

3-D electron temperature and X-ray emission tomography of the ICF hotspot at the National Ignition Facility

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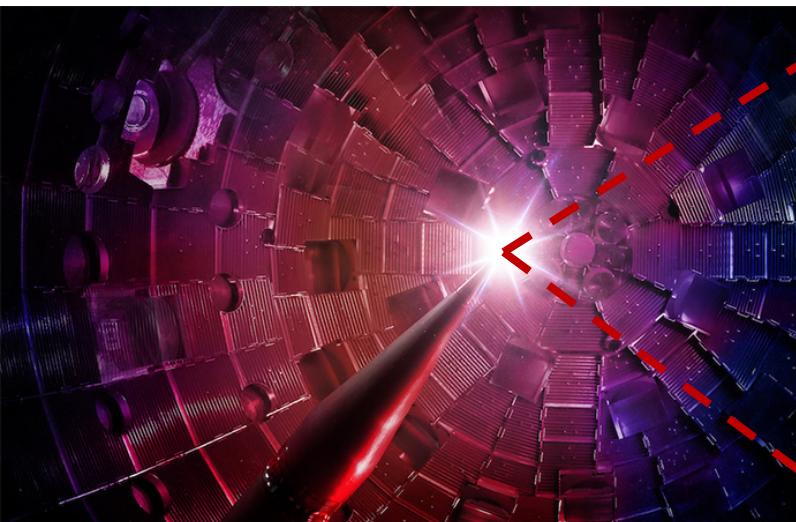
 Lawrence Livermore
National Laboratory

Measuring 3D electron temperature of the ICF hotspot is feasible

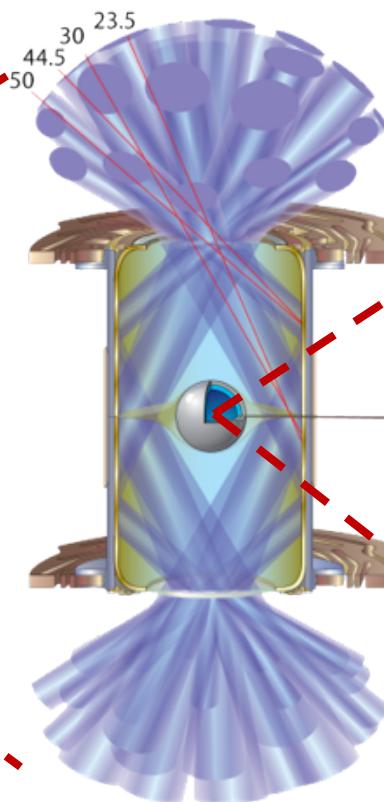
We have

- tested iterative algebraic method ART to reconstruct 3D X-ray emission distributions of the ICF hotspot.
- obtained 3D X-ray reconstructions with two or three LOS and made 3D electron temperature T_e measurement in the ICF hotspot using synthetic and experimental data
- laid out a future path on how to perform 3D T_e measurement on the NIF.

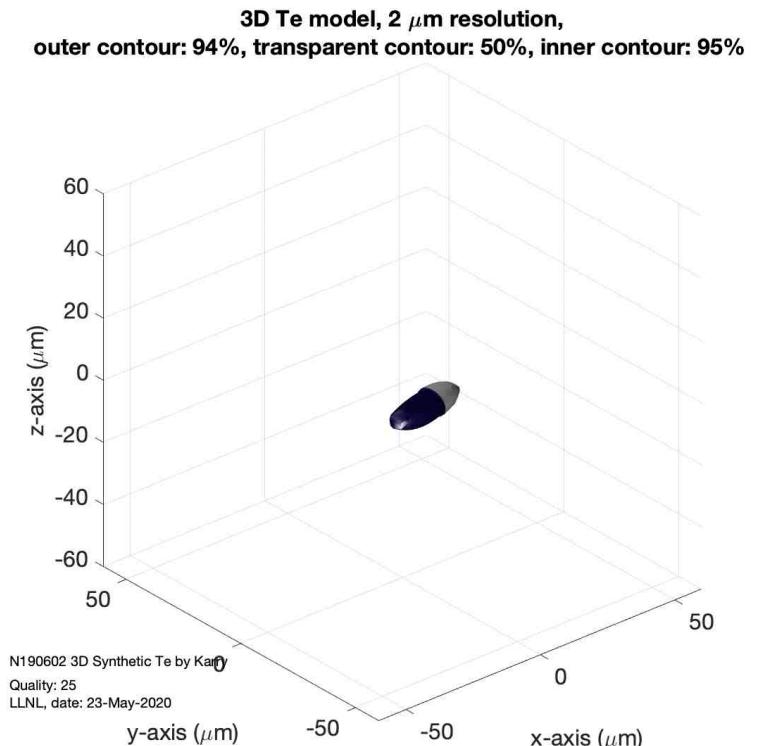
3D hotspot electron temperature T_e measurements can help to further our understanding of the ICF stagnation physics



NIF target chamber



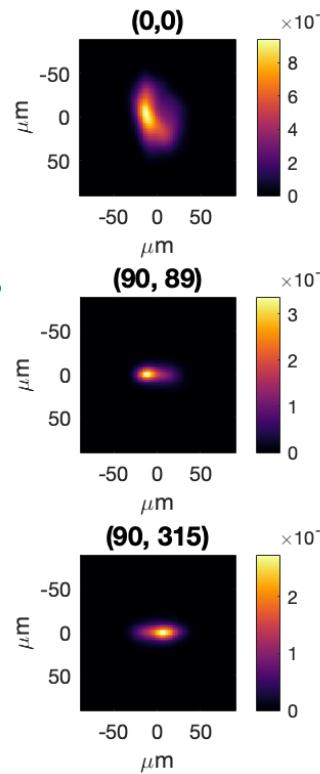
Hohlraum



Hotspot T_e distribution

We reconstruct 3D X-ray emission distributions from 2D projections and infer T_e using different X-ray energy channels

Input:
X-ray images

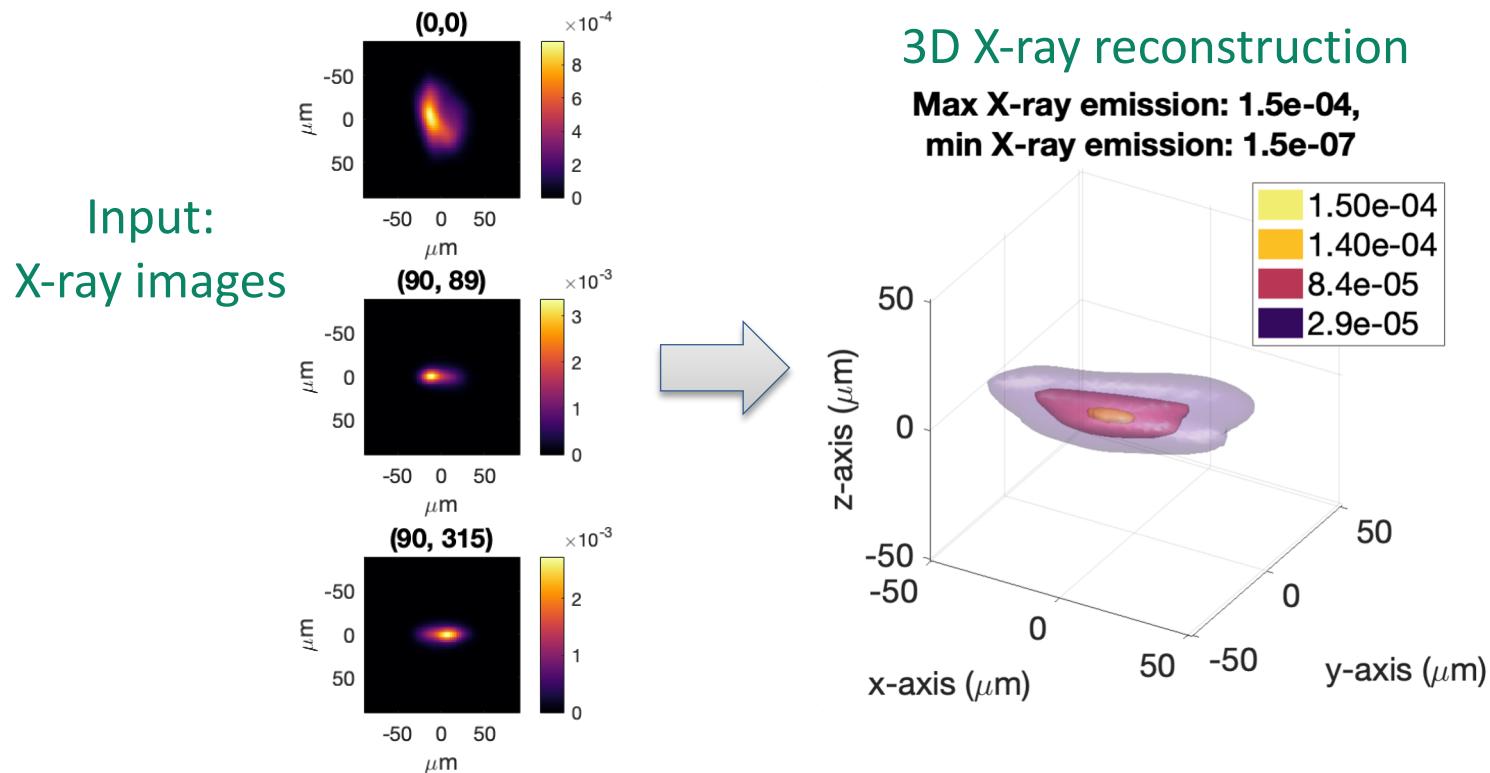


Our goal is to reconstruct a 3D T_e distribution of the hotspot plasma using very few 2D X-ray images from different directions.

Previous work done on 3-D reconstructions of neutron/x-ray source from 2-D projections. Ref:

1. Volegov et al., Neutron source reconstruction from pinhole imaging at national ignition facility. *Rev. Sci. Instrum.* 2014
2. Volegov et al., On three-dimensional reconstruction of a neutron/x-ray source from very few two-dimensional projections. *J. Appl. Phys.* 2015

We reconstruct 3D X-ray emission distributions from 2D projections and infer T_e using different X-ray energy channels

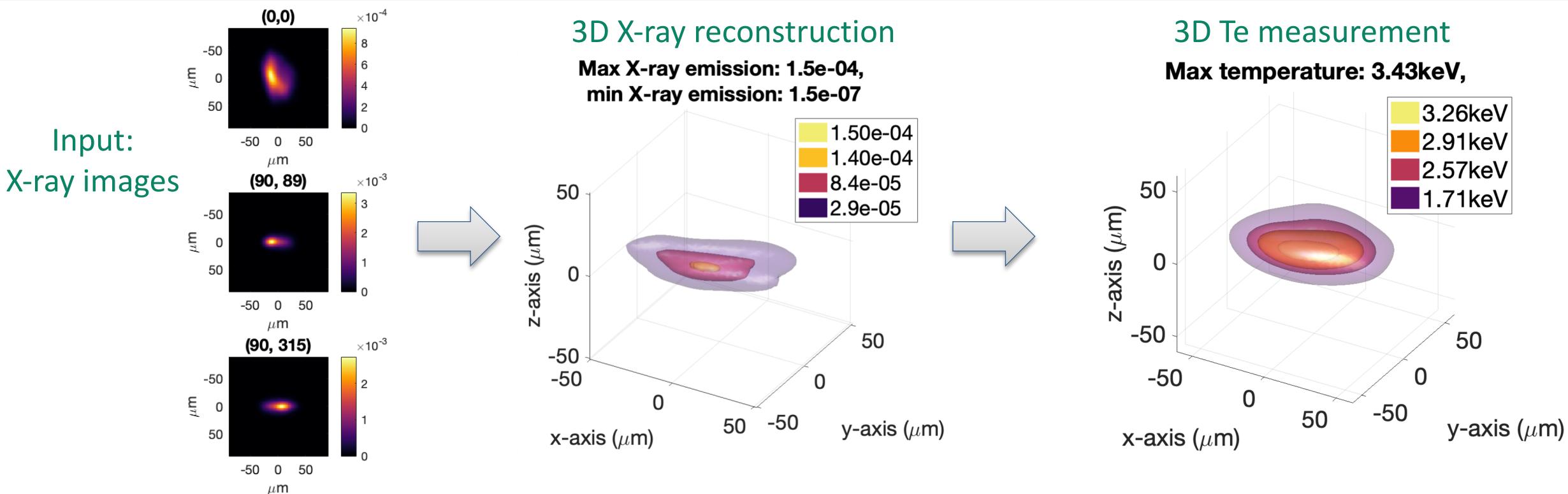


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We reconstruct 3D X-ray emission distributions from 2D projections and infer T_e using different X-ray energy channels

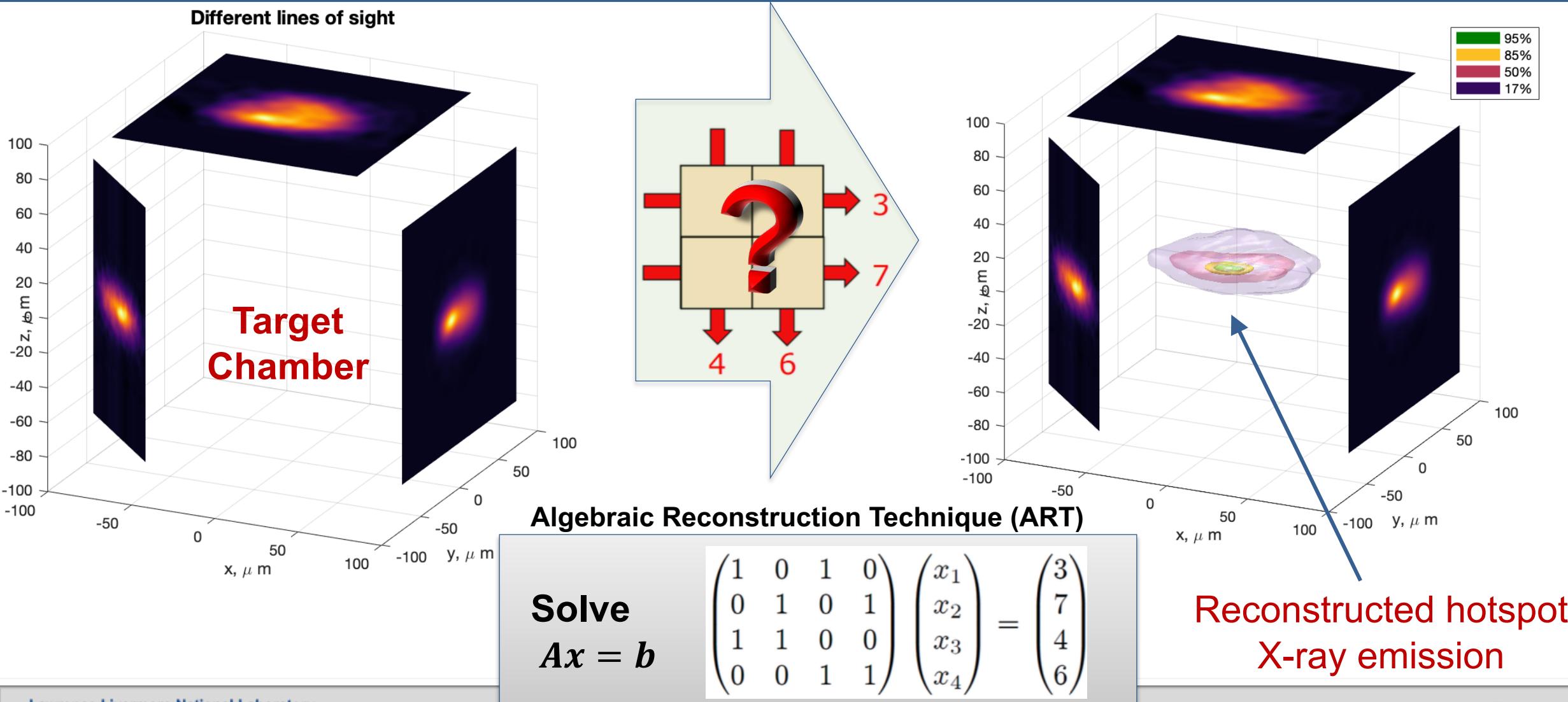


Our goal is to reconstruct a 3D T_e distribution of the hotspot plasma using very few 2D X-ray images from different directions.

