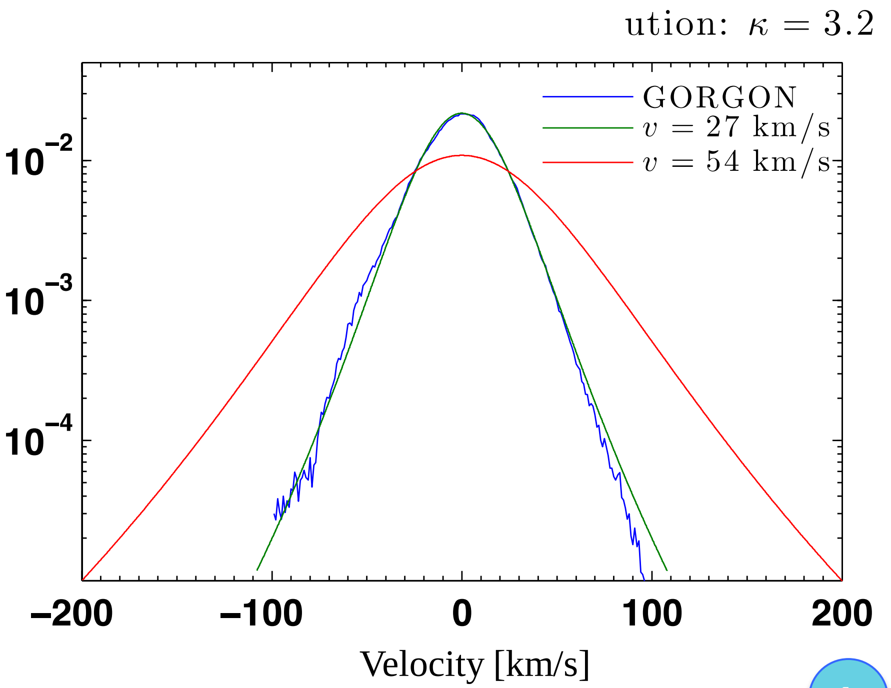
Simulated Axially resolved, burn-weighted x-velocity distribution



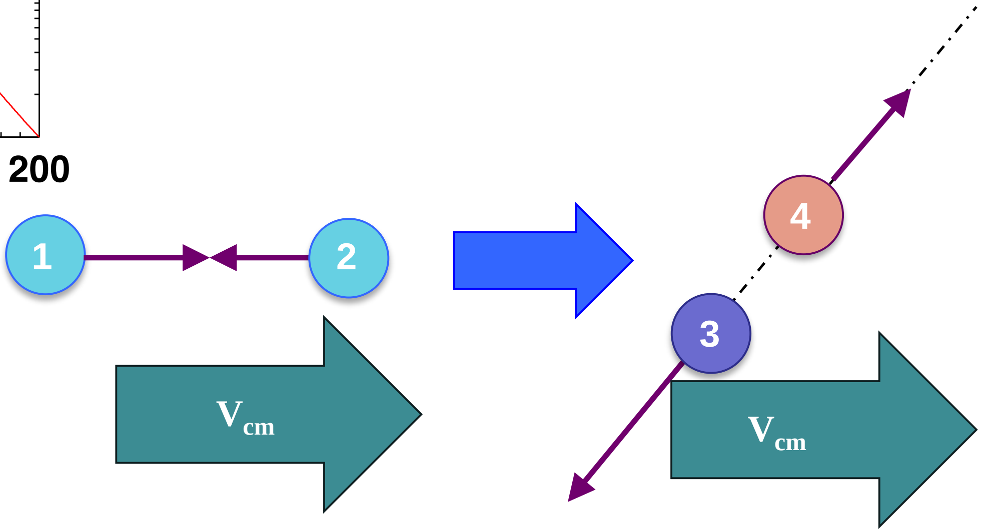
- The time integrated, line-of-sight velocity distribution of the neutron emitting plasma is ~Gaussian centered on 0 km/s with a FWHM of ~38km/s.
- There is fairly significant axial variation in this velocity distribution
  - Including bulk shifts varying with position (possibly resulting from helical structure)



