A Compton camera design for prompt gamma imaging during BNCT

K. Nutter, T. Price, Tz. Kokalova,
S. Green, B. Phoenix.

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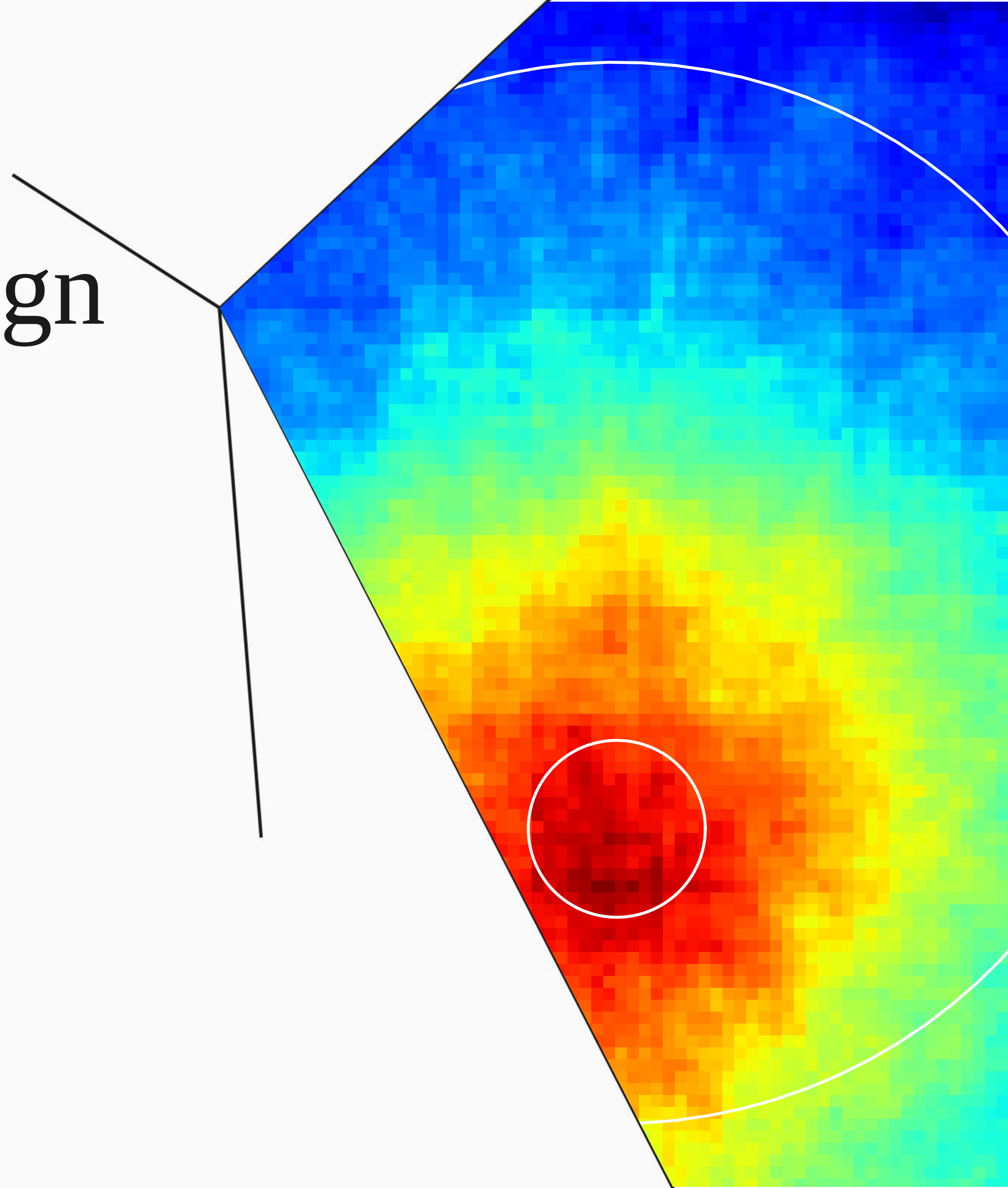

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Boron Neutron Capture Therapy (BNCT)

- Binary cancer therapy that utilises biological and physical targeting of the tumour

- Neutron capture produces short-range, high linear energy transfer (LET) particles

- Research has focused on brain, head and neck cancers

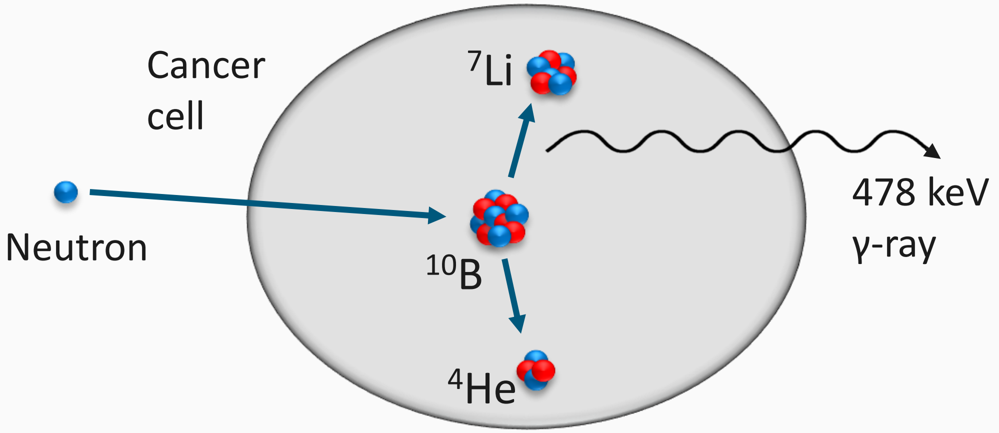

Fig 1. Visual representation of the fundamental interaction utilised during BNCT.

- Cross section for thermal neutron capture on ^{10}B is 3840 barns [1]

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[1] D. A. Brown et al. ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data, Nucl. Data Sheets, 148:1-142 (2018).

Boron Neutron Capture Therapy (BNCT)

- Binary cancer therapy that utilises

However, obtaining accurate dosimetry is challenging!!!

and neck cancers

neutron capture on ^{10}B is 3840 barns [1]

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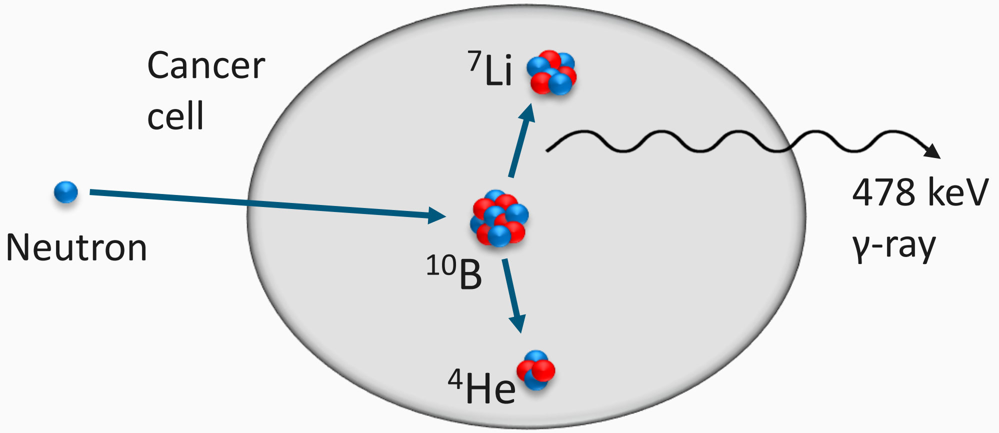
Prompt Gamma Imaging for BNCT



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Prompt Gamma Imaging for BNCT

- A 478 keV prompt gamma ray is produced after 93.9% of the neutron capture interactions
- Delivered dose could be inferred by imaging the production vertices of these gamma rays

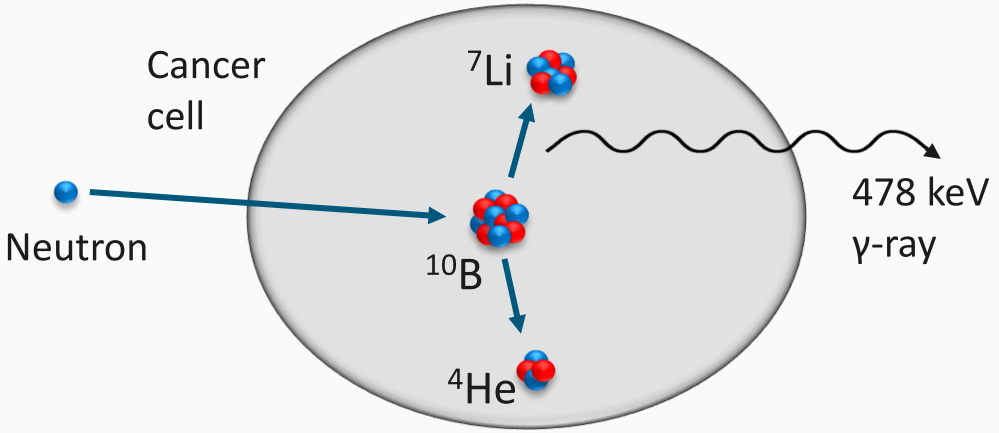

Fig 1. Visual representation of the fundamental interaction utilised during BNCT.

$$^{10}B + n \rightarrow {}^{7}Li + \alpha + 2.79\ MeV \quad (6.1\%)$$
$$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha + 2.31\ MeV \quad (93.9\%)$$
$$^{7}Li^{*} \rightarrow {}^{7}Li + \gamma\ (0.478\ MeV)$$

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Prompt Gamma Imaging for BNCT

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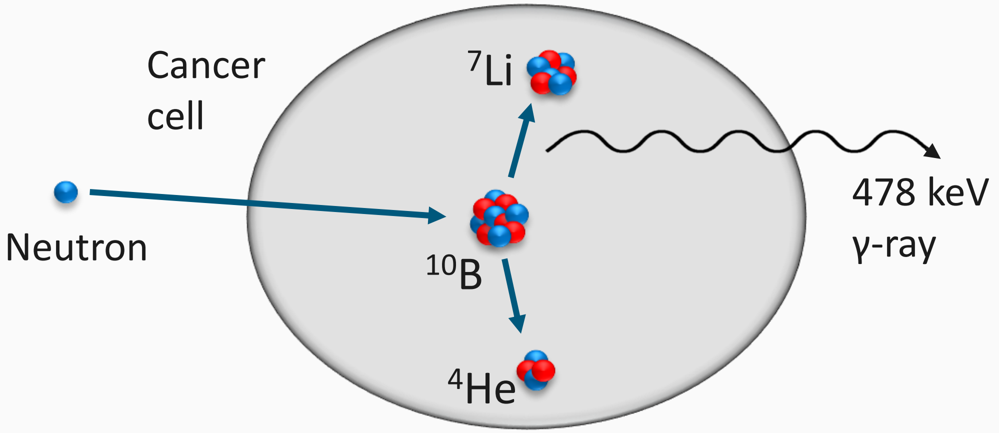
- Delivered dose could be inferred by imaging the production vertices of these gamma rays

- Imaging could be done with SPECT or Compton camera systems



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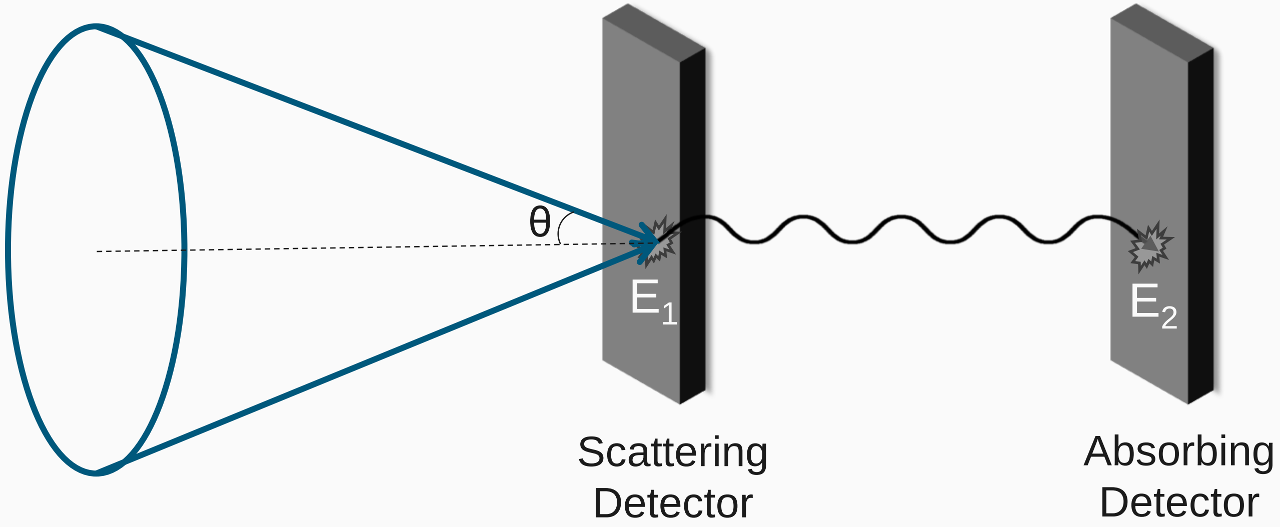
Compton Camera

- Combining axis between interaction points with scattering angle gives a **conical surface** from which the photon must have originated



$$\cos\theta = 1 - \frac{m_e c^2 E_1}{E_2(E_1 + E_2)}$$

Fig 2. Principle of operation of a Compton camera.

