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Neutron Source Reconstruction Methods for One-Dimensional Neutron Images from the Z Facility

Z Fundamental Science Workshop

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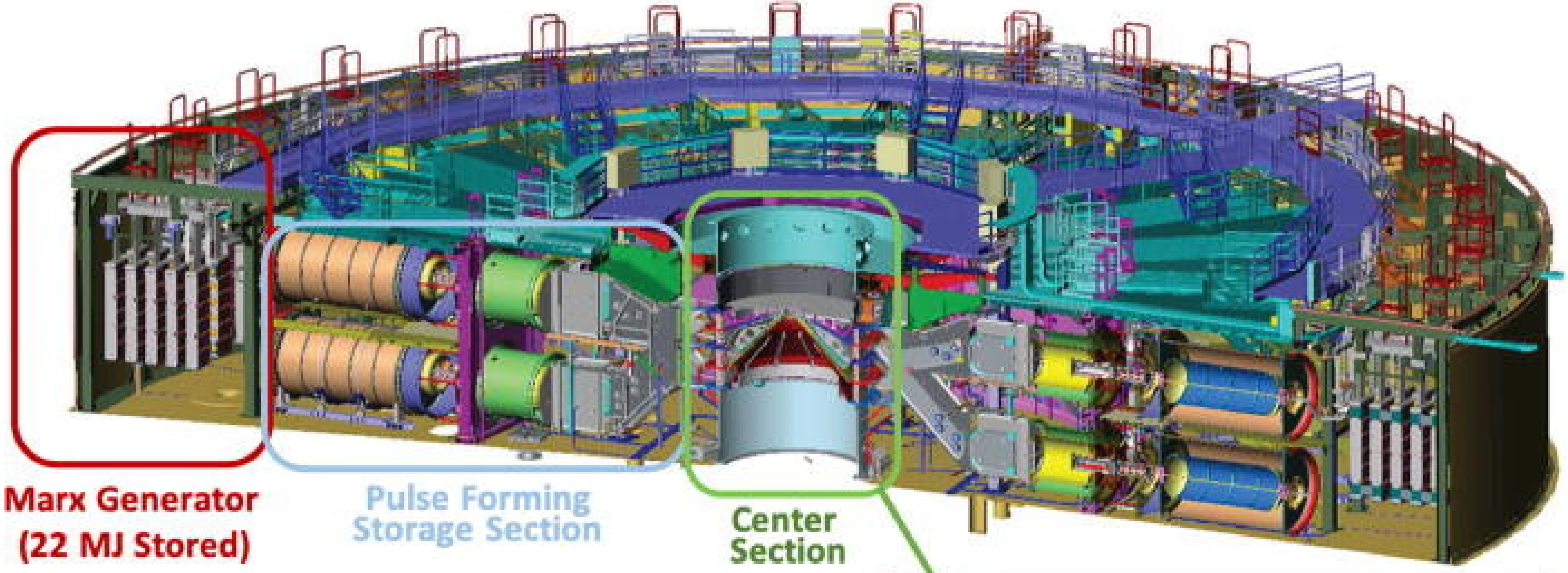
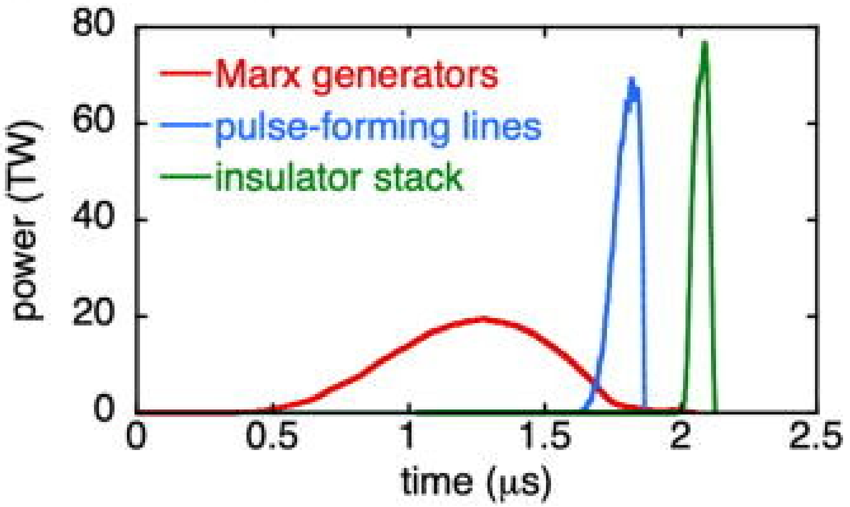
Outline

- Overview of Z machine and MagLIF
- One-Dimensional Imager of Neutrons (ODIN)
- Image Reconstruction Methodology
- ODIN Data Image Reconstruction

Overview of Z machine and MagLIF

Z Machine

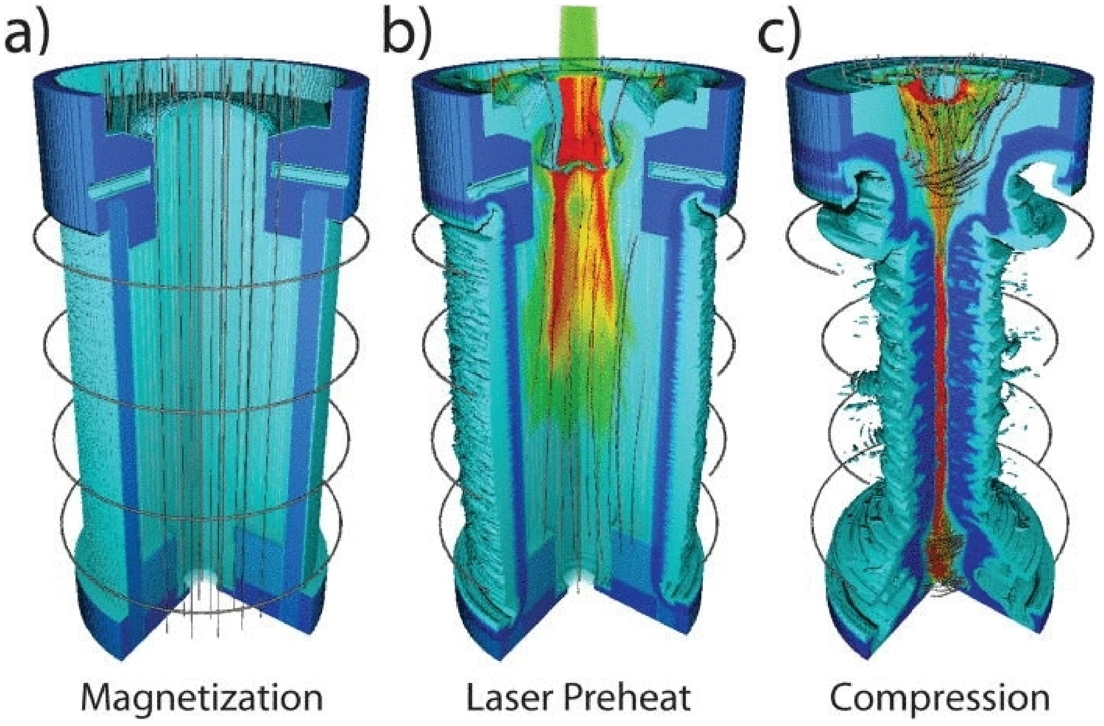




D. B. Sinars et al., “Review of pulsed power-driven high energy density physics research on z at sandia,” Physics of Plasmas., vol. 27, no. 7, 2020.

Magnetized Liner Inertial Fusion (MagLIF)

- Magnetization stage applies a magnetic field around the target to reduce radial thermal conduction loss
- Laser Preheat stage raises the fuel temperature to reduce the required compression for fusion conditions
- Compression stage implodes the target from the magnetic field of the electrical pulse

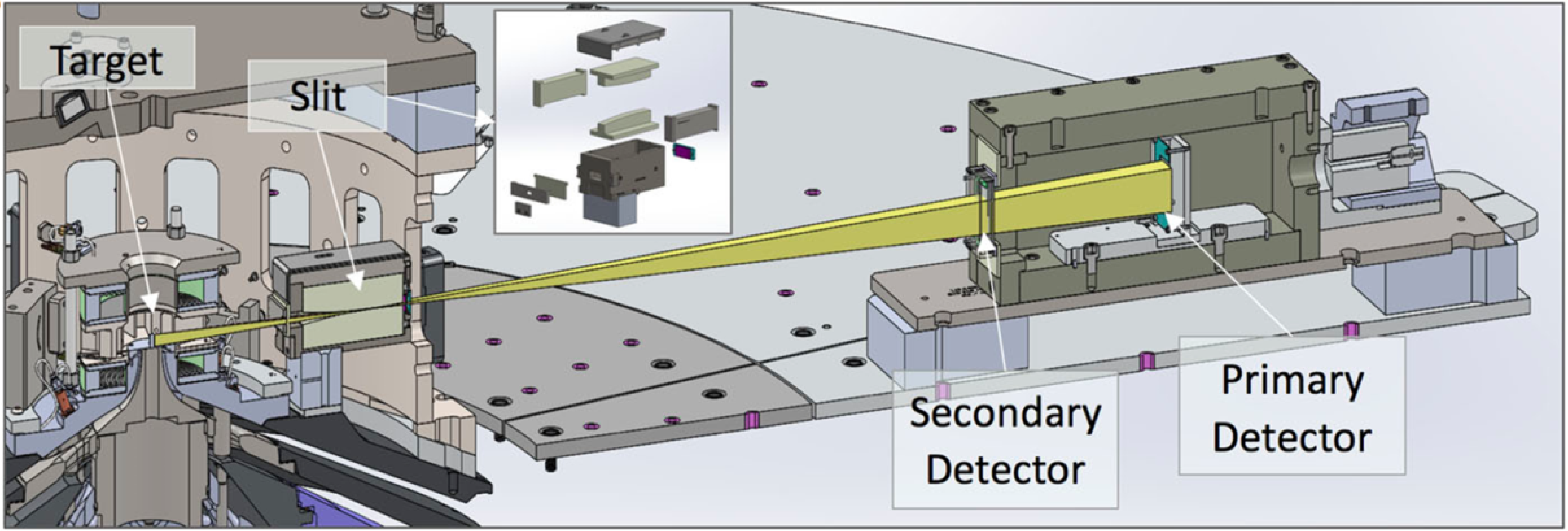


$$D + D \rightarrow {}^{3}He\,(0.8\,MeV) + n(2.45\,MeV)\ 50\%$$
$$\rightarrow p(3.02\,MeV) + T(1.01\,MeV)\ 50\%$$
$$D + T \rightarrow \alpha\,(3.6\,MeV) + n(14.1\,MeV)$$

P. F. Knapp et al., “Effects of magnetization on fusion product trapping and secondary neutron spectra,” Physics of Plasmas., vol. 22, no. 5, 2015.

One-Dimensional Imager of Neutrons (ODIN)

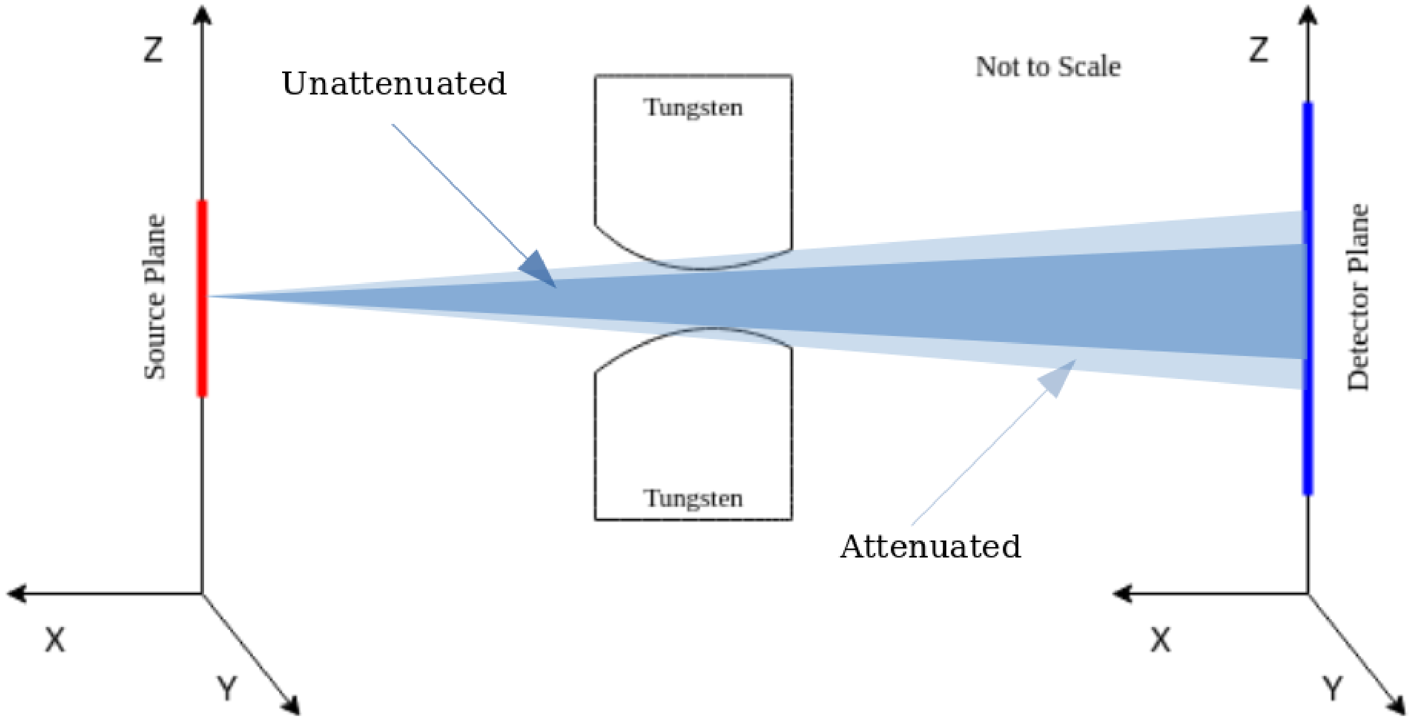
One-Dimensional Imager of Neutrons (ODIN)