# We can model the effect of broadening on the resulting neutron spectra using MonteBurns*



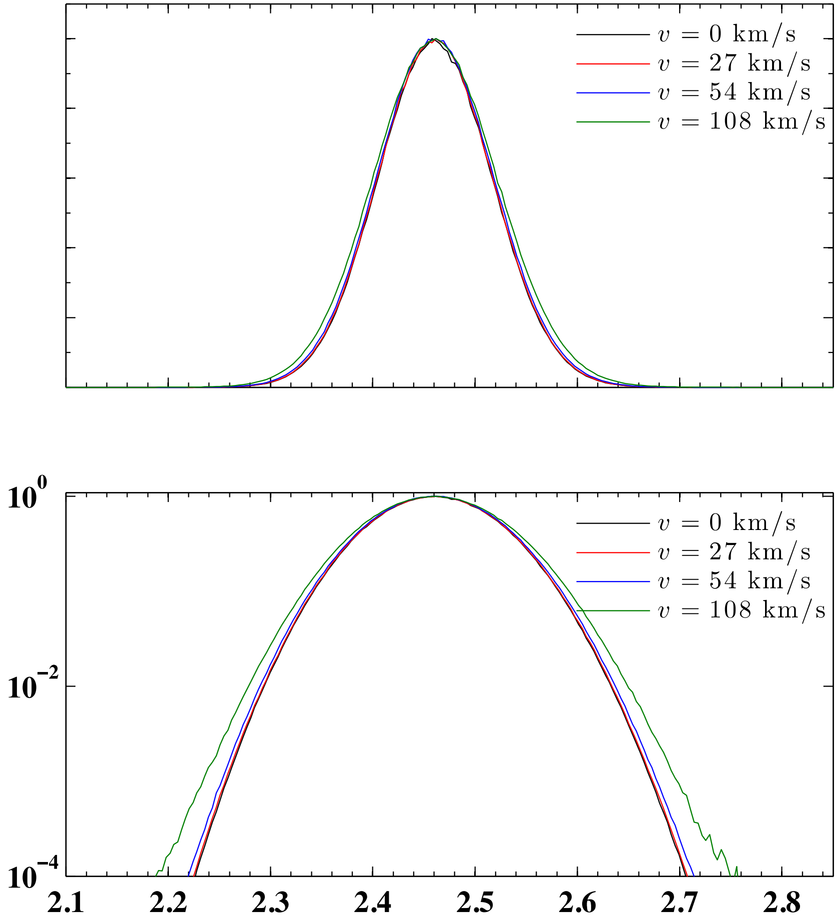
- The residual velocity scale is small
- The burn averaged LOS-velocity distribution fits well to a Kappa distribution with κ=3.2 and v=27 km/s (quasi-Gaussian with extended tails)
- The line-averaged velocity is only 16 km/s



- Velocities of ions 1 and 2 are randomly drawn from a Maxwellian distribution
- The center of mass velocity is randomly chosen from the residual velocity distribution above

*Knapp et al., Phys. Plasmas **20**, 062701 (2013)

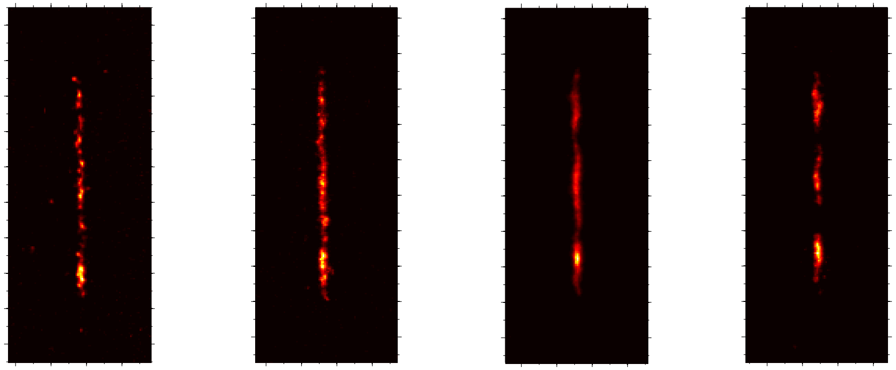
# Using a Maxwellian plasma with $T_i$=2.5 keV we calculate the effect of this velocity distribution on the DD neutron spectrum

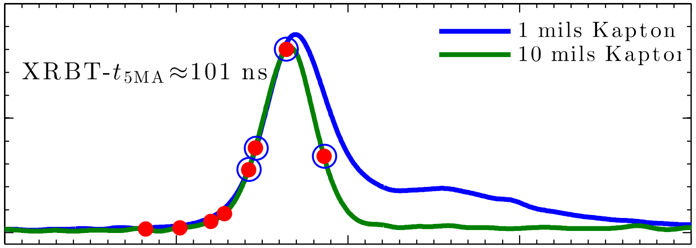


- Assume fluid velocity distribution is isotropic
- Both plots on the left are the same data (bottom is on a log scale)
- Using the nominal fitted distribution (v=27 km/s, κ=3.2), the spectrum is indistinguishable from the unbroadened spectrum
- The effect only becomes noticeable at v~100 km/s, even then it is small