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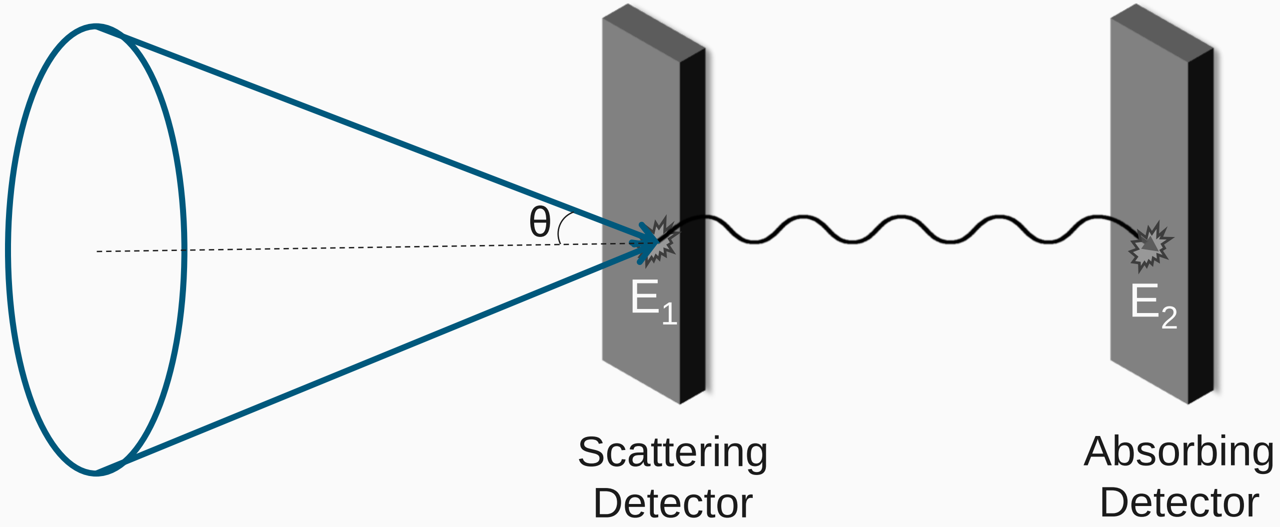

Fig 2. Principle of operation of a Compton camera.

$$\cos\theta = 1 - \frac{m_e c^2 E_1}{E_2(E_1 + E_2)}$$

★ No reliance on mechanical collimation

★ Higher possible camera efficiencies

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$LaBr_3$ Detector Array

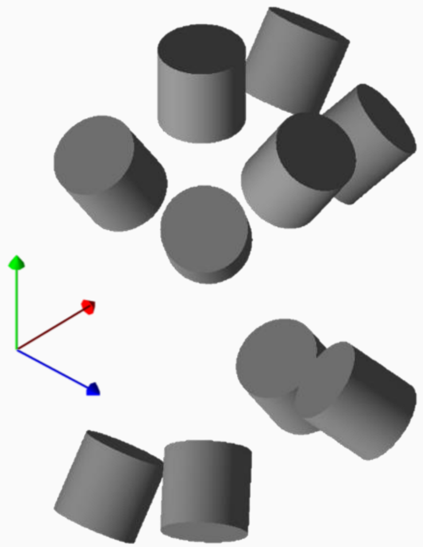

Fig 3. Original 10 detector array.

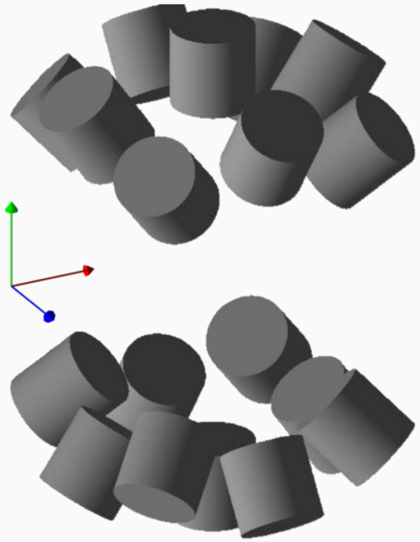

Fig 4. Extrapolated 18 detector array.

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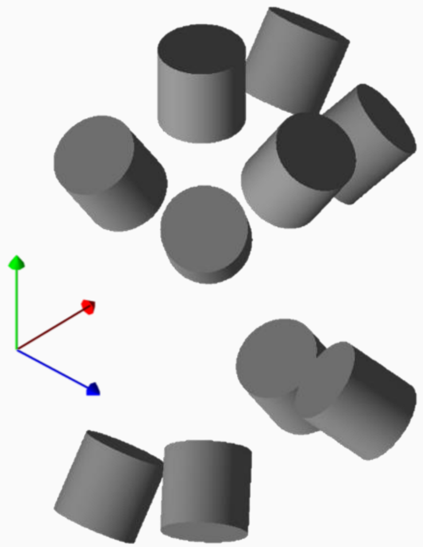
$LaBr_3$ Detector Array



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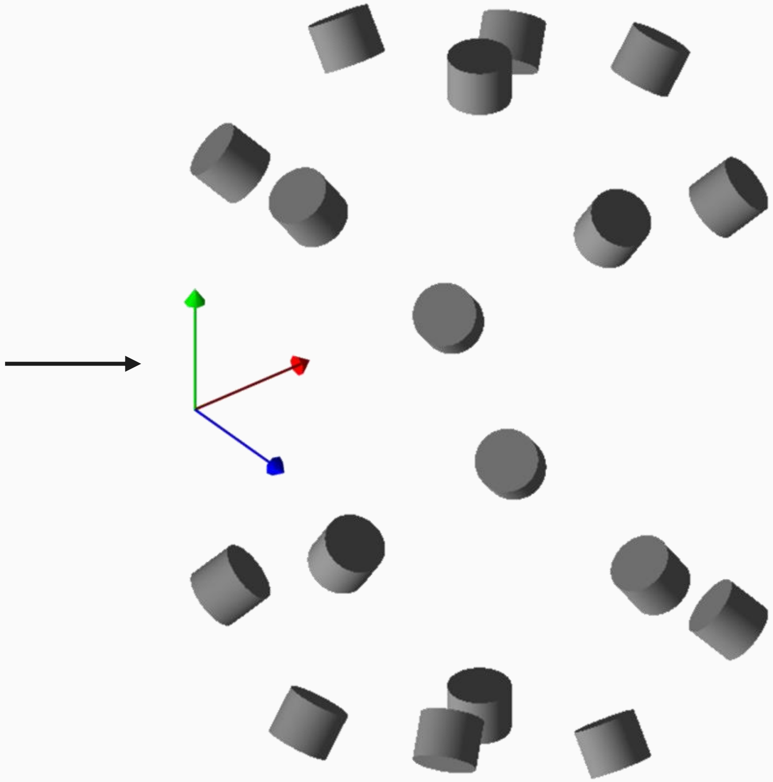
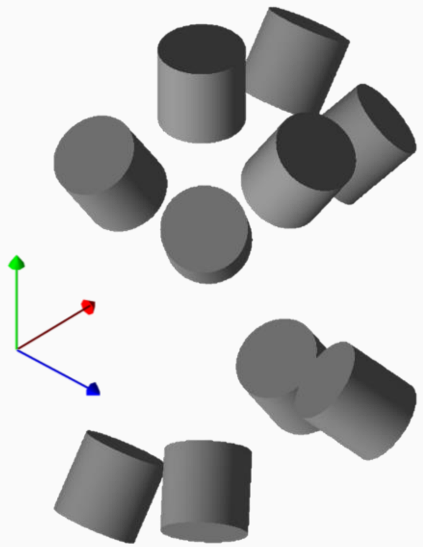


Fig 5. Extrapolated 18 detector array 30 cm from centre.

$LaBr_3$ Detector Array



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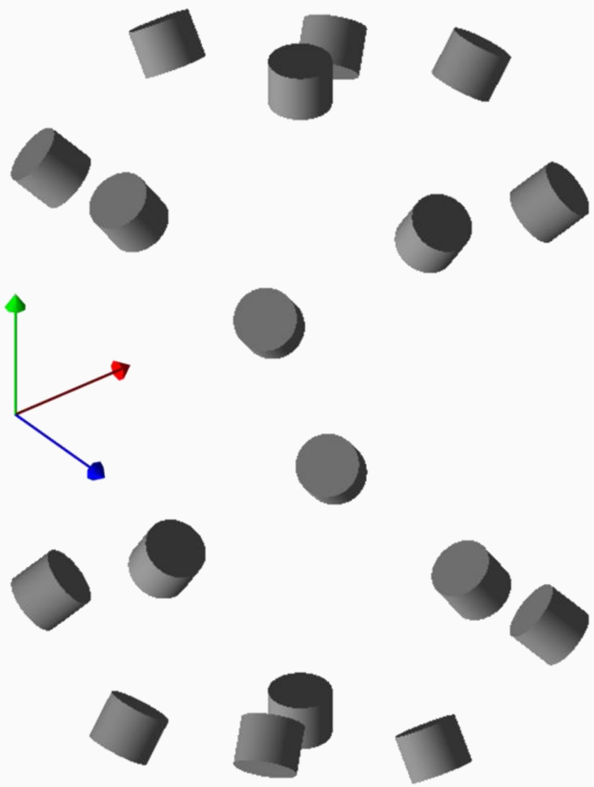

Fig 5. Extrapolated 18 detector array 30 cm from centre.