Previous work done on 3-D reconstructions of neutron/x-ray source from 2-D projections. Ref:

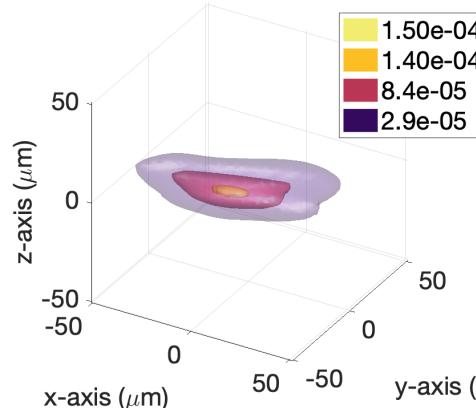
1. Volegov et al., Neutron source reconstruction from pinhole imaging at national ignition facility. *Rev. Sci. Instrum.* 2014
2. Volegov et al., On three-dimensional reconstruction of a neutron/x-ray source from very few two-dimensional projections. *J. Appl. Phys.* 2015

Step 1: We reconstruct 3D X-ray emission distribution using very few 2D X-ray projections via ART – like solving a “3D Sudoku” puzzle



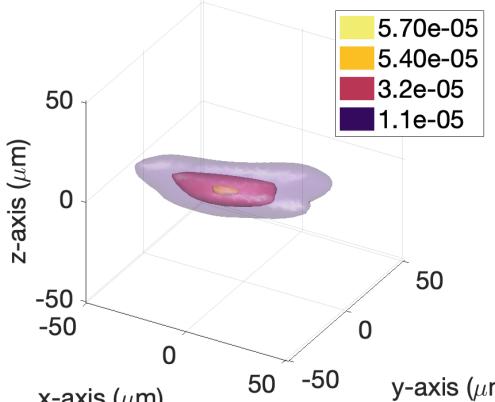
Step 2: We compute T_e measurement from the ratio of detected X-ray emission values in channels 1 and 2

Max X-ray emission: 1.5e-04,
min X-ray emission: 1.5e-07



X-ray reconstruction in Channel 1

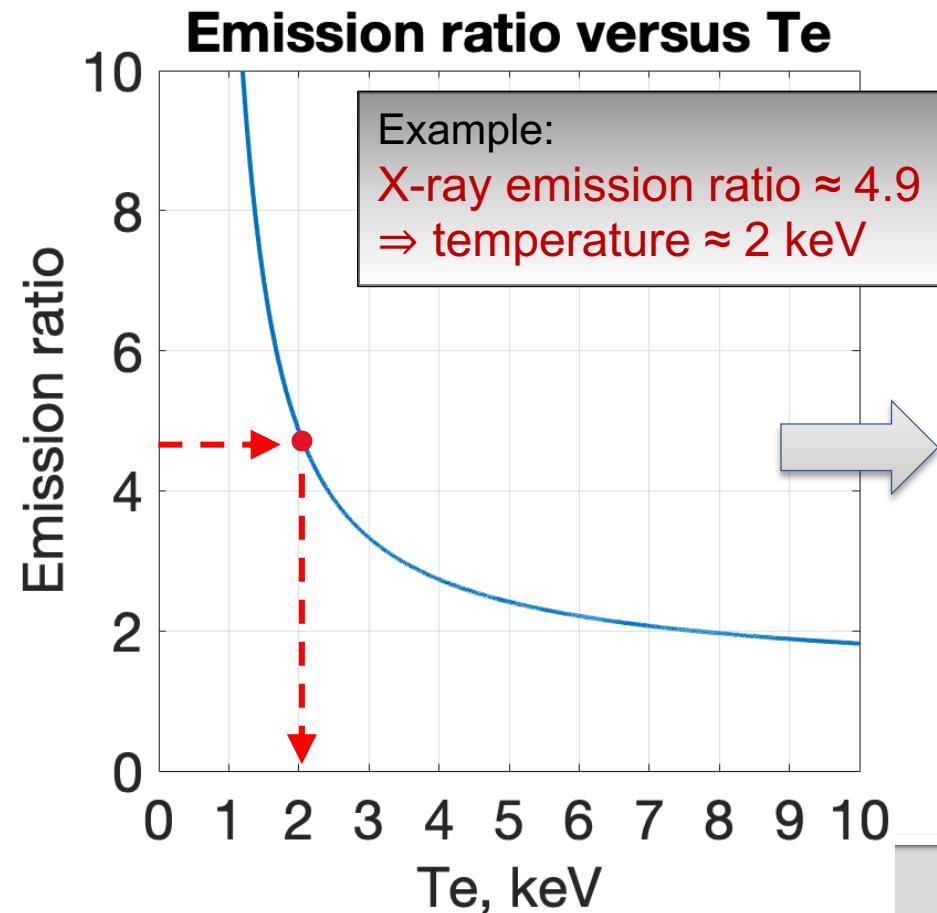
Max X-ray emission: 5.7e-05,
min X-ray emission: 5.7e-08



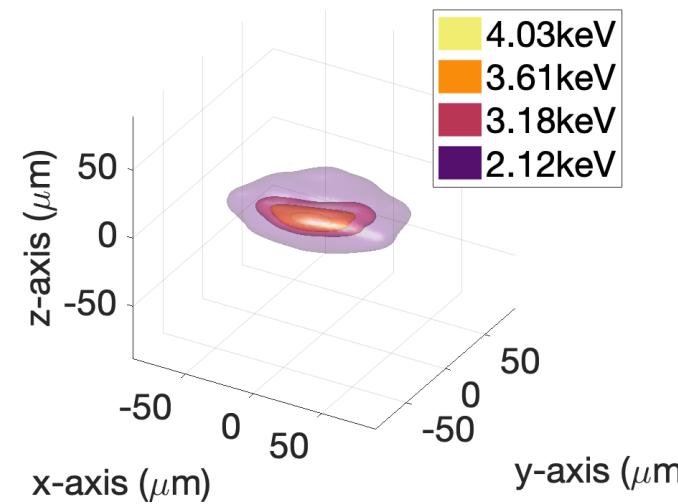
X-ray reconstruction in Channel 2

$$f(T_e) = \frac{\tilde{\varepsilon}_1(T_e)}{\tilde{\varepsilon}_2(T_e)} = \frac{\int \varepsilon(h\nu, T_e) \cdot s_1(h\nu) d(h\nu)}{\int \varepsilon(h\nu, T_e) \cdot s_2(h\nu) d(h\nu)},$$

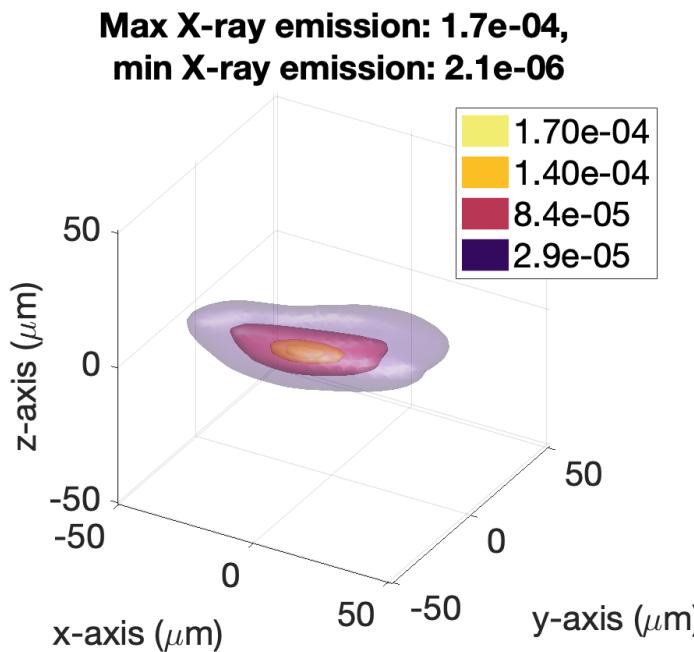
$\tilde{\varepsilon}$ detected x-ray emission
 ε x-ray emission
 s_i system response



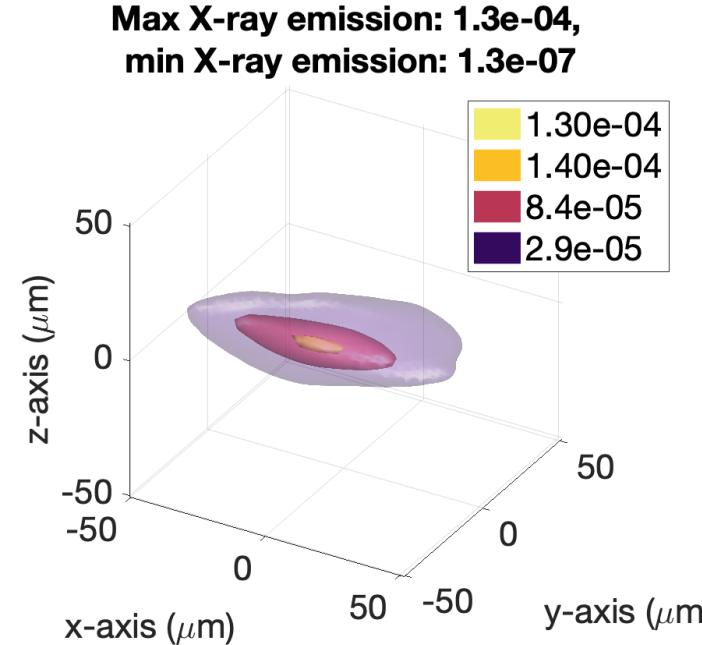
Max temperature: 4.25keV,
min temperature: 2keV



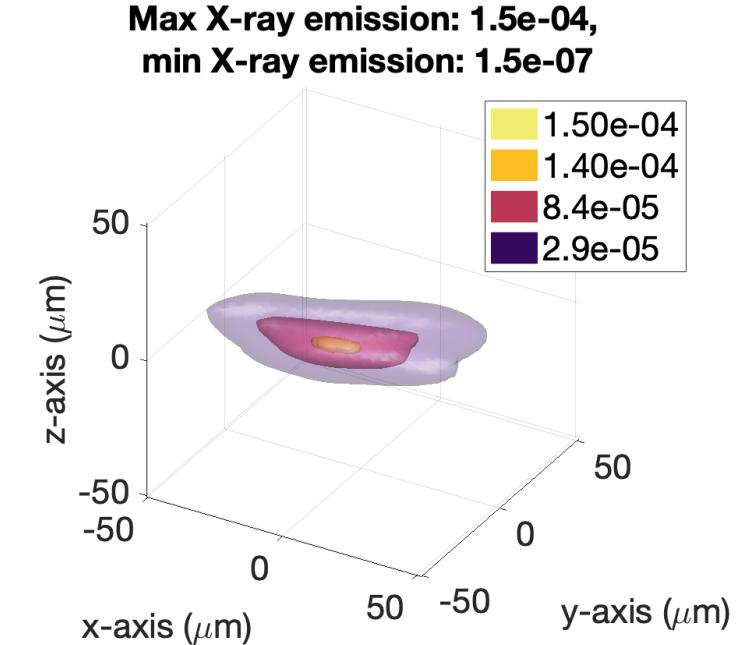
Synthetic data study: 3D X-ray reconstructions with two versus three LOS



Synthetic data



Reconstruction using 2 LOS

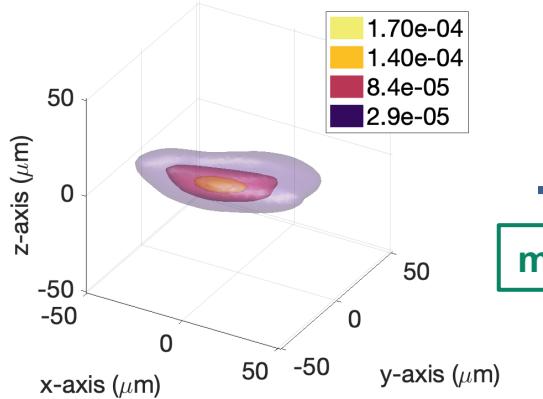


Reconstruction using 3 LOS

Contour percentages from innermost to outermost: 95%, 85%, 50%, 17%

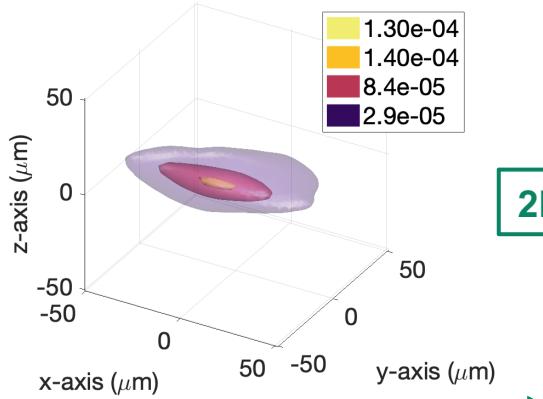
Reconstruction using three LOS has a more similar shape to the original model