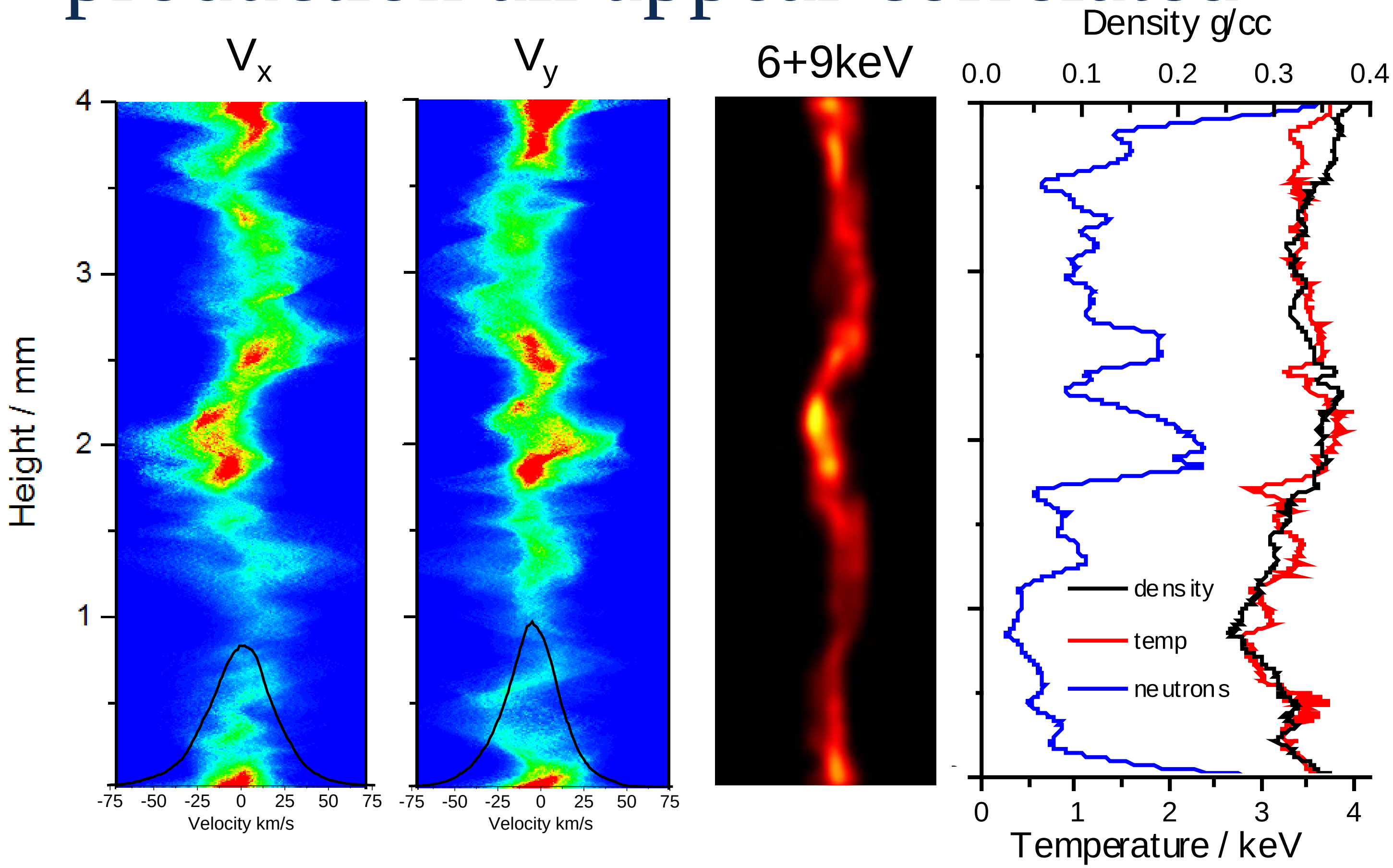
# Even though we likely do not have a true *stagnation*, the neutron measurements appear to be representative of a real “burn averaged” $T_i$

- Remember, the physics of our stagnation is different from that of hot-spot implosions
  - Due to preheat, the implosion is *subsonic* (v<100 km/s)
  - Stagnation is not impulsive (shock driven), the entire implosion is *adiabatic*
- This doesn’t mean that residual velocity is *not* impacting performance, just that it is not likely impacting our interpretation