- Each detector can act as a scattering and absorbing detector

- Requires large angle scatters

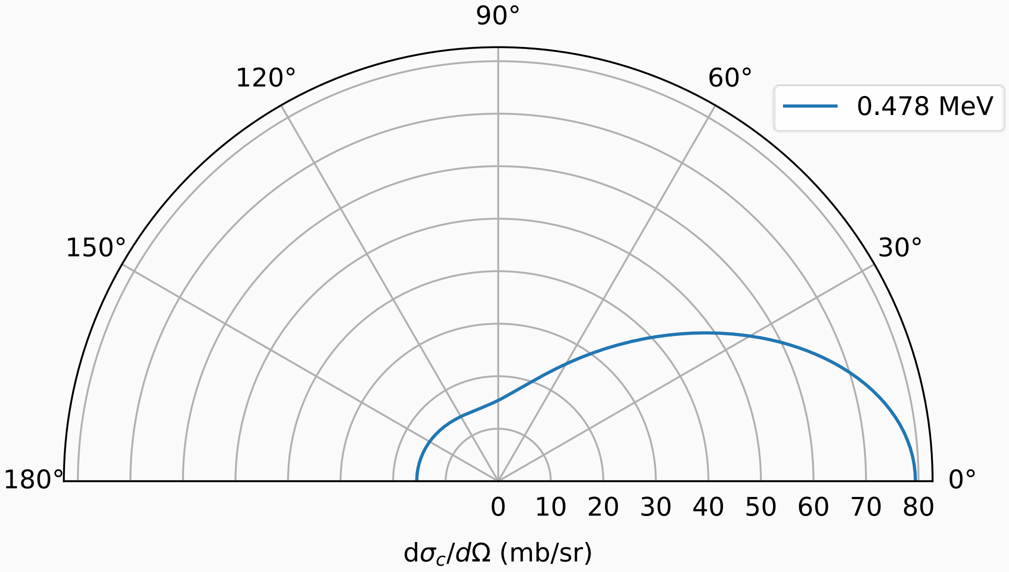

Fig 6. Klein-Nishina distribution for a 478 keV photon.

Modified Compton Camera Advantages

- Significantly increases the number of detection channels

Detection channel - a distinct pair of a scattering and absorbing detector.

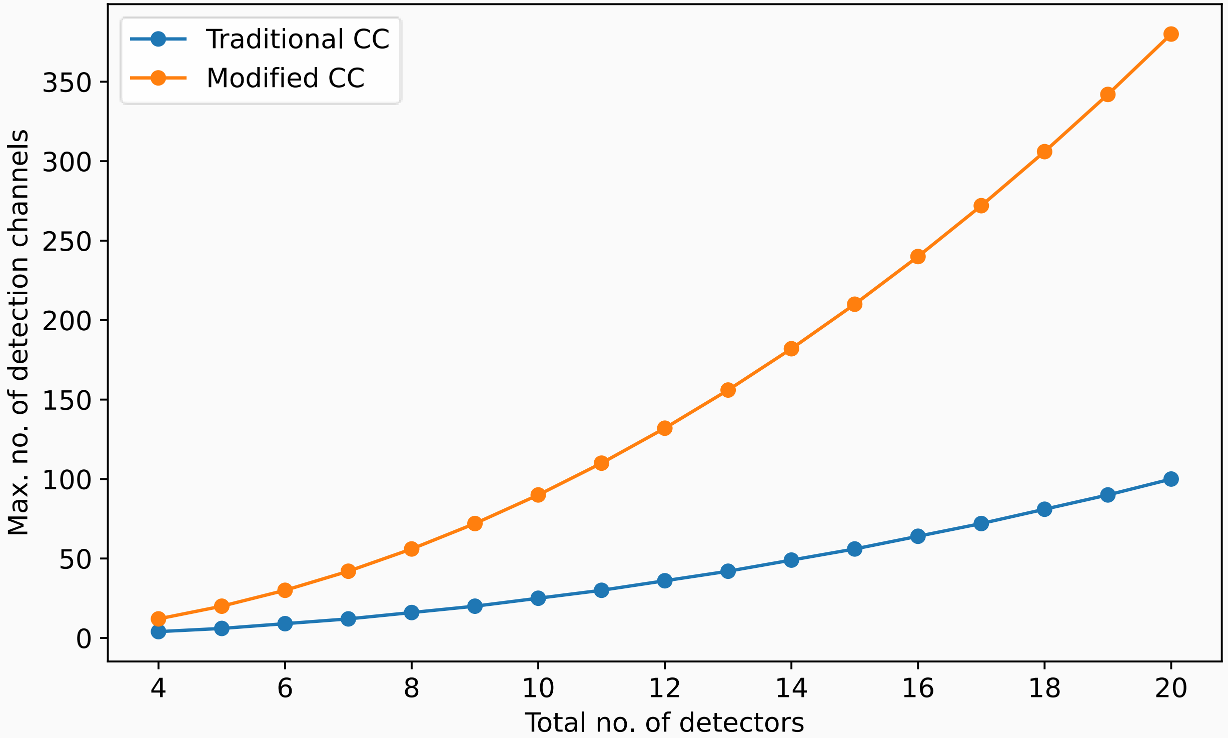

Fig 7. Maximum detection channels achieved when using a traditional and modified Compton camera design.

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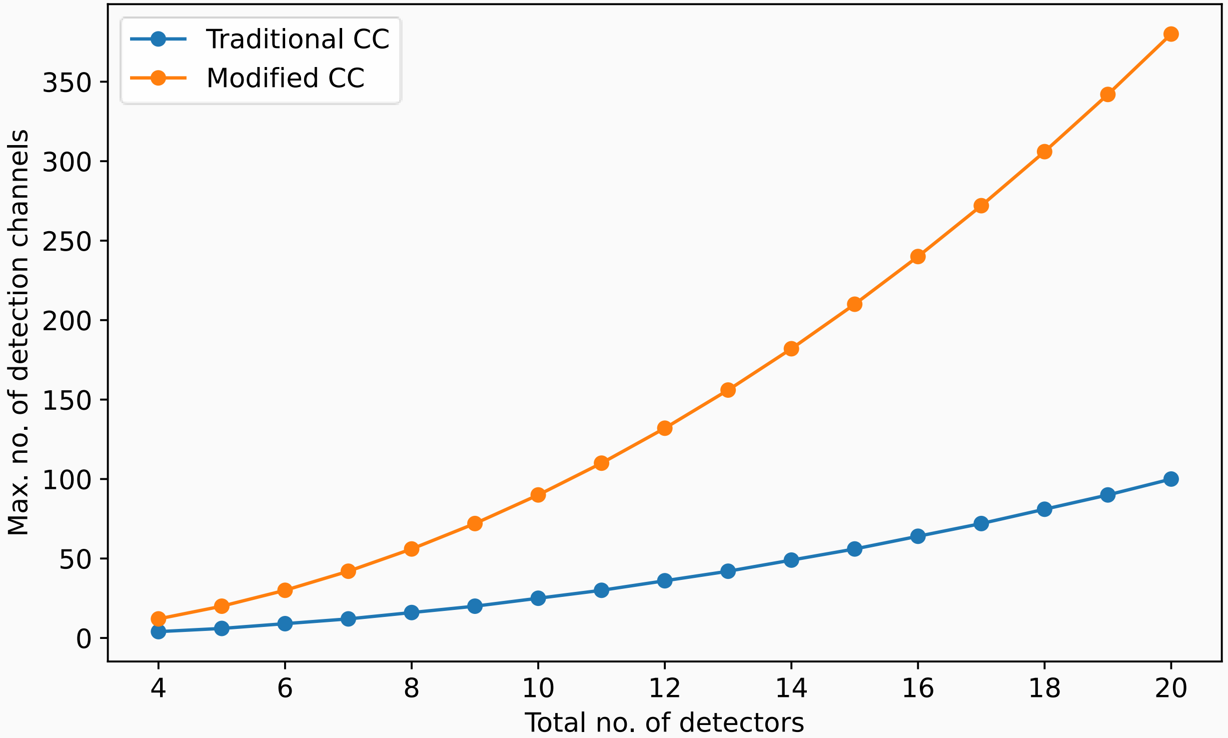
Modified Compton Camera Advantages

- Significantly increases the number of detection channels
- This increase helps to counteract lower scattering probability
- Greater variety of cones produced should improve spatial resolution

Detection channel - a distinct pair of a scattering and absorbing detector.



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Simulation Setup

- Initial testing and validation of detector response using 478 keV point source
- Then introduced neutron beam and phantom

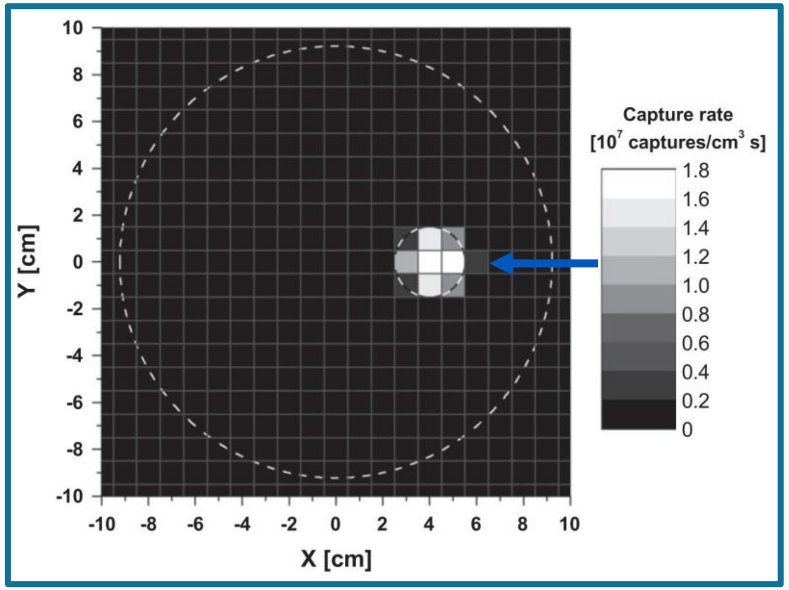

Fig 8. Tomographic image of boron neutron capture rate from Minsky et al [2].

- Tumour contained 400 ppm ^{10}B

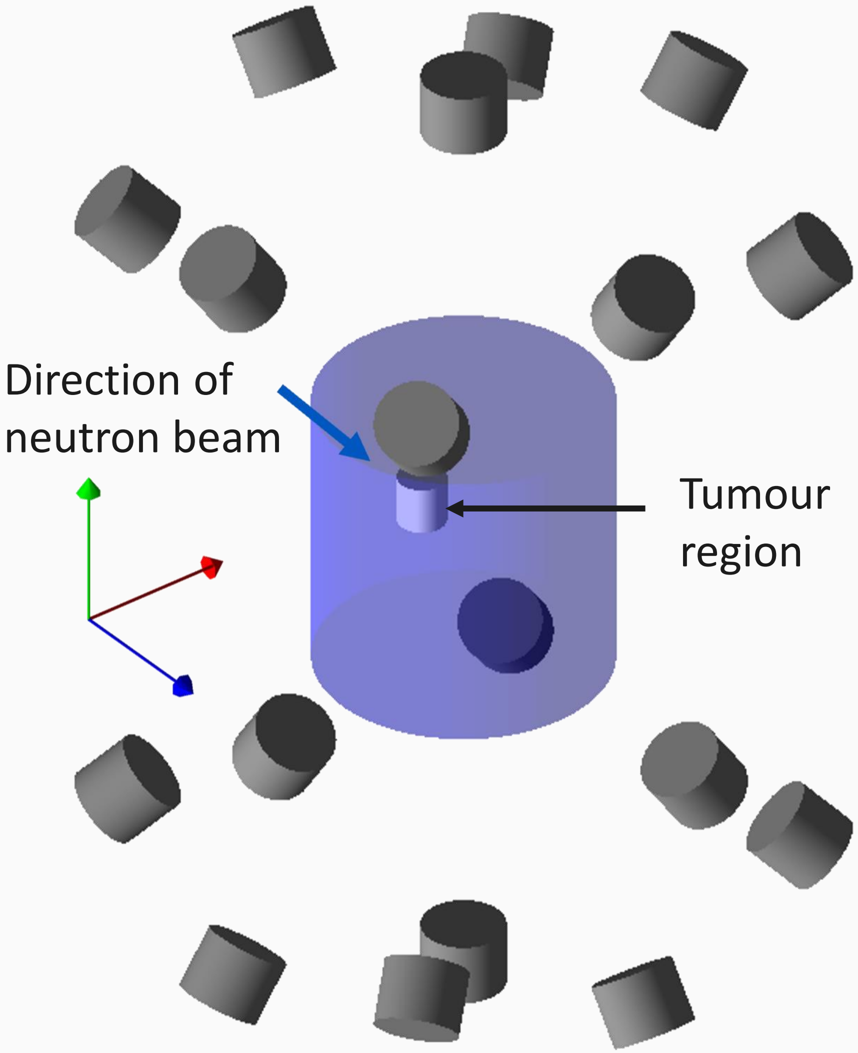

Fig 9. Visualisation of the phantom within the 18 detector array.

