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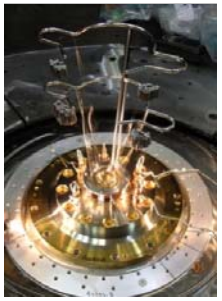

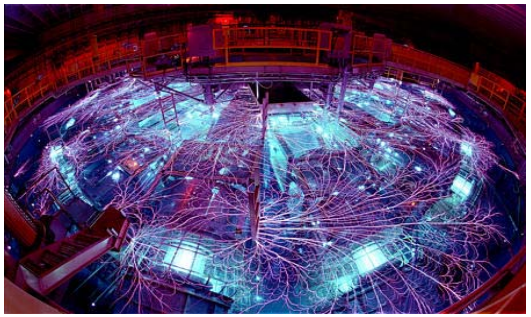

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Unfolding nTOF Datasets to Reveal Neutron Spectrum and Time History

Brent Jones*, Carlos L. Ruiz, Gordon A. Chandler, Kelly D. Hahn, David L. Fehl, Alan J. Nelson, José A. Torres, Christine A. Coverdale, Joel S. Lash, Patrick Knapp, Matt Gomez, Stephanie B. Hansen, Eric C. Harding, L. Armon McPherson, Greg A. Rochau, Paul F. Schmit, Adam B. Sefkow, and Daniel B. Sinars

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October 15, 2014

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Overview

- **How can we extract the most information about ion temperature and time dependence from an nTOF dataset?**
- **What neutron diagnostic set (and signal-to-noise) is required to characterize the neutron spectrum and pulse shape?**

- **Several methods have been studied to unfold nTOF data:**
  - **Maximum entropy method** I. Tiseanu and T. Craciunescu, Nucl. Sci. Eng. **122**, 384 (1996).
  - **Monte Carlo algorithms** I. Tiseanu *et al.*, Nucl. Instrum. Methods Phys. Res. A **373**, 73 (1996).
  - **Basis set expansion (BASEX) method** B. Jones and C. L. Ruiz, RSI **84**, 073510 (2013).

- **Example of BASEX applied to a D_2 gas puff z-pinch on Z (and pitfalls)**

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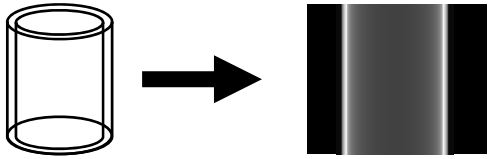
- **Example of BASEX applied to a D_2 gas puff z-pinch on Z (and pitfalls)**

The BASEX method turns an ill-posed inverse problem into a linear algebra transform between the source and data spaces

- Technique proposed for an Abel inversion problem Dribinski *et al*., Rev. Sci. Instrum. **73**, 2634 (2002).

- Define basis set and calculate analytic forward transforms **G**
  - e.g. for Abel inversion, consider a source built of nested shells



Limb-brightened forward-transformed image

- Define forward transform of source function

$$\mathbf{P} = \mathbf{CG}$$

Forward transformed basis set

Measured data, projection of source onto detector

Source function coefficients

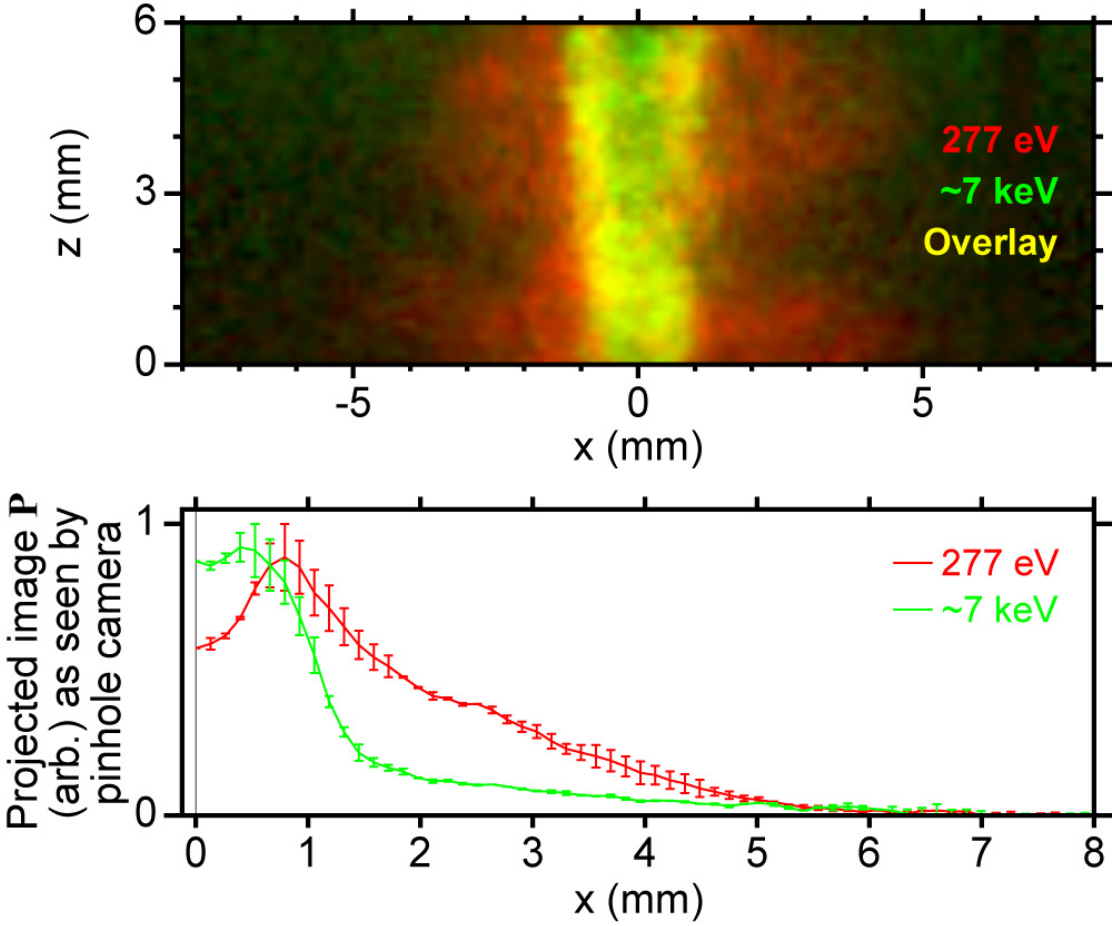
- Invert with Tikhonov regularization to solve (least-squares) for coefficients

$$\mathbf{C} = \mathbf{PA} \qquad \mathbf{A} = \mathbf{G}^{T}(\mathbf{G}\mathbf{G}^{T}+q^{2}\mathbf{I})^{-1}$$