# Velocity, x-ray emission and neutron production all appear correlated

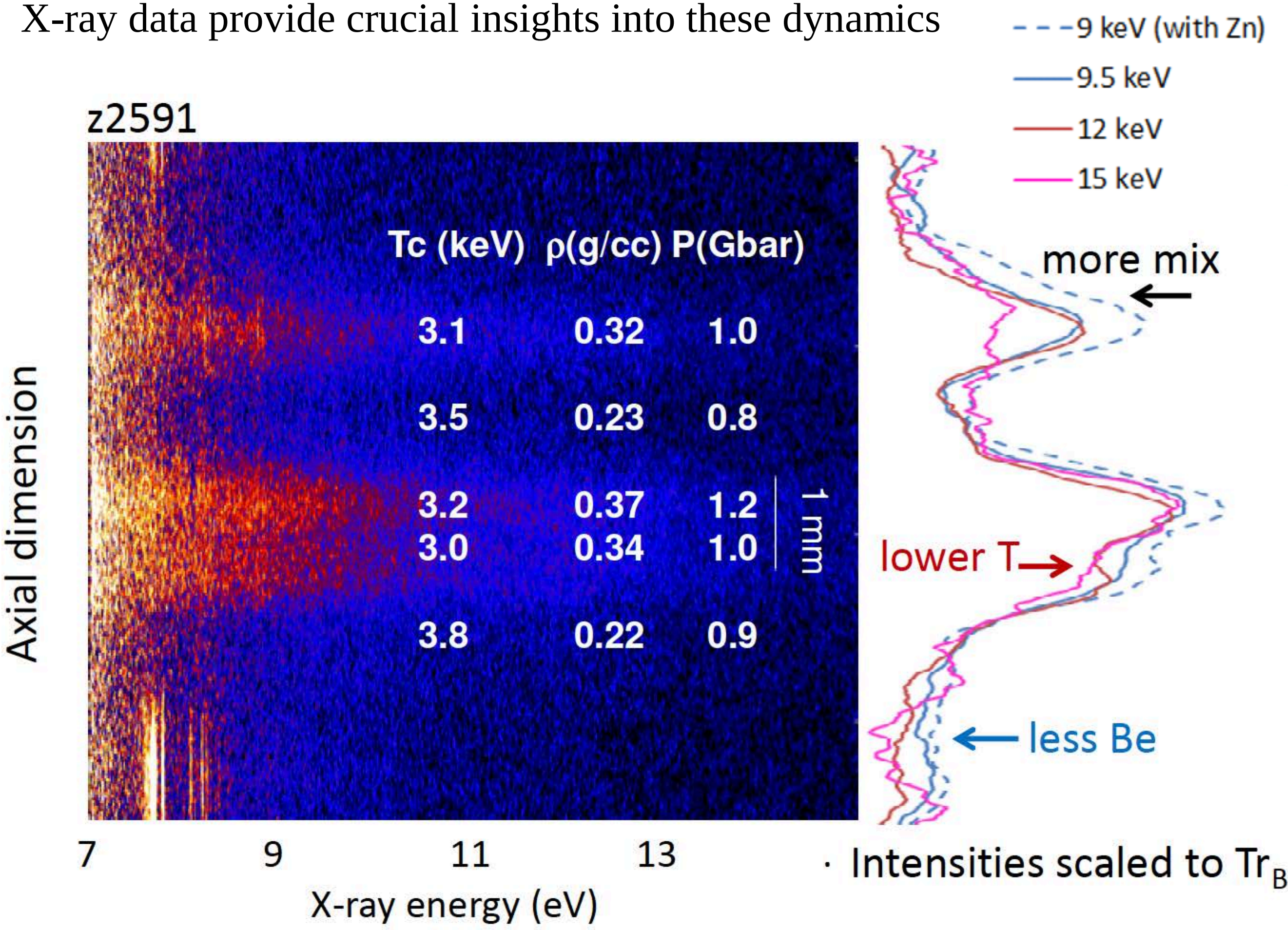


Note: $\rho$ and T are well correlated in GORGON simulation

- Simulations performed by Chris Jennings using GORGON in 3D
- For this calculation neutron yield was 4.6e12 if 7.5mm tall target assumed. This calculation assumed 500J preheat energy. Simulation only modeled the central 4mm, neglecting end losses.
- Proportion of hot fuel at stagnation can be altered by changing the spot size assumed for the laser deposition (changing how much cold fuel is retained on liner wall).

# This picture causes us to wonder about the neutron production in these “bright” regions

X-ray data provide crucial insights into these dynamics



| Tc (keV) | ρ(g/cc) | P(Gbar) |
|---|---|---|
| 3.1 | 0.32 | 1.0 |
| 3.5 | 0.23 | 0.8 |
| 3.2 | 0.37 | 1.2 |
| 3.0 | 0.34 | 1.0 |
| 3.8 | 0.22 | 0.9 |

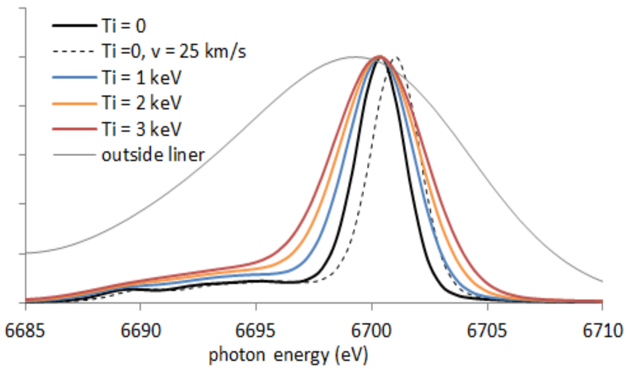
- Intensities scaled to $Tr_{Be}*e^{-e/T}$

- Stagnation appears to be fairly isobaric
- $T_c$ and ρ are anti-correlated
- Bright spots in spectrum are well correlated to bright spots in images

