DOE/NV/03624--0883

High-Fidelity Dynamic Neutron Imaging for Subcritical Experiments and Other Applications
LO-005-19, Year 2

Alice Durand, Rick Freeman, Matt Wallace, Damyn Chipman, Raul Lara, Aimee Neilsen, Eimon Erfanfar, Russell Knight

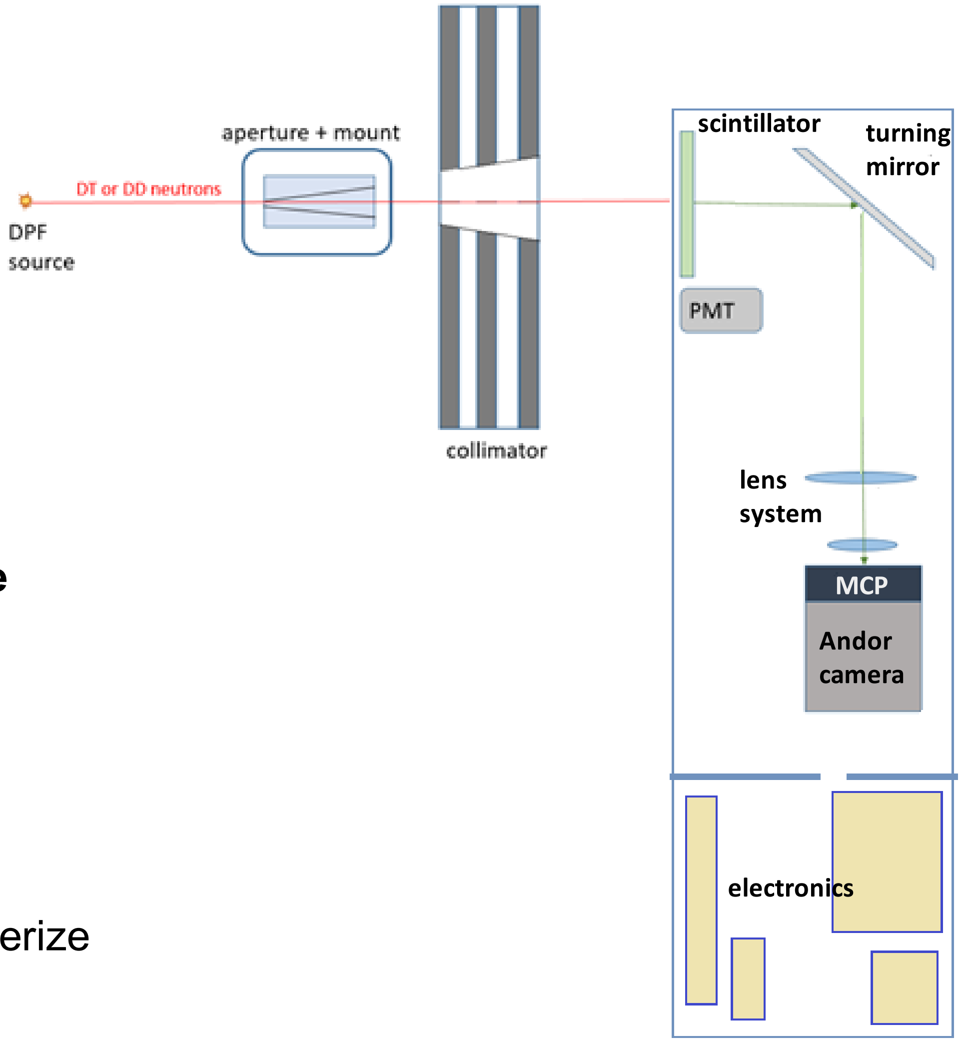
LAO/STL imaging team: J. Bundgaard, J. Tinsley, S. Baker

NLV Area 11 DPF team: D. Lowe, C. Hagen, S. Molnar, B. Gall, N. Sipe, M. Heika, D. Dalley

This work was done by Mission Support and Test Services, LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy and supported by the Site-Directed Research and Development Program. DOE/NV/03624--0883.

Challenge

- There is a need for neutron radiography experiments to be done down-hole using neutrons generated by a dense plasma focus (DPF) device
- However, to understand the radiograph, we need to know the size and shape of the neutron spot generated by the DPF
- Our goal is to build a **portable, short-range neutron imaging detector** to characterize neutron sources
- Accompanying software will perform image analysis in real time (between DPF shots)
- This neutron imager can be used to characterize neutron spots for multiple DPFs



Challenges

1) Penumbral aperture

- The neutron spot at the DPF can move around from shot to shot
- Size is uncertain (range of 0.1 to 1.0 cm)
- High contrast necessary

2) Neutron imager

- Portability (not too heavy)
- Versatility (multiple DPF setups)
- Camera/MCP with short gate time (50 ns gate at minimum) to isolate neutron source

3) Software

- Need easy-to-use and easy-to-edit software
- Want image processing AND image deconvolution all in one place
- Real-time (<30 min) analysis

4) Reconstruction of spot size

- Need simulated point spread function (PSF) with MCNP
- Iterative algorithm(s) required for noise handling
- Incorporate preconditioning of image to delineate between signal and noise

So we need:

1) Aperture with wide enough field of view (FOV), sufficient resolution, several mfp of tungsten for DD and DT neutrons
2) Lightweight enclosure that is easy to assemble, with a high-quality camera (Andor iStar sCMOS)
3) Python software developed in-house (MIPS)
4) MCNP simulations of DPF setup for accurate PSF, testable reconstruction algorithm

Innovations

Penumbral imaging aperture

- Tungsten aperture with **truncated cone** cross section
  - Robust against different spot locations shot to shot, isoplanaticity allows for straightforward reconstruction (one PSF instead of many)
- Simulations and ray tracing–guided aperture hole dimensions
- Experiments at Area 11 indicated that aperture was a good size
  - Penumbral image had clear dark margins and was reconstructable
  - Possible improvements: better placement in wall collimator and/or slightly wider flare (for larger image)