- We have added a propagation of errors calculation to the method

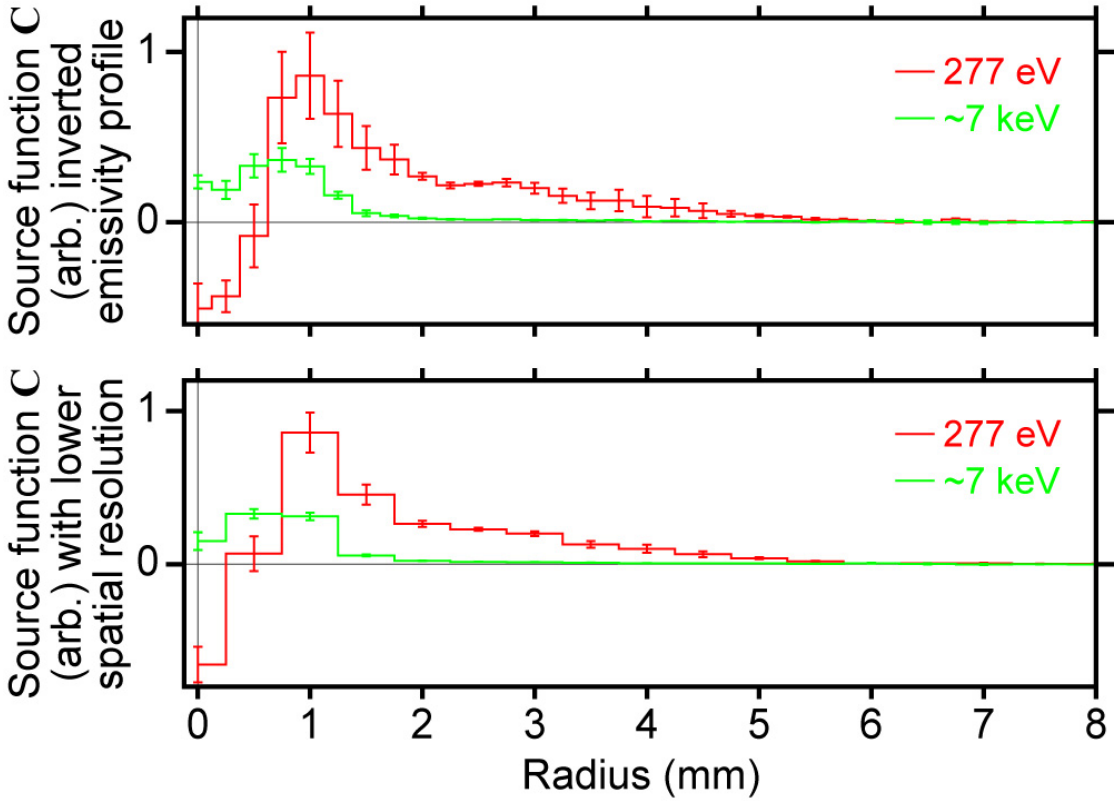
$$\sigma_{C}^{2} = (\mathbf{A}^{T})^{2}\,\sigma_{P}^{2}$$

Abel Inversion Example: Multi-color gated x-ray pinhole camera imaging shows z-pinch stagnation on the Z machine



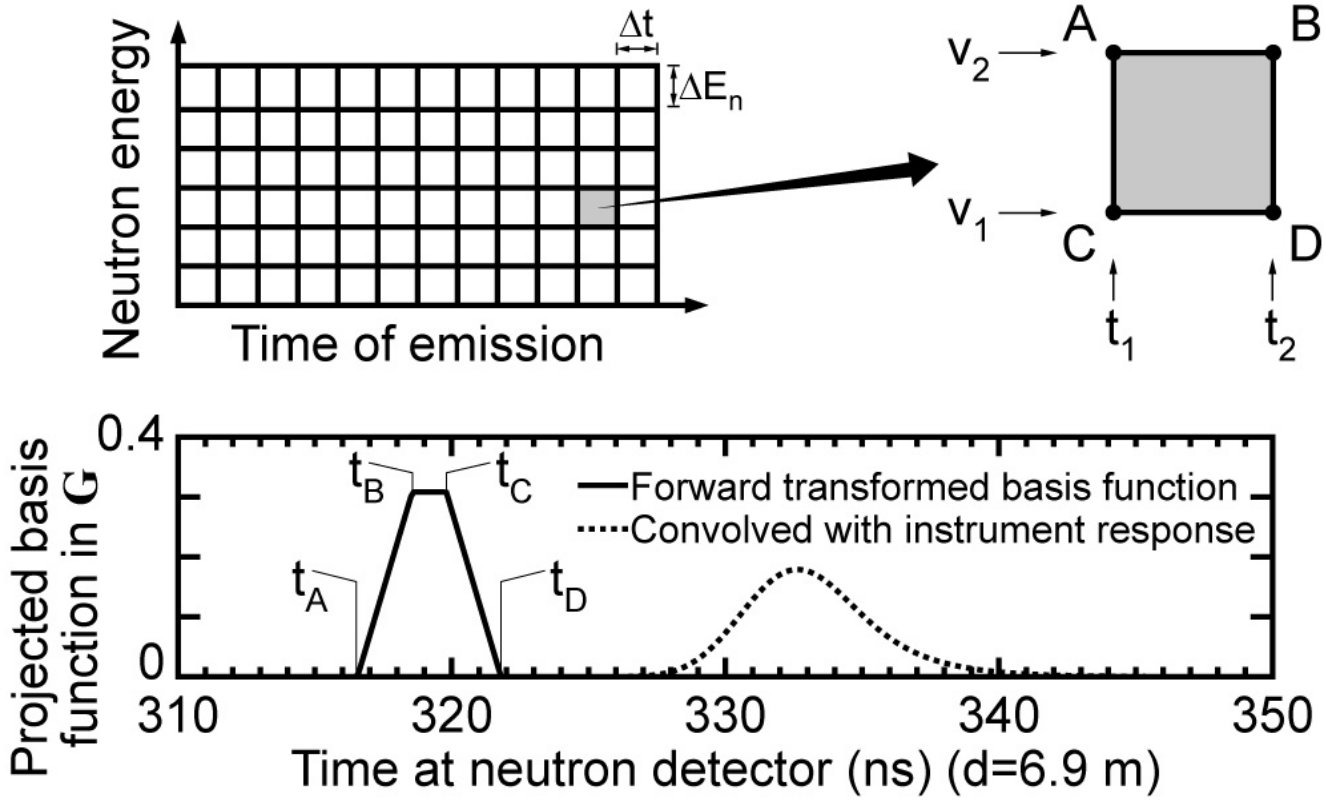
- Nested 65 on 32.5 mm diameter stainless steel wire array implosion (Z1861)
- Composite image shows 277 eV photons from colder trailing mass and ~7 keV K-shell photons from hot stagnating plasma on axis
- Projected image **P** is constructed by averaging axially, error bars represent difference between left and right sides