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[2] D. Minsky, A. Valda, A. Kreiner, S. Green, C. Wojnecki, Z. Ghani. First tomographic image of neutron capture rate in a BNCT facility, Appl. Rad. Iso. 69:1858-61 (2011).

Reconstructed Images of Phantom

- True source of the 478 keV photons extracted from simulation

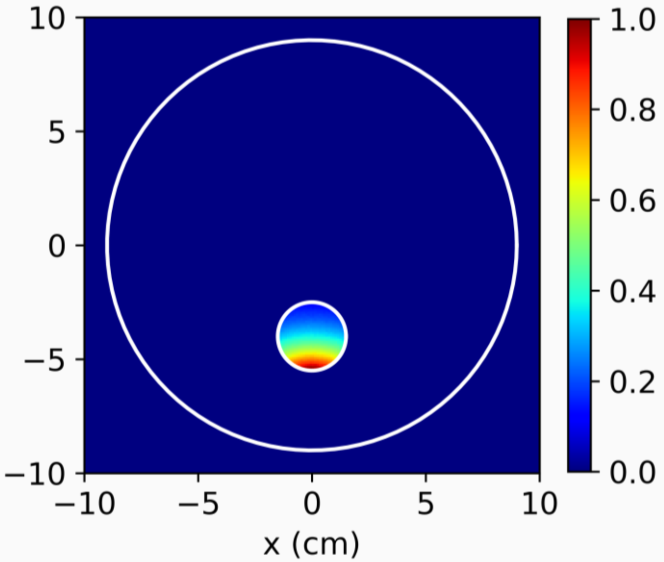

Fig 10. True distribution of the origin of the 478 keV photons.

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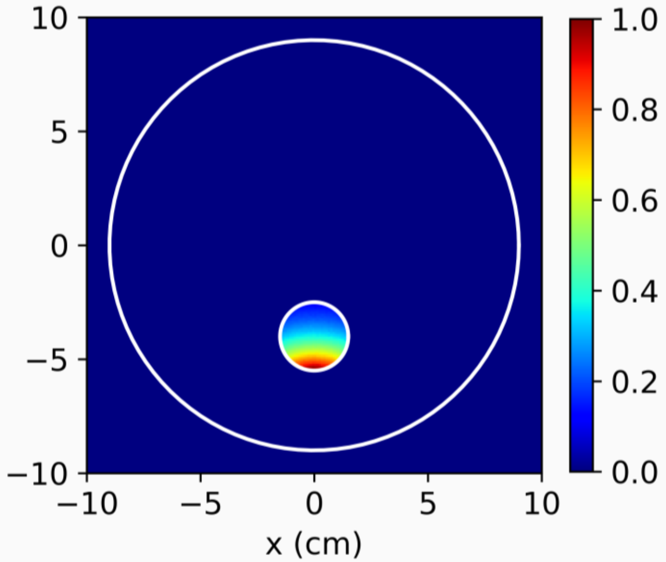
Reconstructed Images of Phantom

- True source of the 478 keV photons extracted from simulation
- Reconstructed image clearly highlights the tumour region – highest intensity at bottom edge
- 0.004% absolute efficiency
- Further study would be required to quantify spatial resolution



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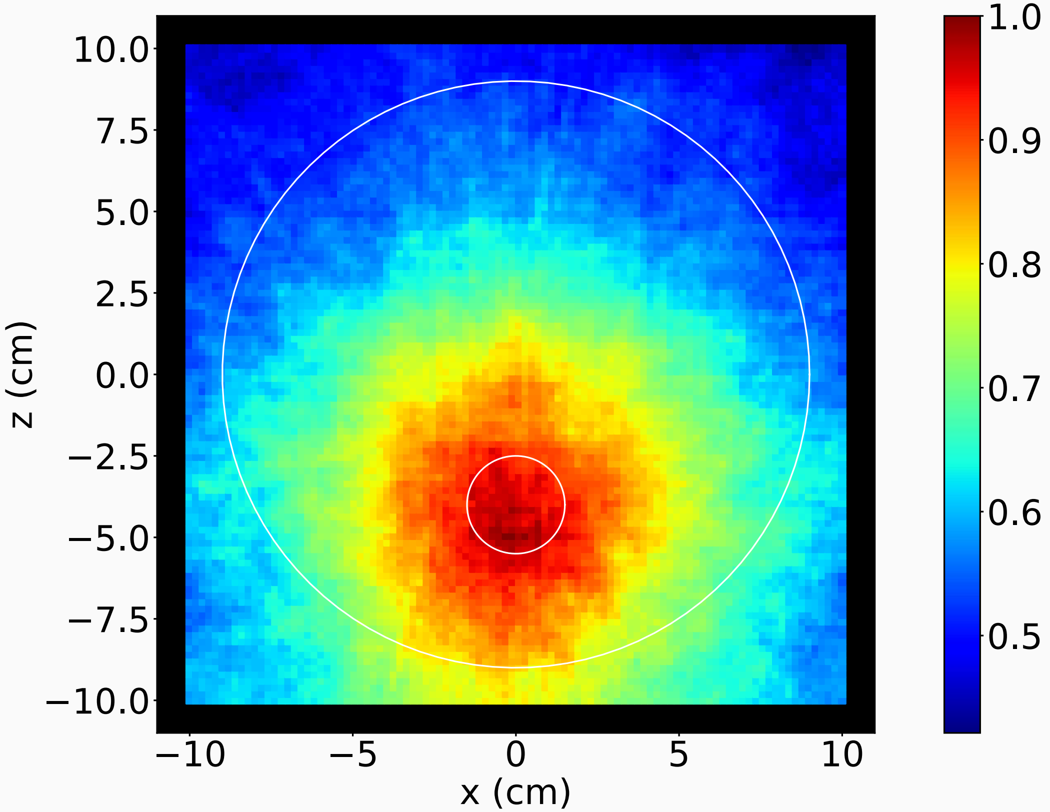

Fig 11. Reconstructed image of the origin of the 478 keV photons.

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Simulation ⟶ Experimental Work

- Simulation study published in February 2024

K. Nutter, T. Price, Tz. Kokalova, S. Green, B. Phoenix**. A feasibility study using an array of $LaBr_3$(Ce) scintillation detectors as a Compton camera for prompt gamma imaging during BNCT.** *Frontiers in Physics* 12, 2024.

- Publication also covered investigation into impact of shielding

- Experimental work to validate the overall camera performance in the simulation was **desirable**

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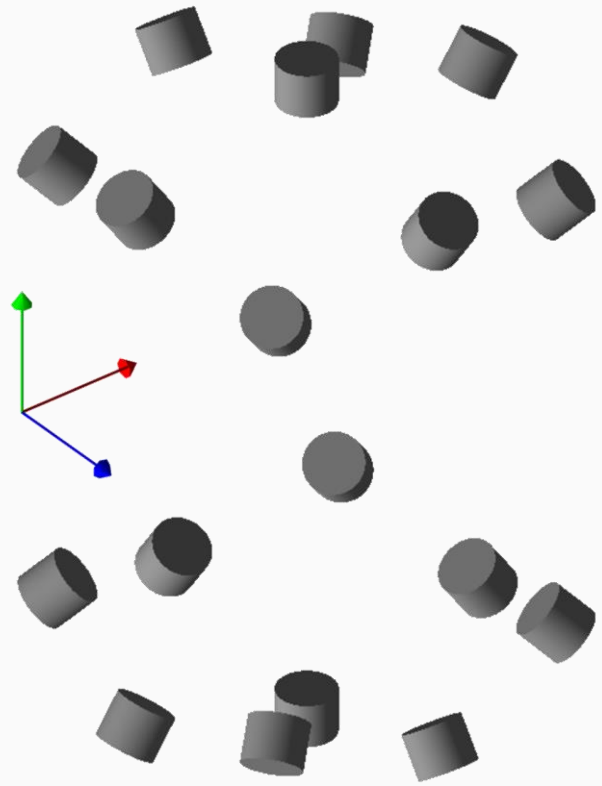
Experimental Setup

- Array of 10 $LaBr_3$ detectors available



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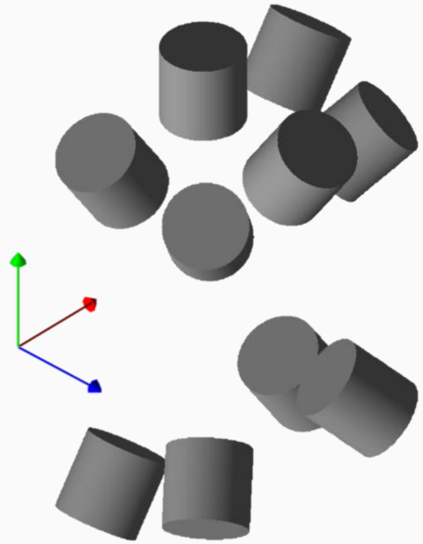

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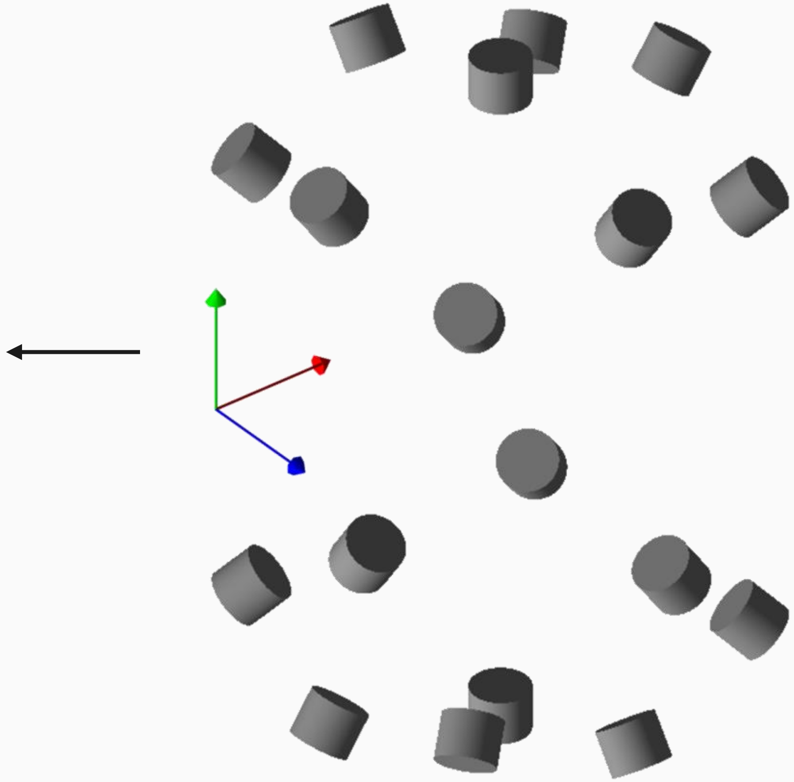

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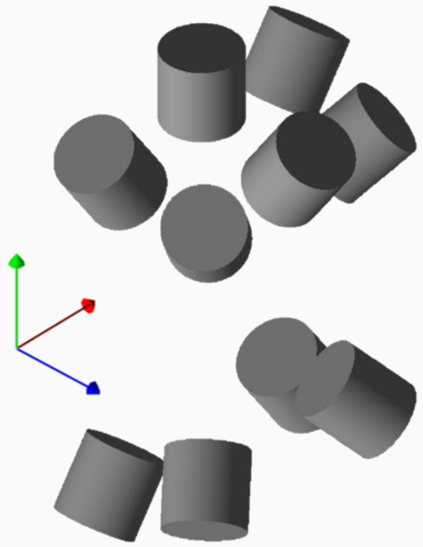

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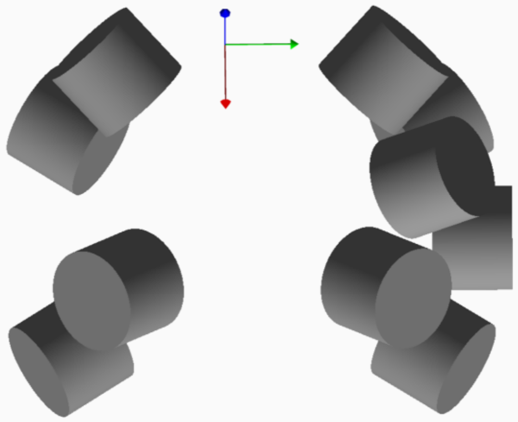

Fig 12. Rotated 10 detector array.