Spot size reconstruction

- Proof-of-concept x-ray source experiments with cylindrical aperture
  - Reconstruction successfully returned original source using existing iterative algorithms
  - PSF used was analytic (top-hat) blurred with noise
- MCNP simulations of PSF done with Area 11 distances, environment
  - Simple and complex PSFs both gave essentially identical spot reconstructions
  - Multiple reconstruction algorithms gave similar results

Innovations

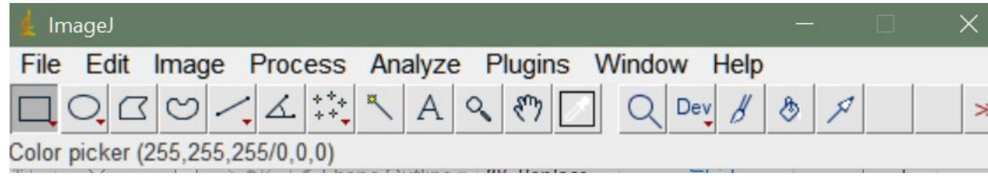
Software – Multiple/MJOLNIR Image Processing Software (MIPS)

- In-house Python code that processes and deconvolutes images
  - Similar to ImageJ, but without the "black box" aspect and more modifiable
  - Contrast stretching, binning, outlier removal, batch processing, deconvolution, edge spread functions
  - User manual and tutorial
- Deconvolution algorithms available as ImageJ plug-ins
  - Algorithms were rewritten in Python with correct preconditioning implemented
  - In process of being incorporated into MIPS

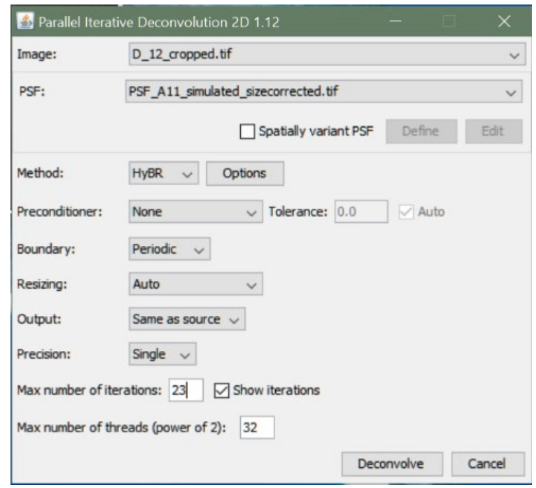
Neutron Imager

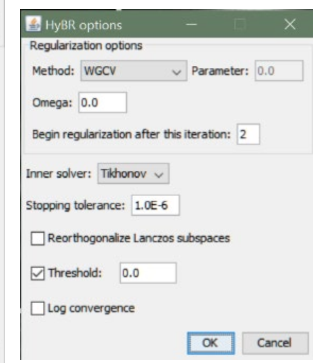
- Andor iStar sCMOS camera purchased, along with optical components + scintillators
- Electrical components have been determined, suppliers found, costs estimated
- Extensive design work done on imager EMP box
  - Decided on "long box" design that allows for adjustable camera distance, separation of electronics while keeping organization simple and accessible
  - EMP "tent" enclosure or lightweight composite rather than solid enclosure for portability

Technical Approach – Reconstruction Algorithms



- **ImageJ** used for iterative deconvolutions
  - Crowd-sourced, well-established tool
  - Plug-ins available for image deconvolution
- Starting images were the binned/dark-fielded images, and the MCNP generated PSF





- The following five algorithms were all used and compared:
  - Parallel Iterative Deconvolution plug-in

    1. MRNSD – Modified Residual Norm Steepest Descent

    2. CGLS – Conjugate Gradient for Least Squares

    3. WPL – Wiener Filter Preconditioned Landweber

    4. HyBR – Hybrid Bidiagonalization Regularization

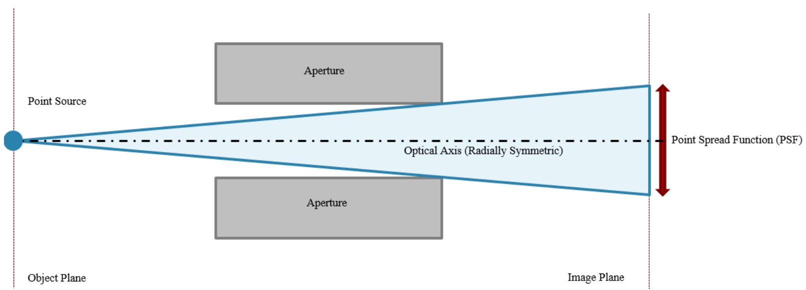
    and
  - **5. Iterative Deconvolution 2** plug-in
    - Based on the DAMAS algorithm – Deconvolution Approach for the Mapping of Acoustic Sources
  - Each one of these algorithms is **iterative** and converges to the most likely solution
    - Number of iterations we ran for each algorithm was how many it took to get to convergence

Technical Approach – Point Spread Function

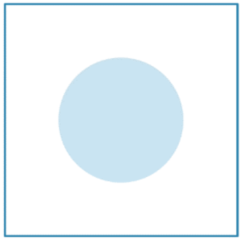
Point spread function: How the imaging system responds to a point source