A general feature of the BASEX method is the trade-off between resolution and signal-to-noise ratio



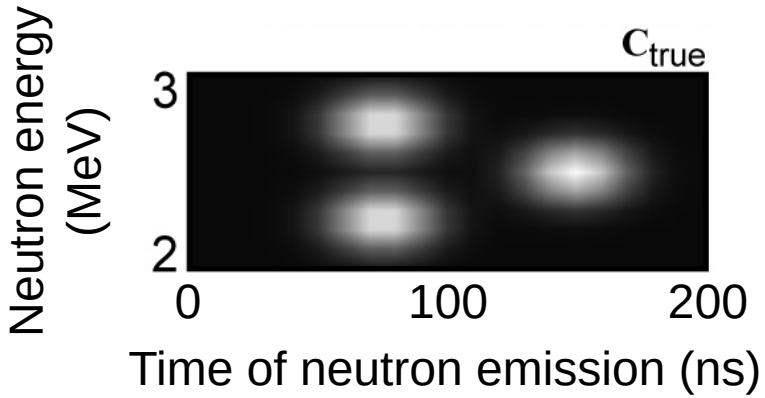
- BASEX inversion at 250 μm resolution of ~7 keV imager shows K-shell emission from inner edge of imploding shell
- Unphysical negative values near axis for 277 eV image may be systematic error due to spatial non-uniformity
- Reducing BASEX bin size to 500 μm resolution of 277 eV imager reduces error bars and leaves only one unphysical negative bin on axis

Instrumental response is accounted for implicitly in the definition of the basis functions for nTOF inversion



- The neutron source emissivity is gridded in neutron energy and time
- Each bin is translated to a neutron detector, and convolved with instrumental response to populate the matrix $\mathbf{G}$ of forward transformed basis functions

BASEX method is tested by application to synthetic data



- A “true” neutron source coefficient set $\mathbf{C}_{true}$ is defined as in Tiseanu *et al.*, Nucl. Instr. Meth. Phys. Res. A **373**, 73 (1996).

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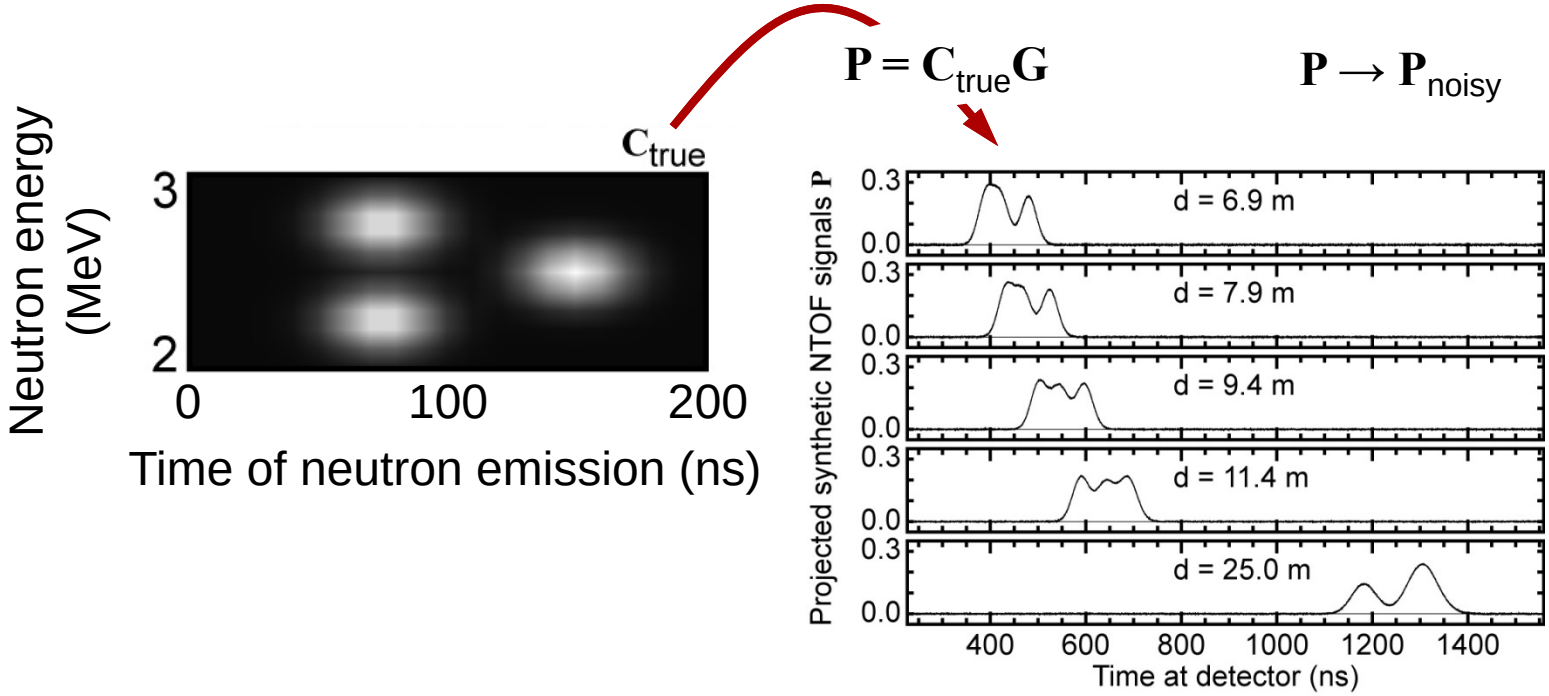