Max X-ray emission: 1.7e-04,
min X-ray emission: 2.1e-06



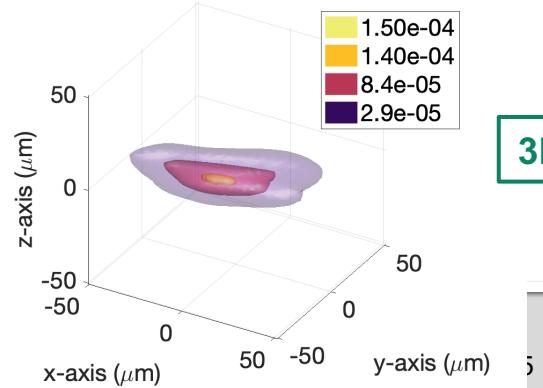
model

Max X-ray emission: 1.3e-04,
min X-ray emission: 1.3e-07



2LOS

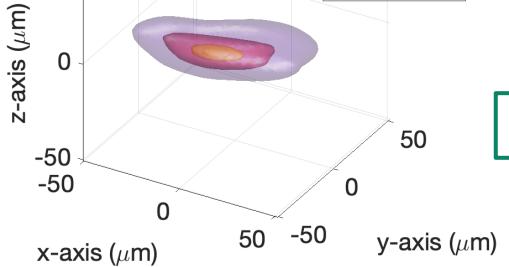
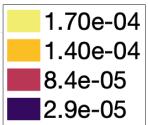
Max X-ray emission: 1.5e-04,
min X-ray emission: 1.5e-07



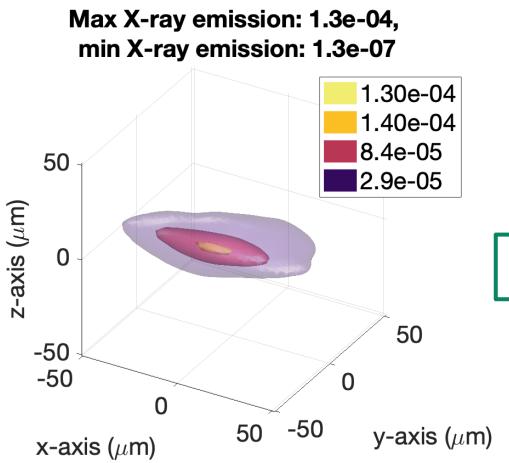
3LOS

X-ray reconstructions using 3 LOS agree better with synthetic models than using 2 LOS

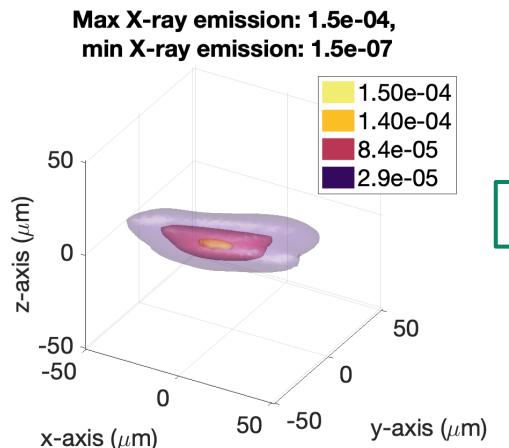
Max X-ray emission: 1.7e-04,
min X-ray emission: 2.1e-06



model

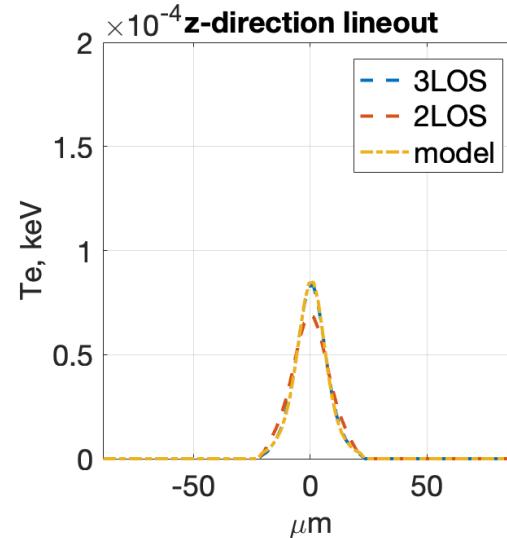
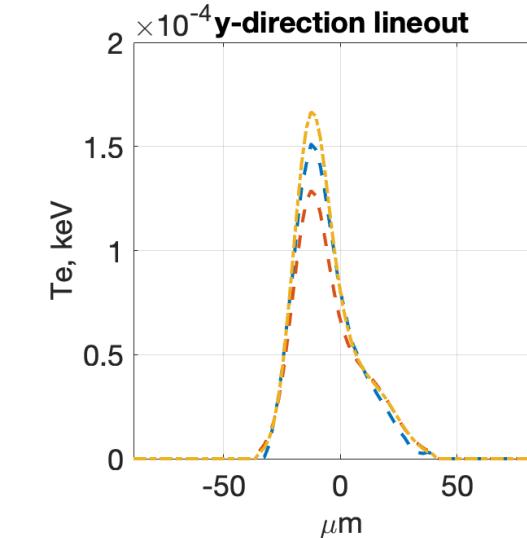
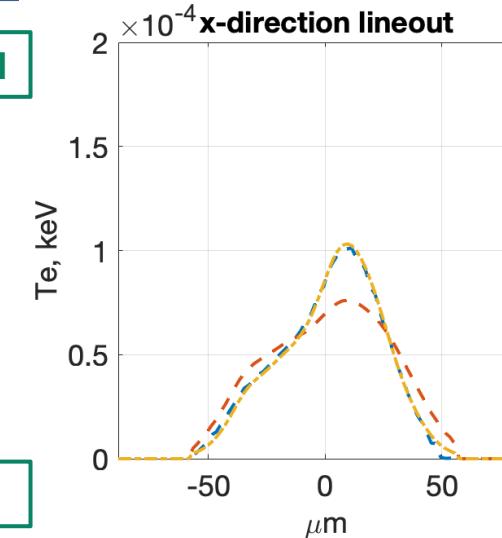


2LOS

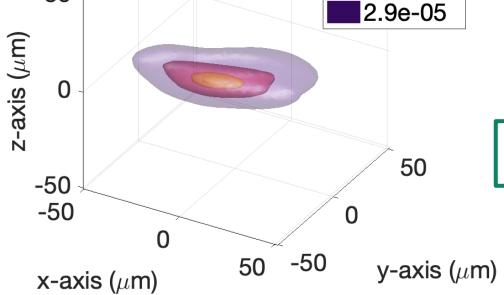
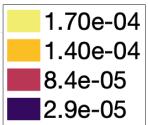


3LOS

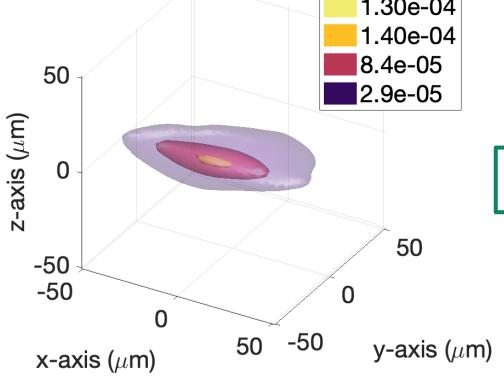
X-ray reconstructions using 3 LOS agree better with synthetic models than using 2 LOS



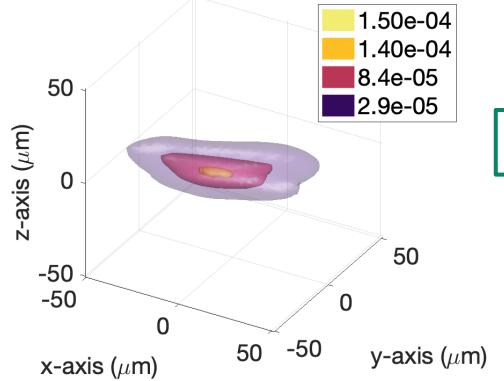
Max X-ray emission: $1.7\text{e-}04$,
min X-ray emission: $2.1\text{e-}06$



Max X-ray emission: $1.3\text{e-}04$,
min X-ray emission: $1.3\text{e-}07$

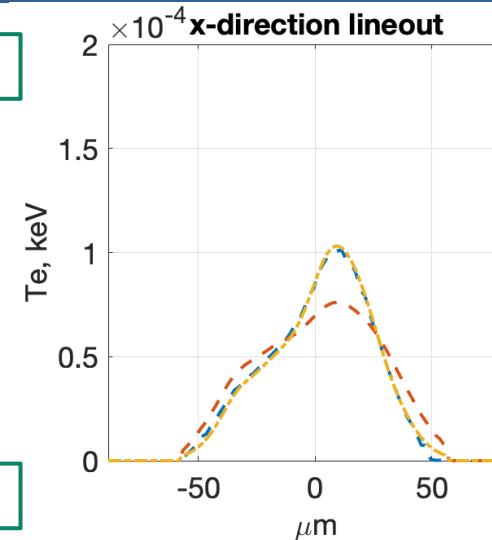


Max X-ray emission: $1.5\text{e-}04$,
min X-ray emission: $1.5\text{e-}07$

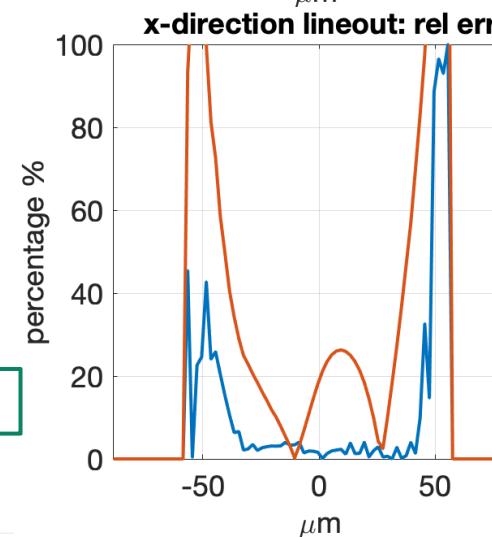


X-ray reconstructions using 3 LOS agree better with synthetic models than using 2 LOS

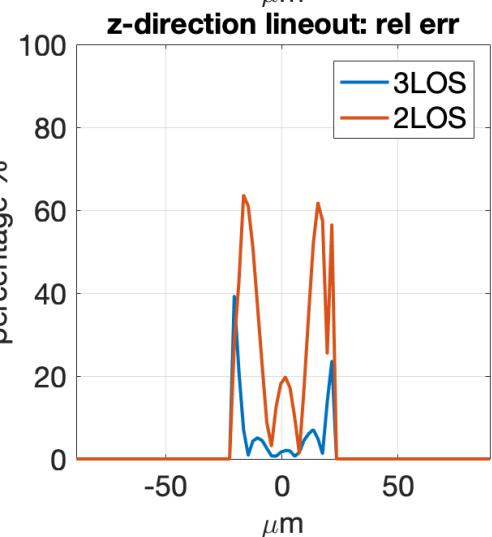
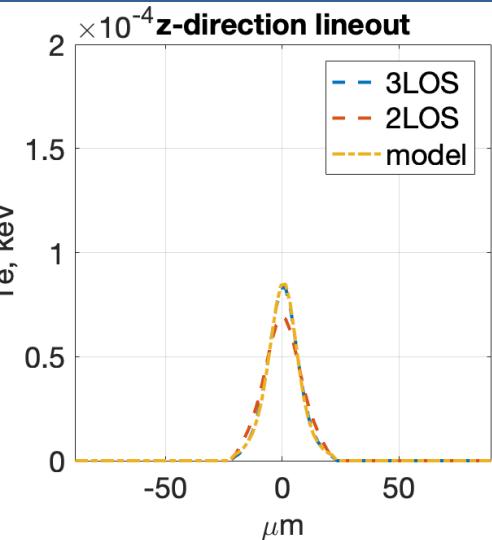
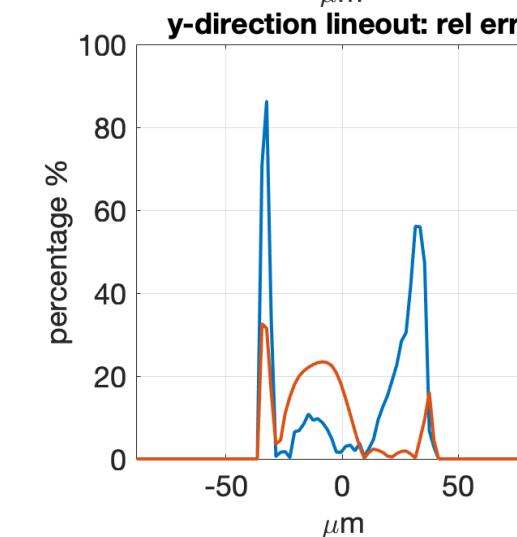
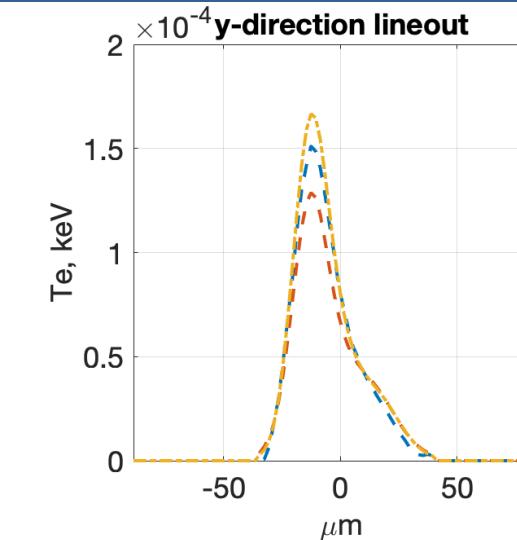
model