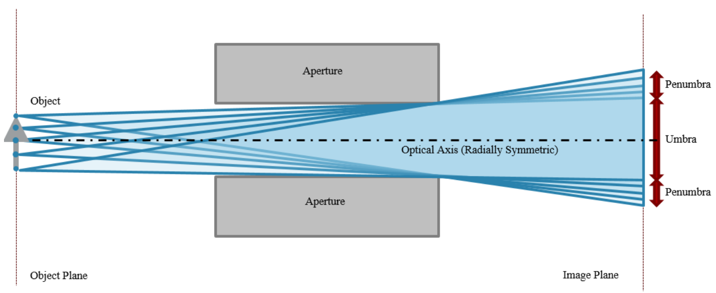
- A **point source** of light/neutrons going through an aperture to a detector plane will produce a smeared-out blur (NOT a single point), i.e., the PSF.
- A **distributed source** will produce a blur that is the superposition of all the component point sources.
- If we know the **PSF** we can simply "divide out" or **deconvolute** the blur/PSF from each point of the distributed source image.
- **To simulate an accurate PSF in MCNP, it is best to include as much of the experiment environment as possible**

Isoplanaticity:
How little the PSF varies depending on the location of the source relative to the aperture *(e.g., for larger sources, the isoplanaticity of a cylindrical aperture is not good).*

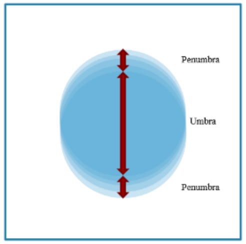


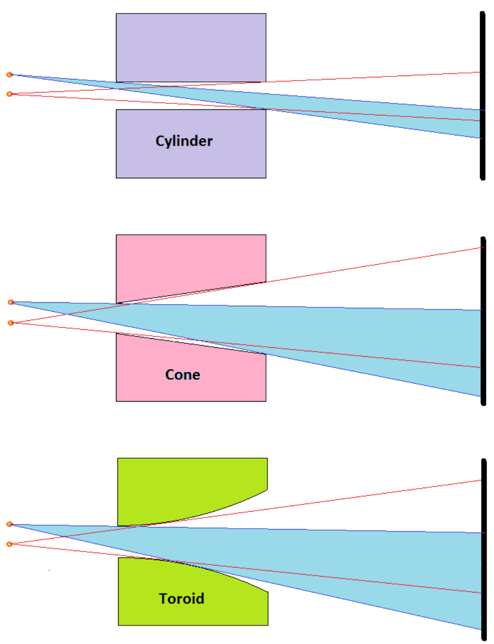
PSF





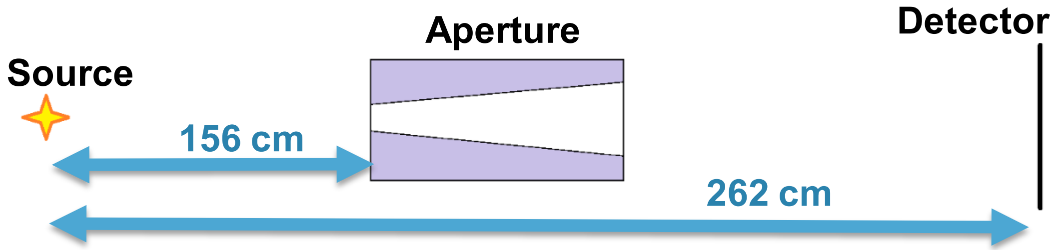
Penumbral image





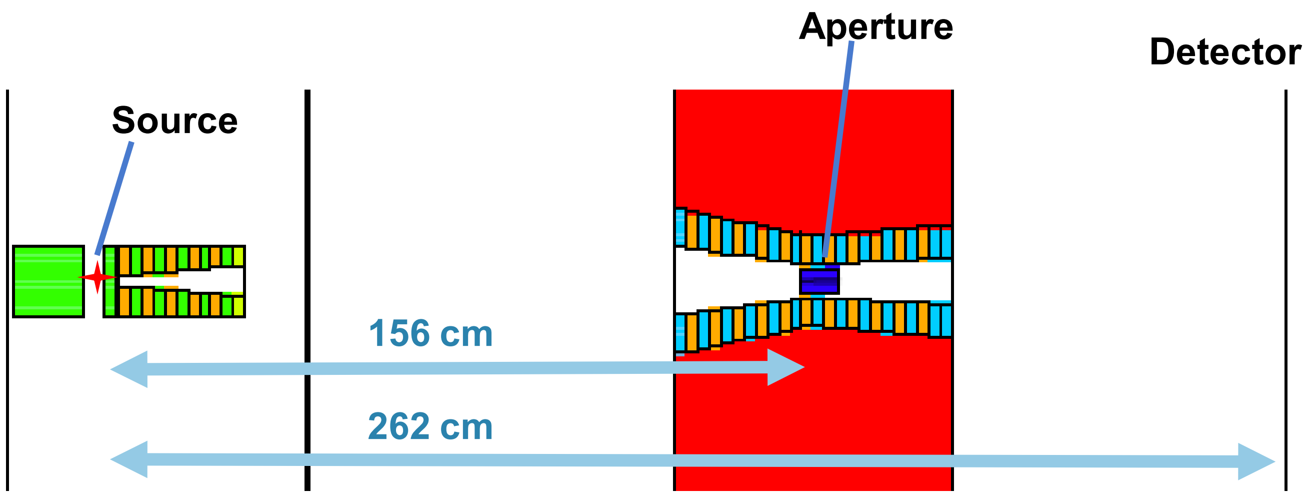
Images courtesy of Damyn Chipman

Results – PSF Simulations with MCNP



(1) Simple point spread function

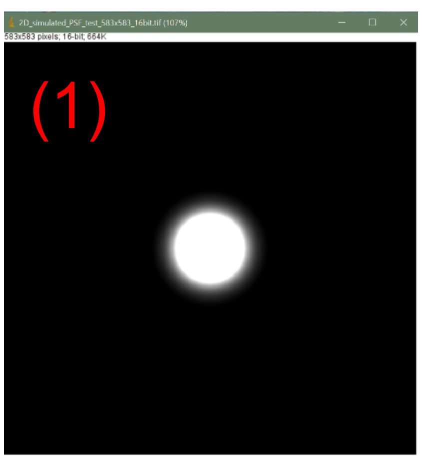
- Simulated PSF in MCNP using same setup/distances as Area 11
- 14.1 MeV DT source (neutrons only)
- Conical aperture