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- Forward transform is calculated, Gaussian noise is added

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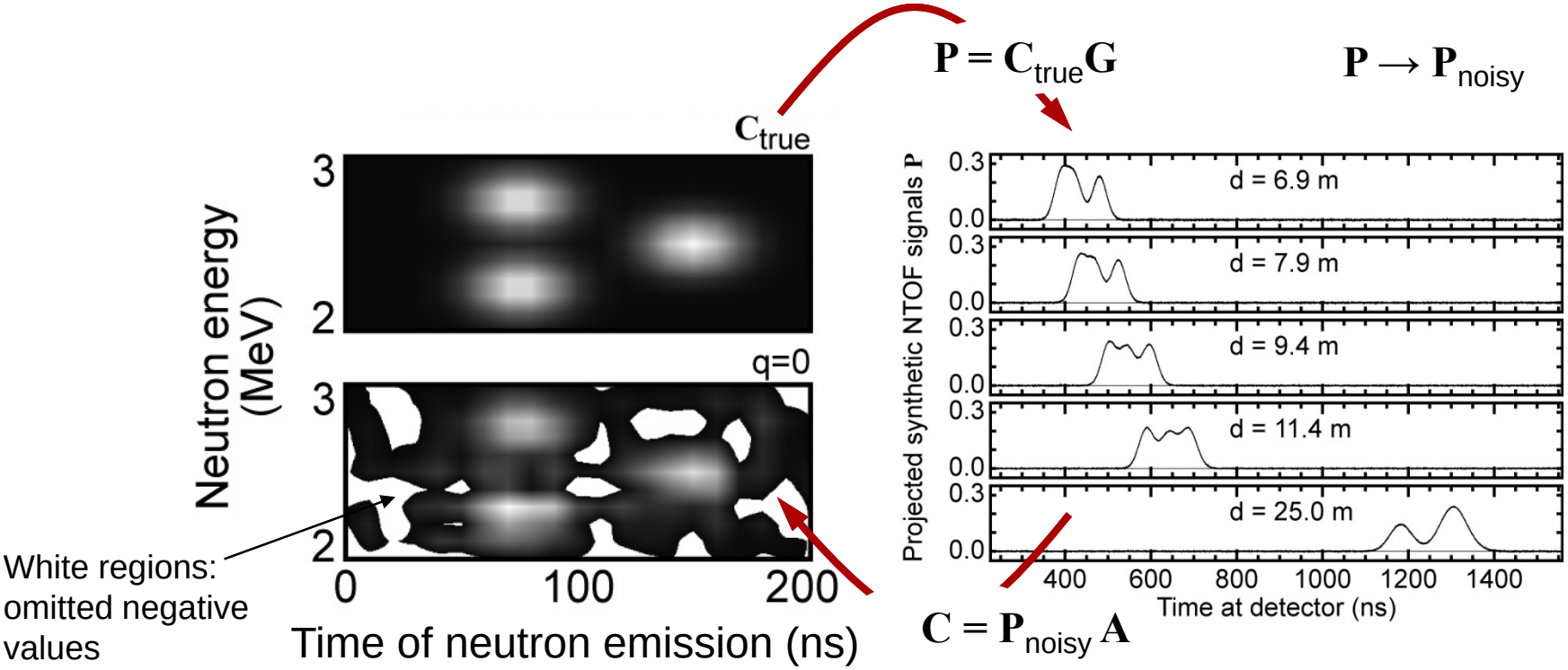
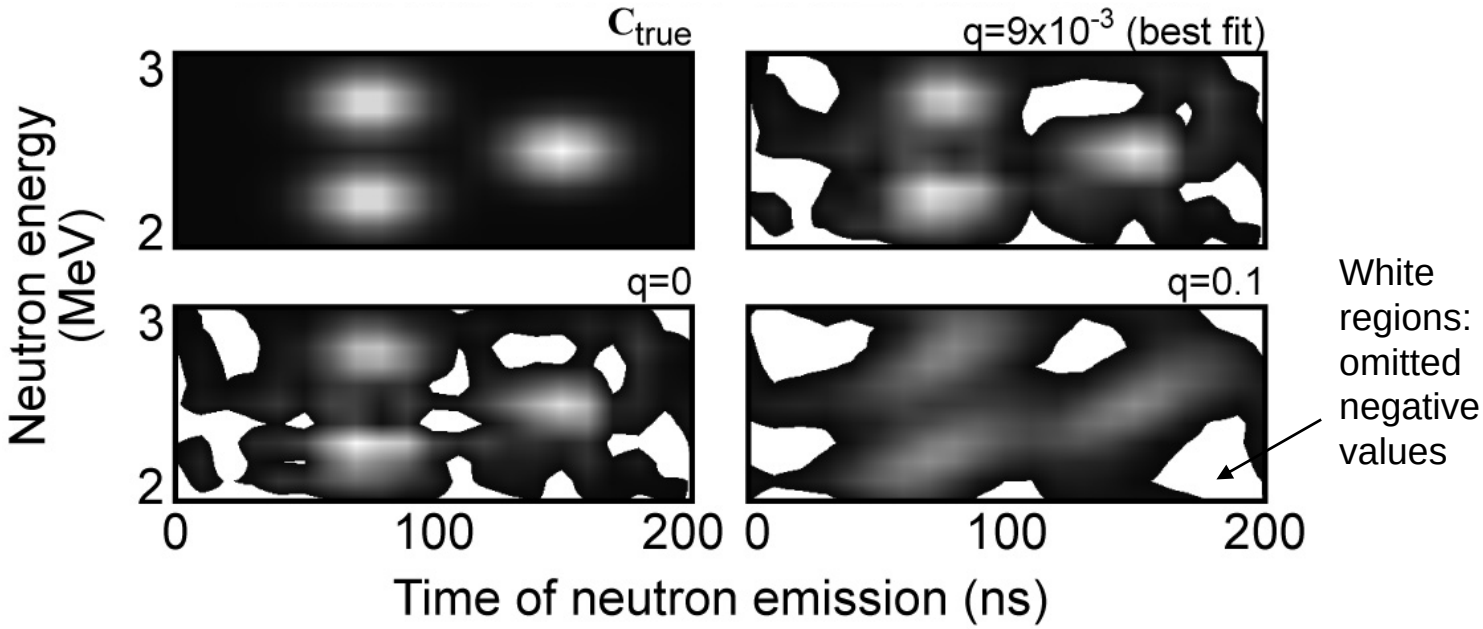