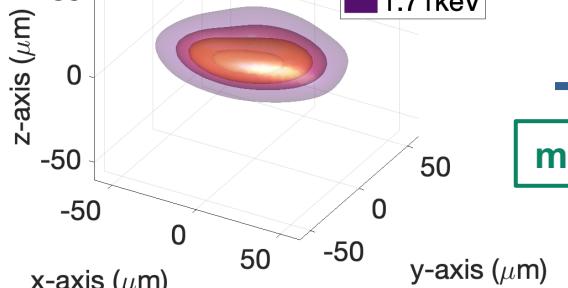
2LOS



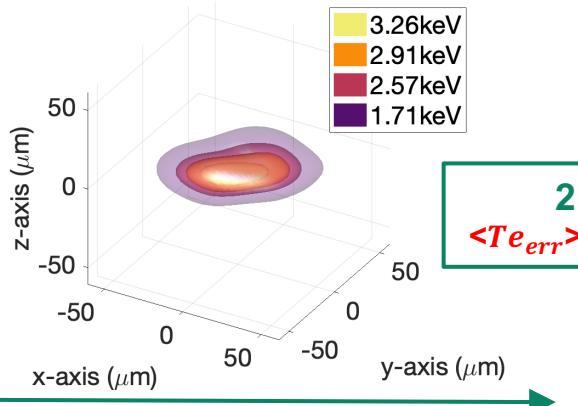
3LOS



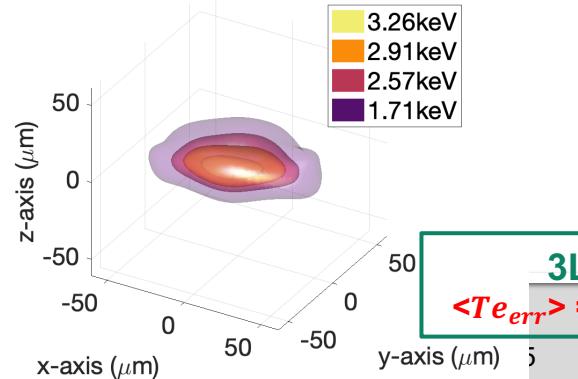
Max temperature: 3.43keV,



Reconstructed model - $\langle T_e \text{ error} \rangle = 0.26\text{keV}$,
max temperature: 3.52keV

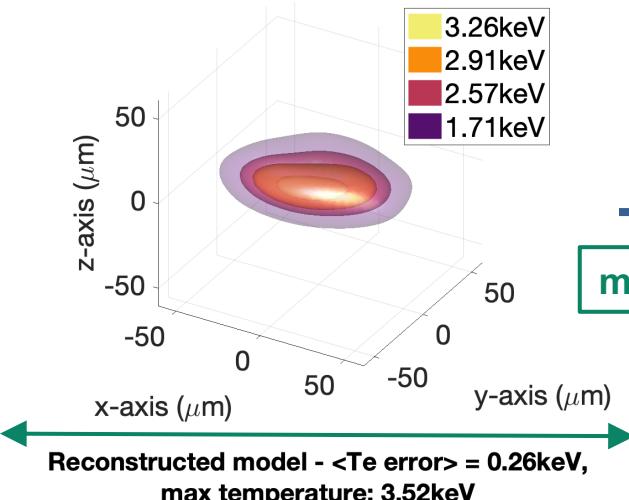


Reconstructed model - $\langle T_e \text{ error} \rangle = 0.094\text{keV}$,
max temperature: 3.46keV

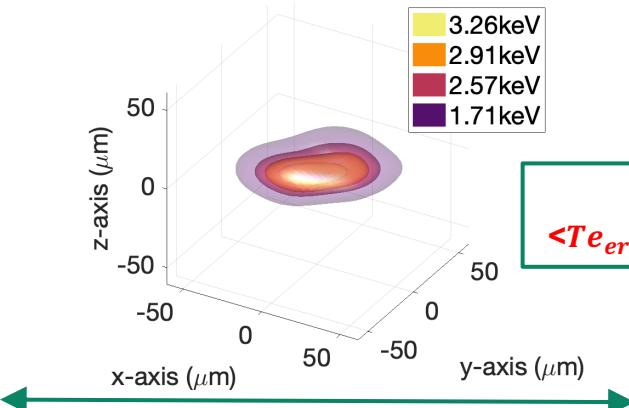


Relative T_e errors improve to below $\sim 10\%$ by fielding a third LOS

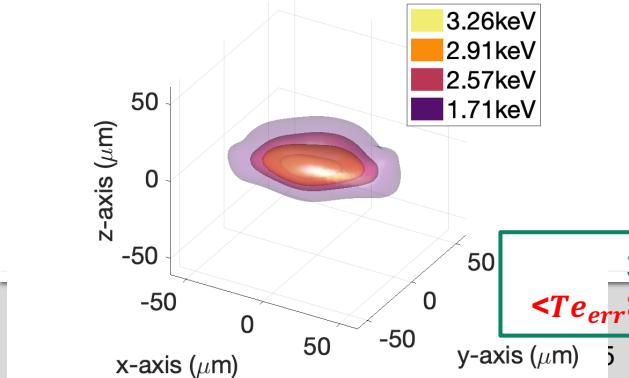
Max temperature: 3.43keV,



Reconstructed model - $\langle T_e \text{ error} \rangle = 0.26\text{keV}$,
max temperature: 3.52keV

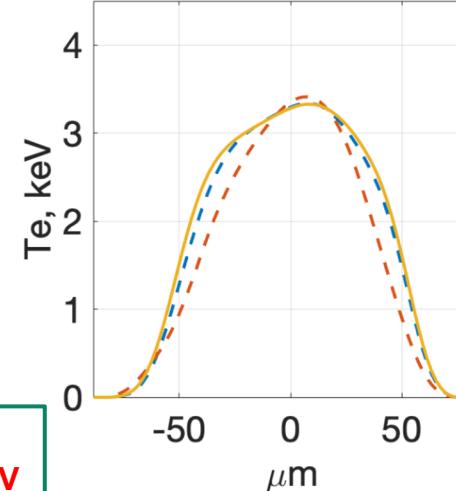


Reconstructed model - $\langle T_e \text{ error} \rangle = 0.094\text{keV}$,
max temperature: 3.46keV

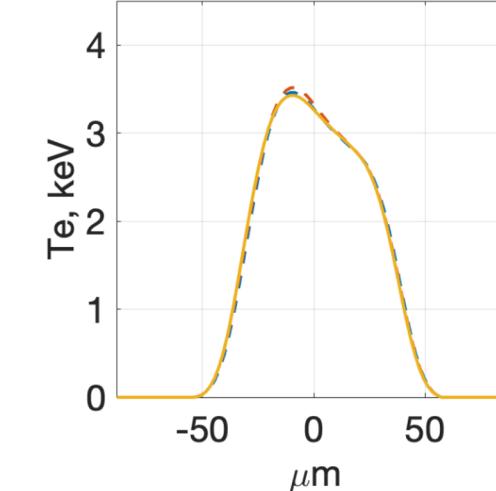


Relative T_e errors improve to below $\sim 10\%$ by fielding a third LOS

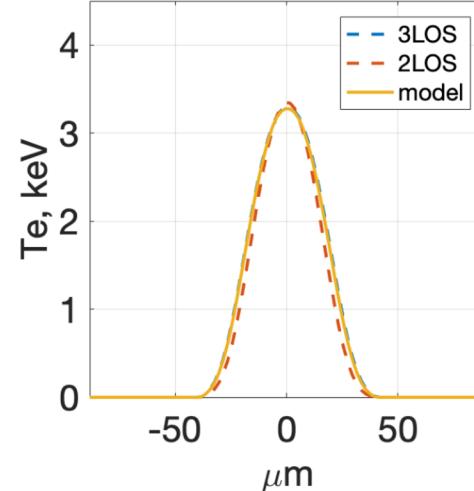
x-direction lineout



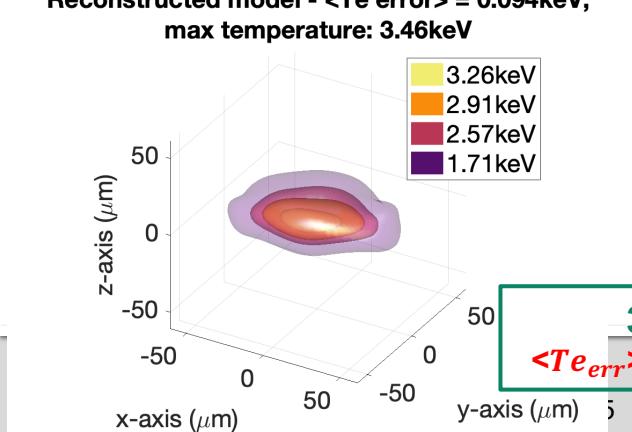
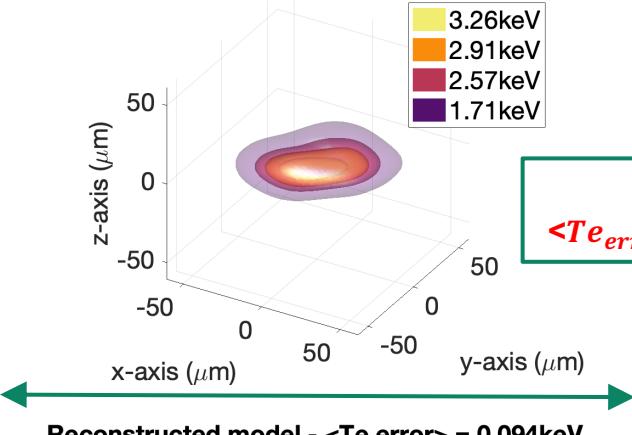
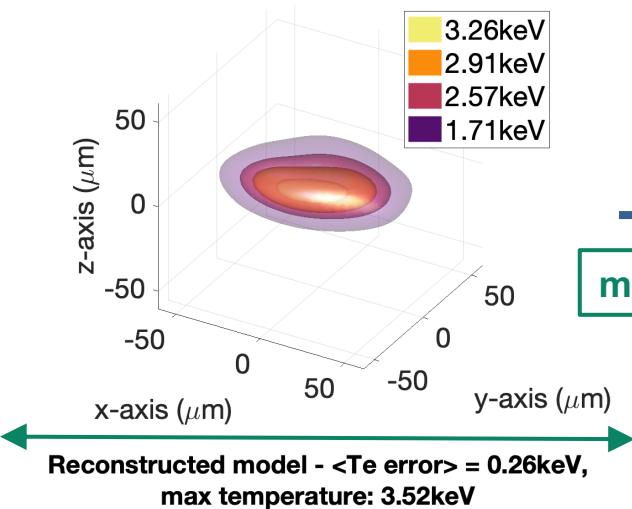
y-direction lineout