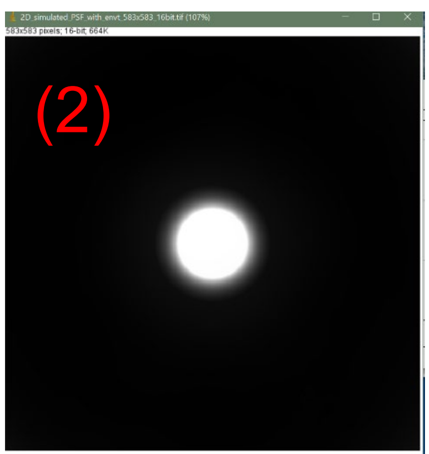


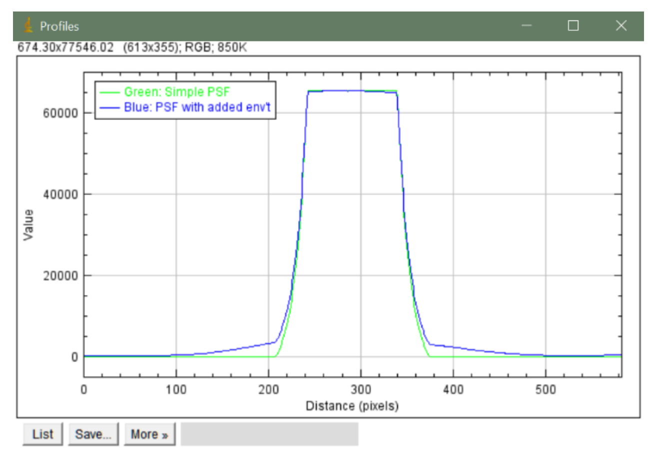
(2) PSF 2.0 with environment more specific to Area 11

Added in:

- Anode (Cu)
- Inny (Cu/poly) + Cu beam stop
- Garage door between DPF and collimator (steel)
- Concrete wall
- Wall collimator (steel/poly)







Note very little visual difference between the PSFs – will it matter in the deconvolution?

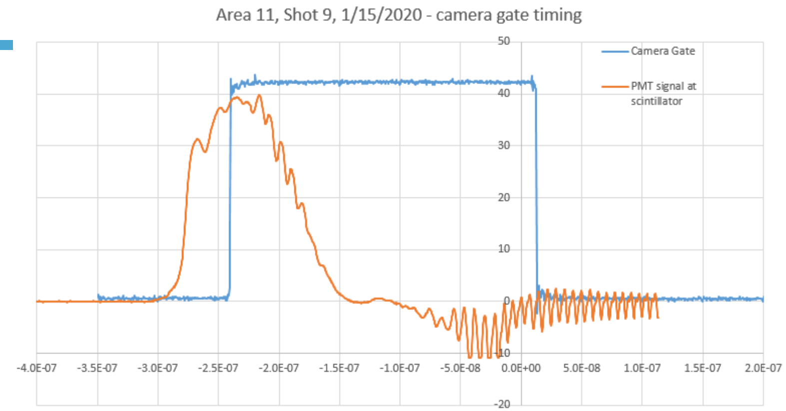
SDRD SITE-DIRECTED RESEARCH & DEVELOPMENT