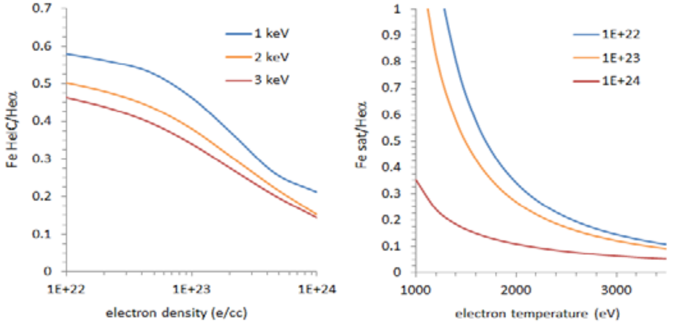
Material provided by Stephanie Hansen

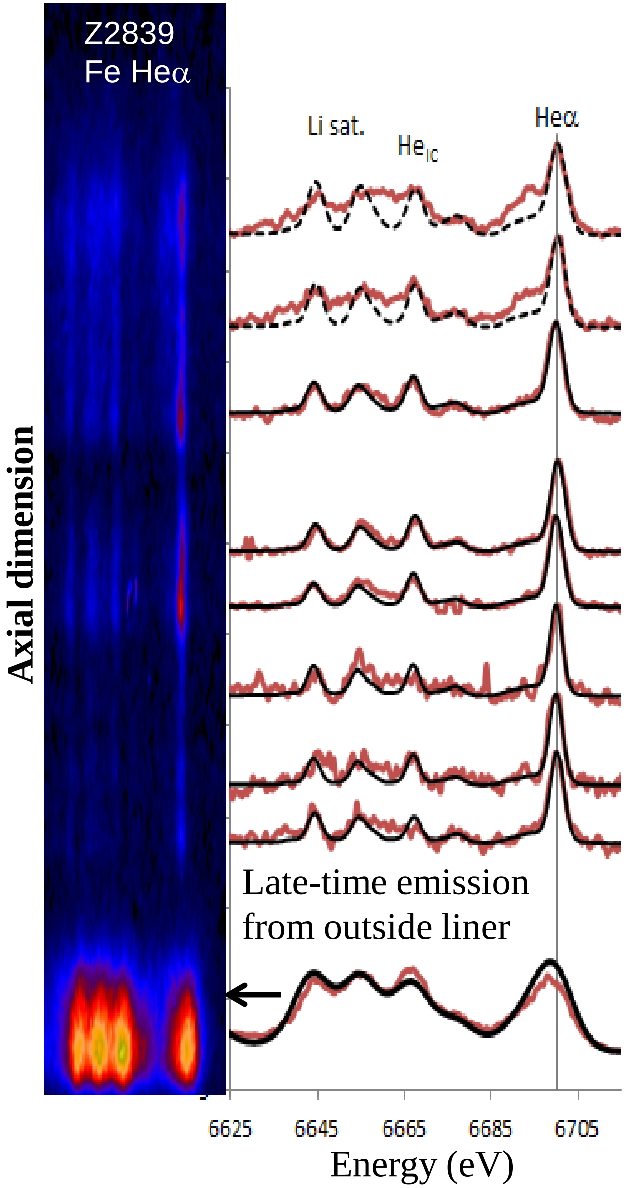
# Details about stagnation from high-res, axially resolving XRS3* spectrometer

Line shapes →$T_{ion}$, $v_{bulk}$, & $r_{source}$

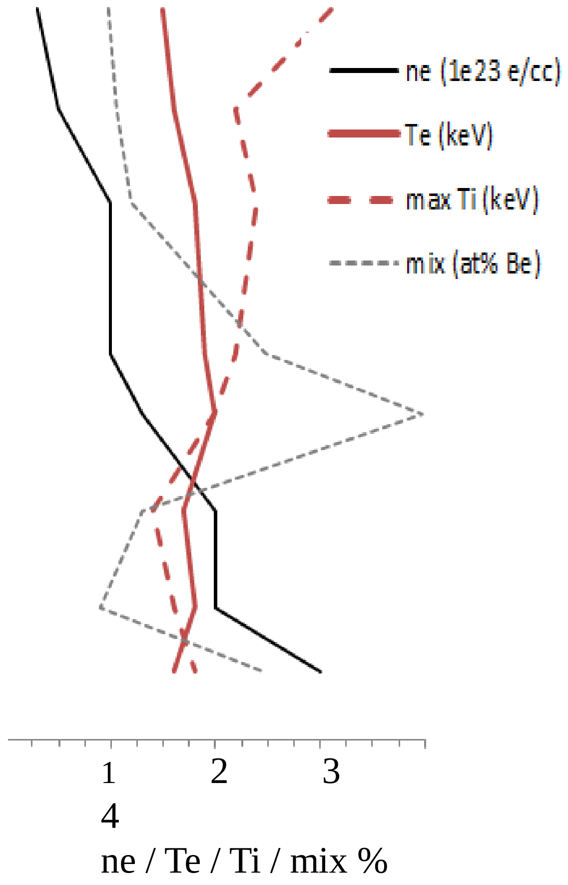


Line ratios →$T_e$, $n_e$, & mix





Late-time emission from outside liner



Line shifts indicate $v_{bulk}$ < ~15 km/s
Consistent with GORGON

*E.C. Harding et al., Rev. Sci. Inst. 86, 043504 (2015)

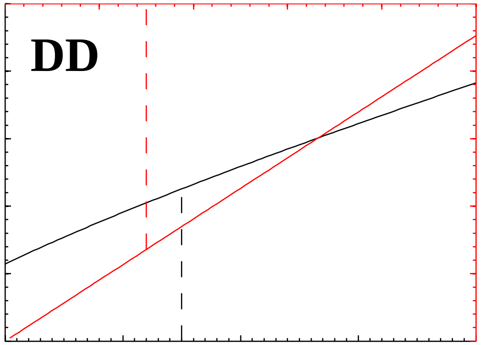
Material provided by Stephanie Hansen and Eric Harding