- Images neutrons emitted by MagLIF experiments on the Z facility
- Yields range from ~$1X10^{12}$ to ~$1X10^{13}$ from ~1cm tall target which are recorded as tracks on CR-39 pieces

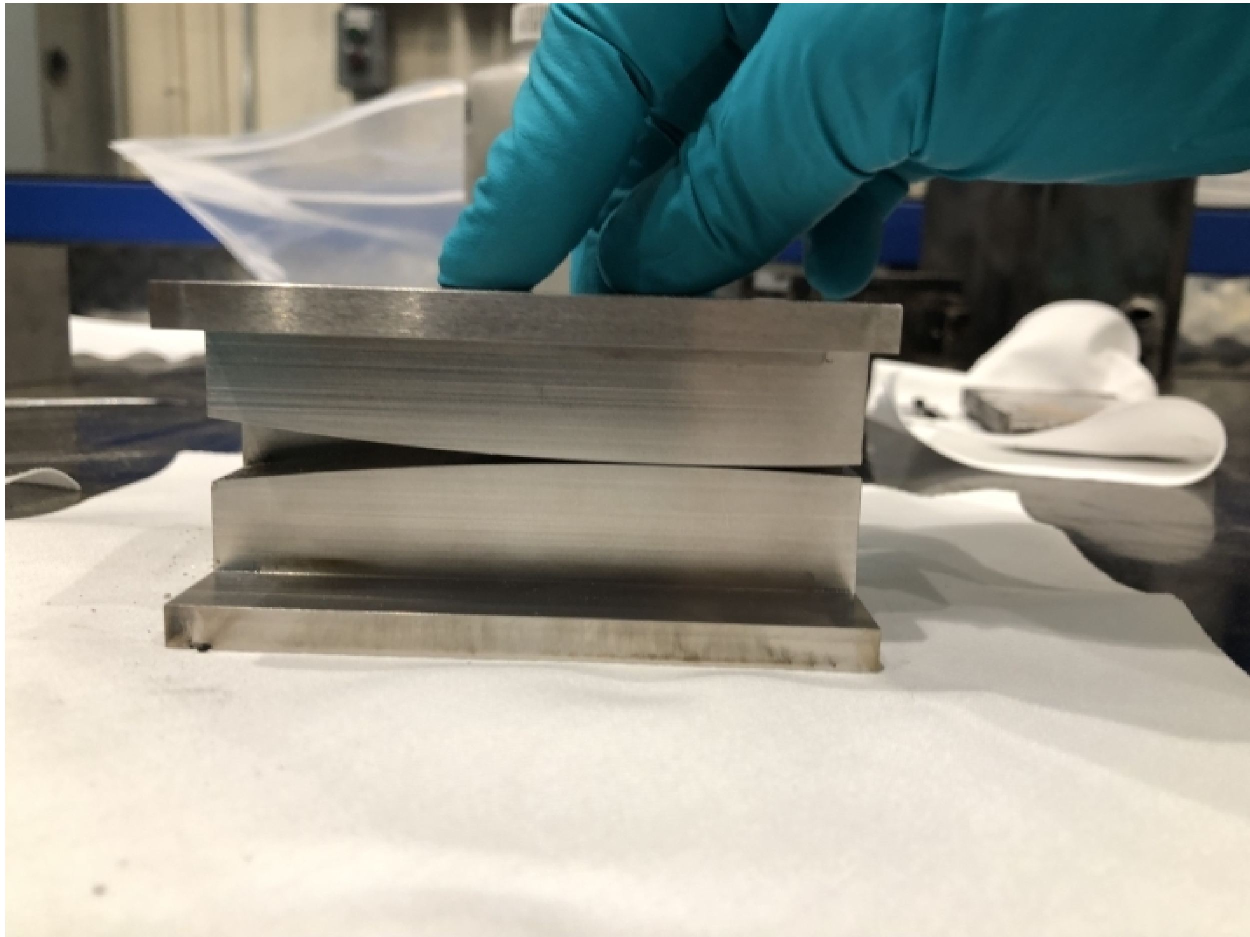
David J. Ampleford, et al. "One dimensional imager of neutrons on the Z machine", Review of Scientific Instruments 89, 10I132 (2018)

Forward Model: Neutrons from source through aperture to detector



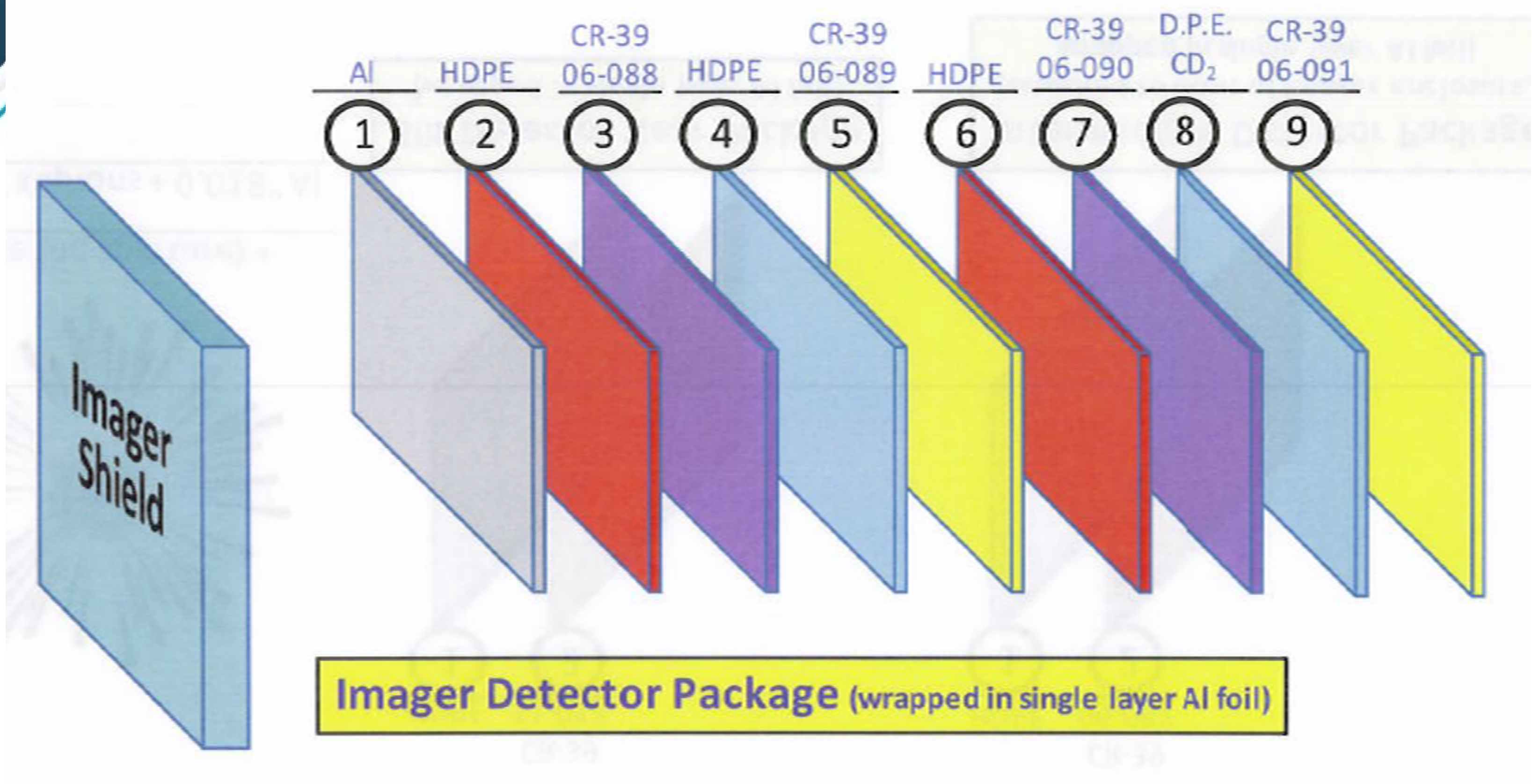
- Rays from source points are generated towards interaction points along the detector plane
- Neutrons can attenuate through the tungsten or pass freely through the aperture

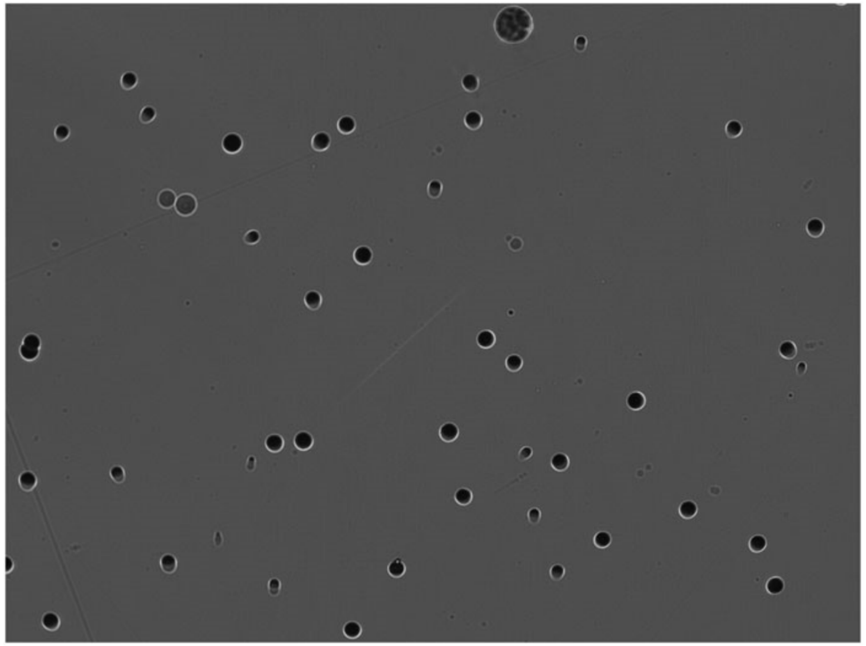
ODIN: Rolled edge and mounting location



- The aperture is 10 cm long, with a nominal spacing of 250 μm

ODIN: Detector package configuration



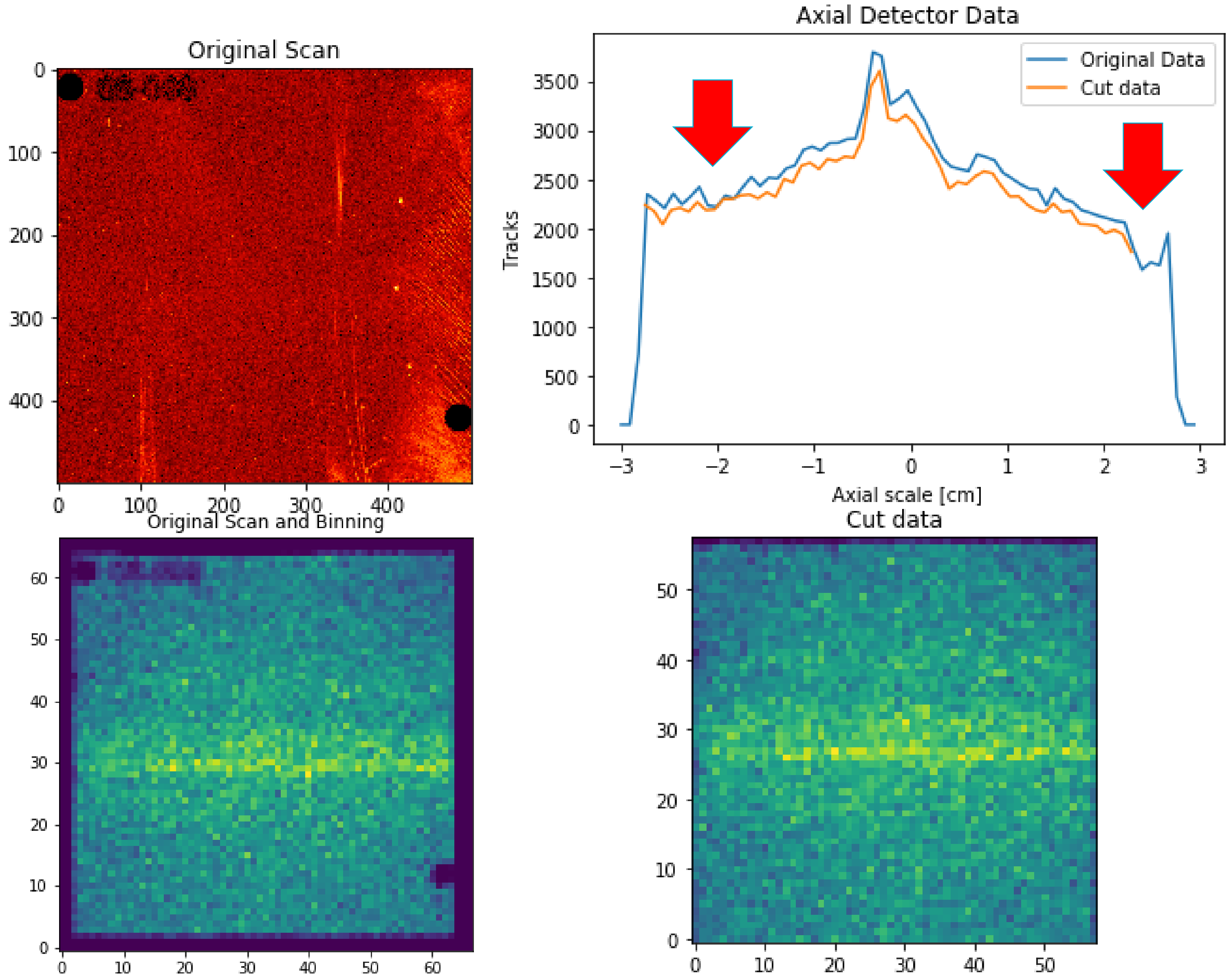


- DD Neutrons elastically scatter and produce recoil protons which leave destructive tracks
- High density polyethylene is placed in front of the CR-39 to increase the detection efficiency
- Microscope scans provide information on track location, diameter, contrast, and eccentricity for discrimination of incident neutrons