Fig 13. Photograph of the experimental setup of the 10 detector array.

- All tests used ^{137}Cs as the source

Experimental Results – 1 Central Source

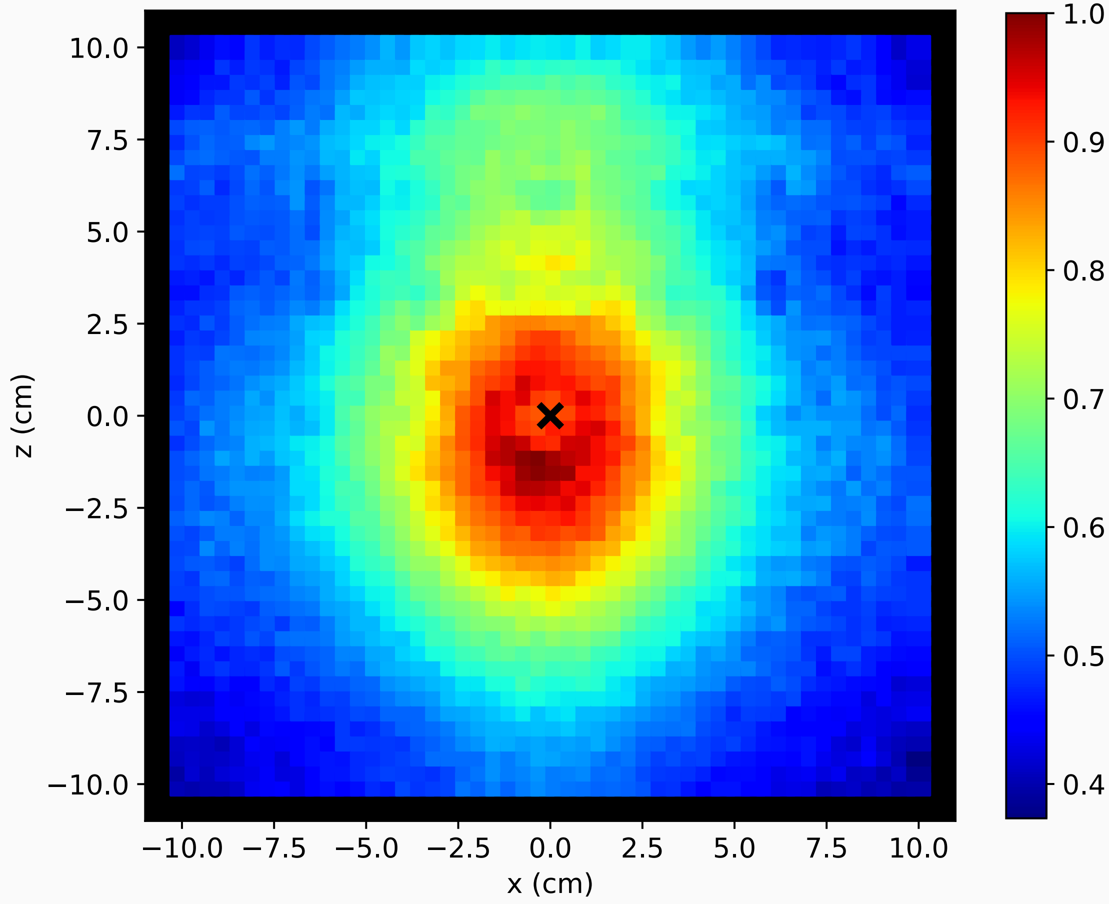

Fig 14. **Simulation image** of a central 662 keV point source. Image displays the XZ plane at y = 0

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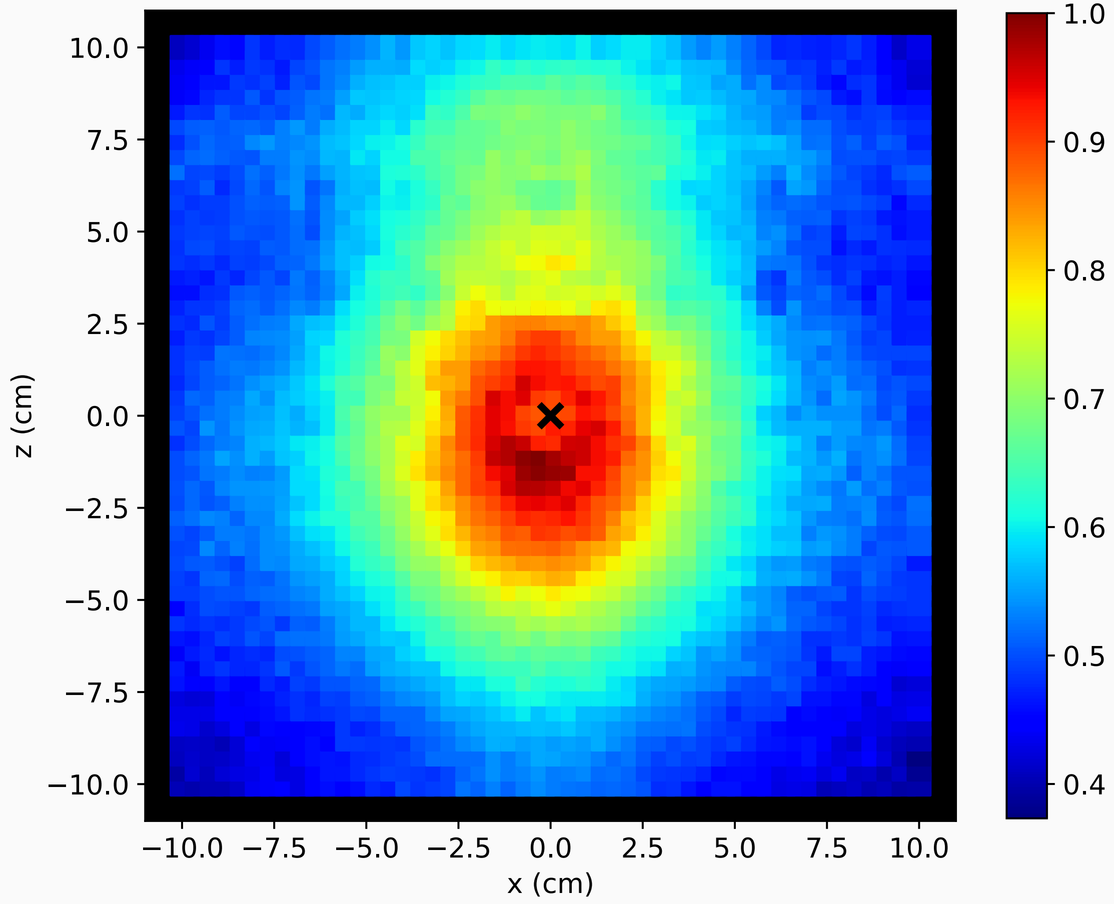
Experimental Results – 1 Central Source



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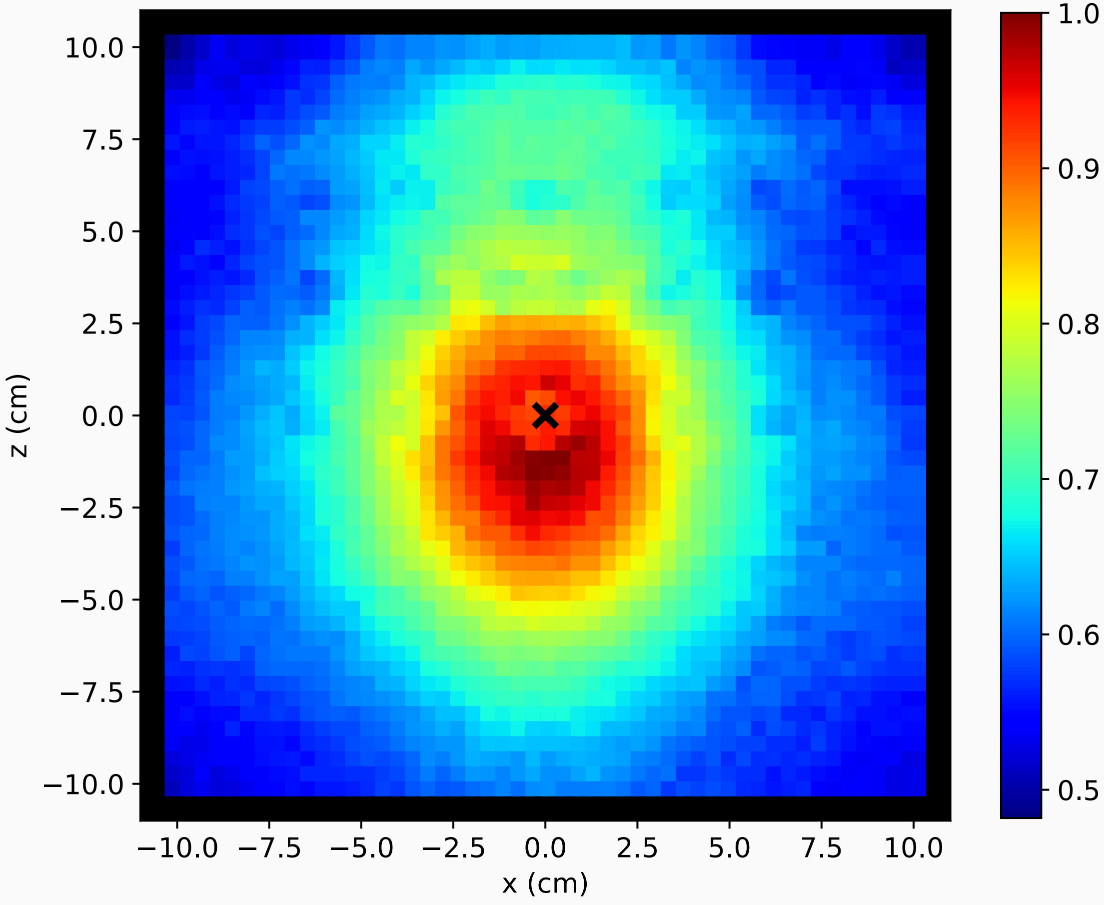

Fig 15. **Experimental image** of a central 662 keV point source. Image displays the XZ plane at y = 0