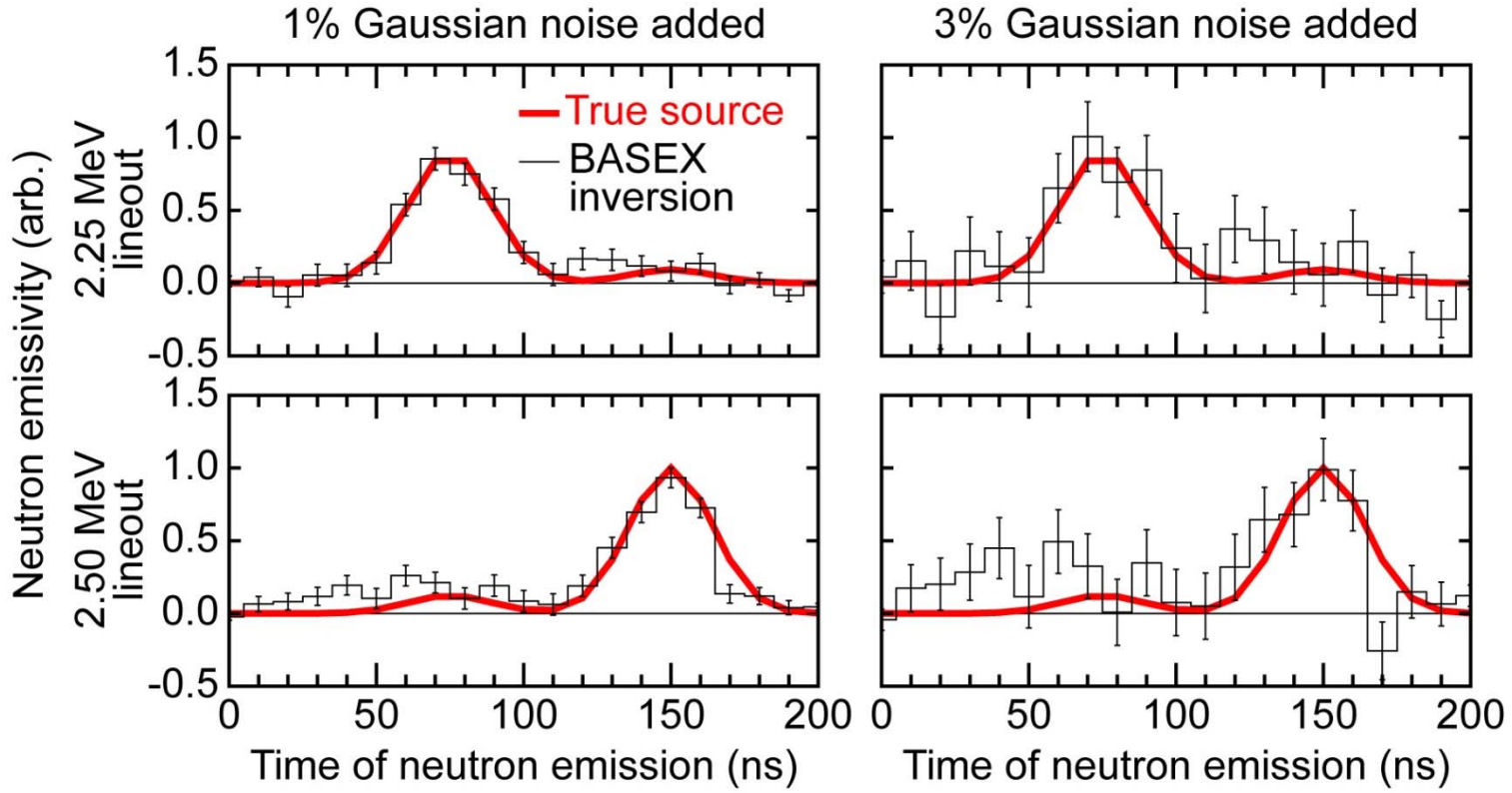
- A "true" neutron source coefficient set $\mathbf{C}_{true}$ is defined as in Tiseanu *et al.*, Nucl. Instr. Meth. Phys. Res. A **373**, 73 (1996).
- Forward transform is calculated, Gaussian noise is added
- Data are inverted and compared to the "true" source