B. Lahmann et al. "CR-39 nuclear track detector response to inertial confinement fusion relevant ions," Rev Sci Instrum 1 May 2020; 91 (5): 053502. https://doi.org/10.1063/5.0004129

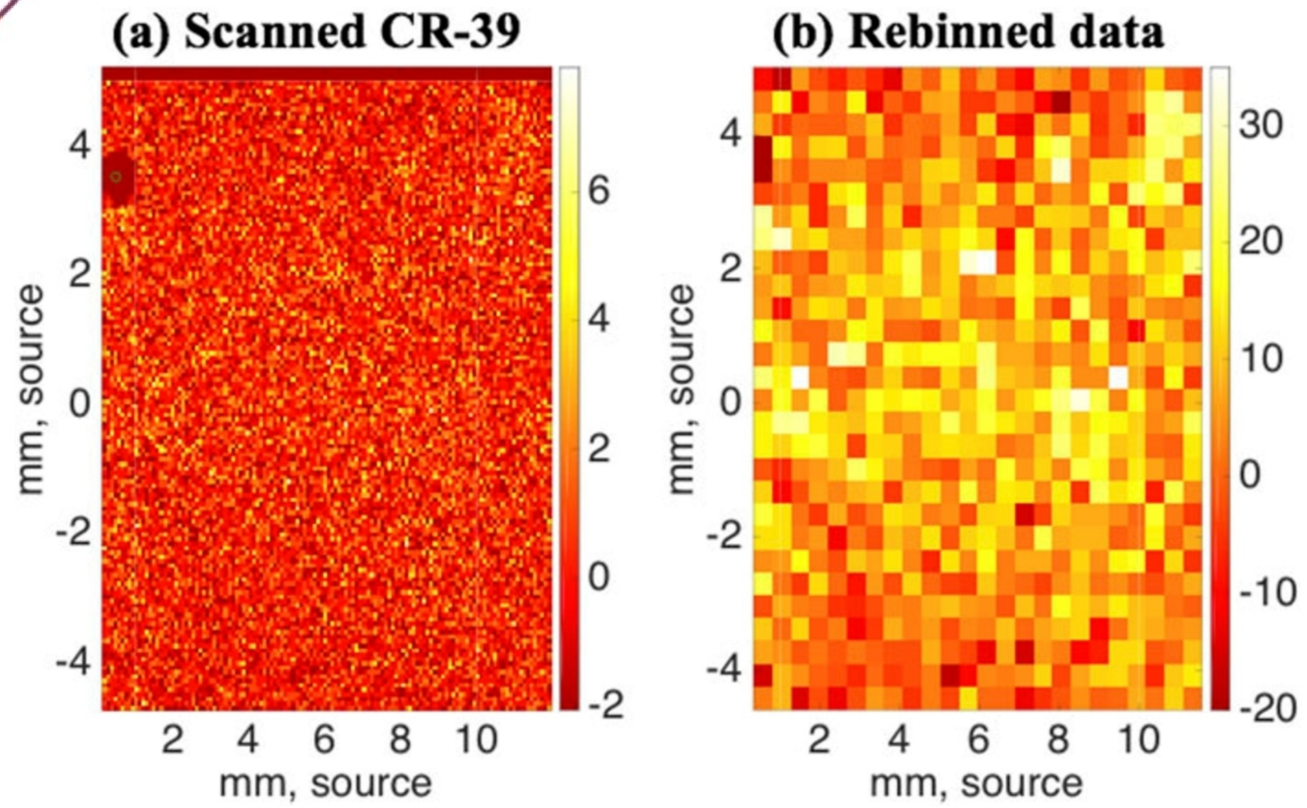
Z3289 ODIN data

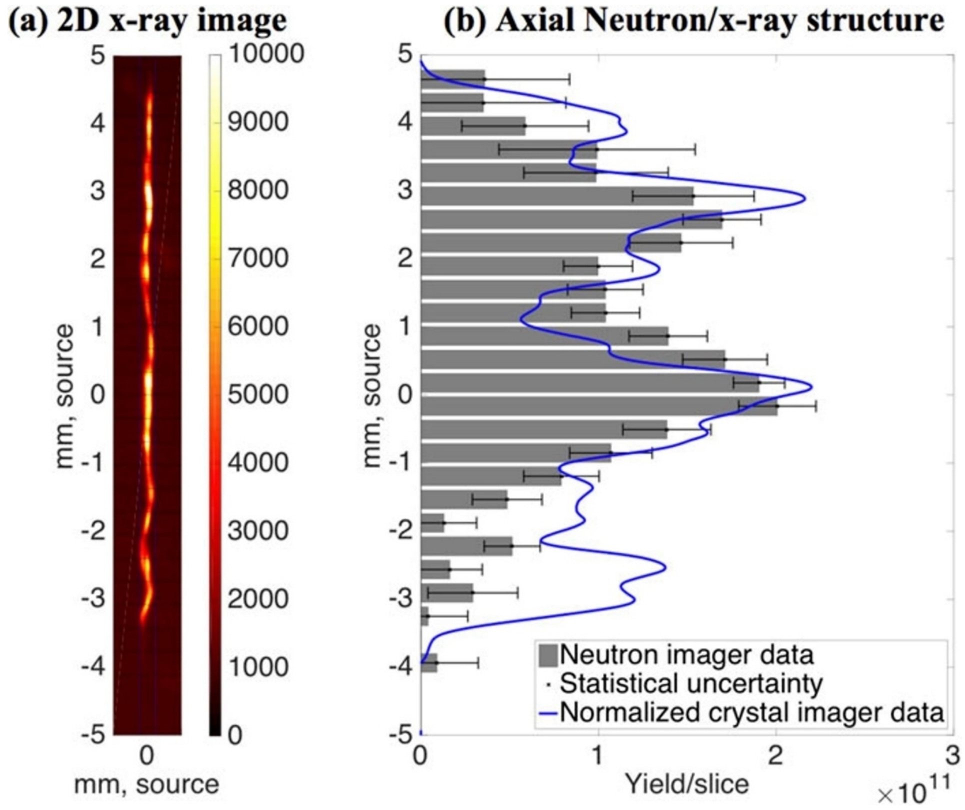
- Non-incident neutrons are filtered out, data rebinned to ODIN's resolution
- Data is integrated along the resolving axis to produce an axial detector measurement
- A subset of the data is used to remove the pinholes and tag number



S. A .Ricketts et al. "Neutron source reconstruction of one-dimensional imager of neutron images through maximum likelihood methods," Conference presentation, APS Division of Plasma Physics Meeting, 2022

ODIN Previous Analysis





- No further reconstruction has been attempted
- **Objective: Use image reconstruction methods to improve imaging of the spatial distribution of neutron emissions from the stagnation column**

David J. Ampleford, et al. "One dimensional imager of neutrons on the Z machine", Review of Scientific Instruments 89, 10I132 (2018)

Image Reconstruction Methodology

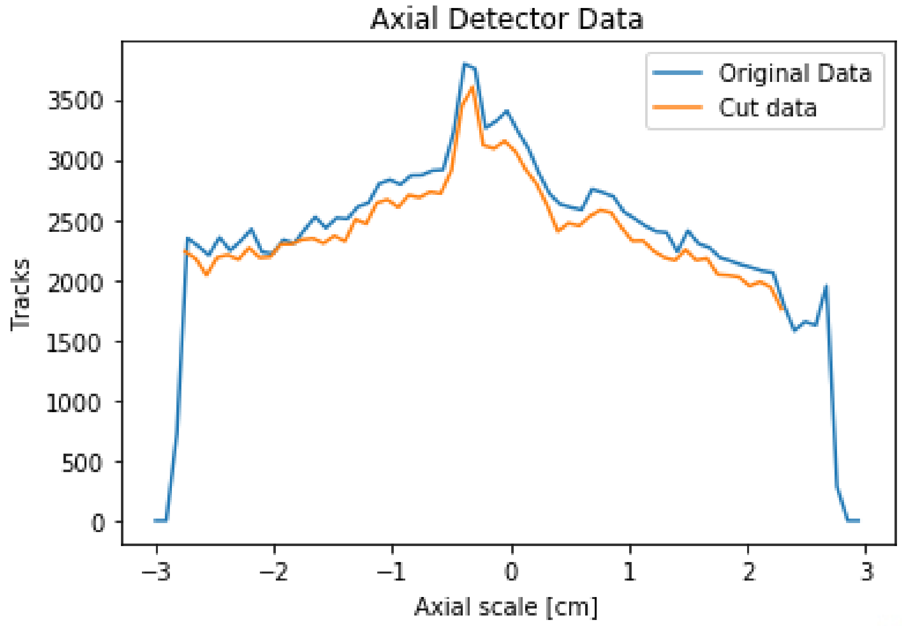
Fredholm Integral Equation of the First Kind

$$\int_a^b K(x,y)G_0(y)dy = N_0\,(x), c \le x \le d$$

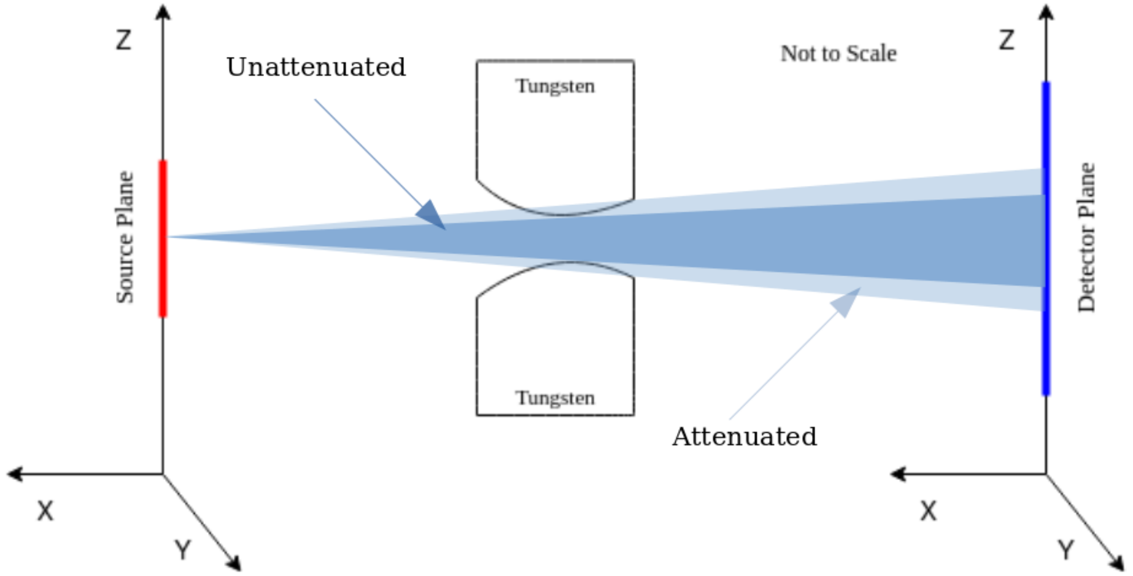
Kernel/ Instrument Response Function

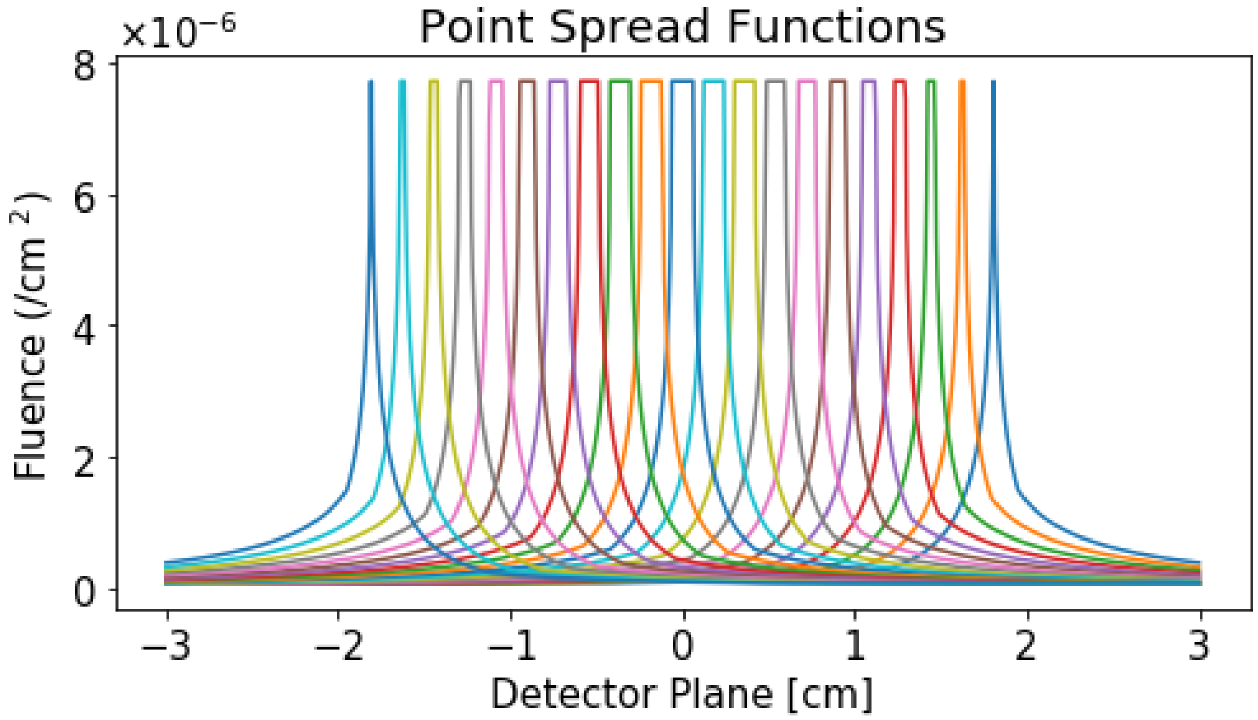
Neutron Source

Neutron Image Data



Instrument Response Function from Forward Model





- Fluence amplitude is in agreement with Monte Carlo N-Particle Transport Code (MCNP) simulations (J. D. Vaughan et al.)
- For a uniform source ~635 tracks/cm^2 (D. J. Ampleford et al. ~650 tracks/cm^2)