z-direction lineout

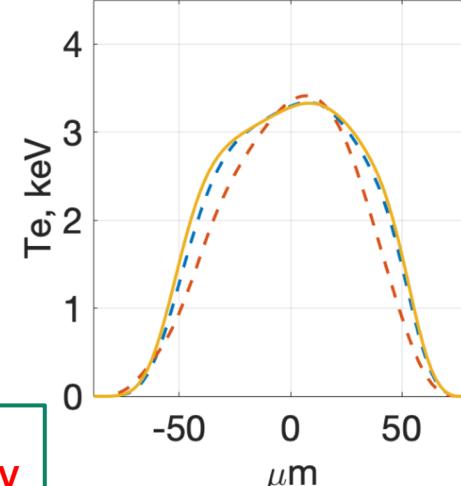


Max temperature: 3.43keV,

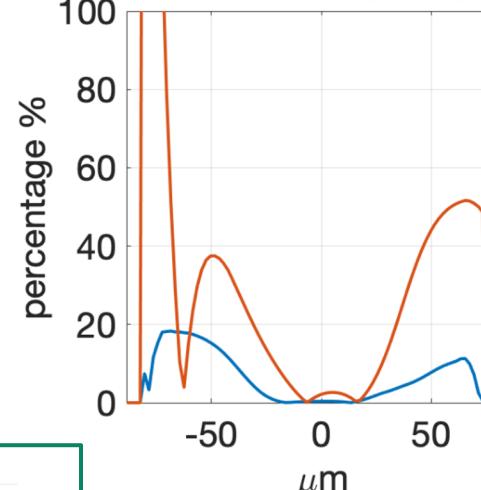


Relative T_e errors improve to below $\sim 10\%$ by fielding a third LOS

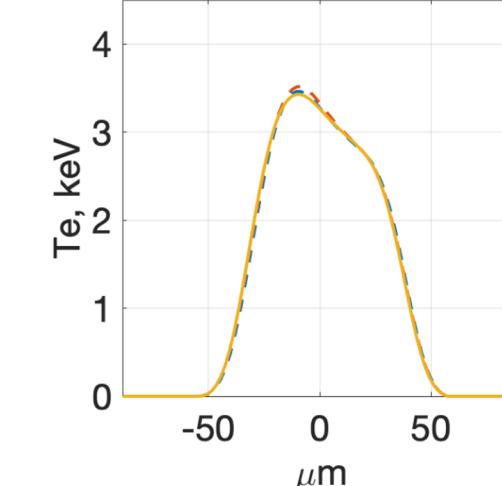
x-direction lineout



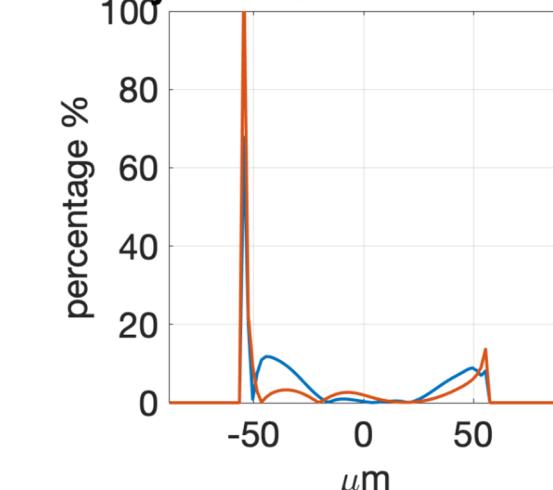
x-direction lineout: rel err



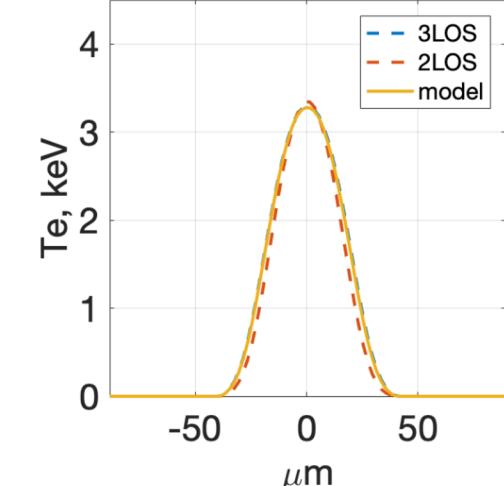
y-direction lineout



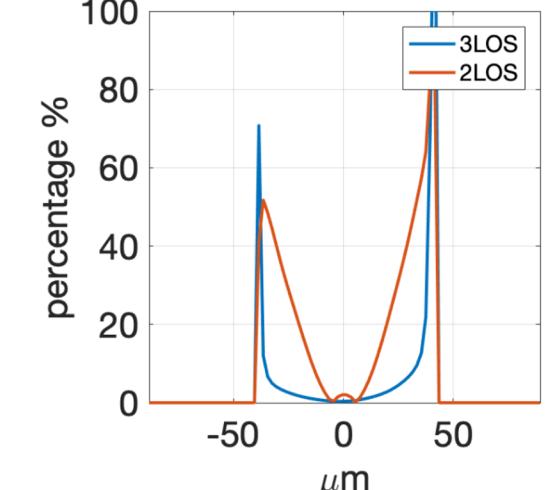
y-direction lineout: rel err



z-direction lineout



z-direction lineout: rel err

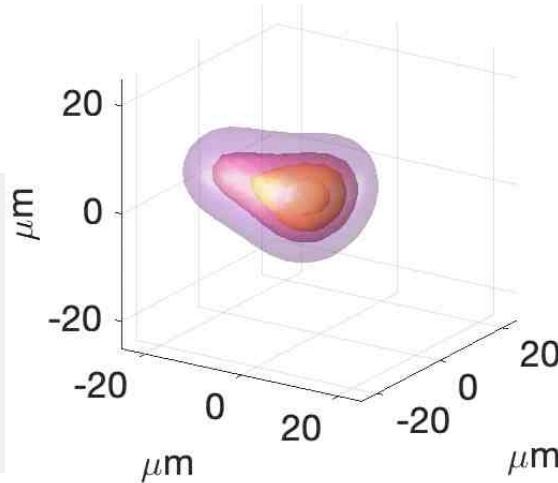


We tested a collection of synthetic T_e models with various shapes

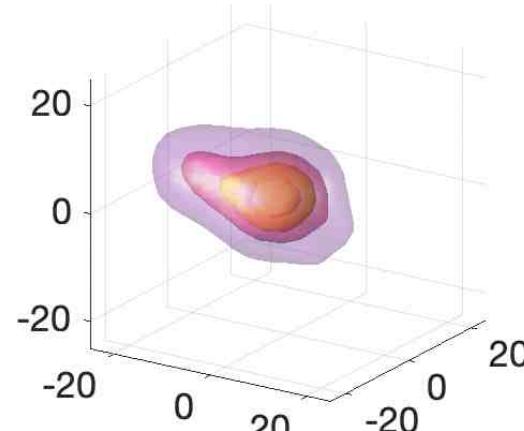
Synthetic model



Model 1



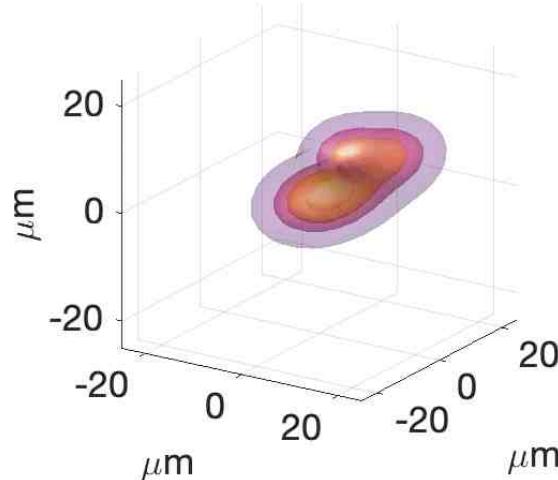
$\langle T_{e_{\text{err}}} \rangle = 0.11 \text{ keV}$



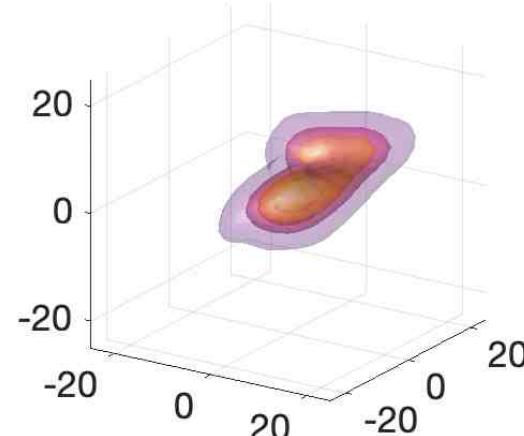
T_e measurements

Contour percentages from innermost to outermost:
95%, 85%, 75%, 50%

Model 2

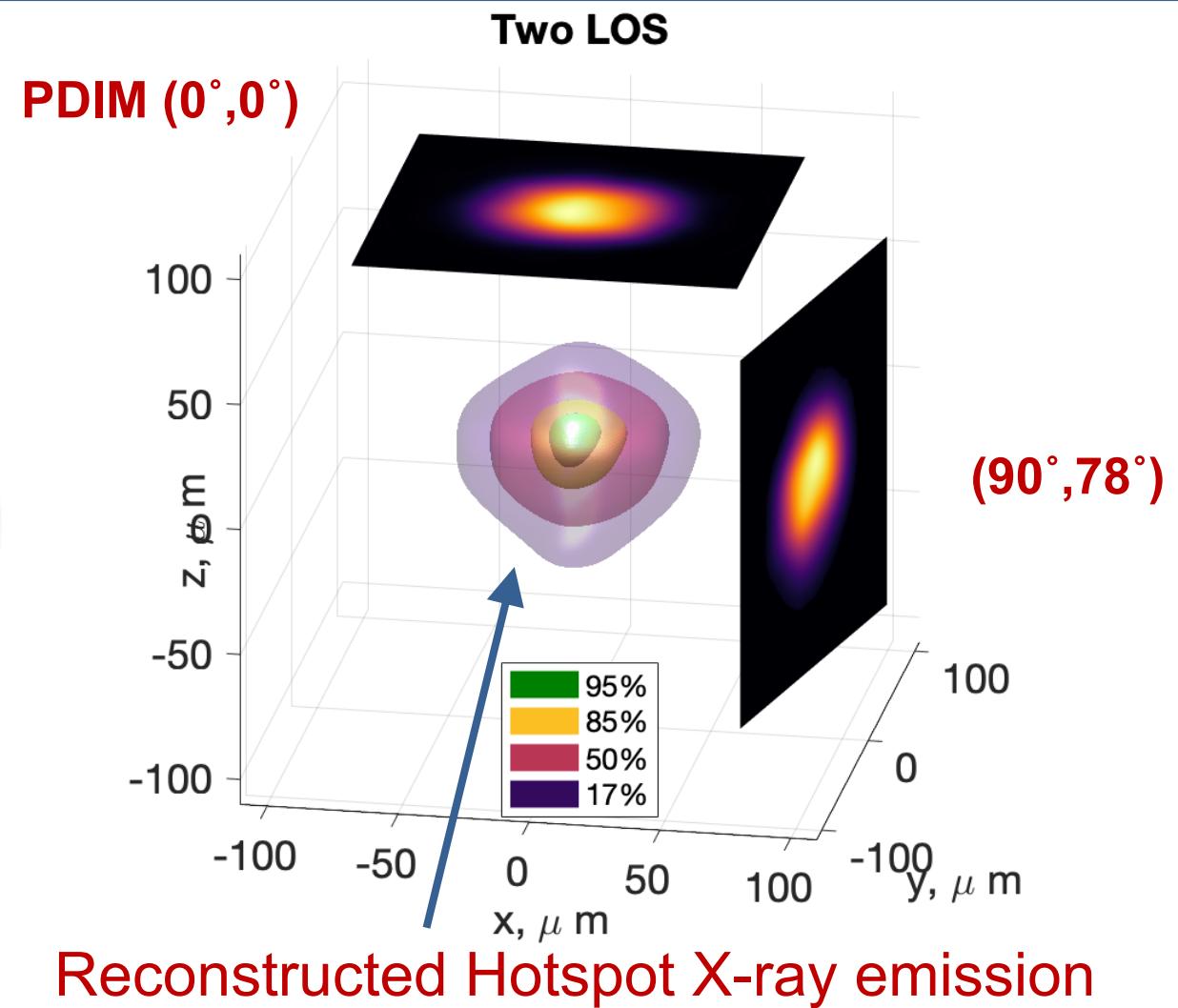
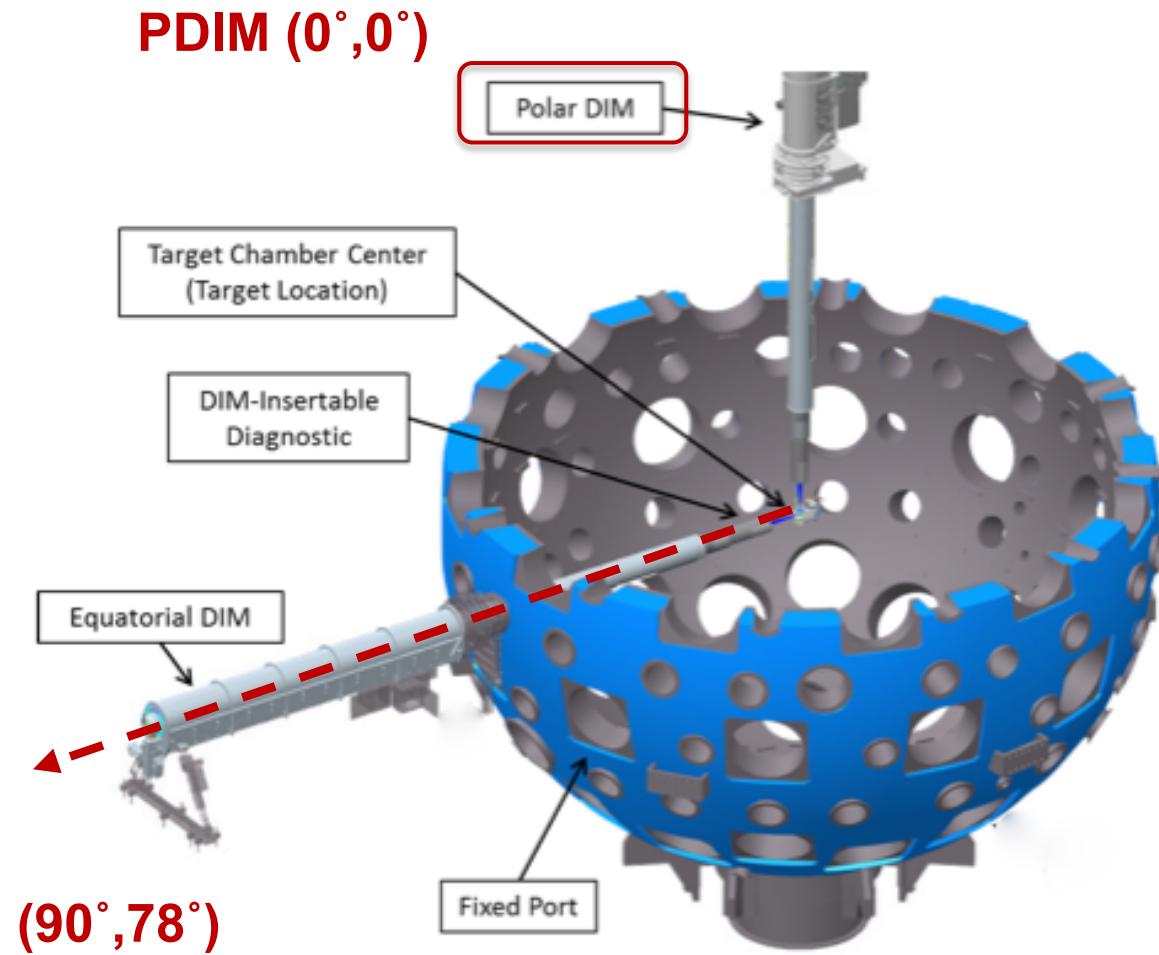