BASEX method is tested by application to synthetic data



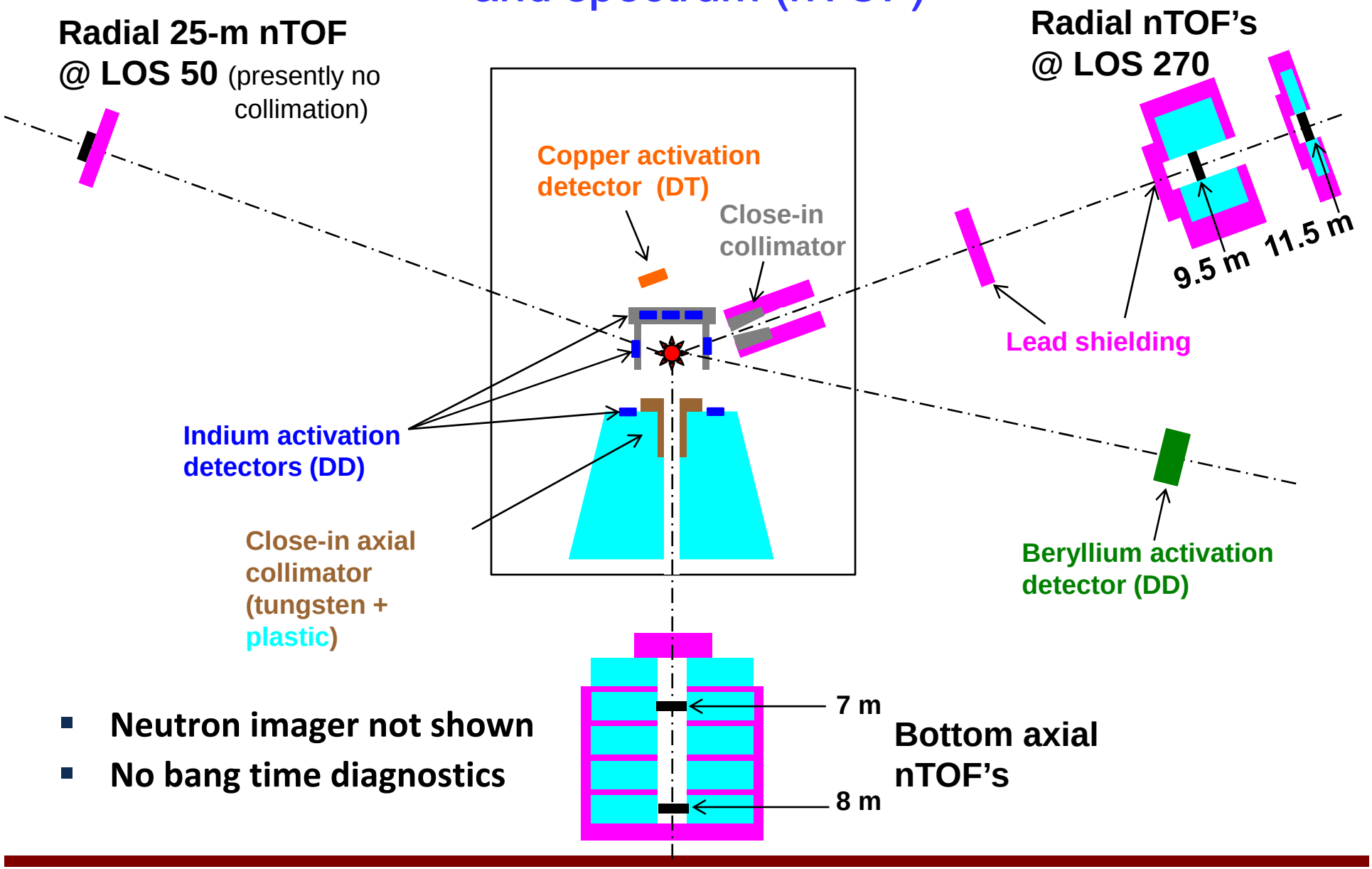
- A "true" neutron source coefficient set $\mathbf{C}_{true}$ is defined as in Tiseanu *et al.*, Nucl. Instr. Meth. Phys. Res. A **373**, 73 (1996).
- Forward transform is calculated, Gaussian noise is added
- Data are inverted; a value of regularization parameter q can be chosen as a best fit to the true source (lower q introduces more noise, too large a q introduces artifacts)
- Problem: BASEX with Tikhonov method admits unphysical negative values

Propagation of error calculation gives reasonable error bar estimates for inversion, fairly sensitive to noise



- Calculated error bars reasonably predict deviation between “true” source and lineouts of reconstructed source
- Highlights need for low-noise data (or more nTOF detectors)

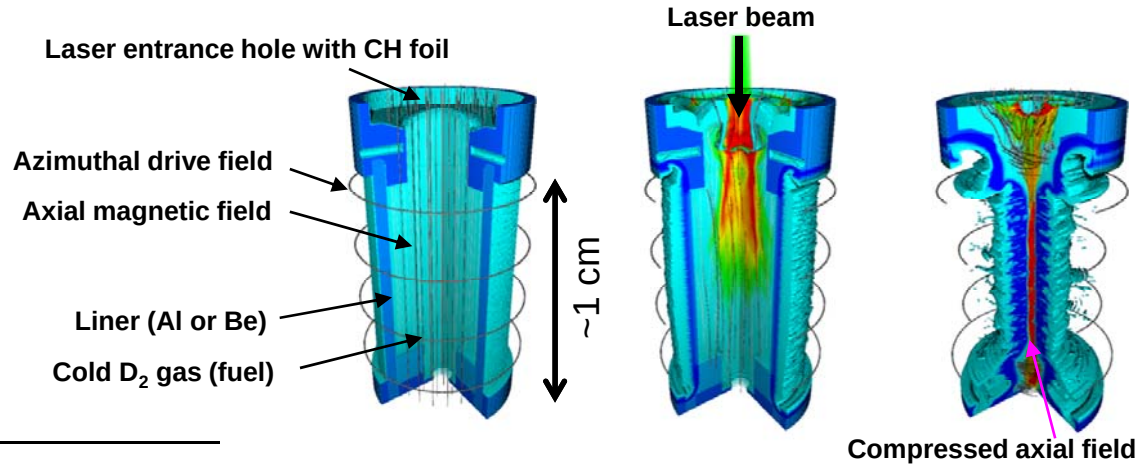
The Z neutron diagnostic suite characterizes yield (activation) and spectrum (nTOF)

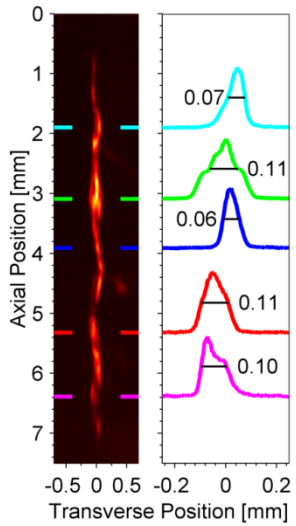


- Neutron imager not shown
- No bang time diagnostics

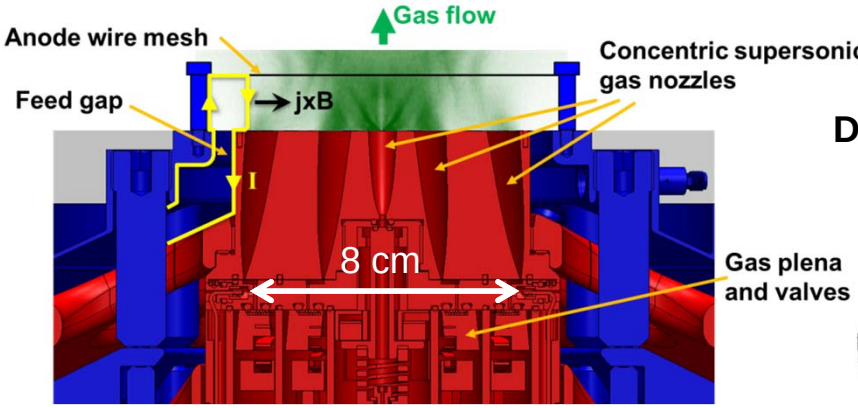
ICF neutron sources at Z can have very different implosion dynamics and plasma conditions