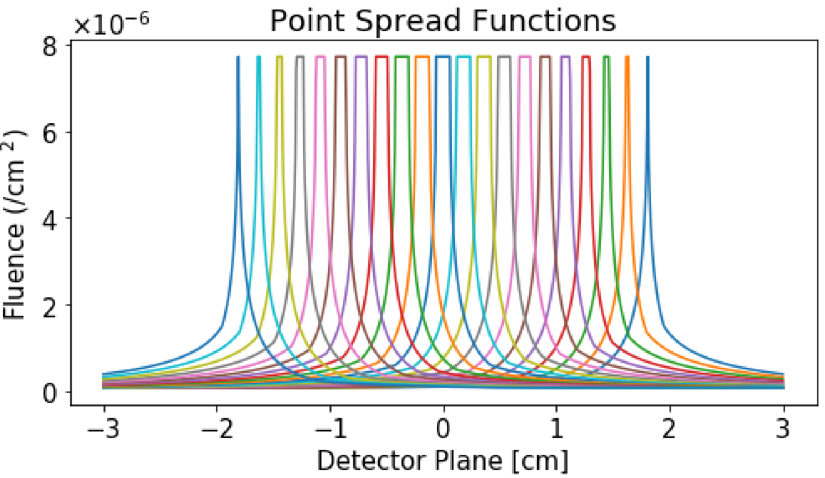
Fredholm Integral Equation of the First Kind: Solving for neutron source

$$\int_a^b \underline{K(x,y)}\,\underline{G_0(y)}\,dy = \underline{N_0\,(x)}, c \leq x \leq d$$

Kernel/ Instrument Response Function

Neutron Source

Neutron Image Data



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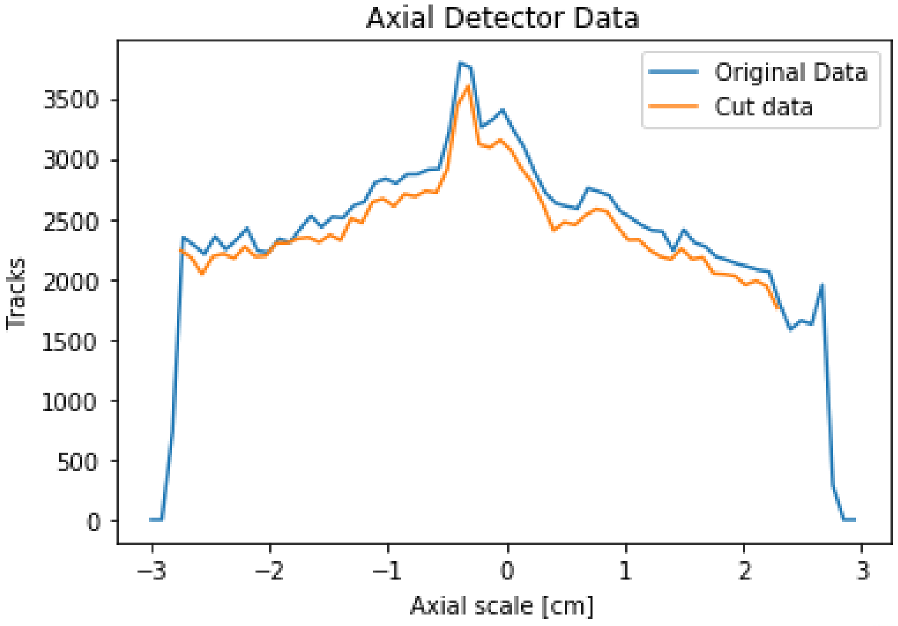
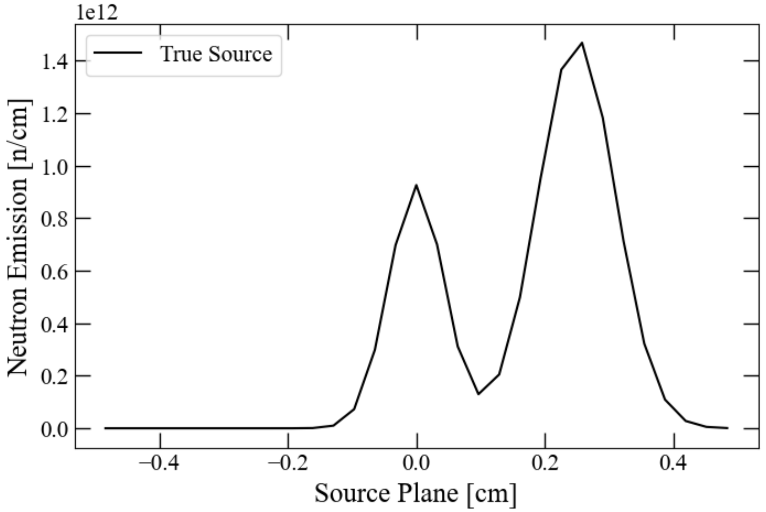
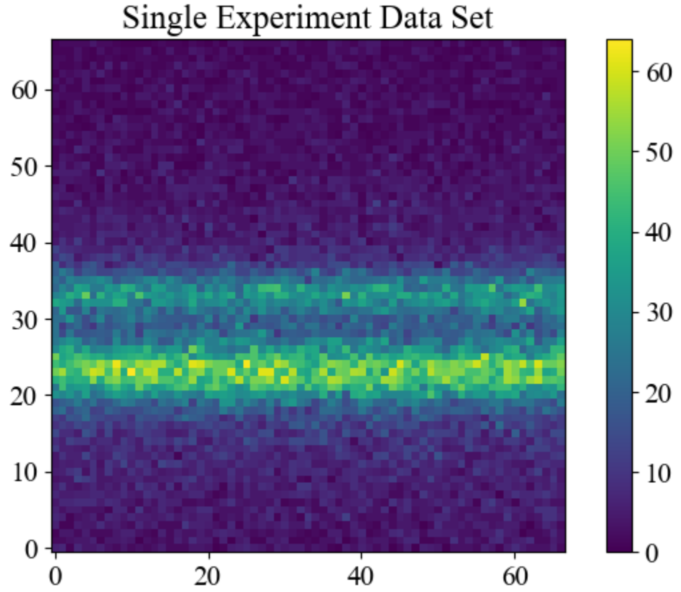


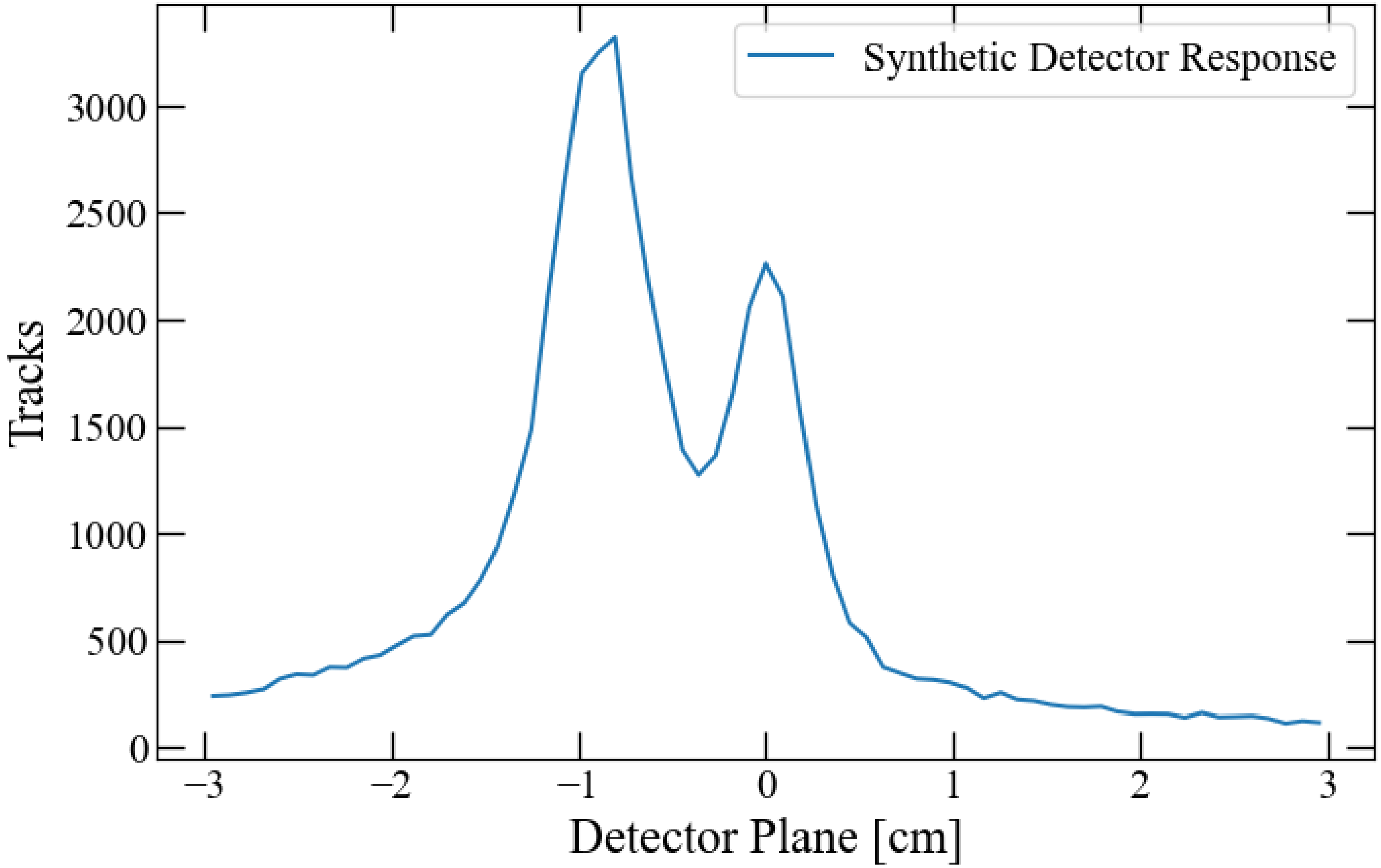
Image Reconstruction Methods Investigated

- Least Squares Fit
  - Selects a solution which minimizes the square of the residual
- Non-Negative Least Squares Fit
  - Implements non-negativity constraint for Least Squares Fit
- Maximum Likelihood Estimation (MLE)
  - Iterative algorithm which converges to a solution that maximizes a likelihood function
  - Can factor in the type of noise (Gaussian or Poissonian)
  - Poissonian has non-negativity constraint
- Generalized Expectation Maximization (GEM)
  - Iterative algorithm with a regularization parameter **1/β** which implements a smoothing to the solution
  - Low β smooths the solution
  - Large β has no smoothing and approaches Maximum Likelihood Poissonian