$\langle T_{e_{\text{err}}} \rangle = 0.13 \text{ keV}$

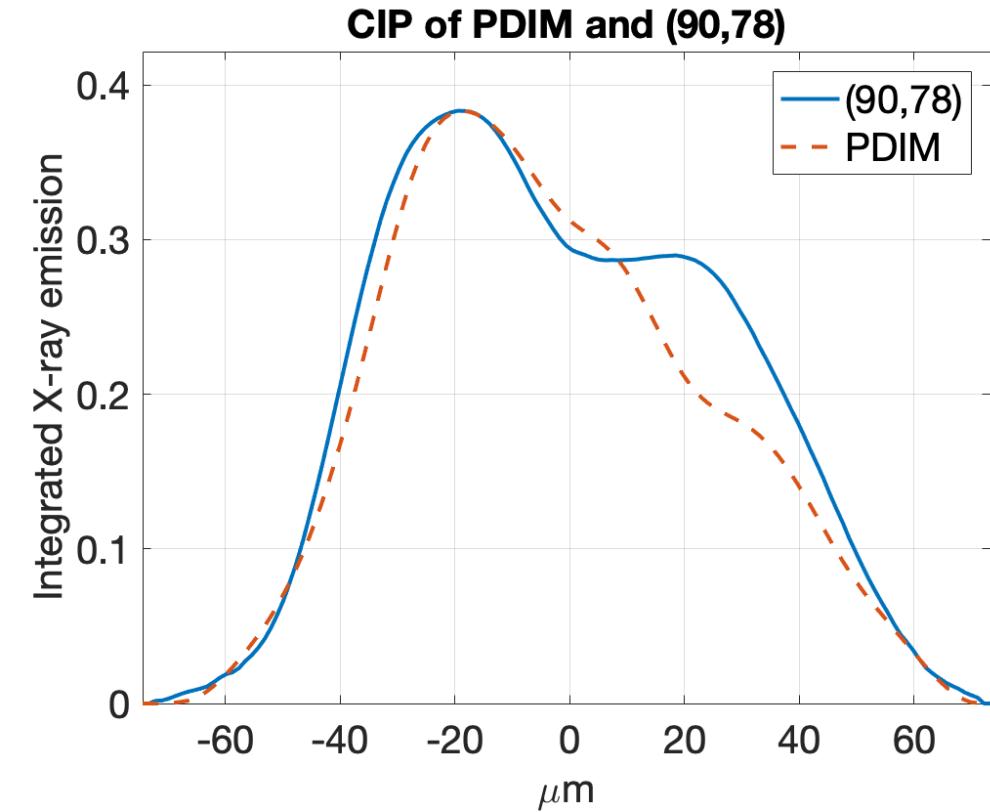
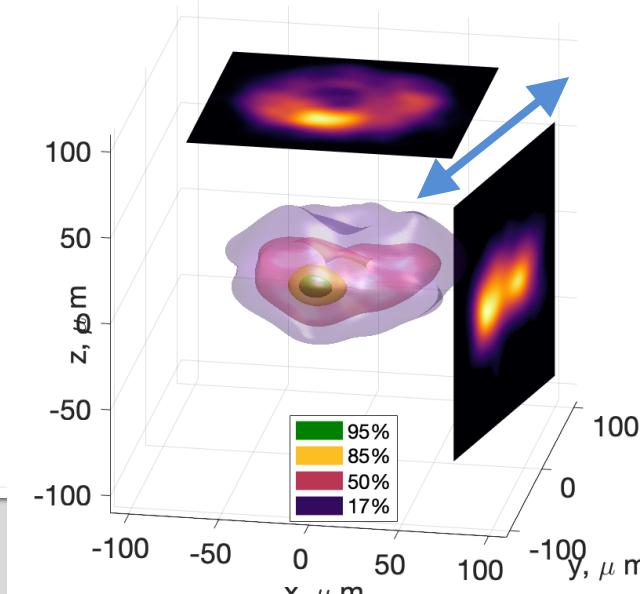
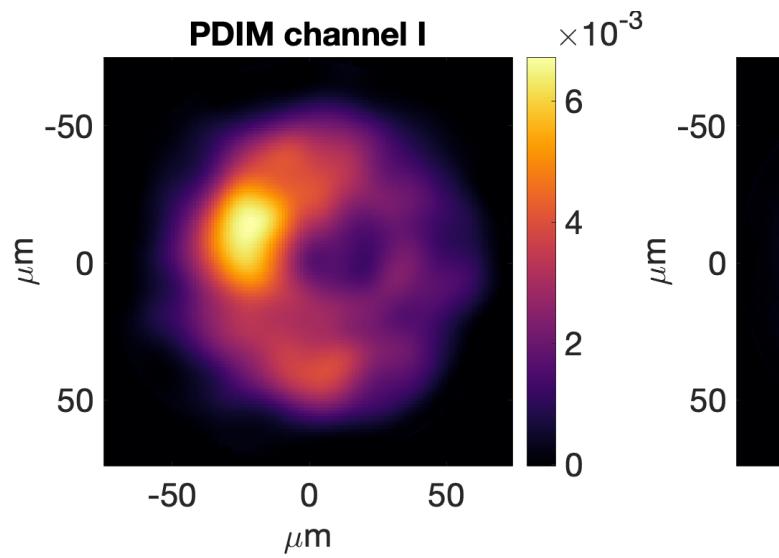


T_e measurements
using 3 LOS have
high accuracy
despite complex
geometries

Experimental data study: experimentally fielded diagnostic at two LOS PDIM ($0^\circ, 0^\circ$) and ($90^\circ, 78^\circ$)

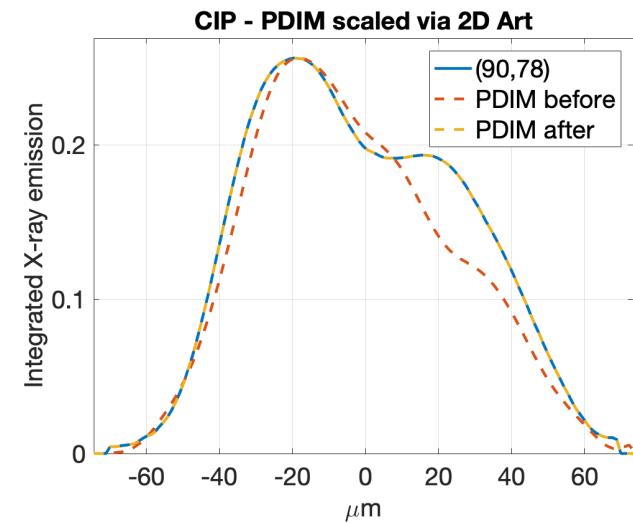
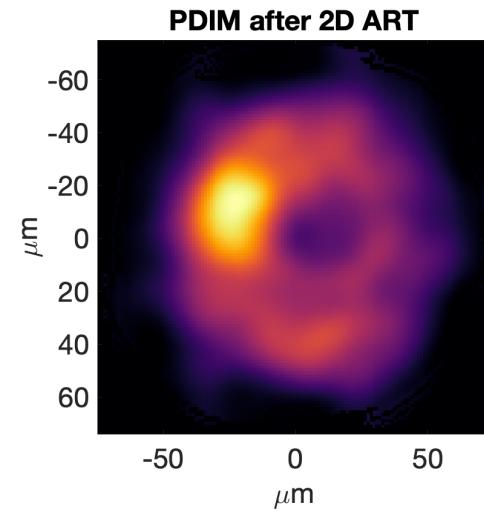
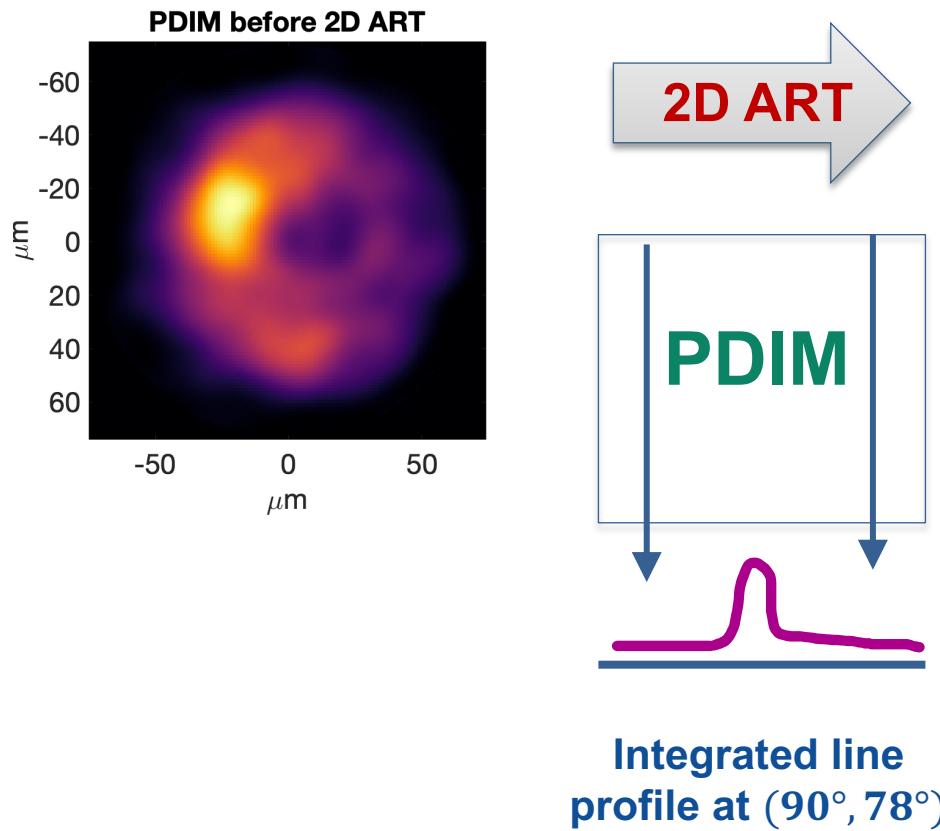


N181007: Noise causes discrepancy in the common integrated profile (CIP) between PDIM and (90°, 78°)

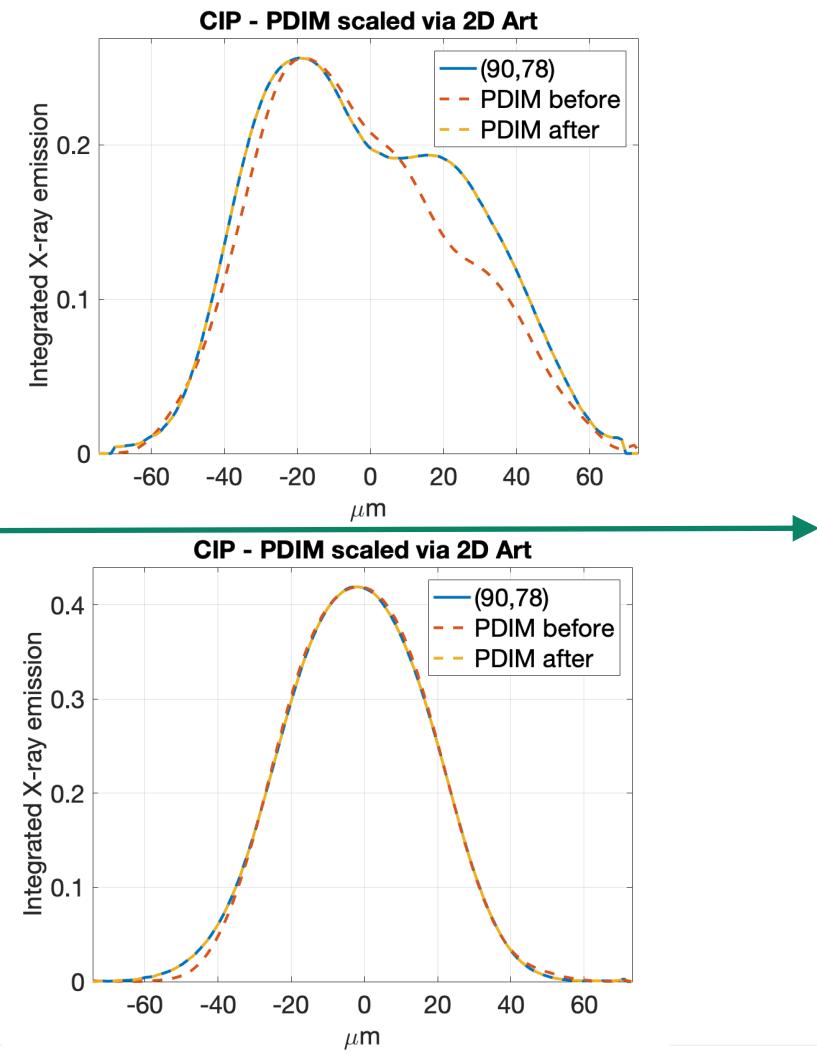
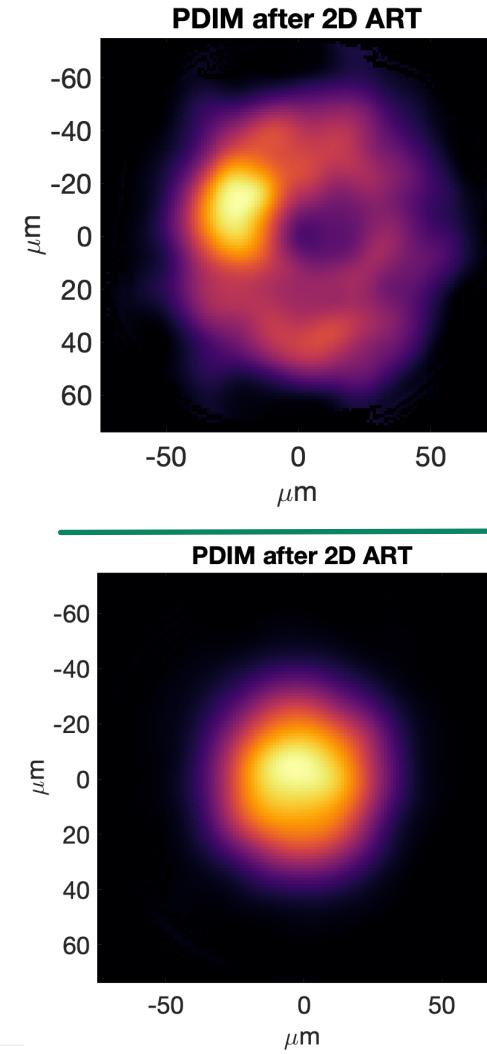
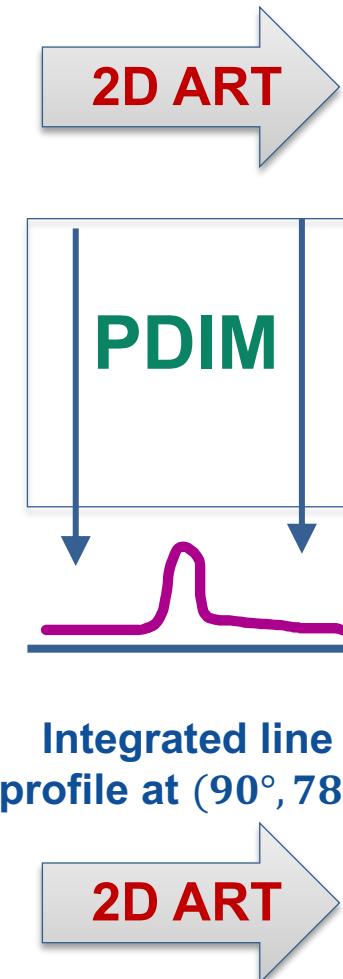
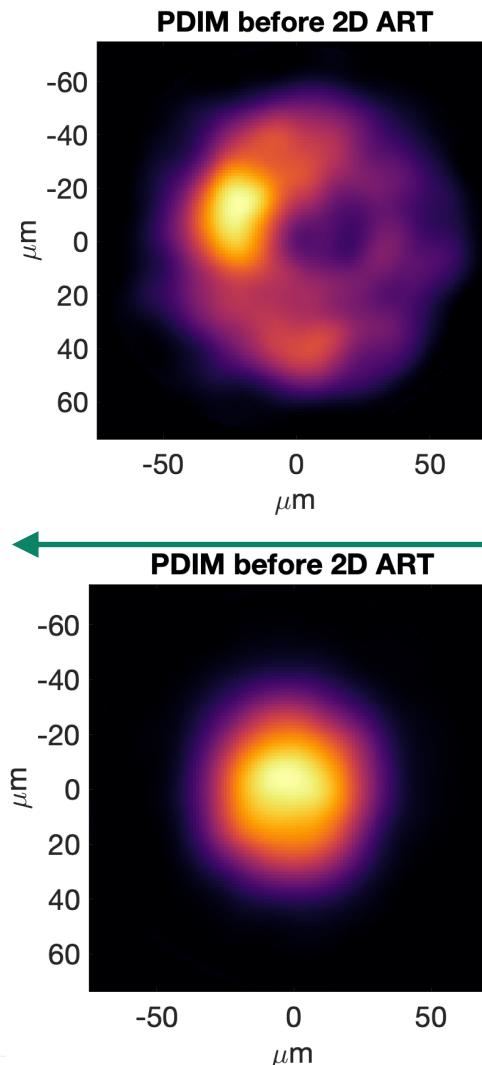


How to match PDIM and (90°,78°)
CIP without compromising the
hotspot structure in input images?