MagLIF

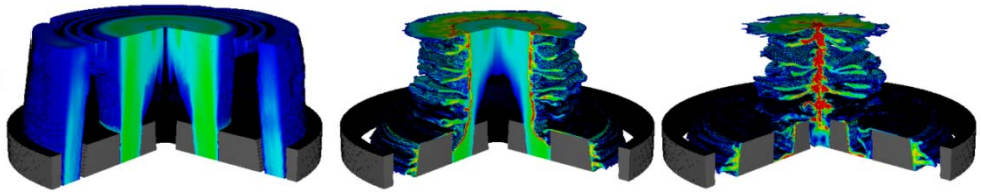




D_2 gas puff

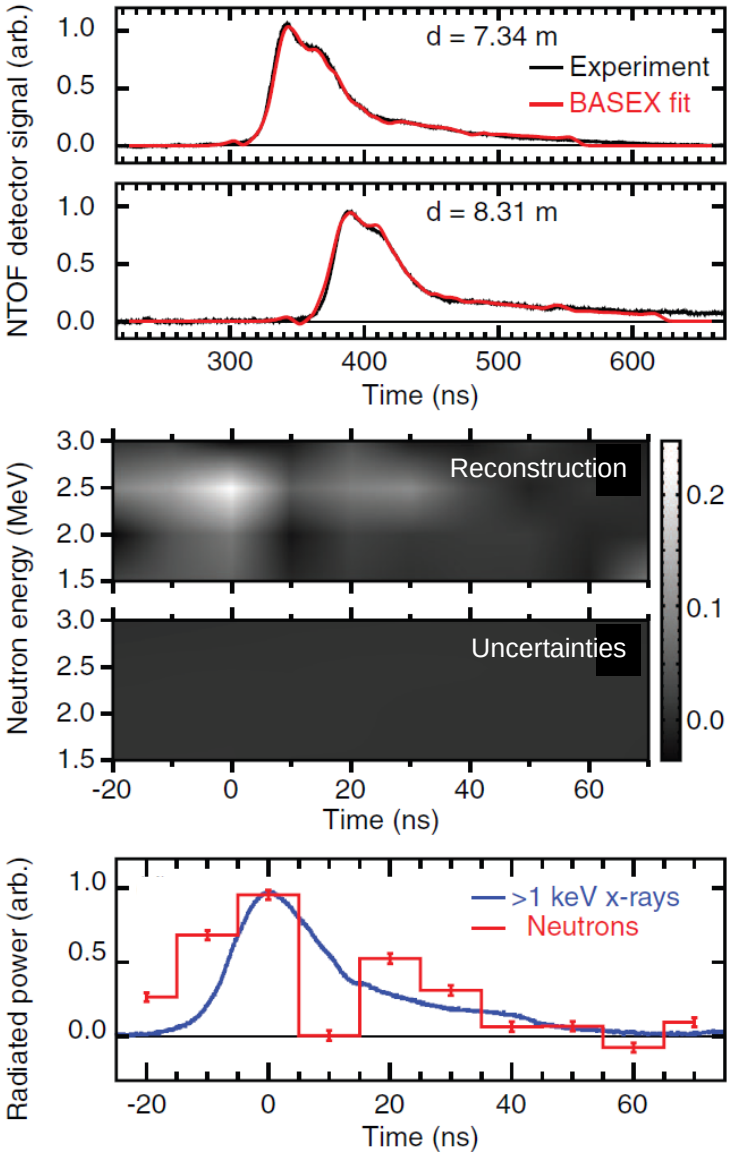


MagLIF: M. R. Gomez *et al.*, accepted to PRL (2014).
D_2 gas puff: C. A. Coverdale *et al.*, PoP **14**, 022706 (2007).



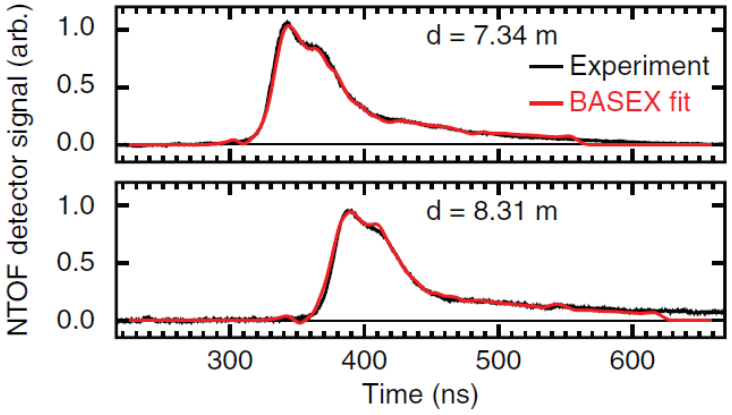
	Y_n(DD)	Y_n(DT)	T_e (keV)	T_i (keV)	n_i (cm^{-3})	Δt (ns)	Diameter
MagLIF	$2x10^{12}$	$5x10^{10}$	~3	2.5	~ 10^{23}	< 2	~50 μm
D_2 gas puff	$4x10^{13}$	$<4x10^{9}$	2.2	~10	$2x10^{20}$	~30	6 mm

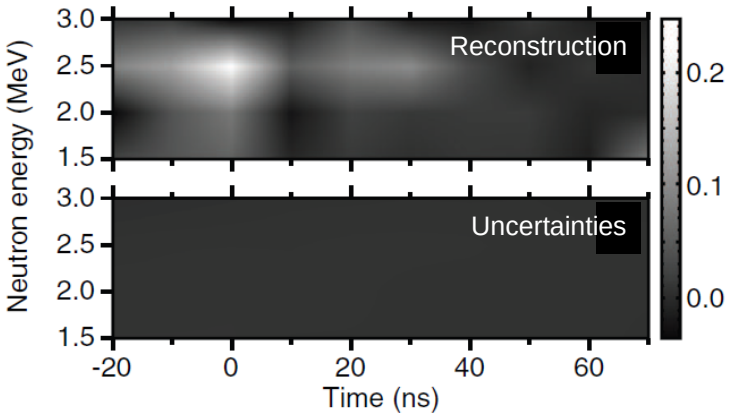
Application of BASEX unfold to a D_2 gas puff on Z shows two neutron pulses with downscatter from adjacent hardware