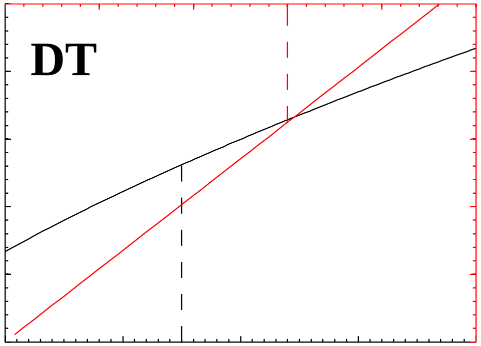
# A space resolved nTOF would require extremely high resolution (E/ΔE~1000) to distinguish velocity shifts

- The bulk velocity shifts are ~ the thermal peak shift
- Situation is better for DT neutrons than DD
- Still extremely valuable for determining 1D variations in neutron emission and "temperature"

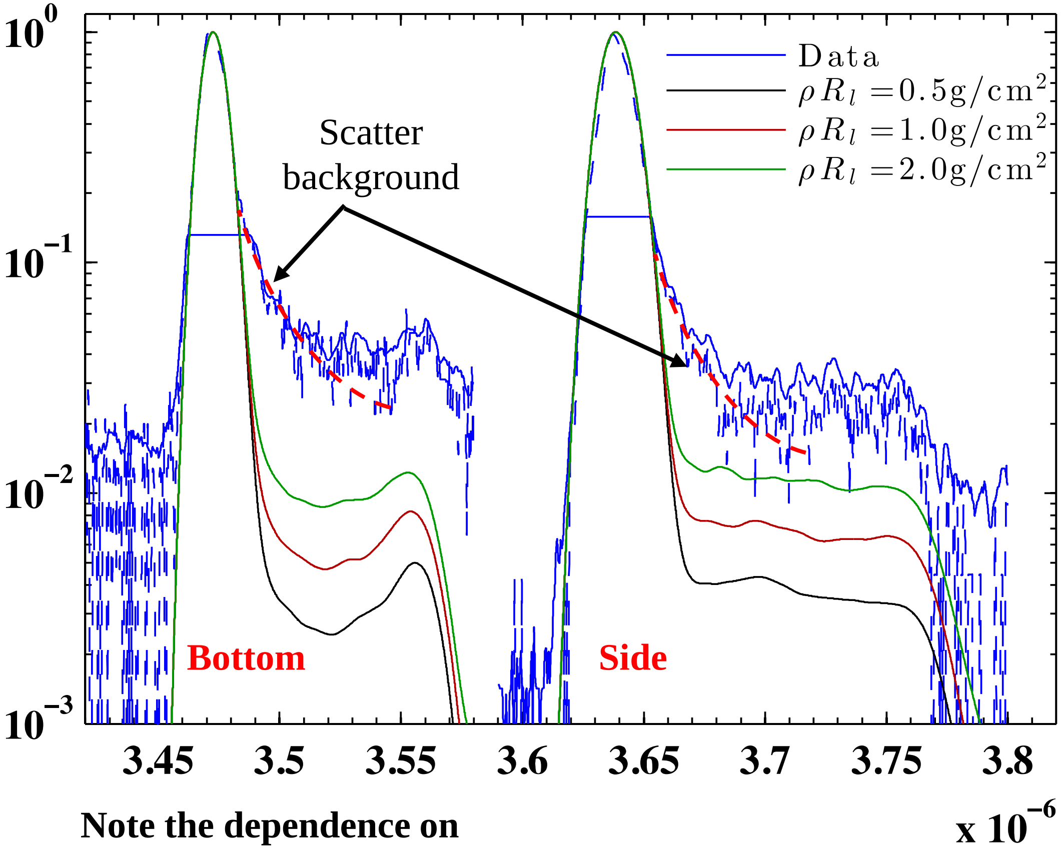
$$\delta v_n = v_n \left( \frac{v_f}{v_n} - \frac{1}{2}\left(\frac{v_f}{v_n}\right)^2 + \cdots \right)$$