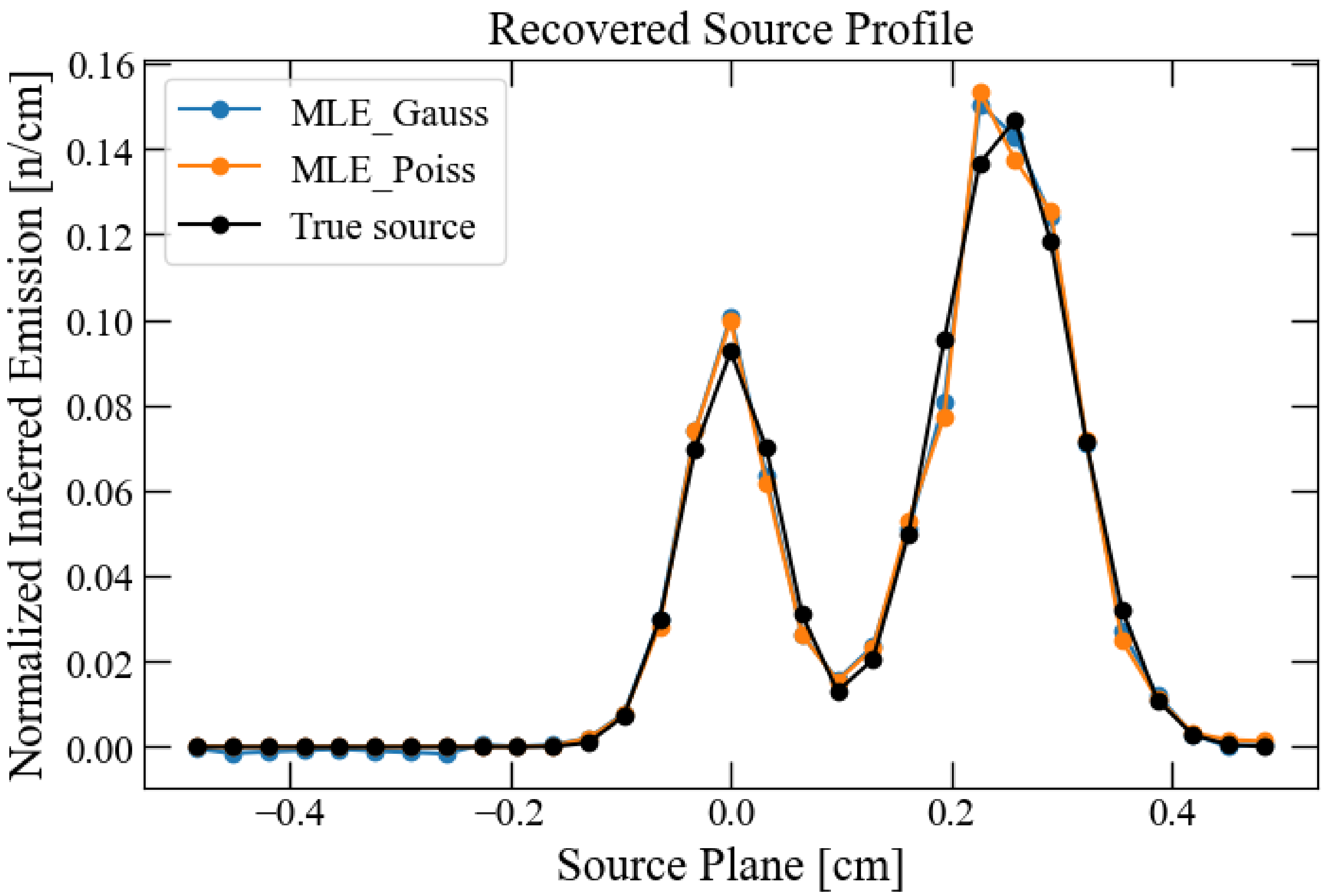
Generating Detector Response using Synthetic Data



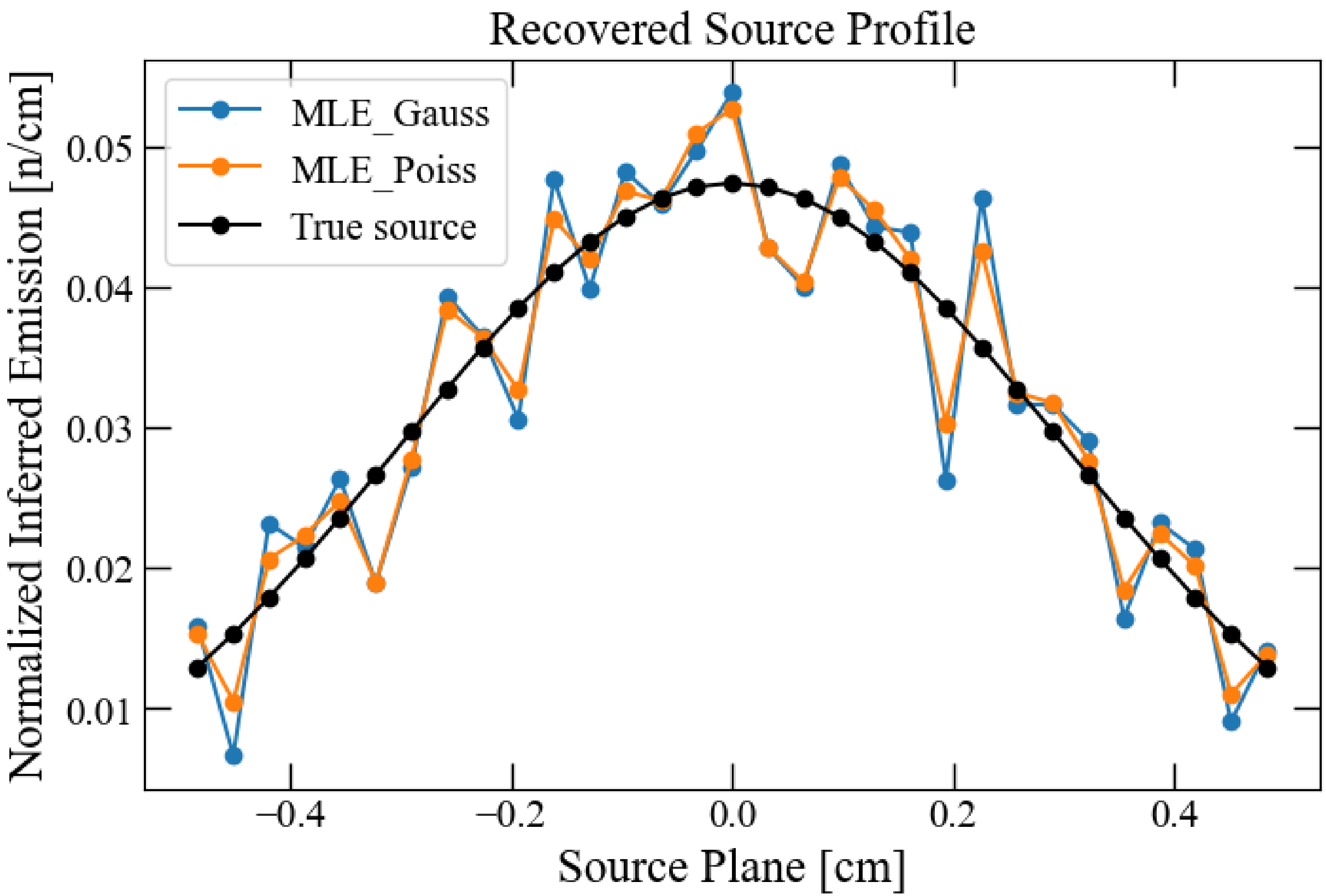




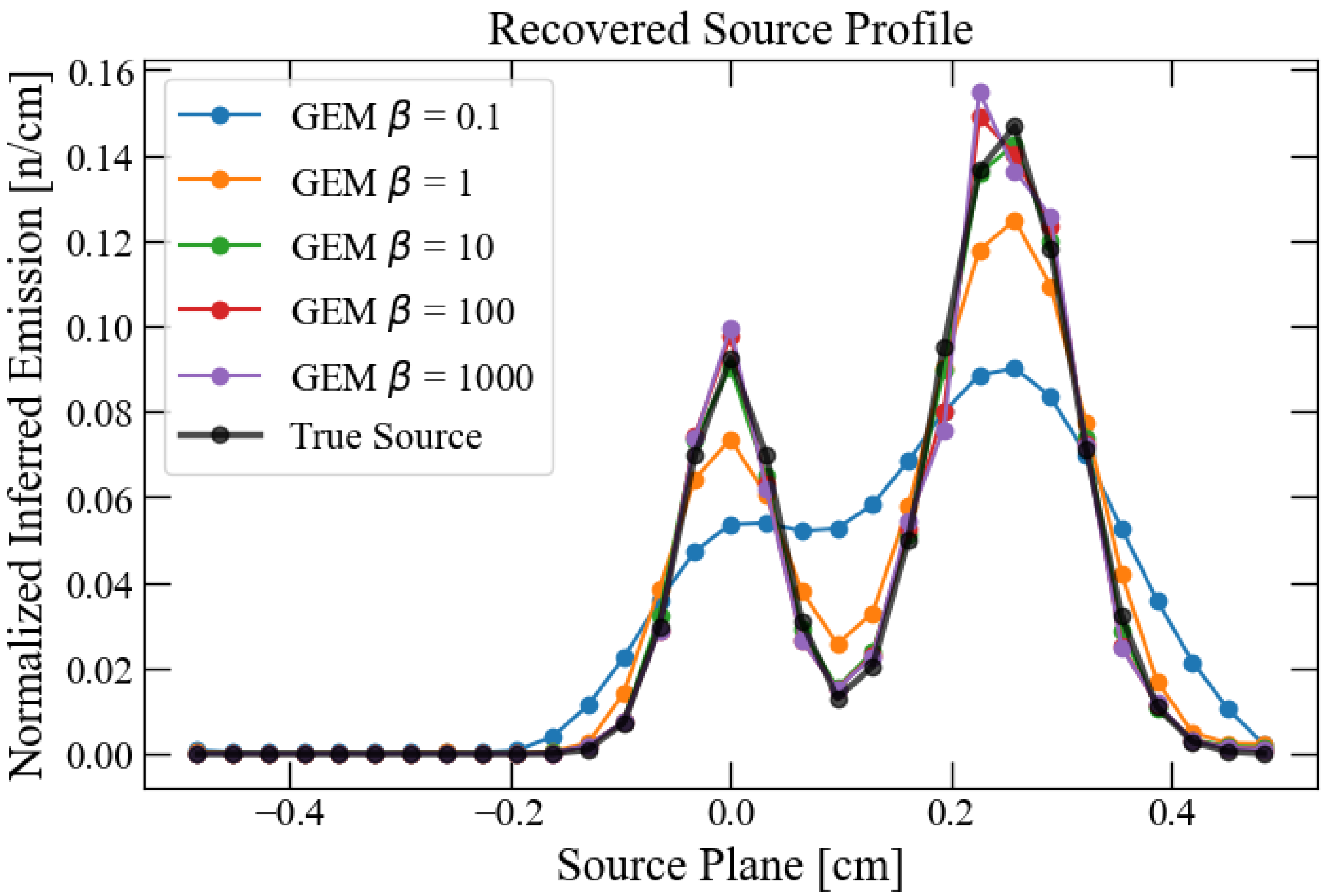
Maximum Likelihood Reconstruction: Gaussian and Poissonian noise models.



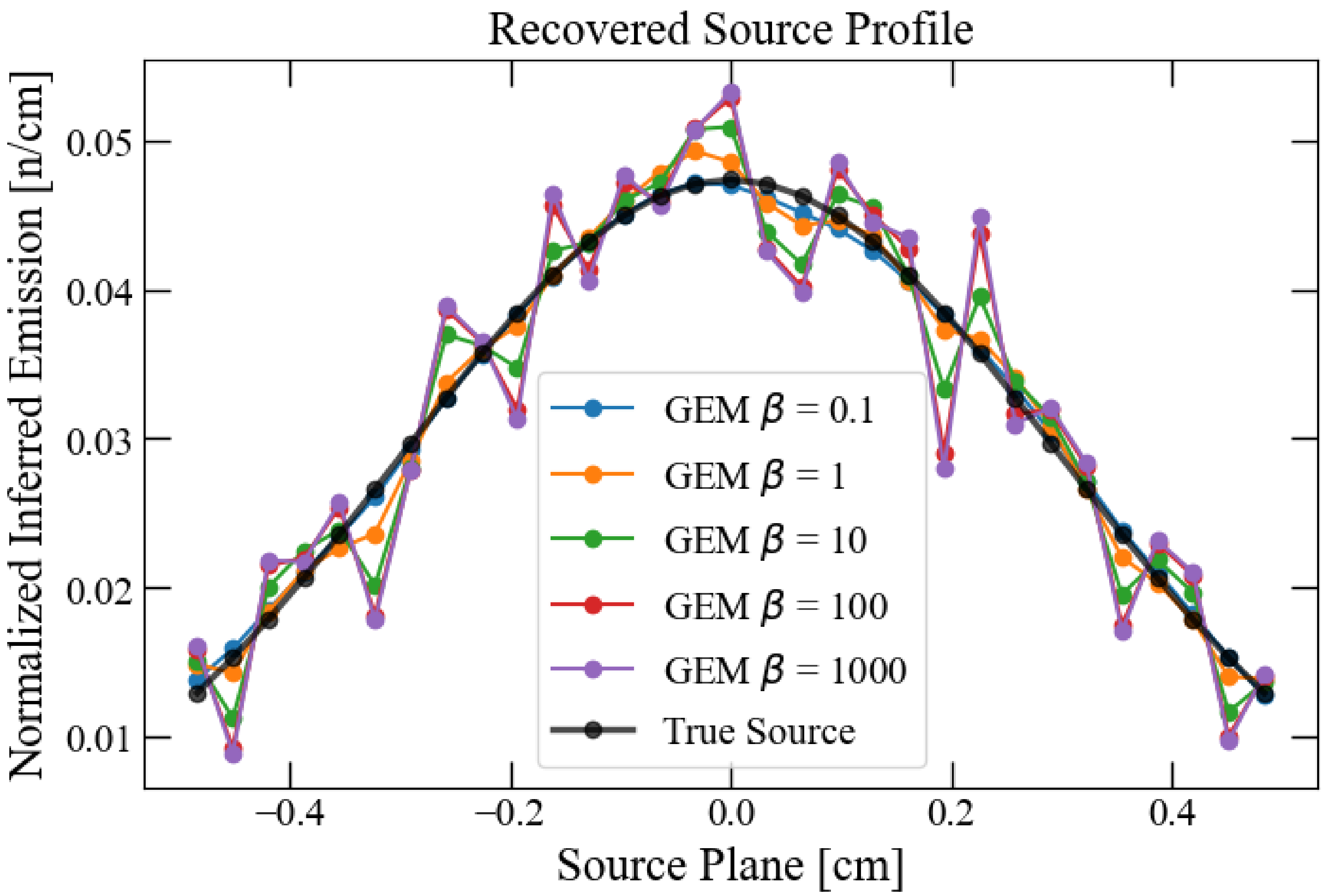
Let’s change up the source, lower frequency source profile