We apply 2D ART to modify PDIM image such that it matches with the CIP of the equatorial image (top row - N181007, bottom row - N190730)

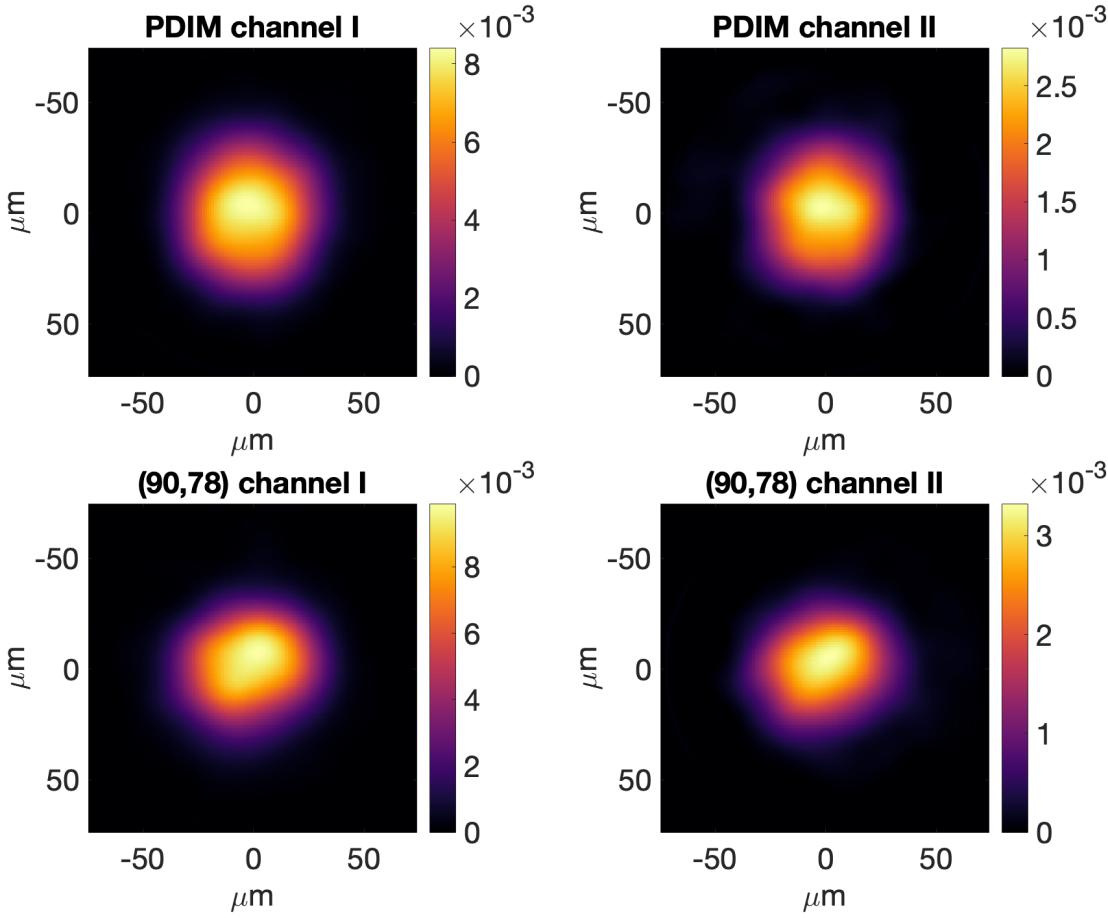


We apply 2D ART to modify PDIM image such that it matches with the CIP of the equatorial image (top row - N181007, bottom row - N190730)



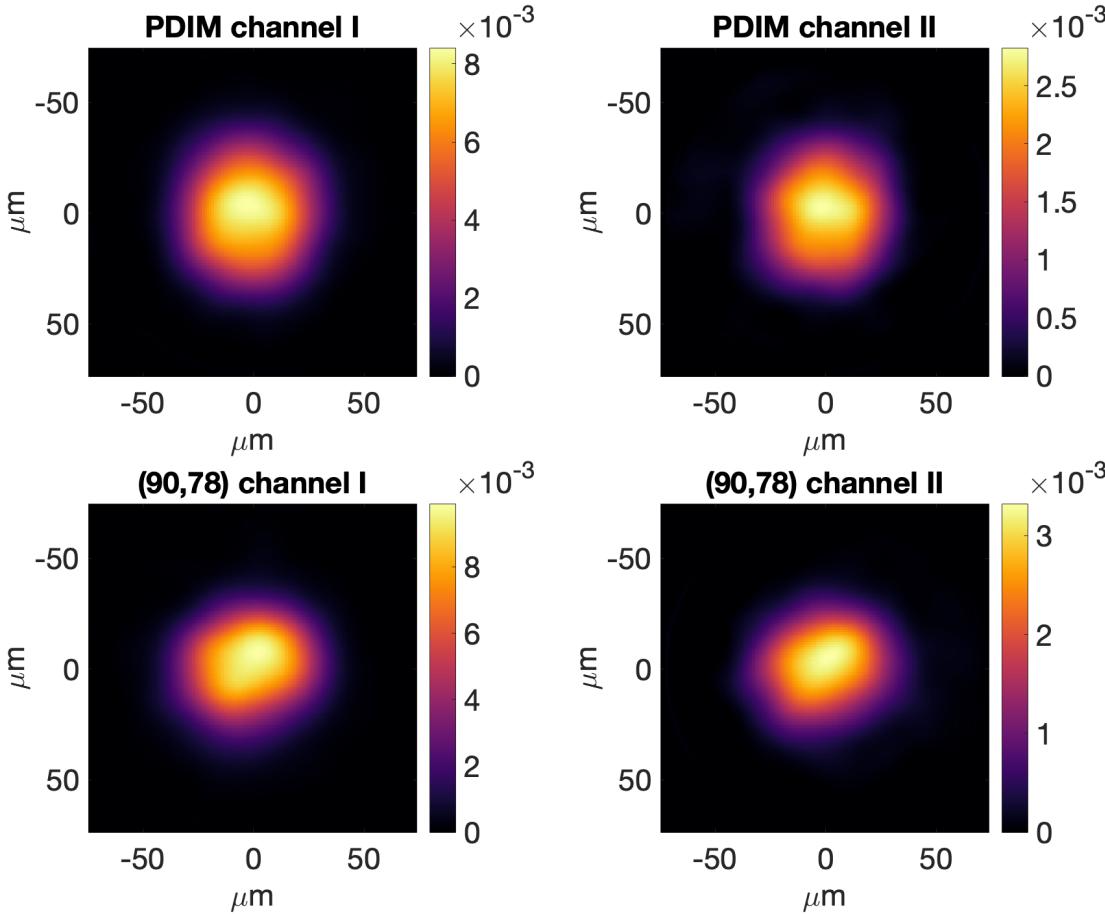
N190730: X-ray images and 3D X-ray reconstructions show a round hotspot