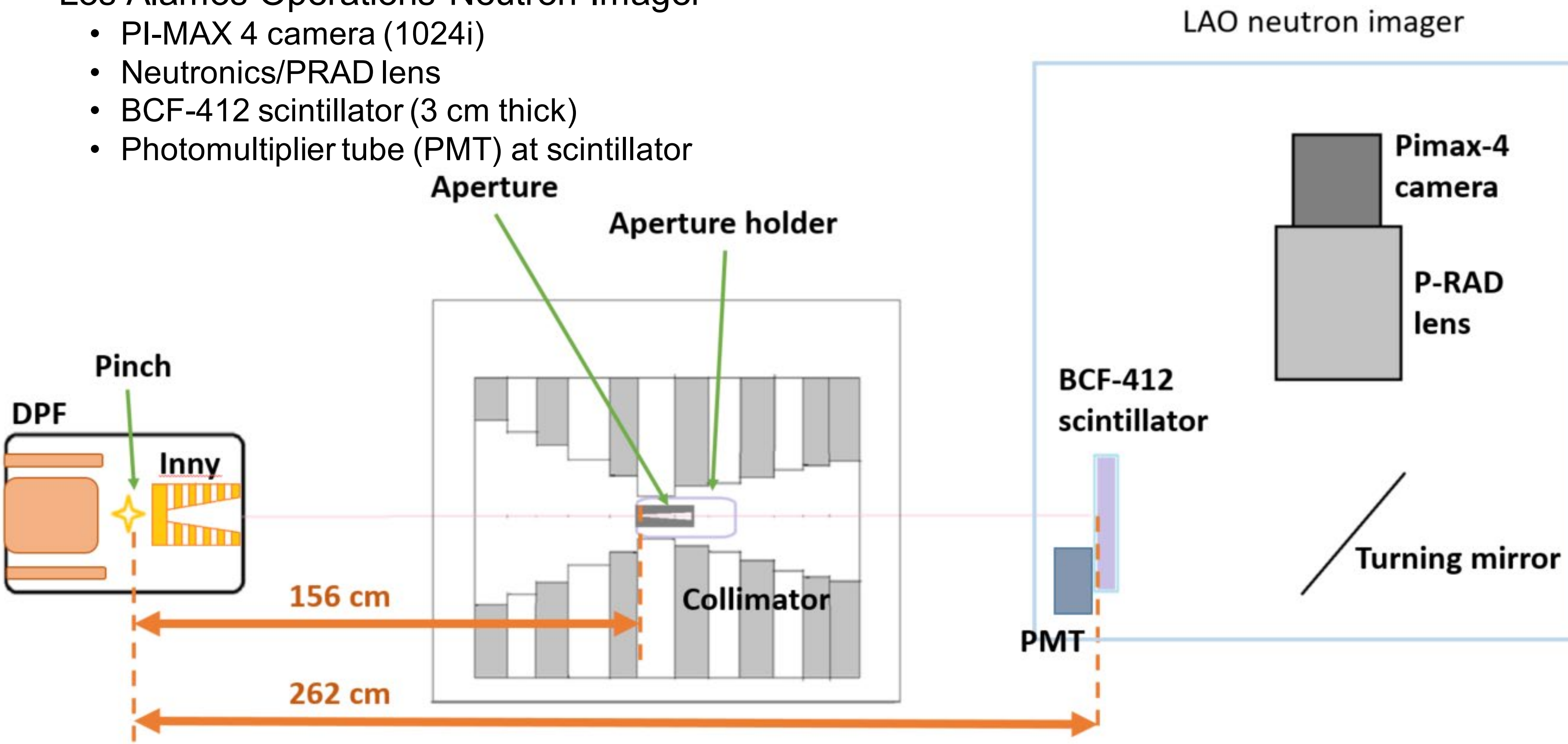
Results – Area 11 Experiment

- January 15, 2020, at Area 11, NNSS
- Dense Plasma Focus machine (sodium) with DT neutrons output

Equipment

- LO penumbral aperture
- LO penumbral aperture holder + insert
- Los Alamos Operations Neutron Imager
  - PI-MAX 4 camera (1024i)
  - Neutronics/PRAD lens
  - BCF-412 scintillator (3 cm thick)
  - Photomultiplier tube (PMT) at scintillator





Results – Spot Size Reconstructions

- **Preliminary results for spot size/shape reconstruction from Jan. 2020 Area 11 data**
  - Used five different algorithms in ImageJ for reconstruction; results were consistent
  - Multiple spots seen in all three images (large MCP time gate)
  - Current spot size estimate is 7–15 mm using FWHM of intensity peak

Raw images
- Cropped

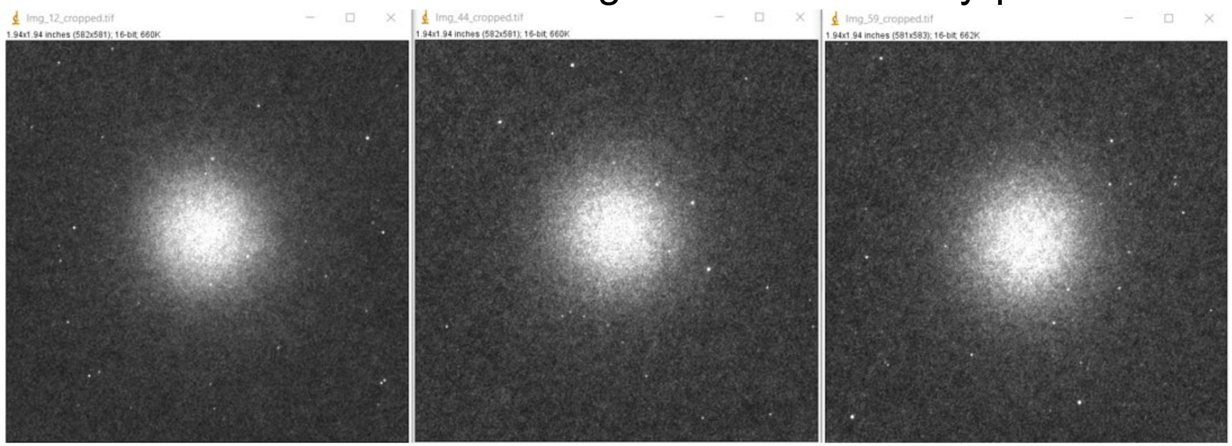
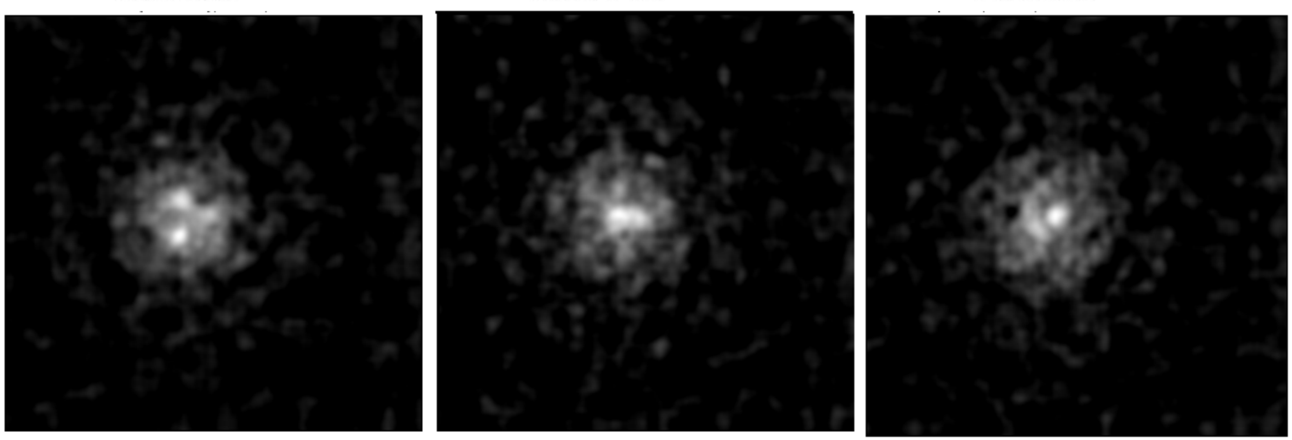