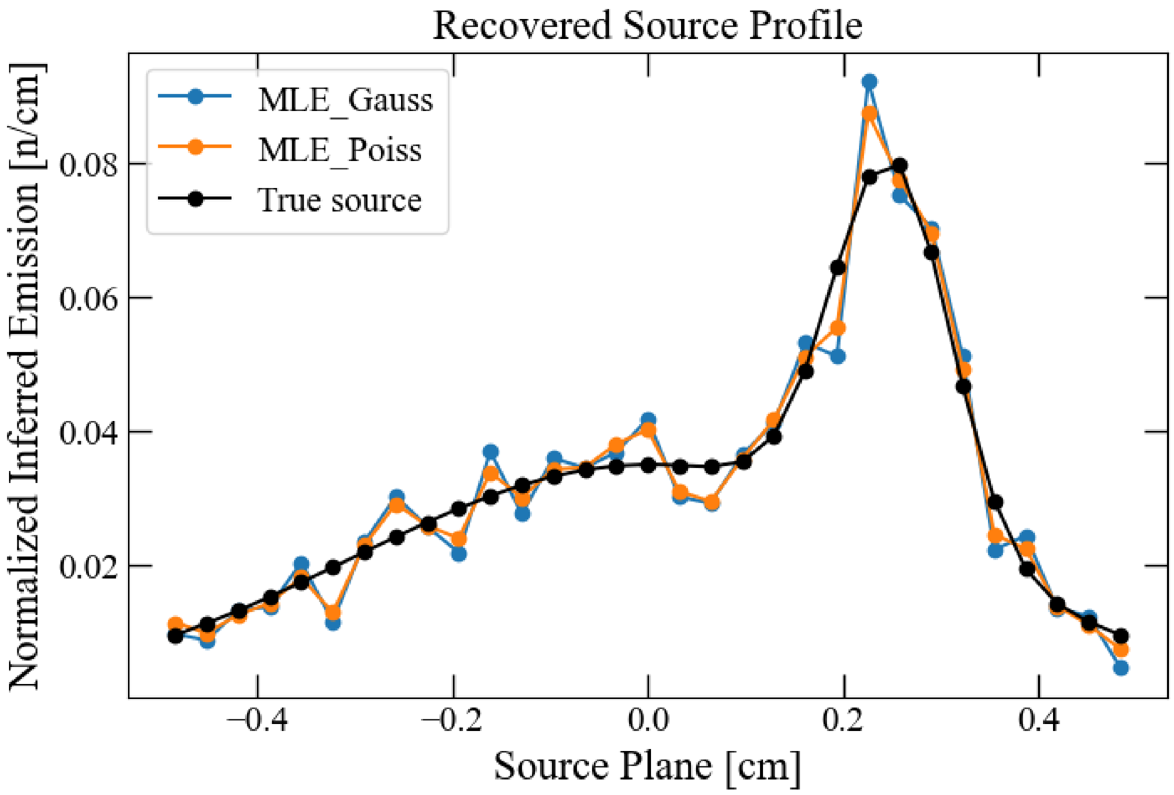
Generalized Expectation Maximization (GEM) with varying regularization parameter, β.

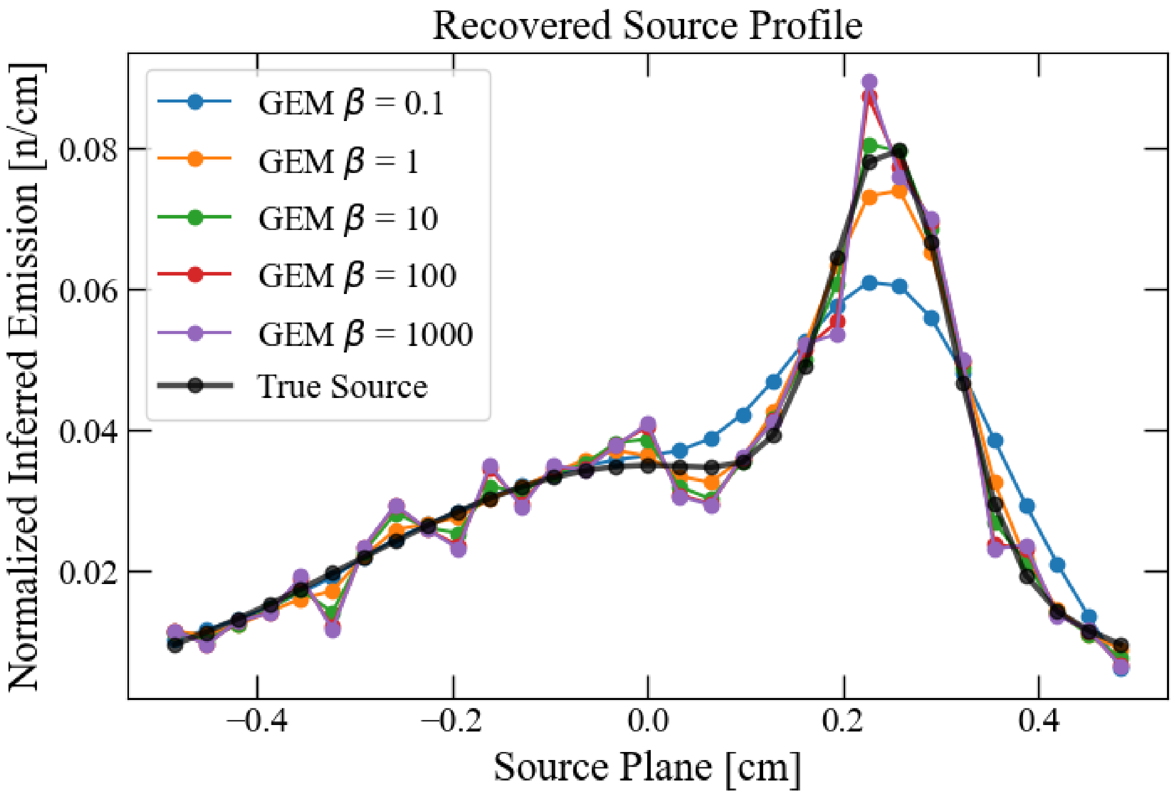


GEM method with low frequency source profile



Low and high frequency synthetic source



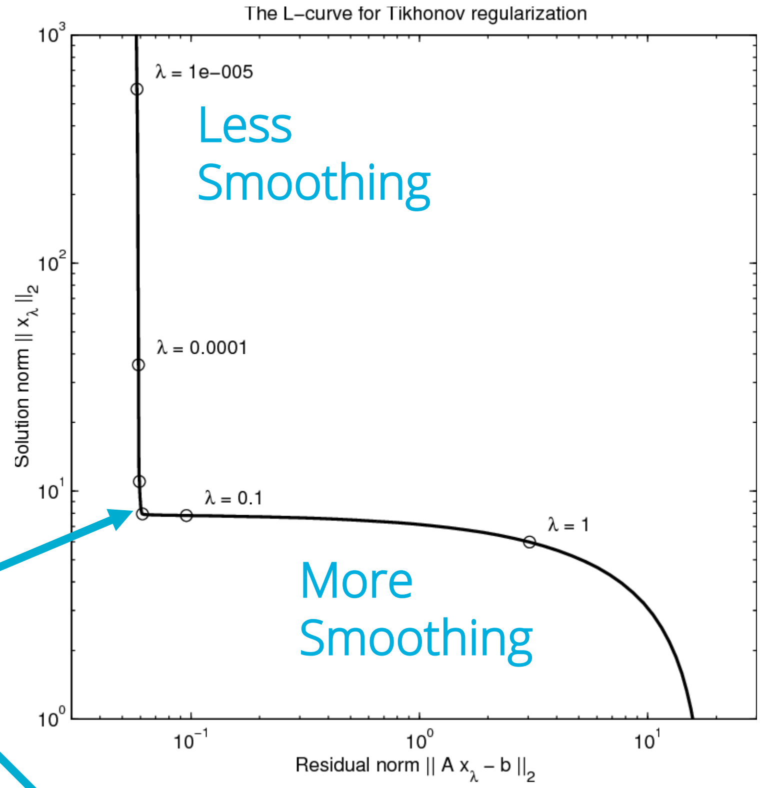


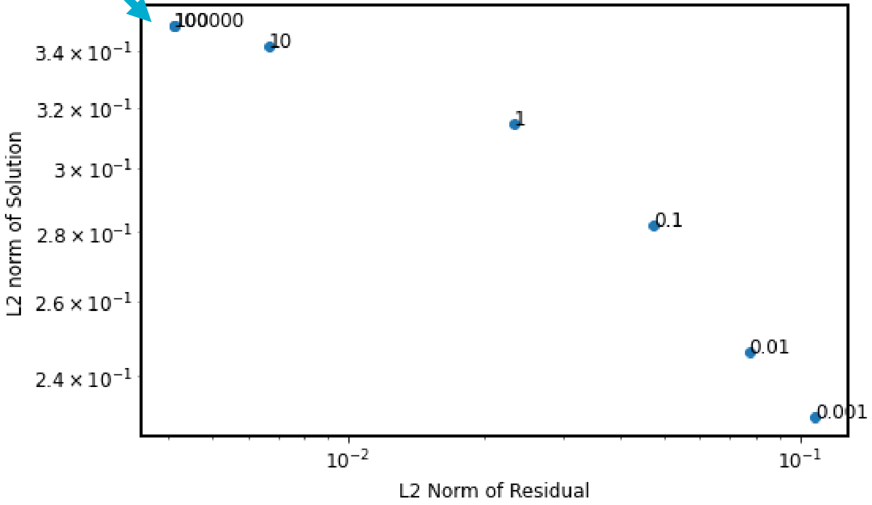
- **How do we pick β in an ill-posed problem?**

Usual methods for choosing β

- Have some understanding of what the source *should* look like
  - This will vary from shot to shot
- L curve is a common method
  - The non-negativity constraint does not allow high frequencies to enter the negative space
  - So there is no upper region to the L curve