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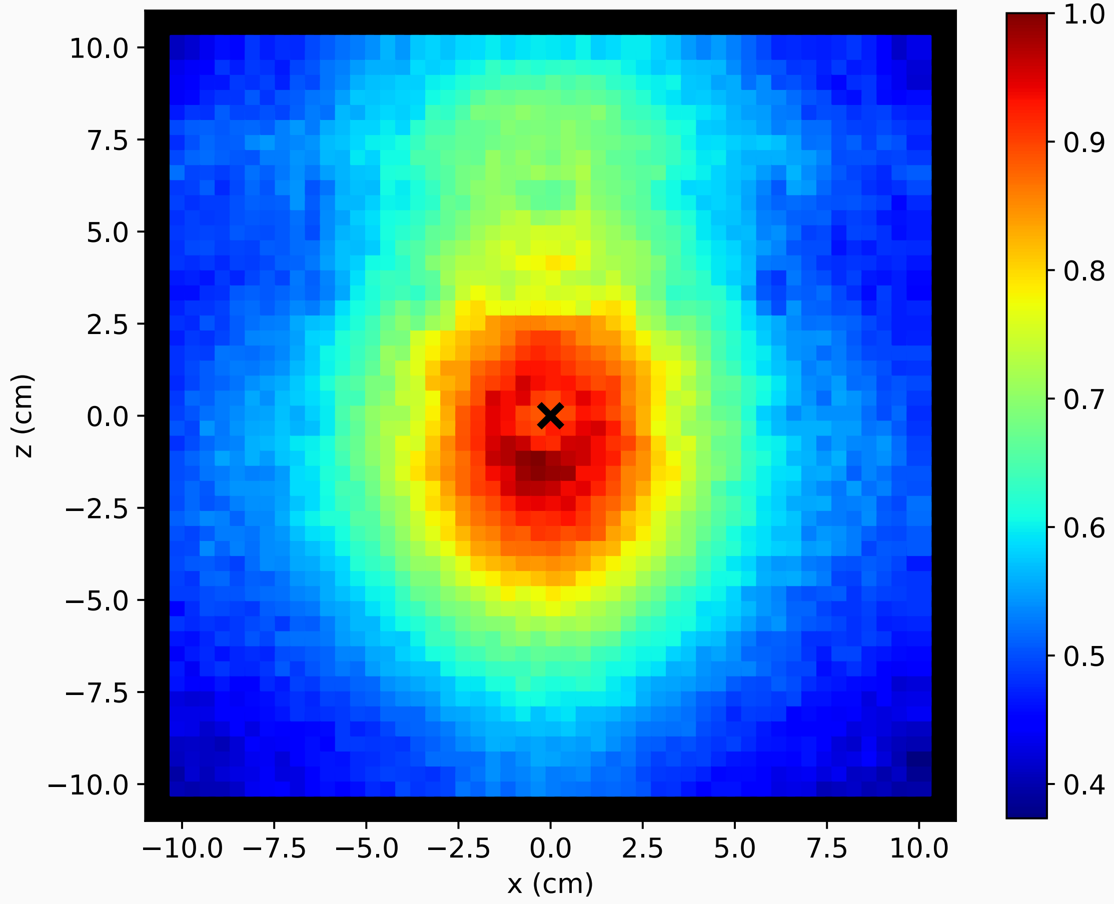
Spot the Difference!



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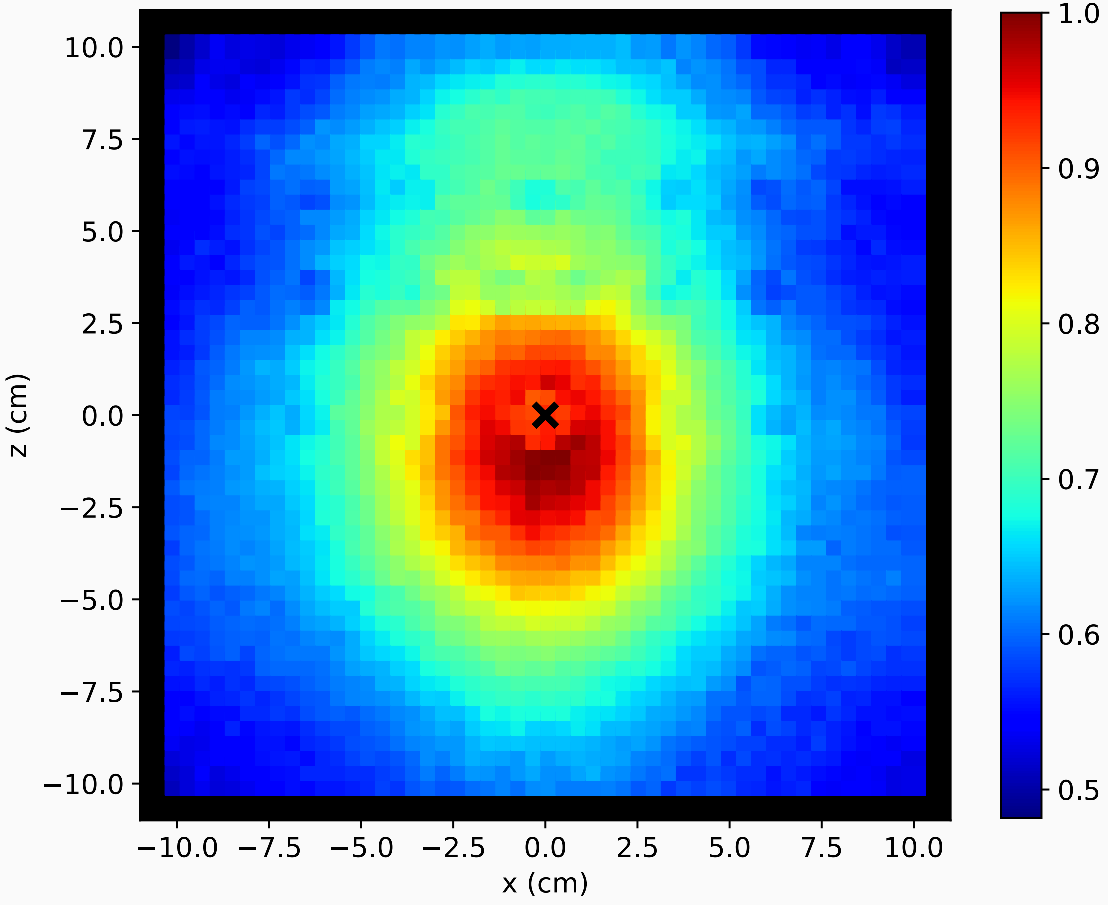

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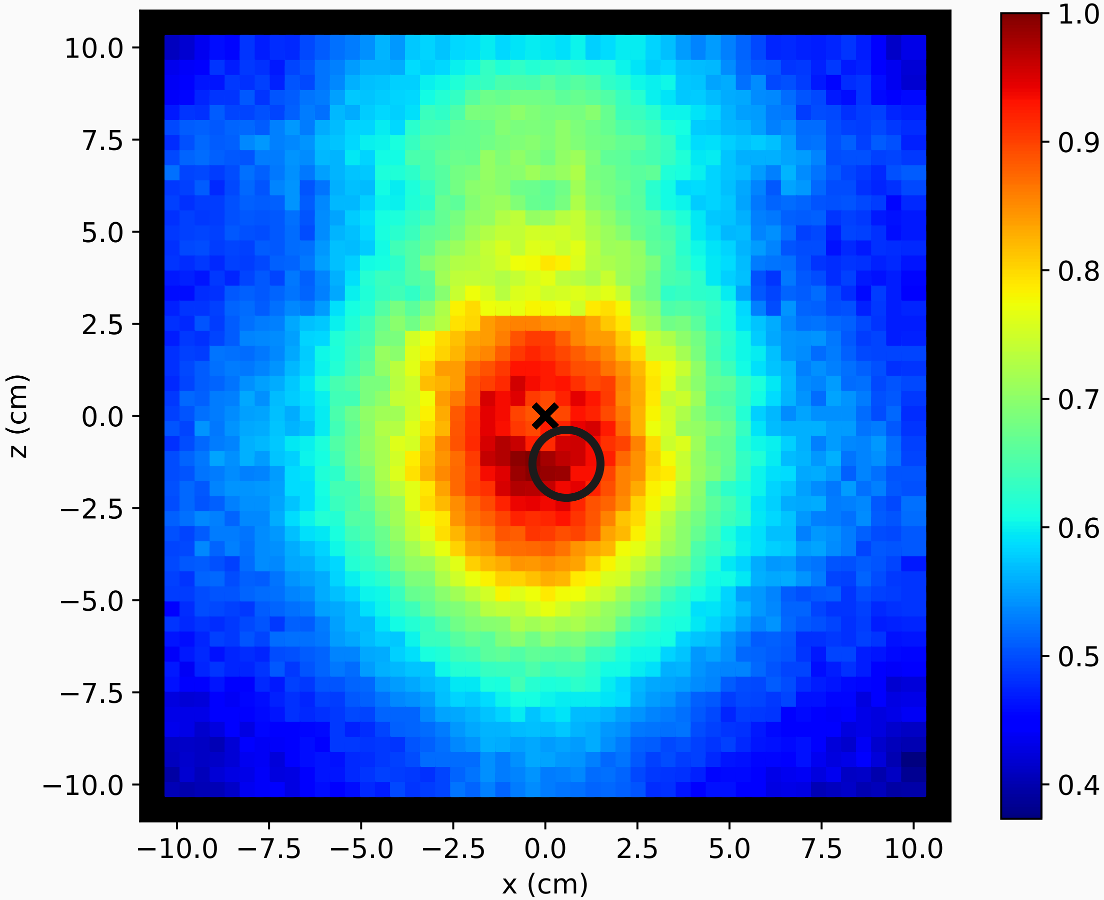

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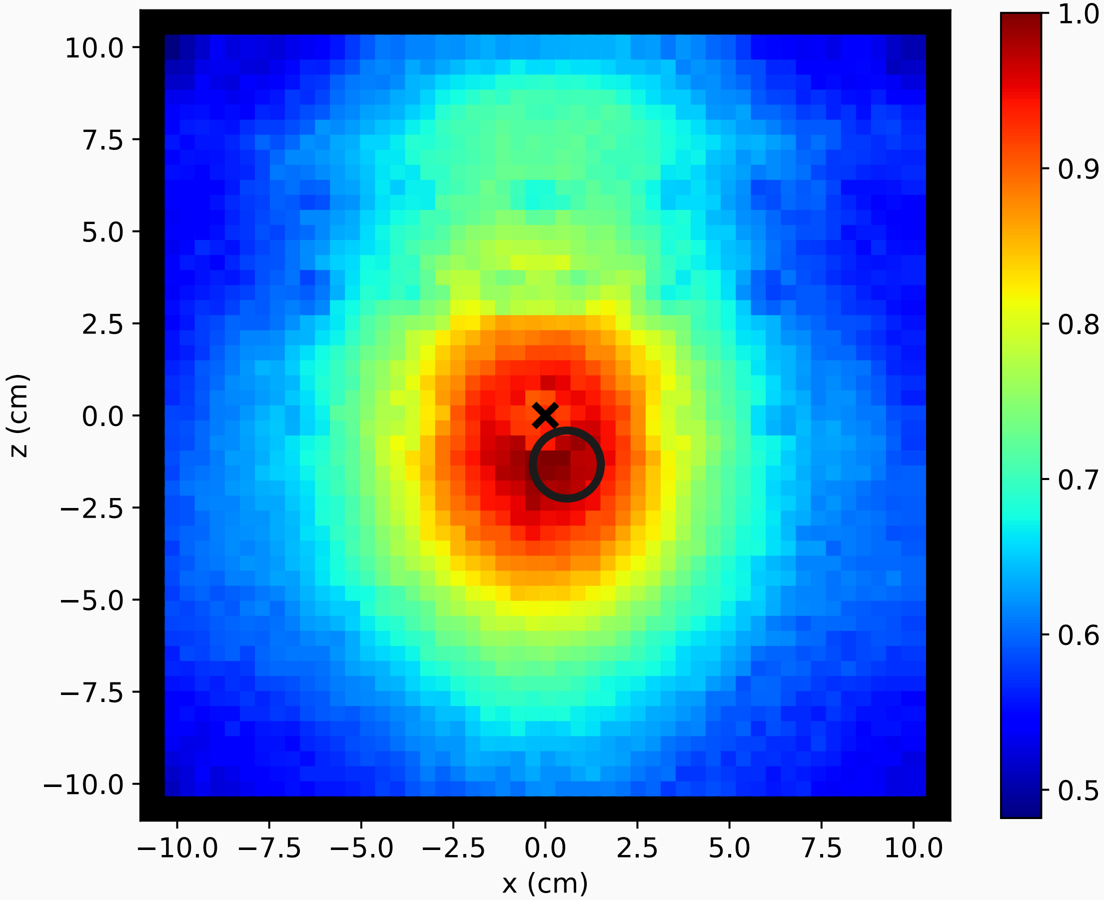