Experimental X-ray images

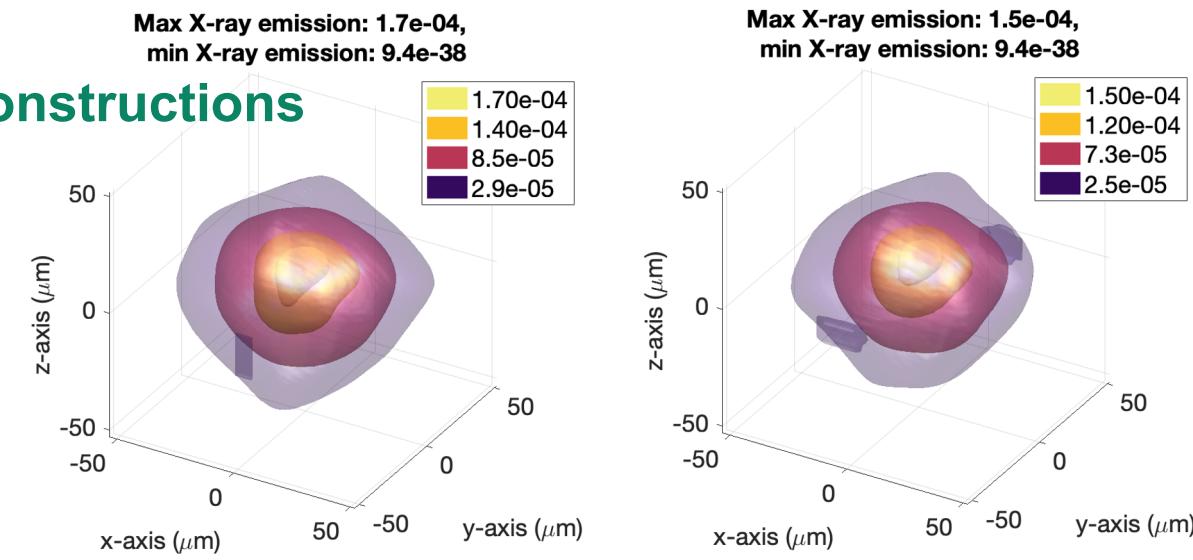


N190730: X-ray images and 3D X-ray reconstructions show a round hotspot

Experimental X-ray images

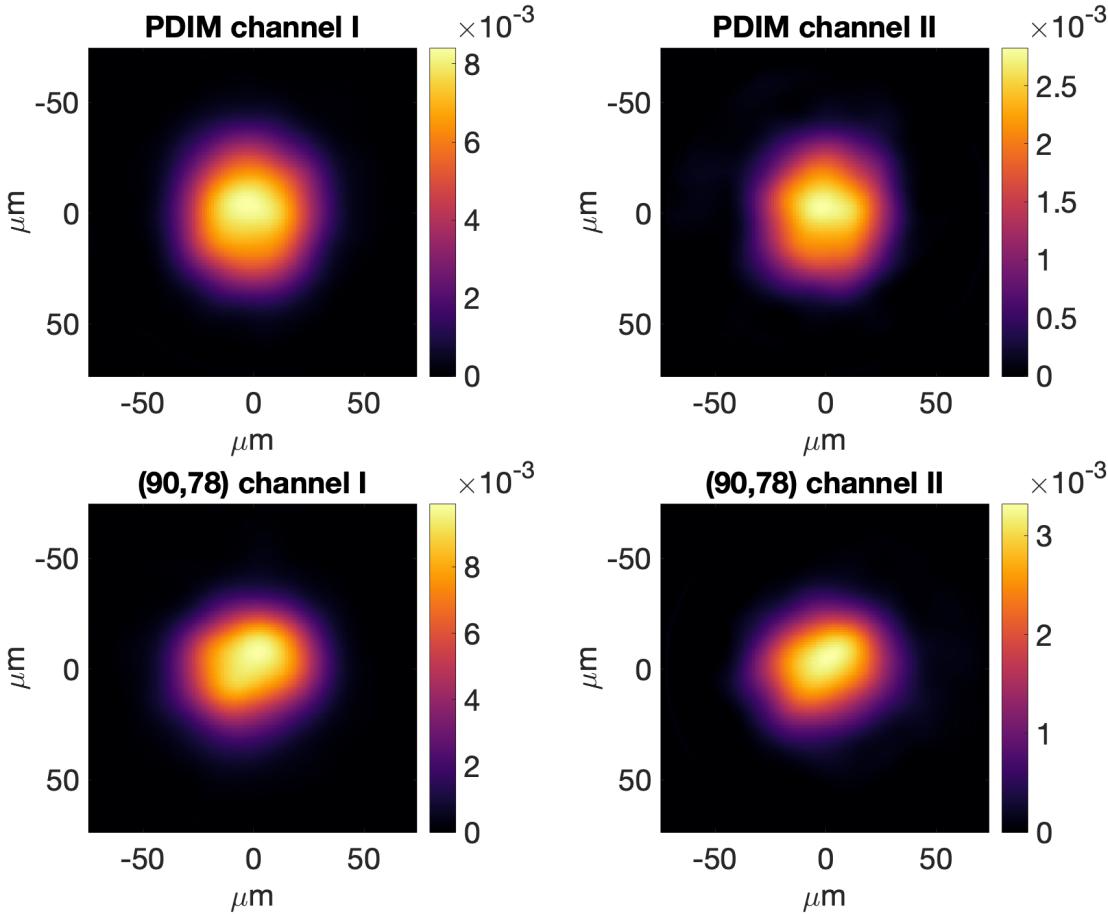


Reconstructions

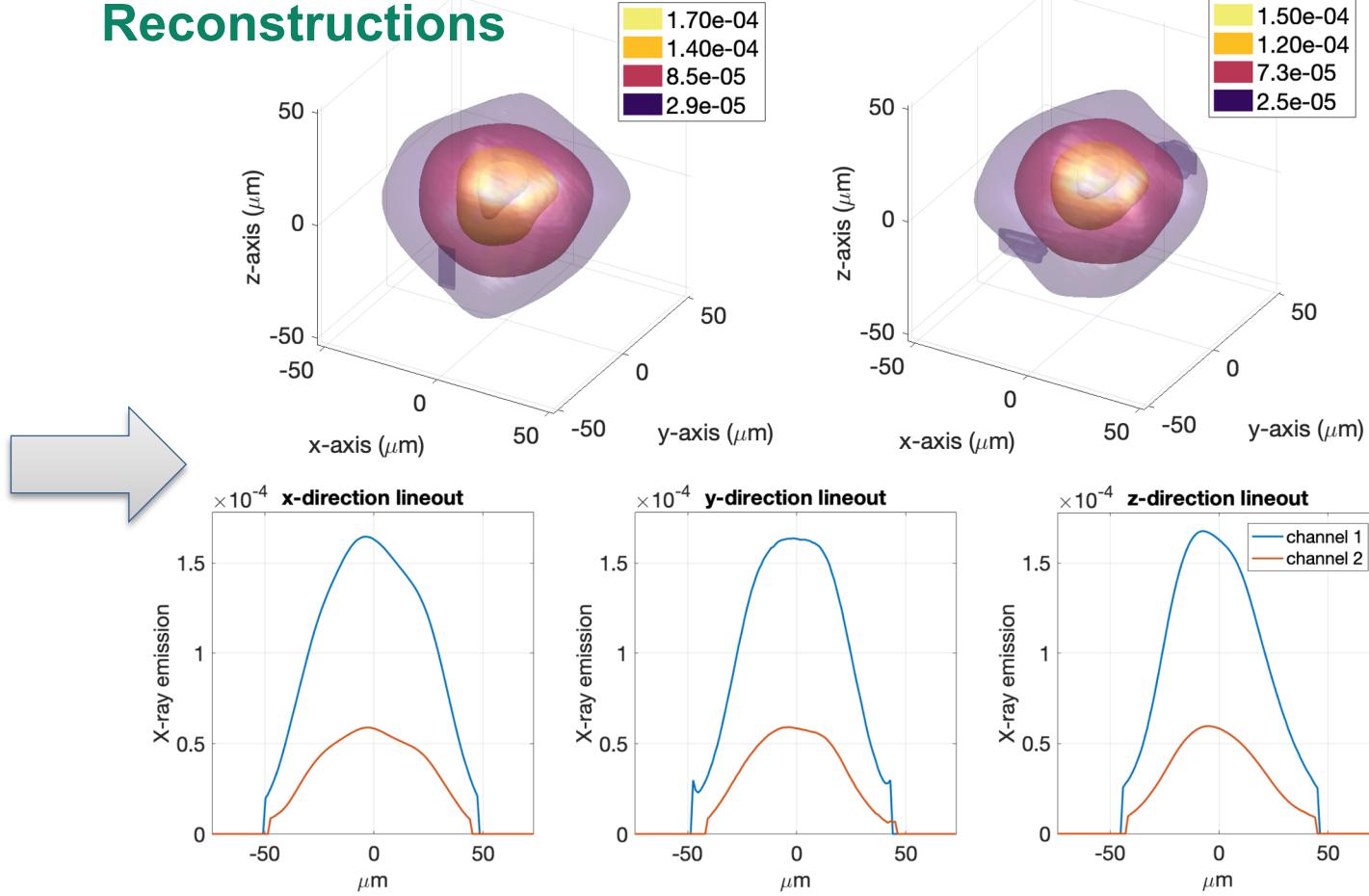


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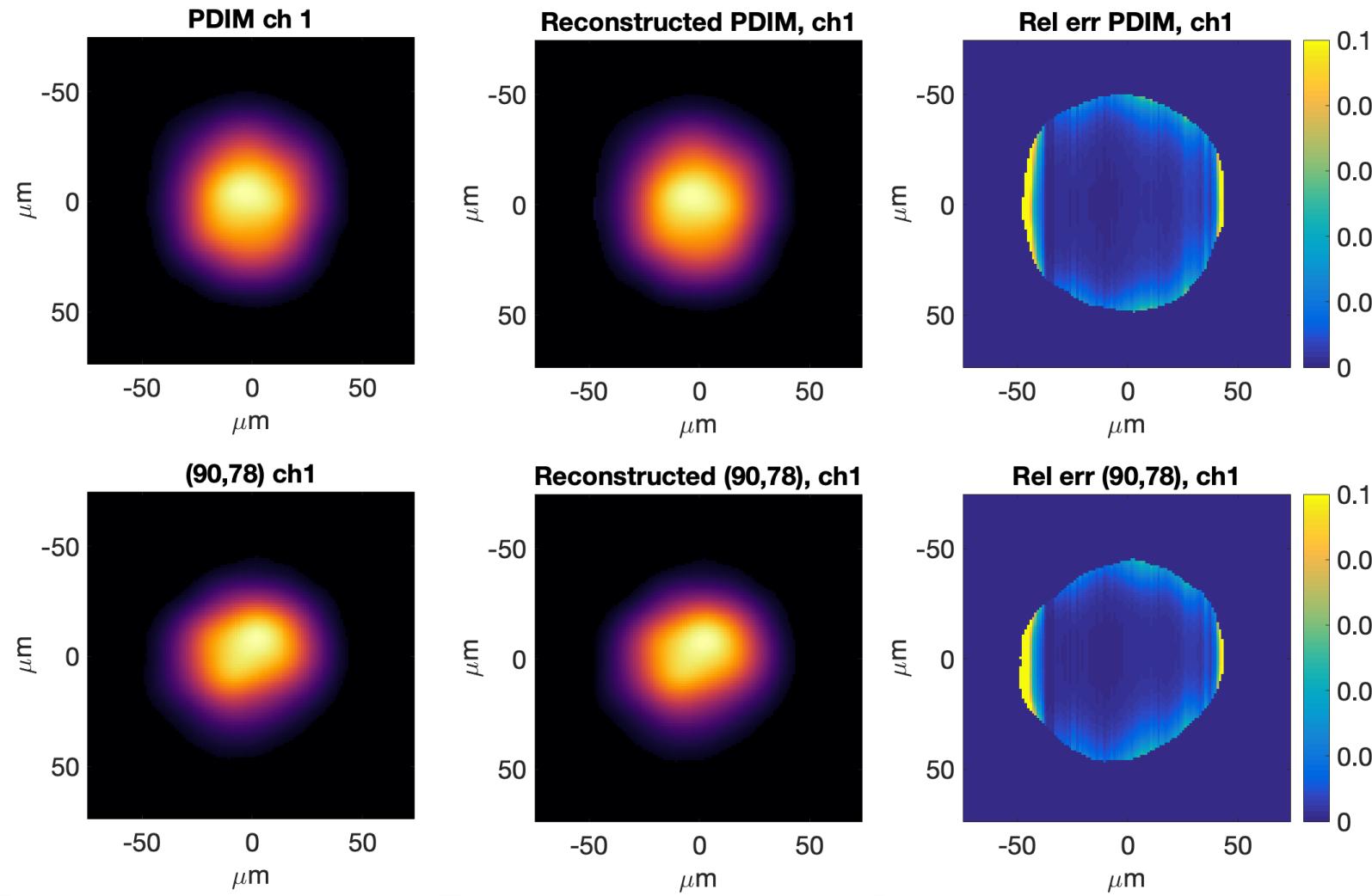
Experimental X-ray images



Reconstructions



Our 3D X-ray reconstruction is consistent to input images

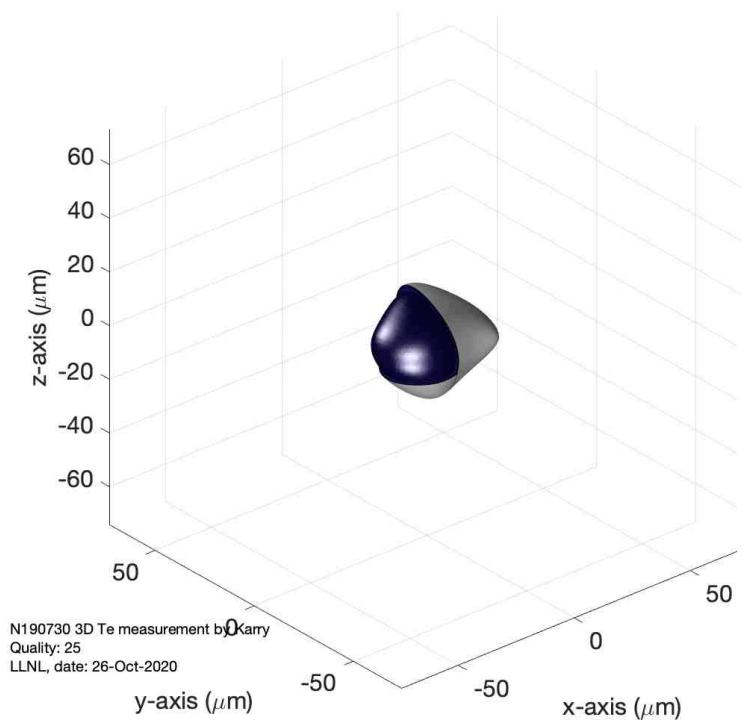


The reconstructed projections agree well with the input experimental images.

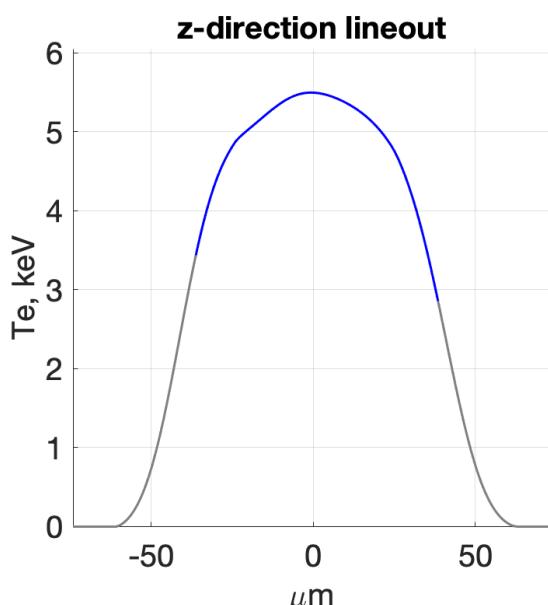
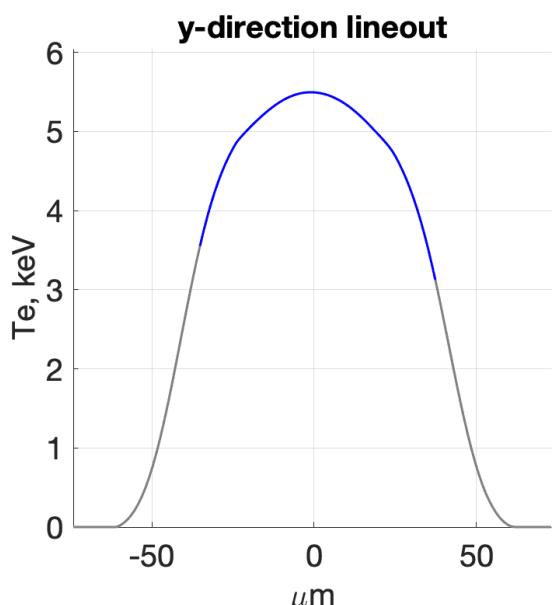
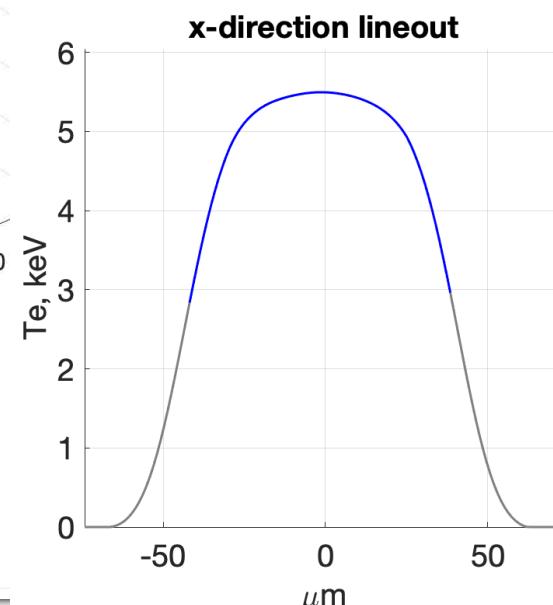
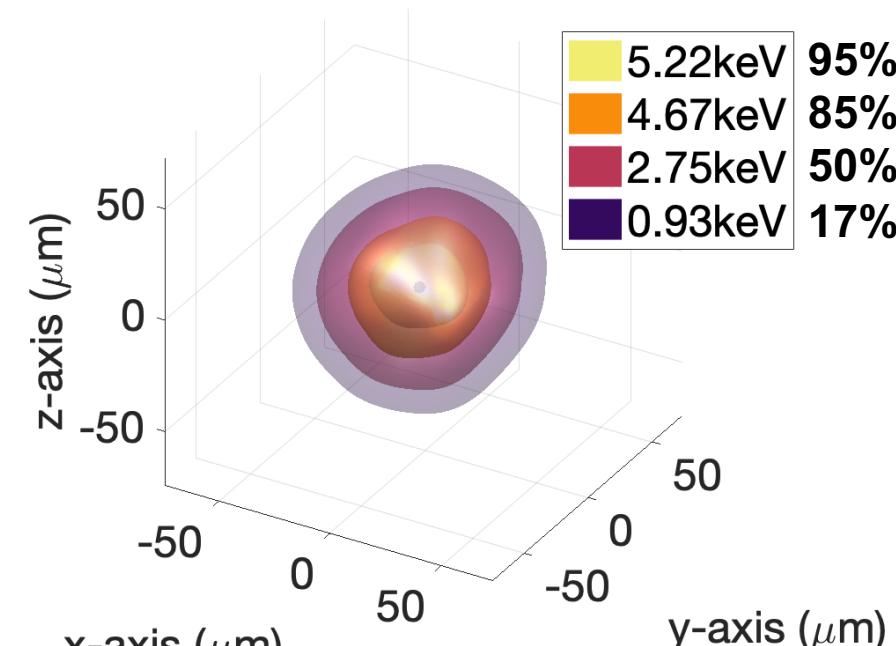
The relative errors in the hotspot are largely zero.

3D T_e measurement of N190730

3D T_e model, 16 μm resolution,
outer contour: 94%, transparent contour: 50%, inner contour: 95%



$\langle T_e \rangle_{(90^\circ, 78^\circ)} \approx 4.5 \text{ keV}$
 $\langle T_e \rangle_{PDIM} \approx 4.2 \text{ keV}$
 Ref. Jarrott et al., PRL 2018.



Measuring 3D electron temperature of the ICF hotspot is feasible

We have

- tested iterative algebraic method ART to reconstruct 3D X-ray emission distributions of the ICF hotspot.
- obtained 3D X-ray reconstructions with two or three LOS and made 3D electron temperature T_e measurement in the ICF hotspot using synthetic and experimental data
- laid out a future path on how to perform 3D T_e measurement on the NIF.

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