Stops here with non-negativity

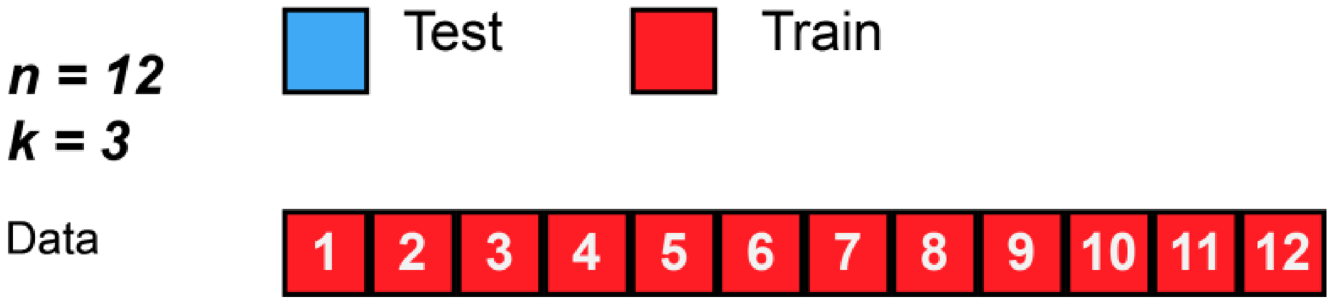




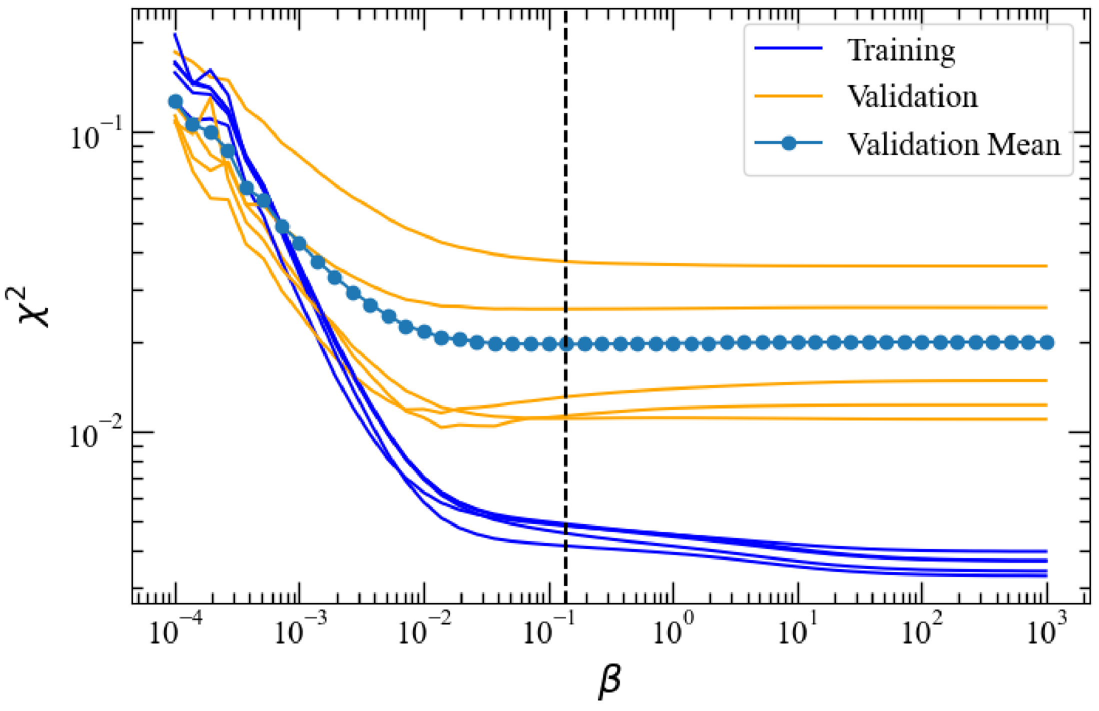
$\lambda \propto 1/\beta$

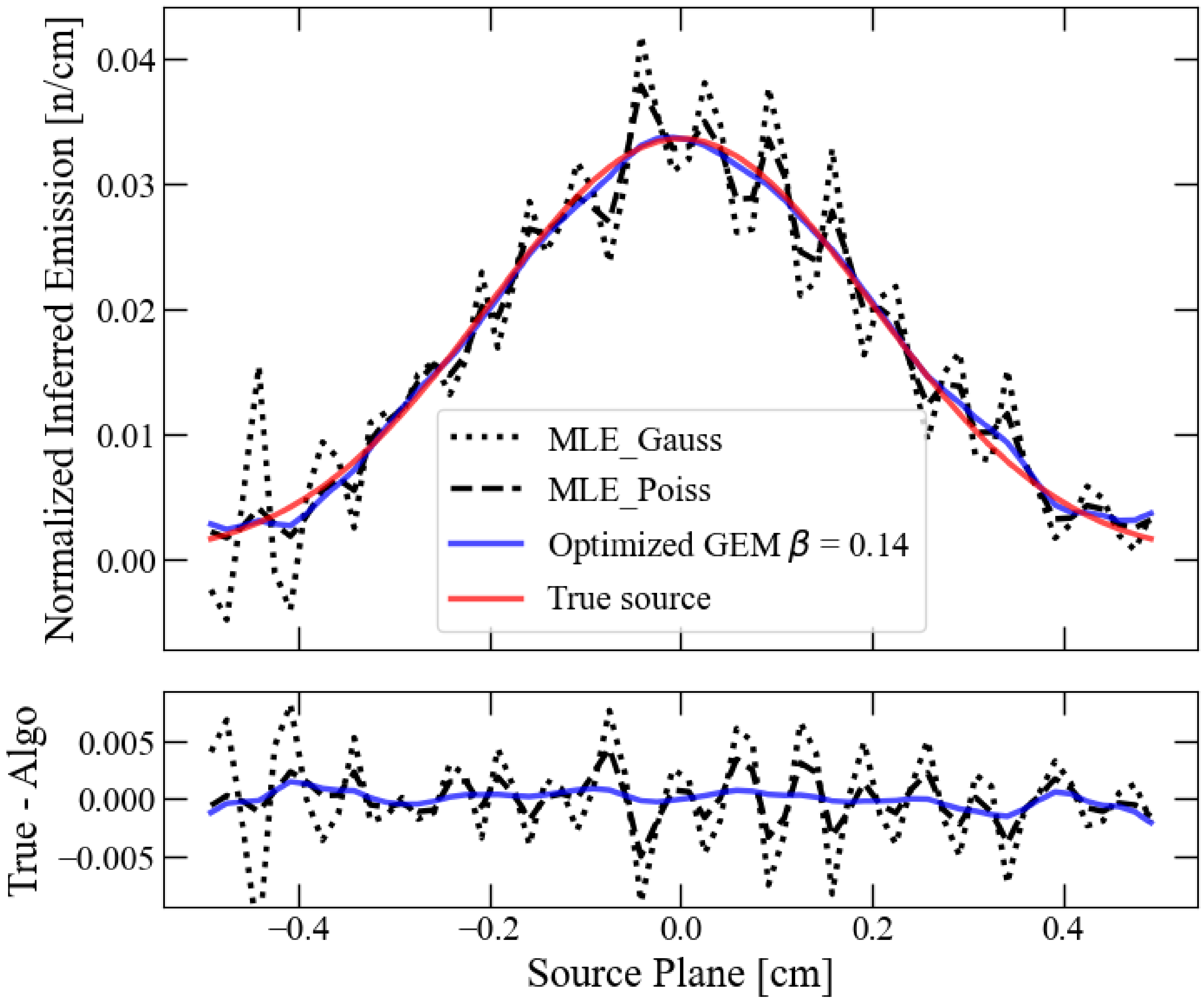
K-Fold Cross Validation for a chosen β

1. Randomize order of data points
2. Split data into k folds
3. First fold becomes testing data points for goodness of fit, remaining folds train the model fit
4. Iterate through each k fold
   - Allows each data point to be part of training and testing
5. Repeat over a range of β values

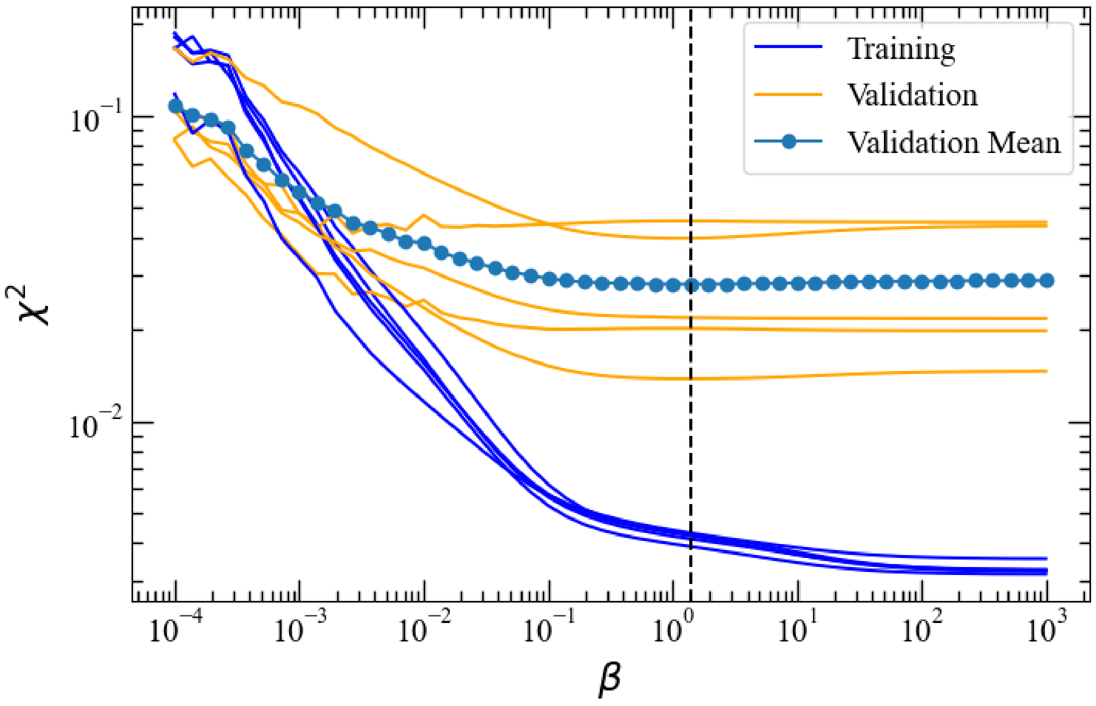


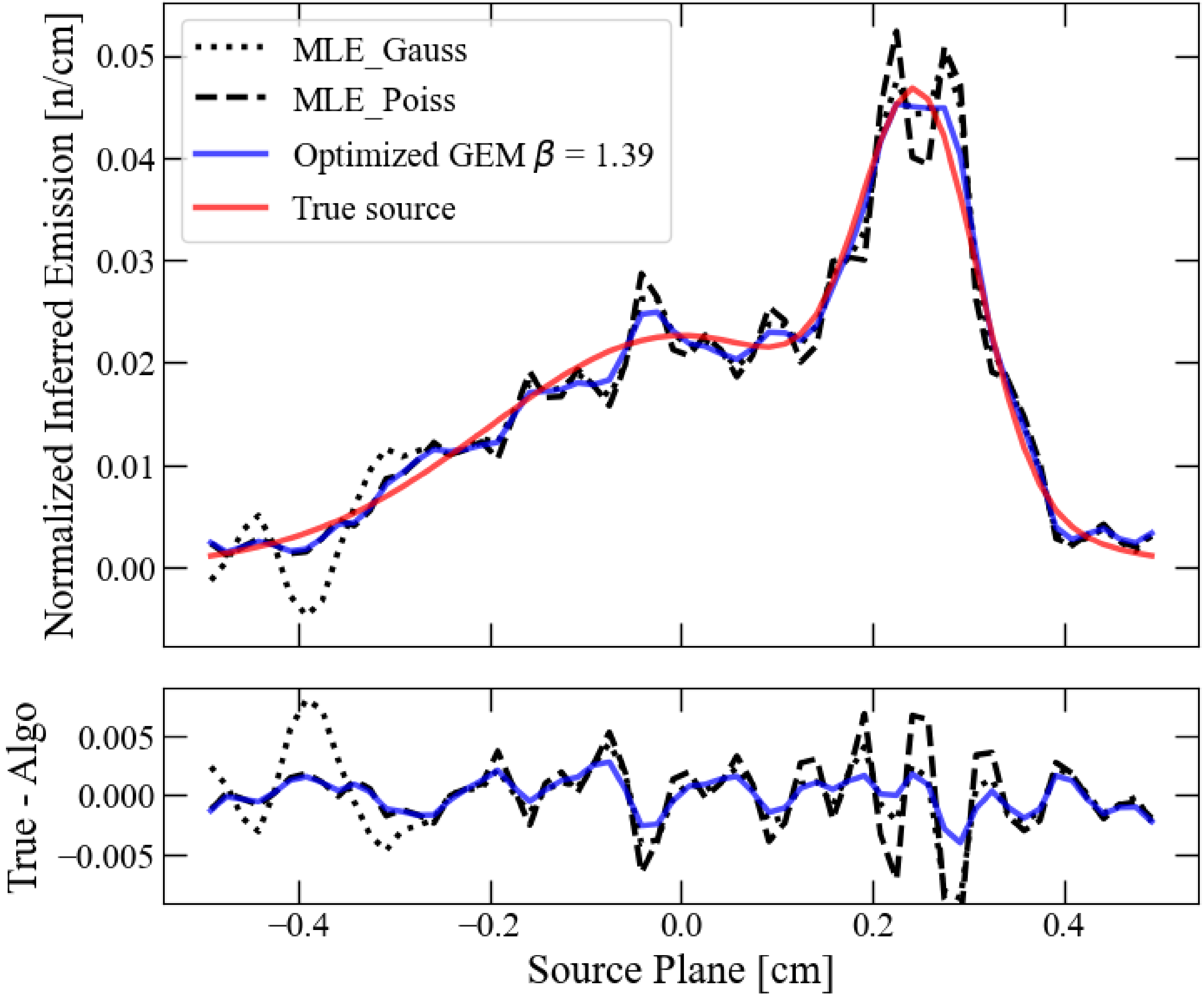
Method of choosing β, low frequency source profile





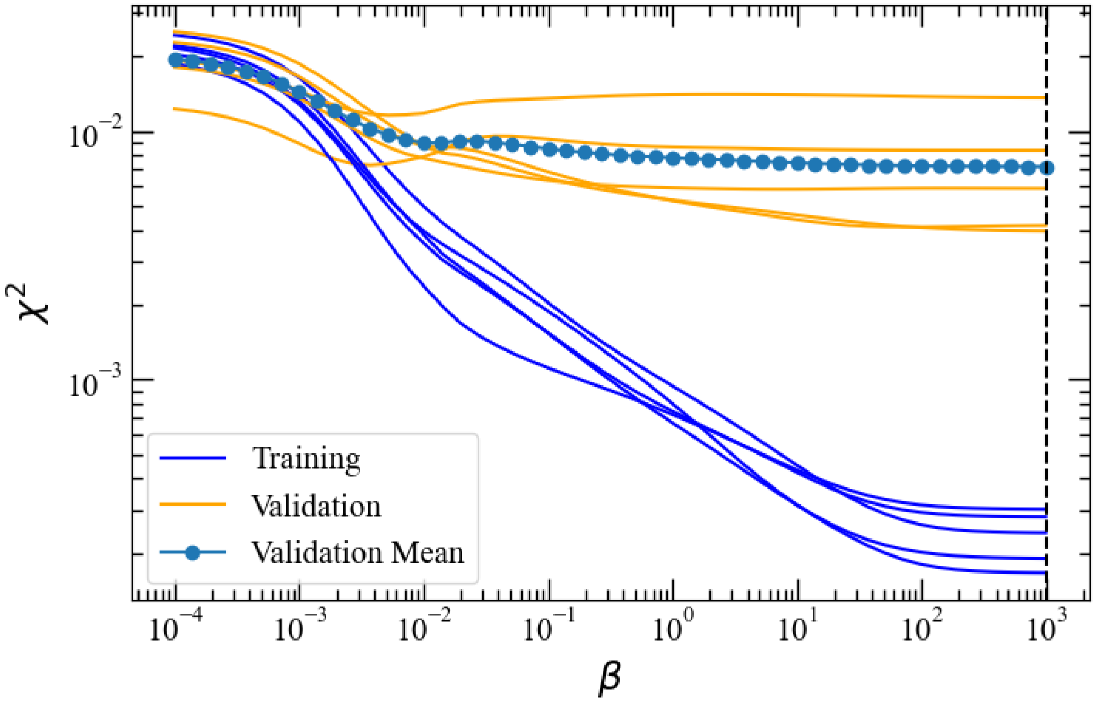
Method of choosing β, low and high frequency source profile