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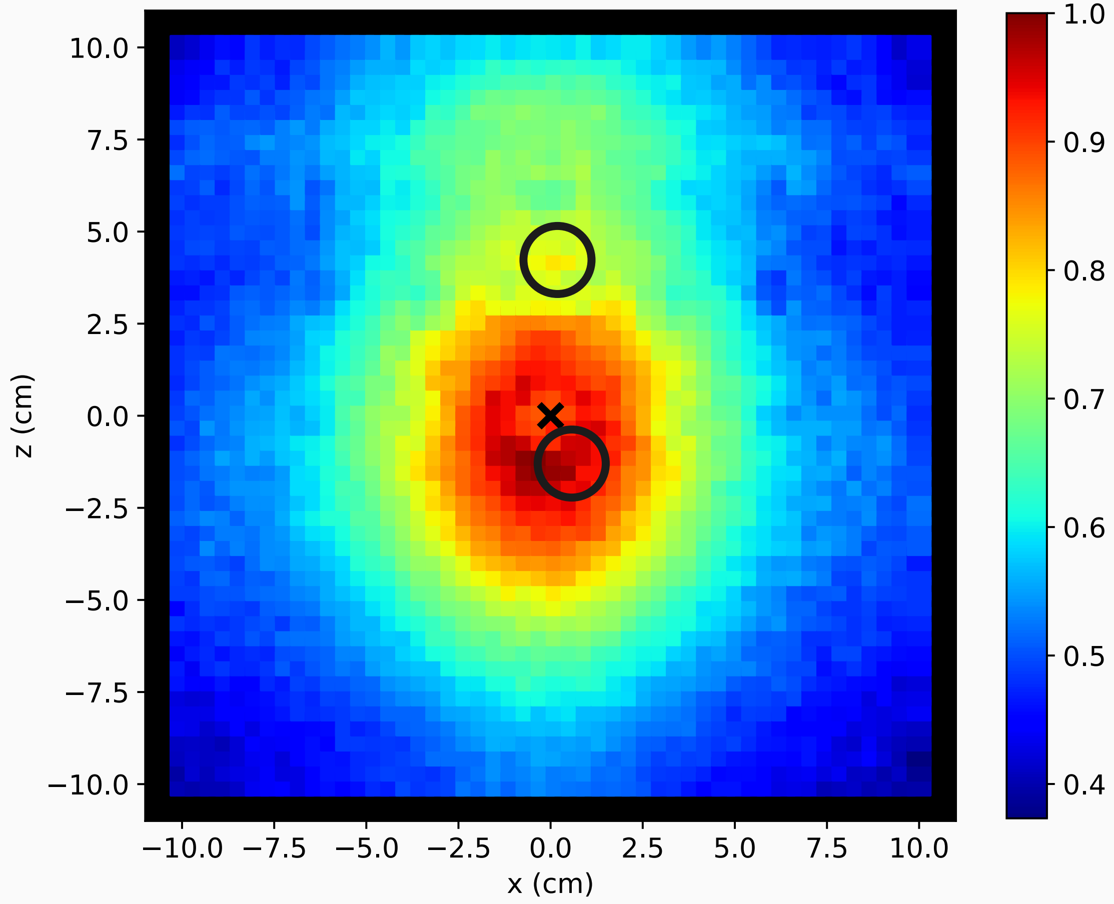

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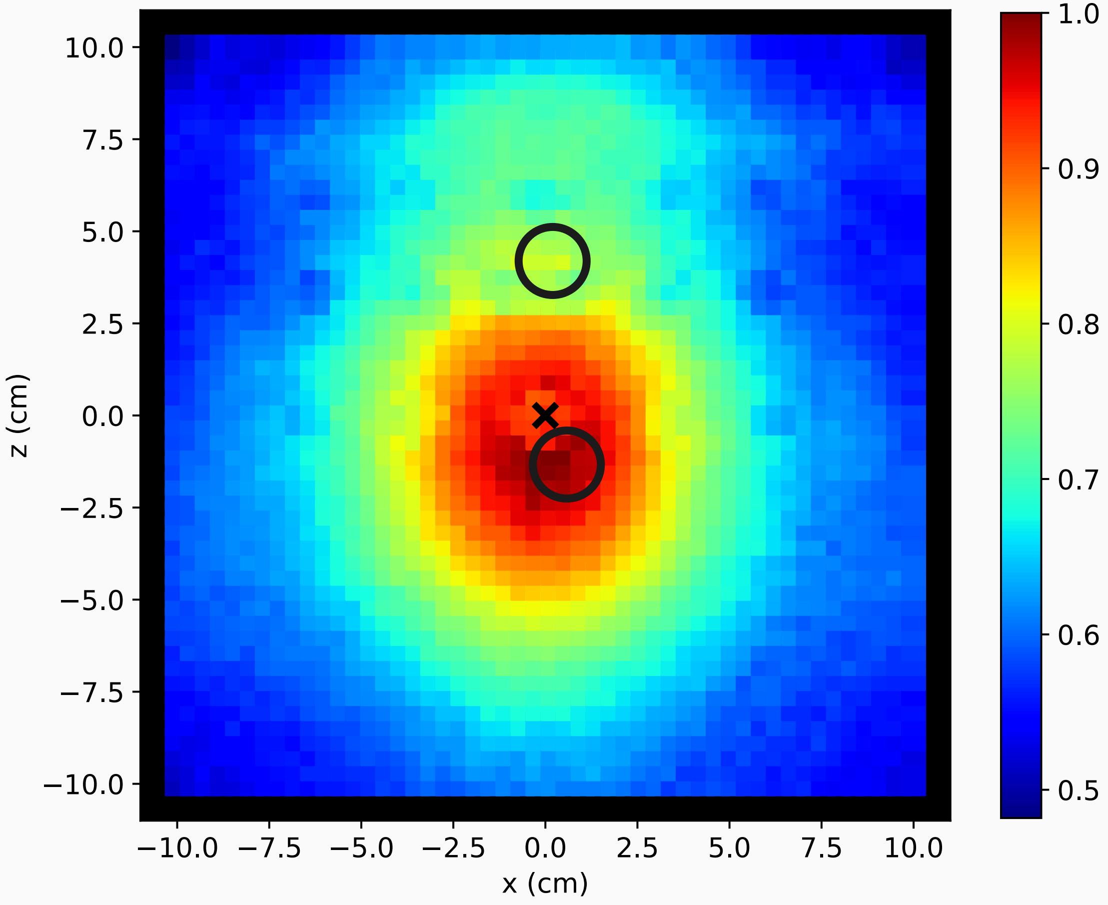

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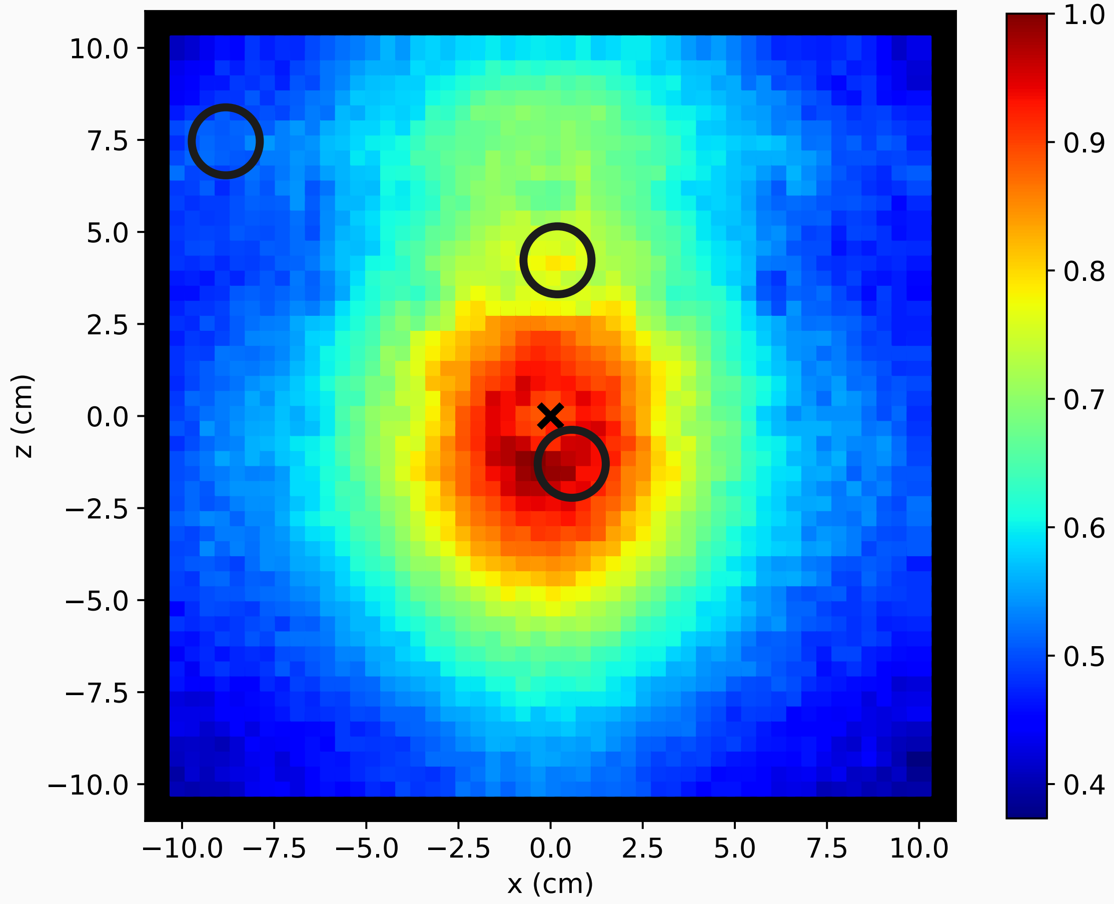

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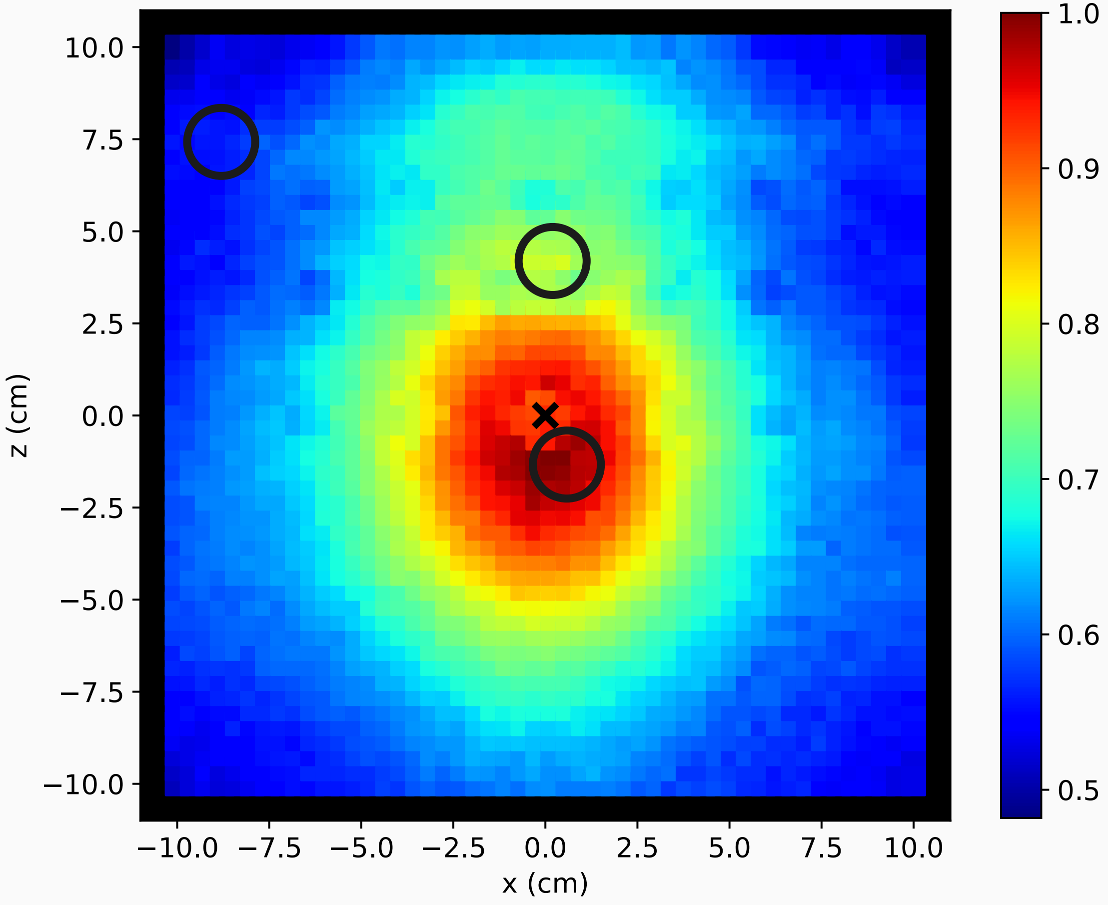