$$\delta v_n \approx v_f$$





# Neutron Downscatter from the compressed liner is observed in the data

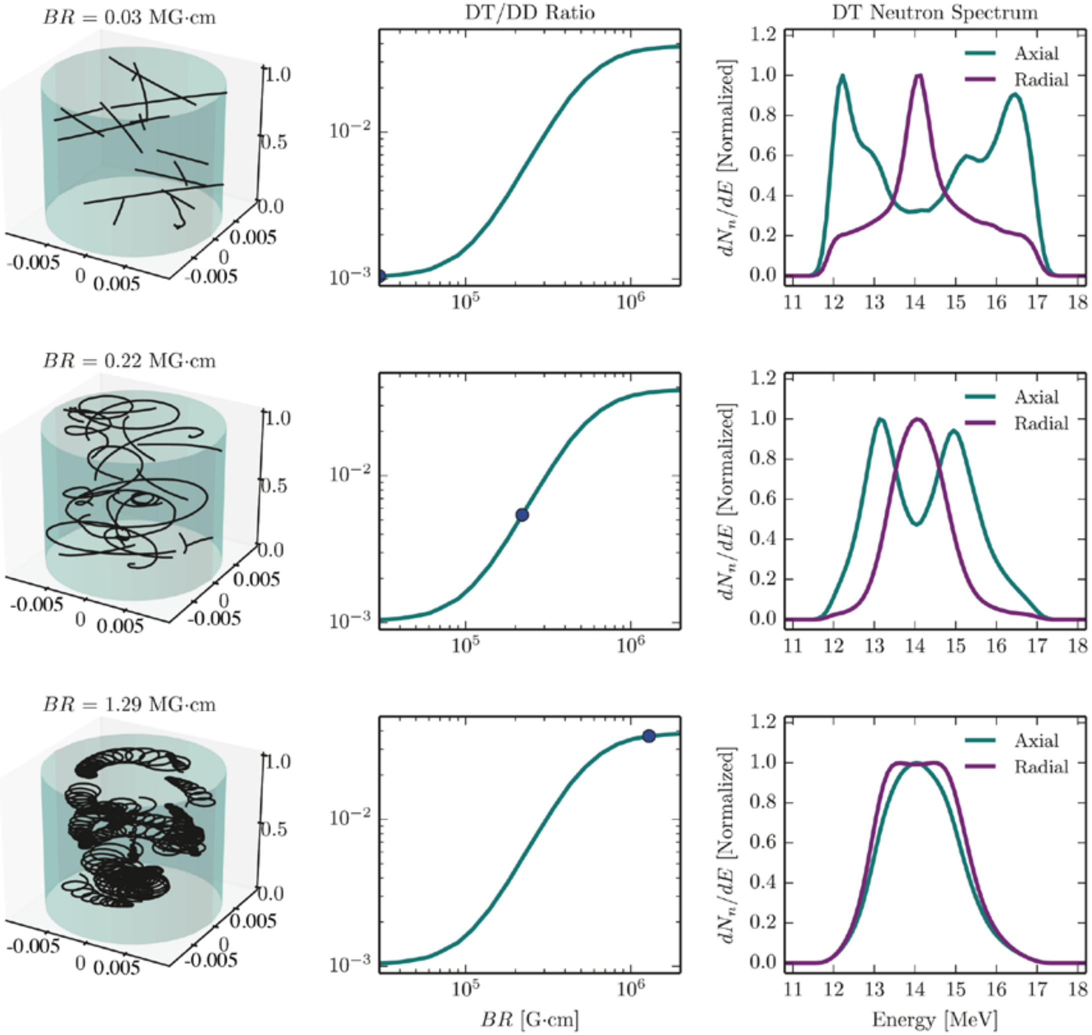


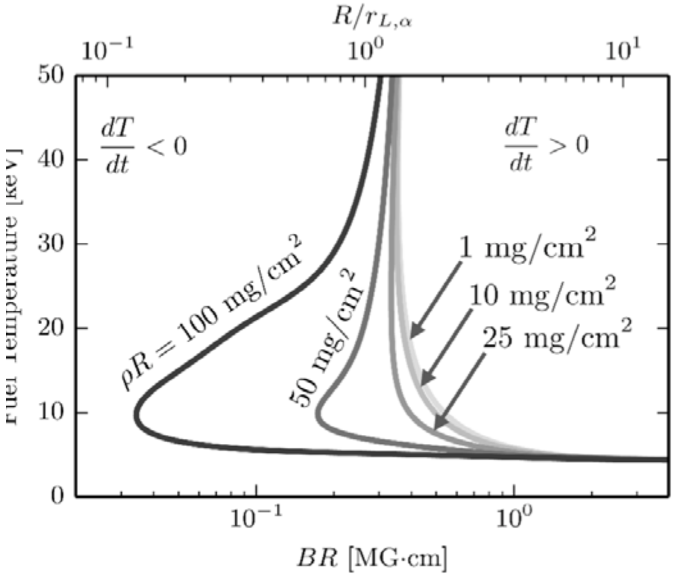
**Note the dependence on viewing angle**

- The important features of neutron downscatter from the liner are present in the data
- Due to high scattering environment, and low signal we can’t be quantitative
- The downscatter model cannot match the data due to a scattering background
- A space-resolving nTOF could help understand the connection between primary neutron production and liner areal density
- At *much* higher yields, gated neutron images showing the spatial dependence of downscatter/backscatter could be extremely useful