Image 12 **Image 44** **Image 59**

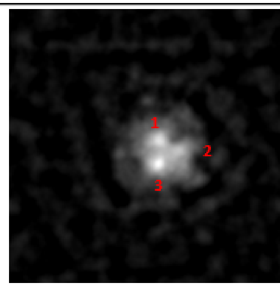
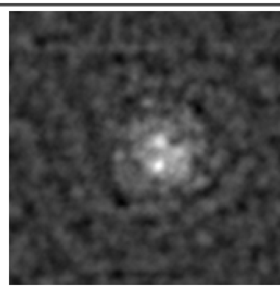
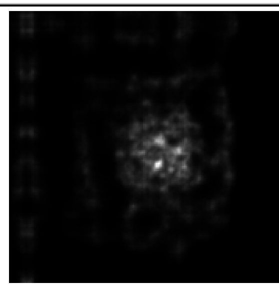
Deconvoluted images
- WPL method
- Used simple PSF

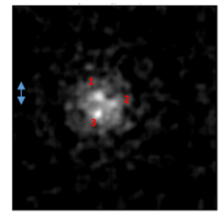
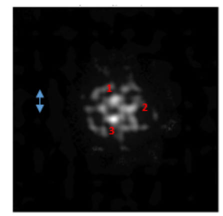


NEVADA NATIONAL NNSS SECURITY SITE
Managed and operated by ***Mission Support and Test Services***

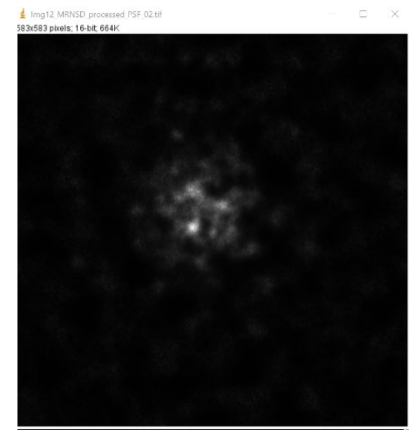
SDRD SITE-DIRECTED RESEARCH & DEVELOPMENT

Results – Spot Size Reconstructions

Method	Deconvoluted image (#12)
HyBR	
CGLS	
MRNSD	

Method	Deconvoluted image (#12)
WPL (WFG = 0.001)	
Iterative Deconvolution 2 (alpha = 5000)	

Note: Using a more complex PSF did NOT significantly change the reconstruction results.



FWHM spot sizes from ImageJ reconstruction methods

Sizes are in mm

Spot sizes are not extrapolated		Image 12						Image 44		Image 59	
		Top spot (1)		Middle spot (2)		Bottom spot (3)		Long spot		Spot	
Method		*Horiz*	*Vert*	*Horiz*	*Vert*	*Horiz*	*Vert*	*Horiz*	*Vert*	*Horiz*	*Vert*
Iterative Deconvolution 2		5.8	3.8	6.7	6.7	5.8	3.8	9.6	8.6	8.6	5.8
PID - MRNSD		5.0		6.0		5.0		10.0	7.0	5.0	5.0
PID - CGLS		10.0		19.0		12.0		15.0	14.0	10.0	18.0
PID - WPL		5.8	6.7	13.4	8.6	7.7	6.7	10.6	10.6	8.6	5.8
PID - HyBR		7.7		14.5		11.1		9.7	7.0	8.7	7.0
Average spot size (mm)		6.9	5.3	11.9	7.7	8.3	5.3	11.0	9.4	8.2	8.3
Conversion	1 px	0.242 mm									
Error	+/-	10%									

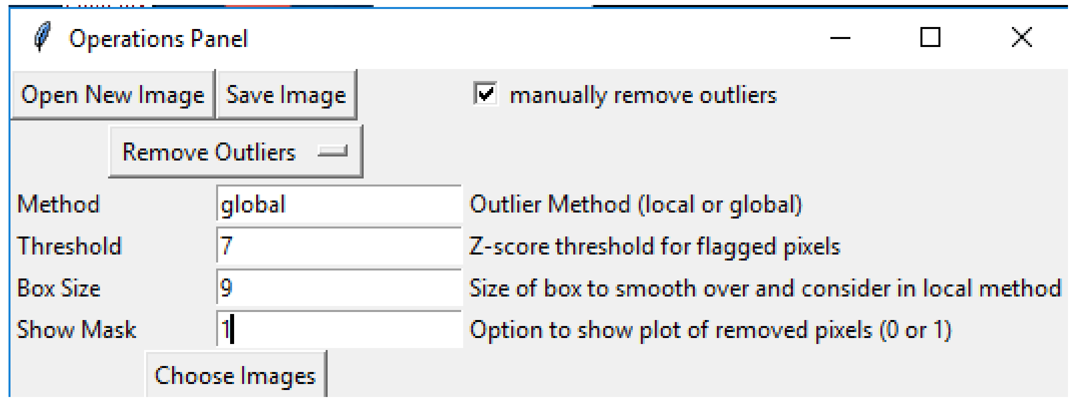
NEVADA NATIONAL NNSS SECURITY SITE

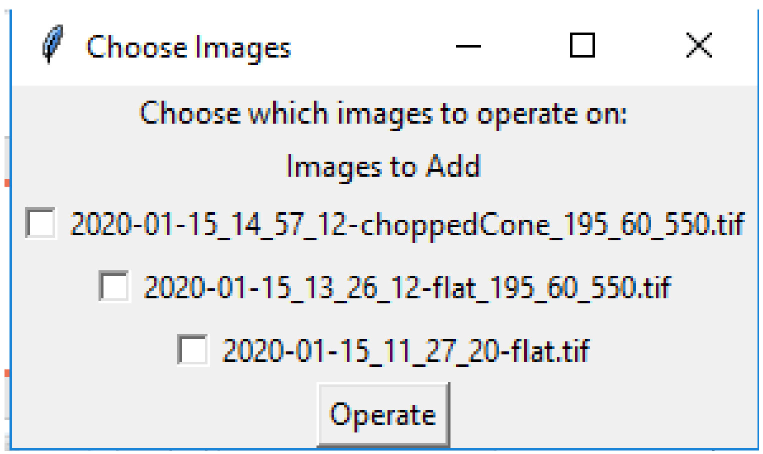
Managed and operated by Mission Support and Test Services