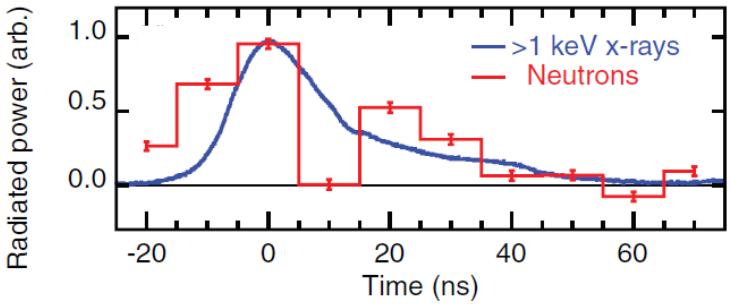


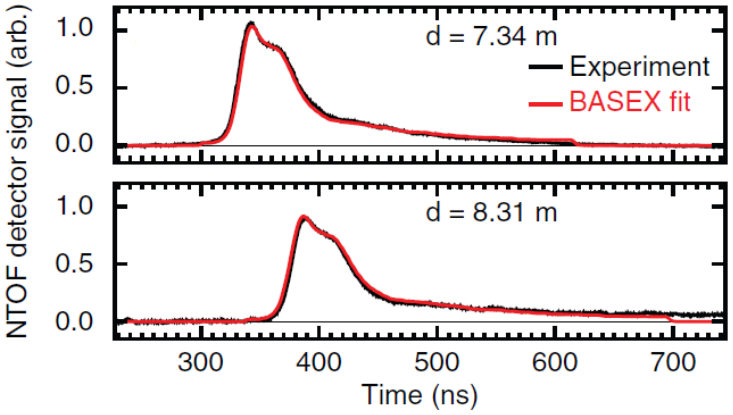
- **Unfold produces a good fit with experimental nTOF data**
- **Resolution is coarse, and limited by signal-to-noise**
- **Attempting the inversion with higher resolution leads to unphysical oscillations to negative values**
- **Inferred neutron pulse shape is consistent with x-ray measurement (PCD) showing main pulse and tail**

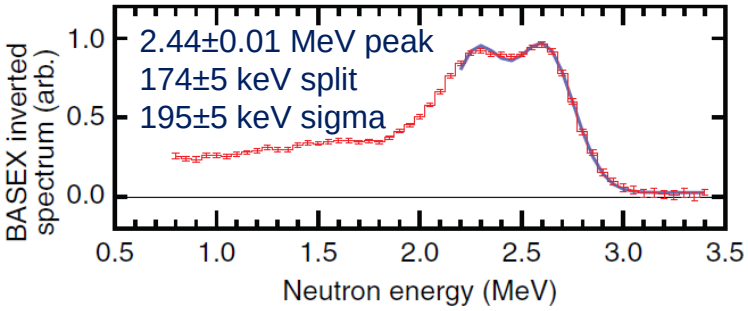
Data spread can be equally well interpreted as due to instantaneous emission with spectral broadening









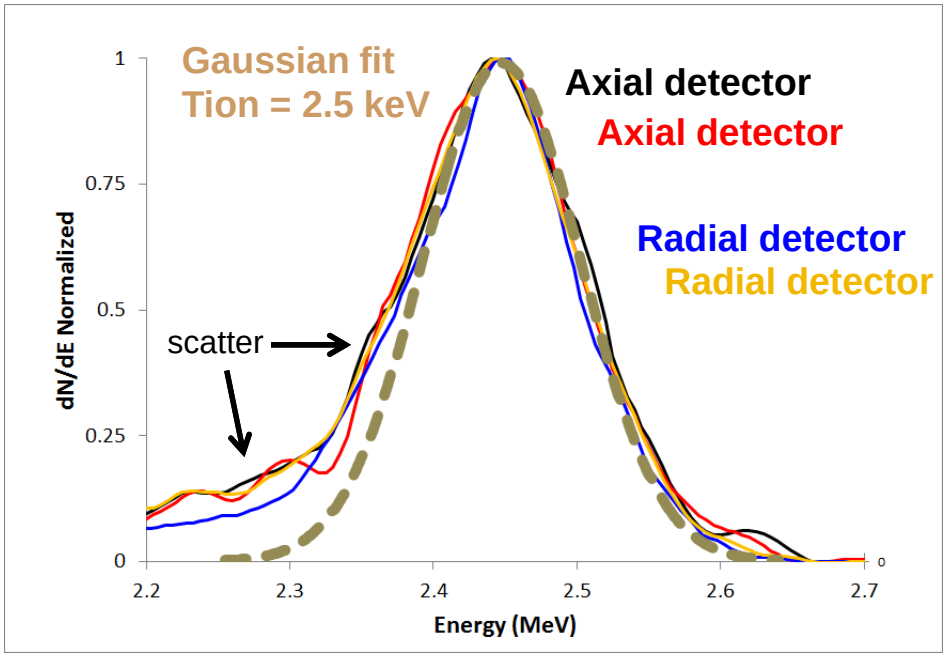


- **Uniqueness of the solution may be a significant pitfall for inversions**
- **More nTOF locations and analysis are required**

MagLIF sources may have too short of a time duration for inversion given the present Z nTOF diagnostic set

2 kJ laser preheat
10 T applied axial B field
19 MA drive current
$5x10^{11}$-$2x10^{12}$ primary DD yields
1-$5x10^{10}$ 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.

Summary

- **Advanced analysis considering the entire set of nTOF (plus burn history) diagnostic data may enable inference of T_i and time evolution**
- **BASEX method presented here has strengths and weaknesses**
  - **Instrumental response and perhaps scattering in the beamline can be accounted for implicitly during the inversion**
  - **Admits unphysical negative solutions, which limits resolution and increases sensitivity to noise**
- **Application of this method to other sources could be interesting**
  - **It will likely be easier to analyze longer duration neutron pulses with more structure in the nTOF waveforms**
- **Synthetic data studies can help to design the diagnostic set**
- **Other inversion methods should also be explored**