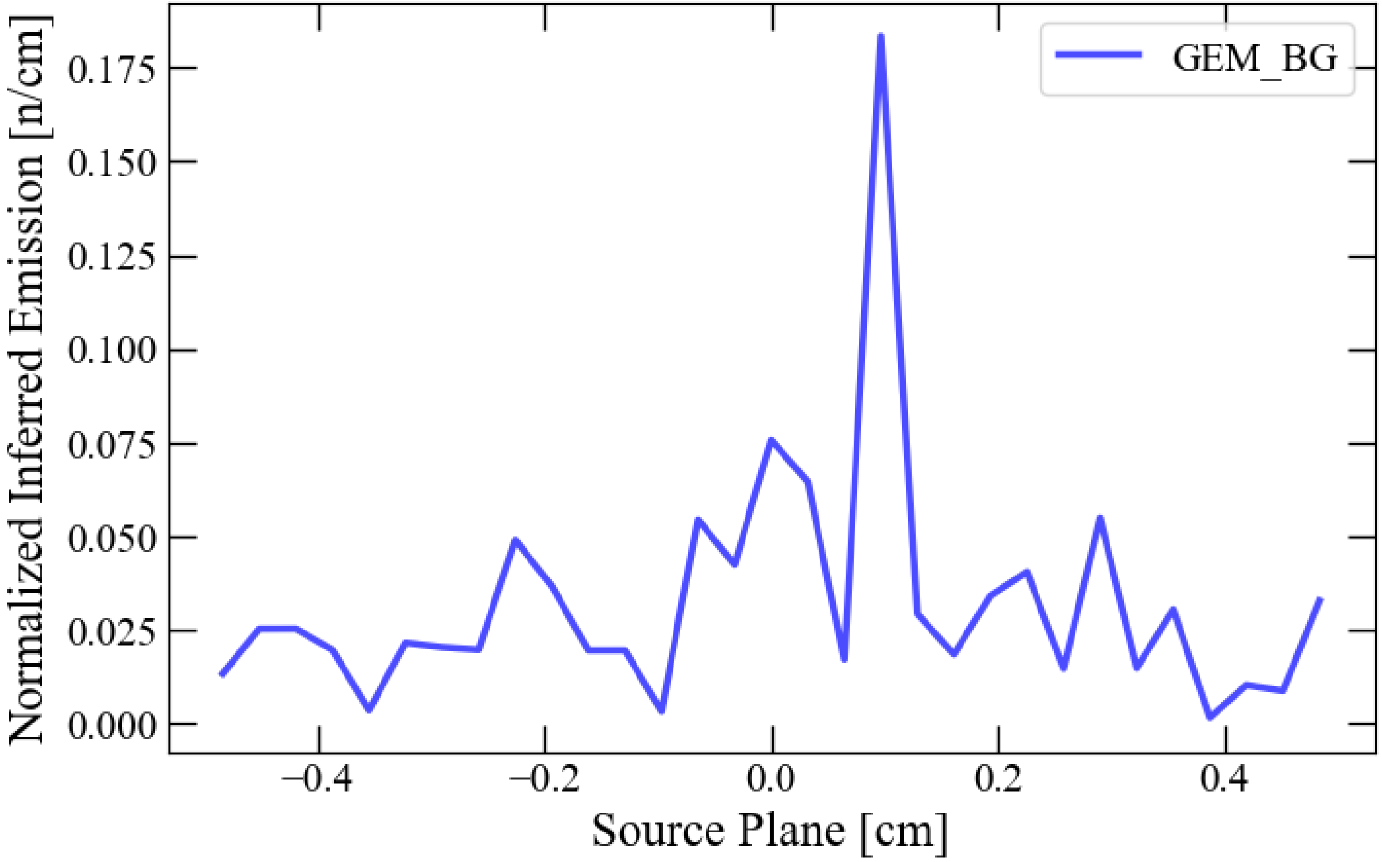




ODIN Data Image Reconstruction

Result: Z3289 Reconstructed Source Profile

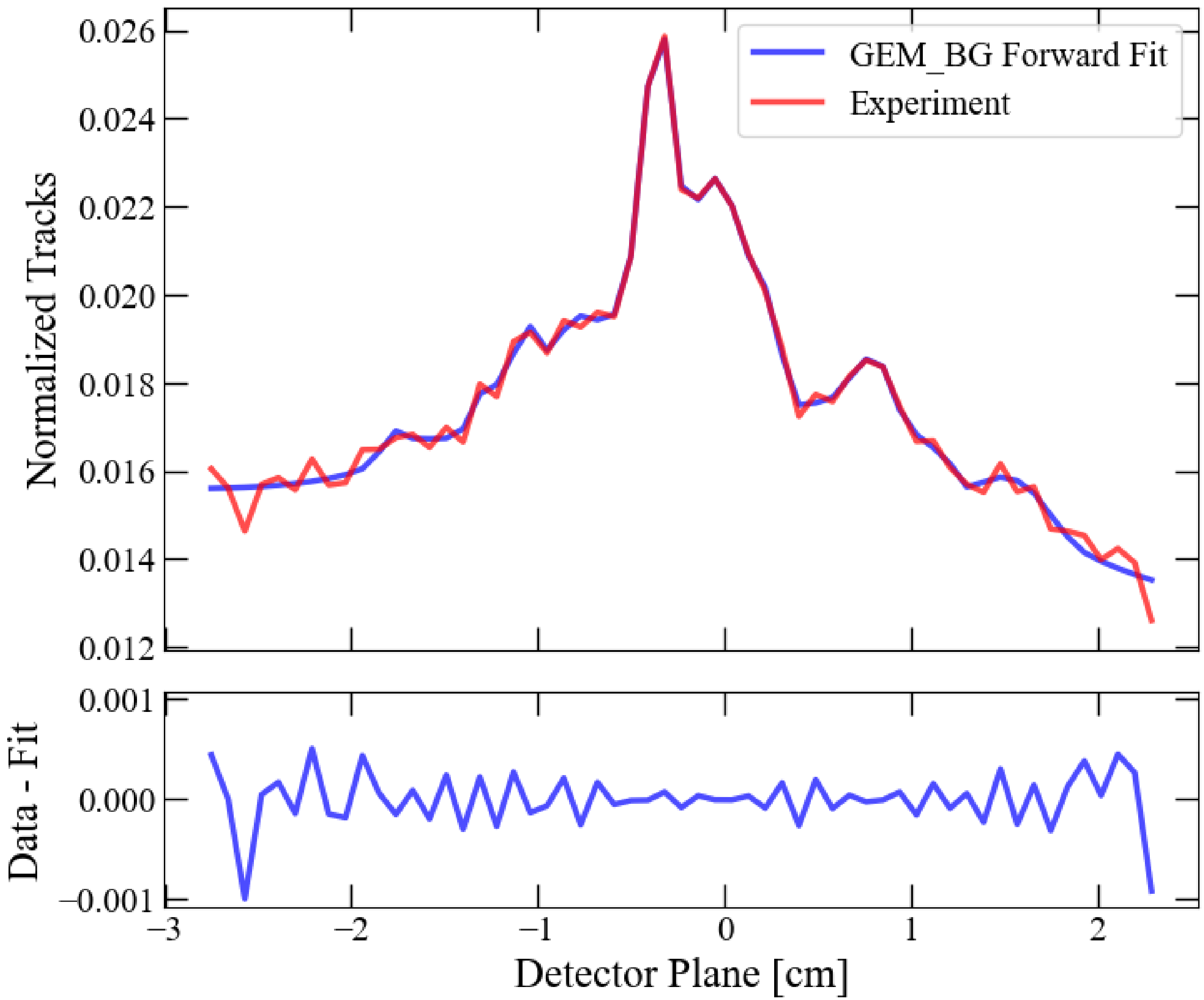




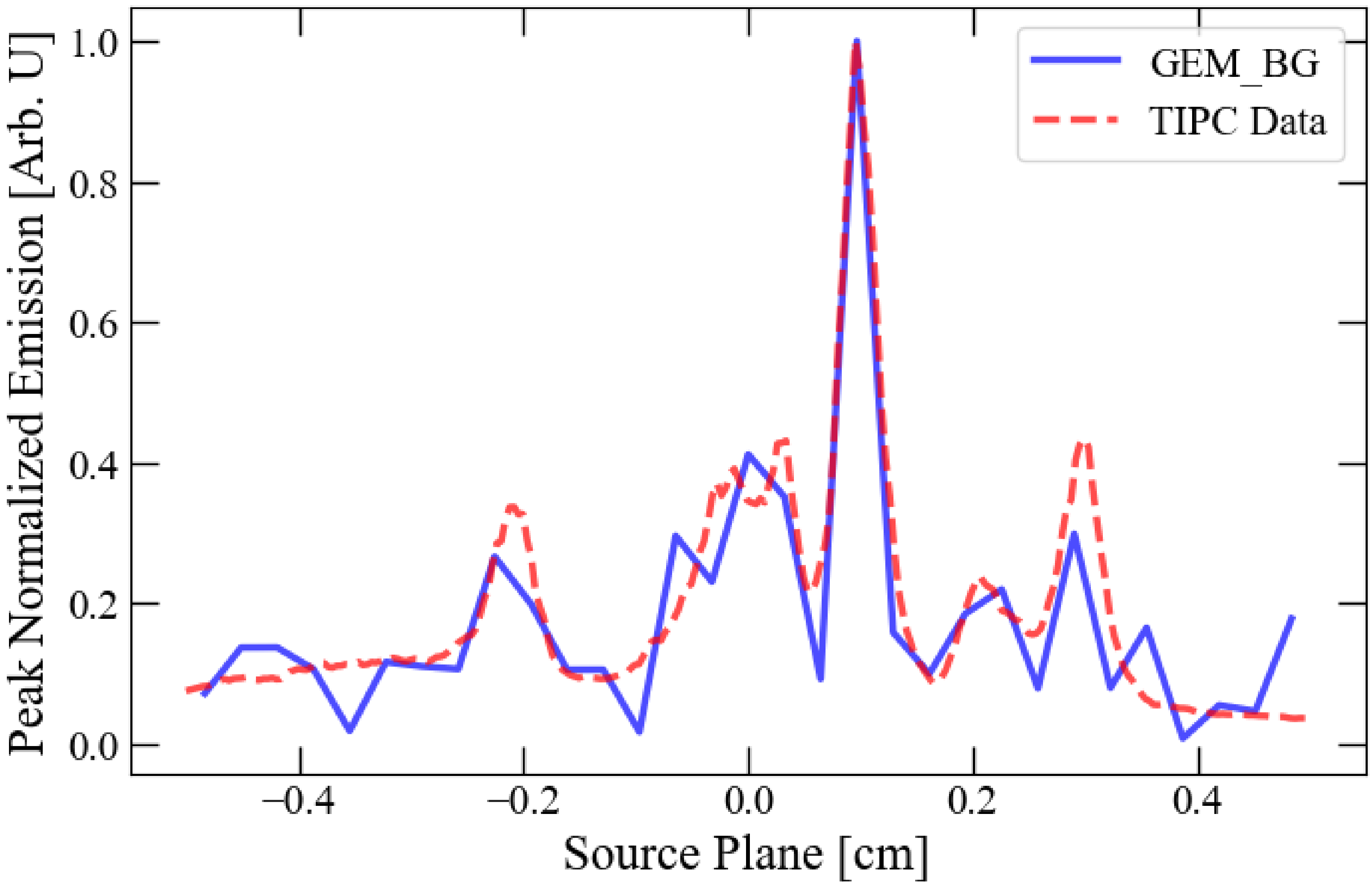
- **How can we check if this solution makes sense?**

* A background subtraction was implemented in these results

Check: Reconstruction Forward Fit Against Experimental Data



Experimental Validation: Reconstructed Source Compared to Time Integrated Pinhole Camera (TIPC) x-ray Emission



*Max peak has been used to spatially align data sets

Questions?

Future Work

- Publication of this work coming soon
- Determine a method for calculating a distribution of optimal Beta values
- Uncertainty quantification
- Deeper comparison with other diagnostics
- 2D-imaging diagnostic

References

[1] M. R. Gomez *et al.*, "Demonstration of thermonuclear conditions in magnetized liner inertial fusion experiments," *Phys. Plasmas*, vol. 22, no. 5, 2015, doi: 10.1063/1.4919394.

[2] D. J. Ampleford *et al.*, "One dimensional imager of neutrons on the Z machine," *Rev. Sci. Instrum.*, vol. 89, no. 10, 2018, doi: 10.1063/1.5038118.

[3] J. A. Frenje *et al.*, "Absolute measurements of neutron yields from DD and DT implosions at the OMEGA laser facility using CR-39 track detectors," *Rev. Sci. Instrum.*, vol. 73, no. 7, p. 2597, 2002, doi: 10.1063/1.1487889.

[4] V. I. Gelfgat, E. L. Kosarev, and E. R. Podolyak, "Programs for signal recovery from noisy data using the maximum likelihood principle," *Computer Physics Communications*. pp. 335–348, 1993.

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[6] J. D. Vaughan *et al.*, "Modeling the one-dimensional imager of neutrons (ODIN) for neutron response functions at the Sandia Z facility," *Rev. Sci. Instrum.*, vol. 89, no. 10, 2018, doi: 10.1063/1.5039366.

References

[7] D. B. Sinars *et al.*, “Review of pulsed power-driven high energy density physics research on z at sandia,” *Physics of Plasmas.*, vol. 27, no. 7, 2020.

[8] P. F. Knapp *et al.*, “Effects of magnetization on fusion product trapping and secondary neutron spectra,” *Physics of Plasmas.*, vol. 22, no. 5, 2015.