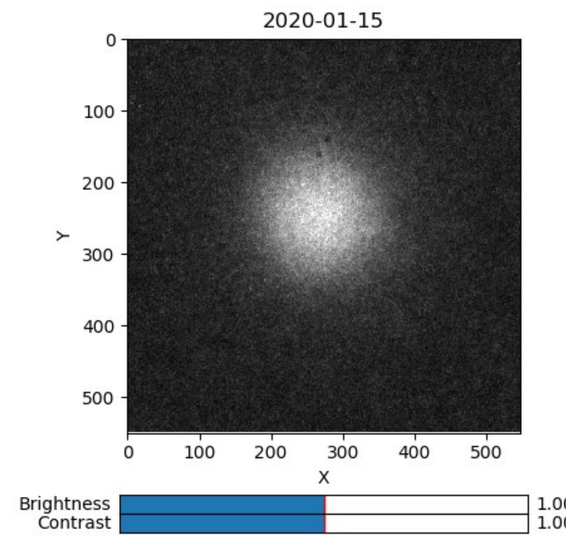
SDRD SITE-DIRECTED RESEARCH & DEVELOPMENT

Results – MIPS Software

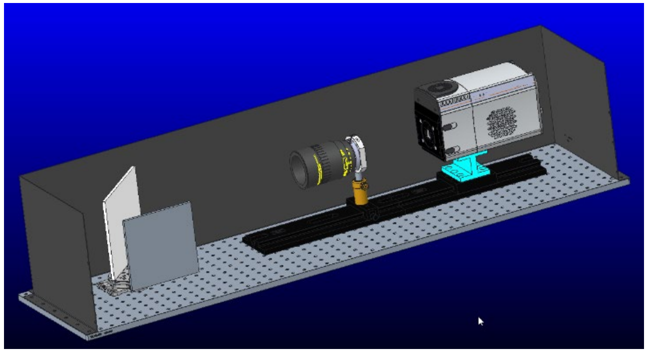
- **MIPS software now has following functionality:**
  - Contrast stretching
  - Histogram
  - Mask display
  - Binning
  - Outlier removal
    - Local, Global, or Manual
  - Image adding
  - Averaging
  - Flat field
  - Dark field
  - Deconvolution
    - Preconditioning
    - Two algorithms (MRNSD, CGLS)

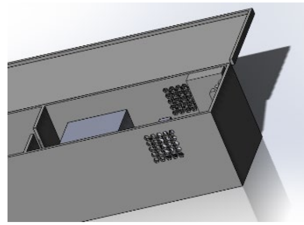


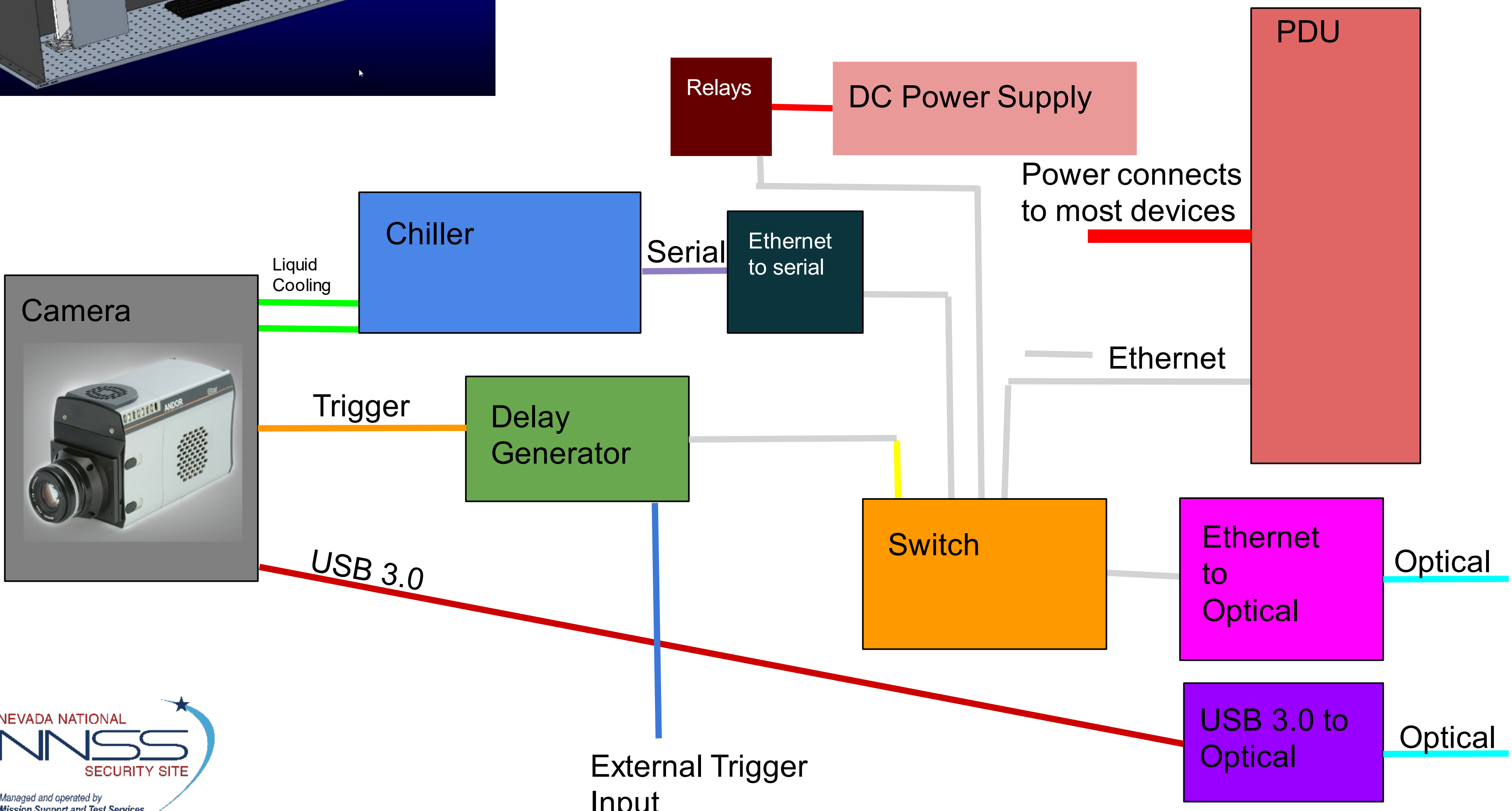




Results – Neutron Imager (electronics/box design)