Be downscatter model developed by Brandon Lahmann (MIT) while interning at SNL

# Secondary DT neutron production is sensitive to fuel magnetization



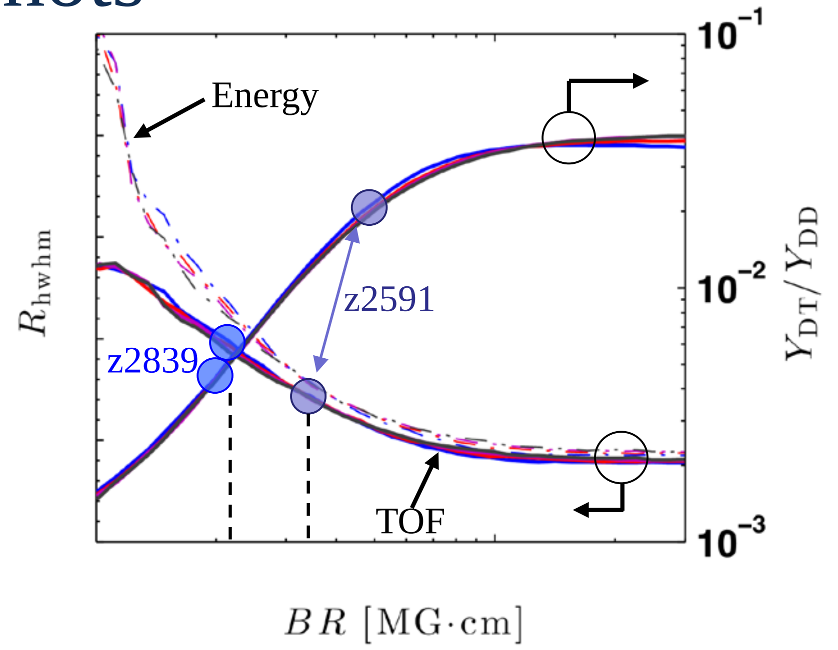


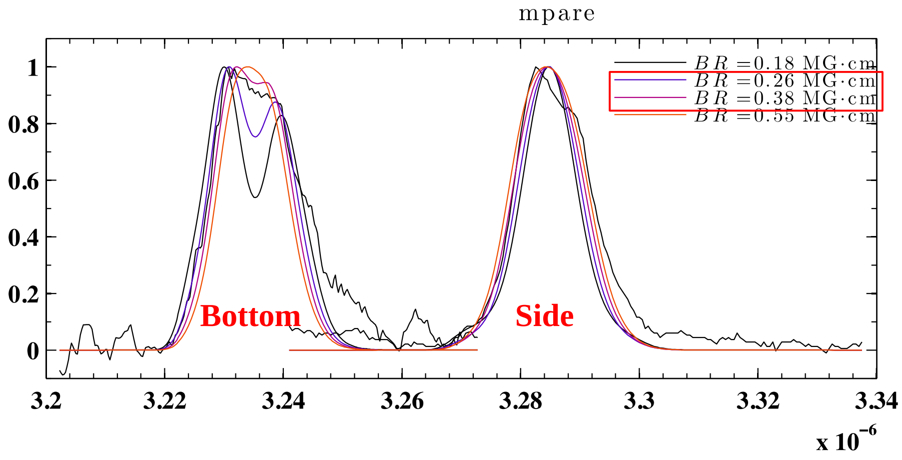
- BR is the fundamental confinement parameter for MIF (supplanting ρR)
- Secondary DT yield and spectra are sensitive to BR in a MagLIF-like stagnation plasma[1,2]
- Effect arises from the change in 1 MeV triton path length when they transition from un-magnetized to magnetized

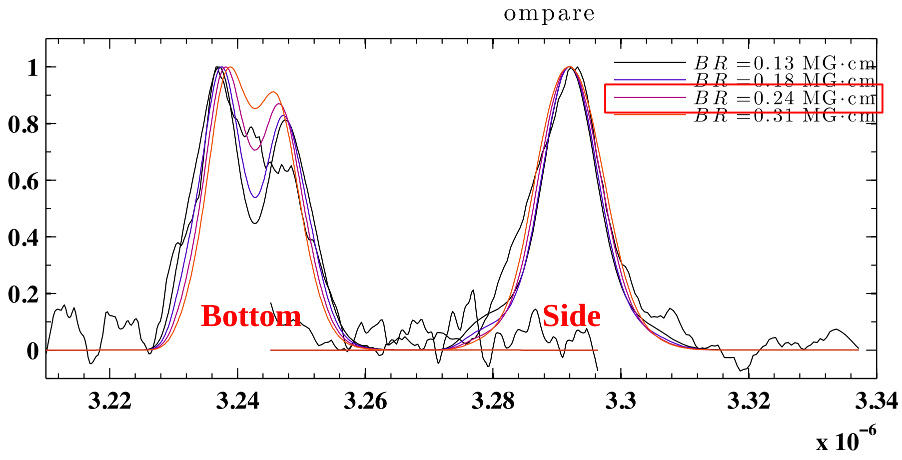
[1] P.F. Knapp and P.F. Schmit et al., Phys. Plasmas, **22**, 056312 (2015)
[2] P.F. Schmit and P.F. Knapp et al., PRL 113, 155004 (2014)

# Despite low signals, we can clearly infer differences in BR between shots

- Previously used unfolded secondary nTOF data for BR analysis[1,2]
- Signals are weak and noisy, the unfold makes this worse
- TOF data can be used directly to estimate stagnation BR
  - Sensitive to determination of “center” of the spectrum
  - $R_{hwhm}$ (or $R_{fwhm}$) is minimally sensitive to mix, fuel ρR, and $T_e$
- Forward method expands number of shots we can use
- Work ongoing to develop a forward fitting model







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# Concluding Remarks

- Yield appears to be thermal
- Fluid motion seems unlikely to be a significant contributor to neutron spectral shape
  - May still be a significant contributor to energy balance
- There is significant axial variation in neutron emission and liner areal density inferred from simulation
  - There is significant variation in x-ray emission data
  - Space resolving nTOF could be an extremely valuable complement to x-ray diagnostics
- Need to understand scattering environment in order to utilize the Be downscatter measurement
- Magnetic field measurement is promising and exciting, but needs higher S/N