Summary of Results

We successfully recorded the emission spots at the Area 11 DPF with a penumbral aperture.

We obtained three images and subsequently recovered three images of the emission spots using a variety of mathematical algorithms.

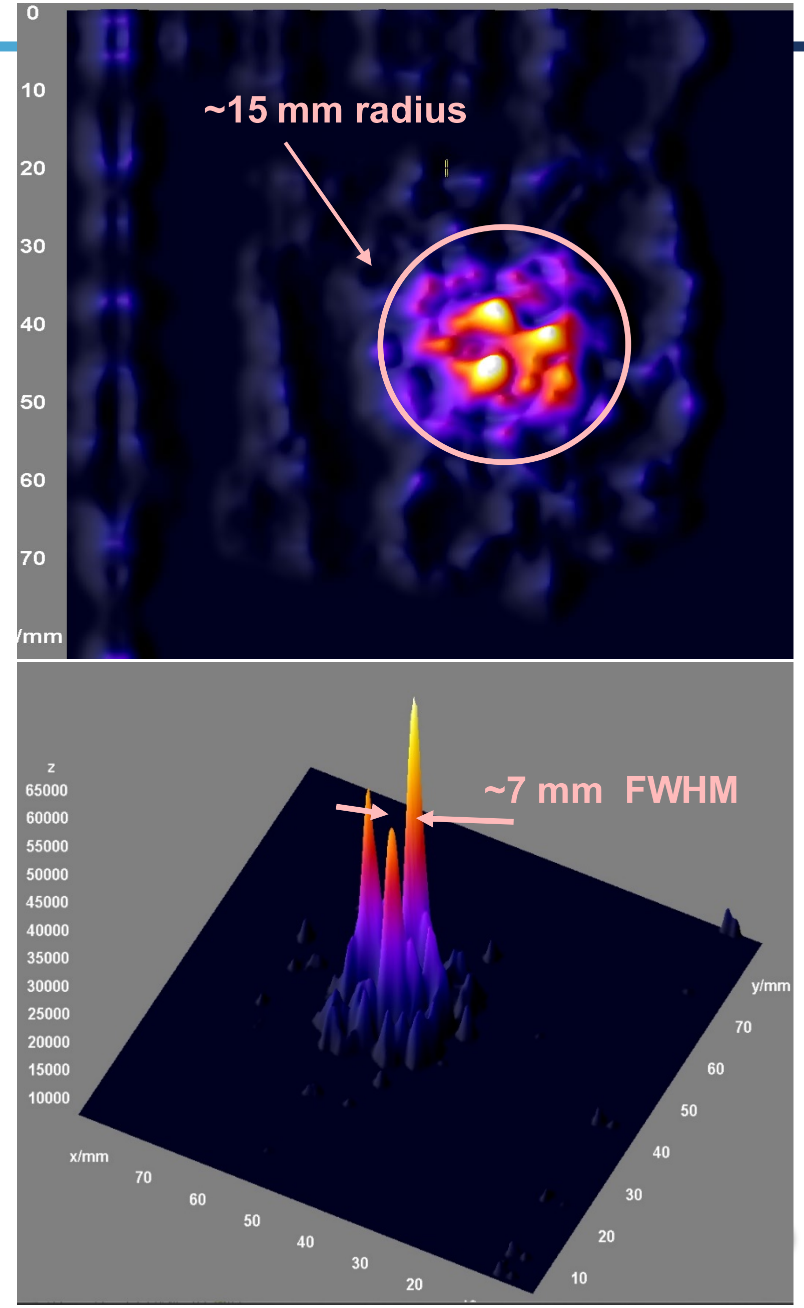
The various mathematical algorithms employed on each of the three images all resulted in essentially the same reconstructed images of the emission spots.

Emission spots were 7-12 mm in diameter all within a transverse circle of radius ~15 mm.

Multiple spots/features are seen in all three images.

- Multiple pinches (may depend on inny or DPF anode/cathode configuration)
- Long time gate (250 ns)
- X-ray AND neutron spots showing up

Our results give us confidence that we can record and analyze, in near real time, the spatial emission characteristics of DPF neutron sources.



Path Forward and Impact

FY2021:

- Build LO neutron imager; test at Area 11, Gemini, MJOLNIR
- Use penumbral aperture with existing imagers, perform experiments with shorter gate times to see effect on number of spots
- Finish implementing deconvolution algorithms into MIPS, test with new data from penumbral aperture
- Determine spot size to higher accuracy (need more data and better metric)
- Improve PSF by incorporating more environmental aspects (e.g., cathode rods) into MCNP simulation
- Also include photon tracking into source/detector
  - Currently only using neutrons due to computing time constraints; want to run simulation on HPC

Impact:

- Paper currently being compiled on Area 11 reconstruction results
- Collaboration with LLNL MJOLNIR group on experiments and MIPS continues to be successful for all involved
- Four interns have contributed significantly in the past two years; three are staying on as casuals
- Powerful new diagnostic tool for DPF emission sources, incorporates neutron imager, penumbral aperture and accompanying software