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Experiment vs. Simulation – 1 Central Source

- The percentage difference for every pixel in the image can be found

- Provides **quantitative measure** of similarity between simulation and experimental images

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- Provides **quantitative measure** of similarity between simulation and experimental images

- Around the source location difference is < 5%

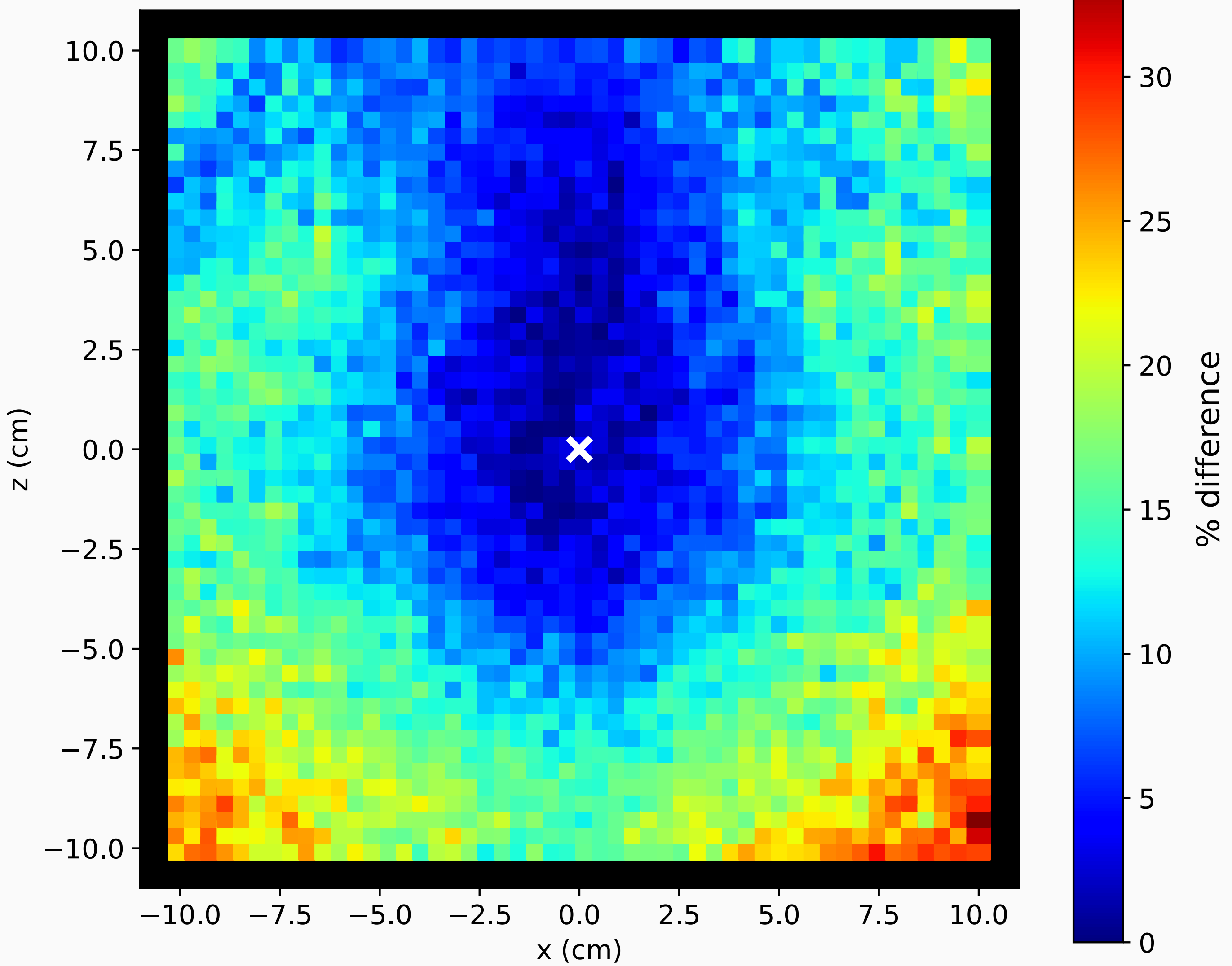

Fig 16. The **percentage difference** between the simulated and experimental images of **the central source** for each pixel in the plane.

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Experimental Results – Two Sources

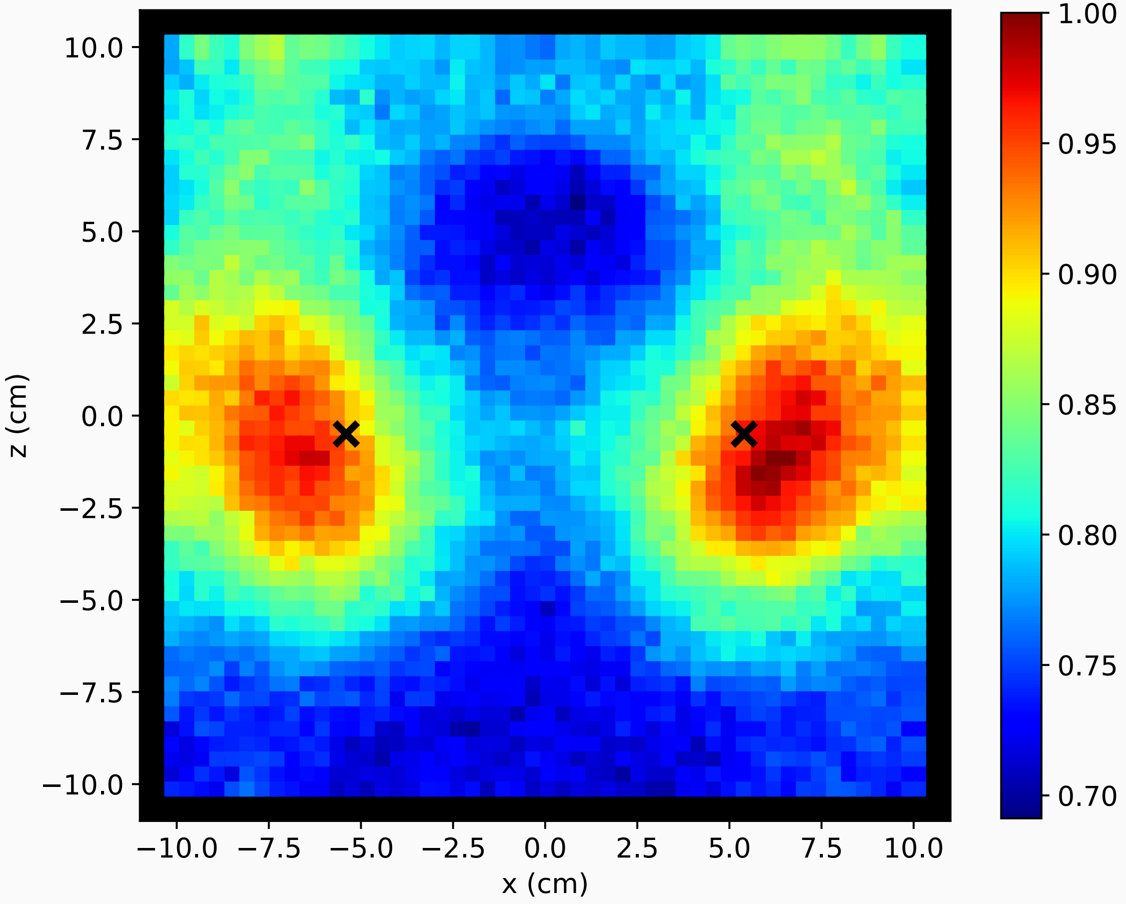

Fig 17. **Simulation image** of dual 662 keV point sources. Image displays the XZ plane at y = 0

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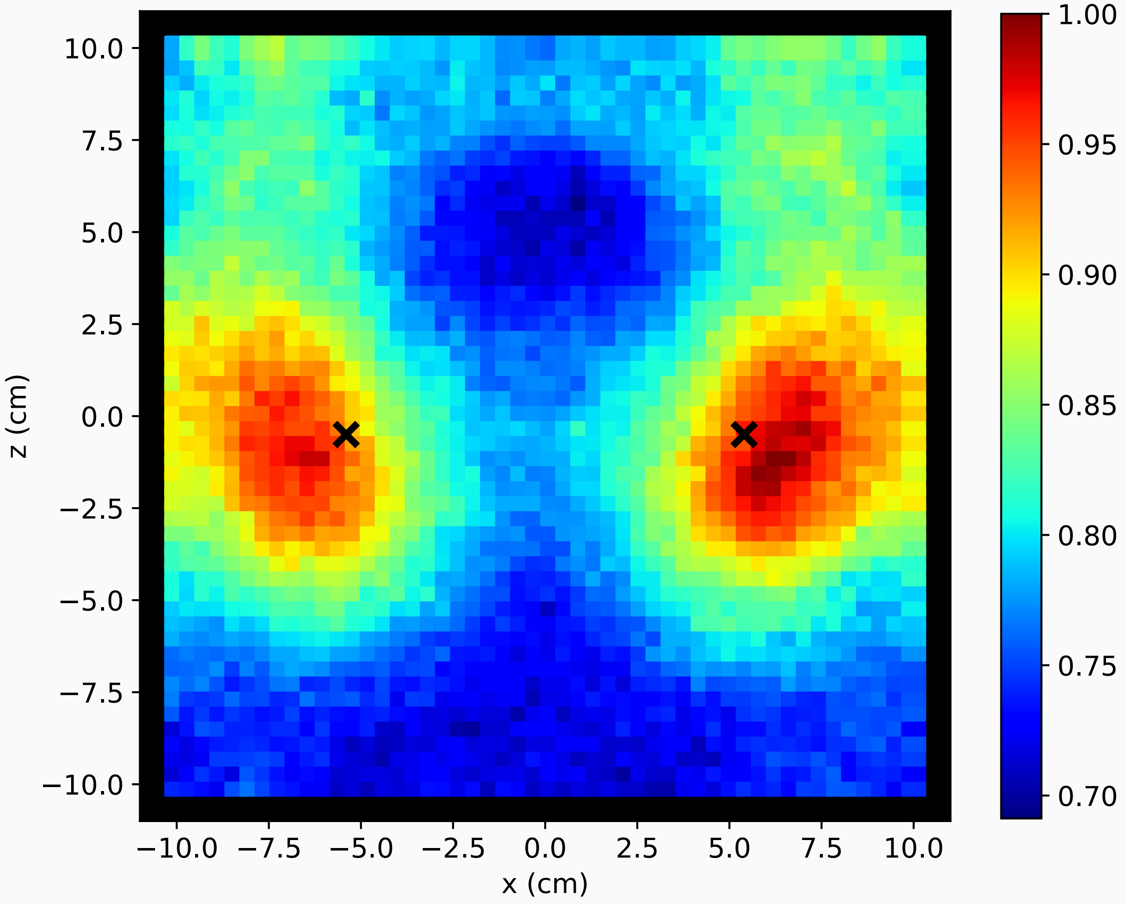
Experimental Results – Two Sources



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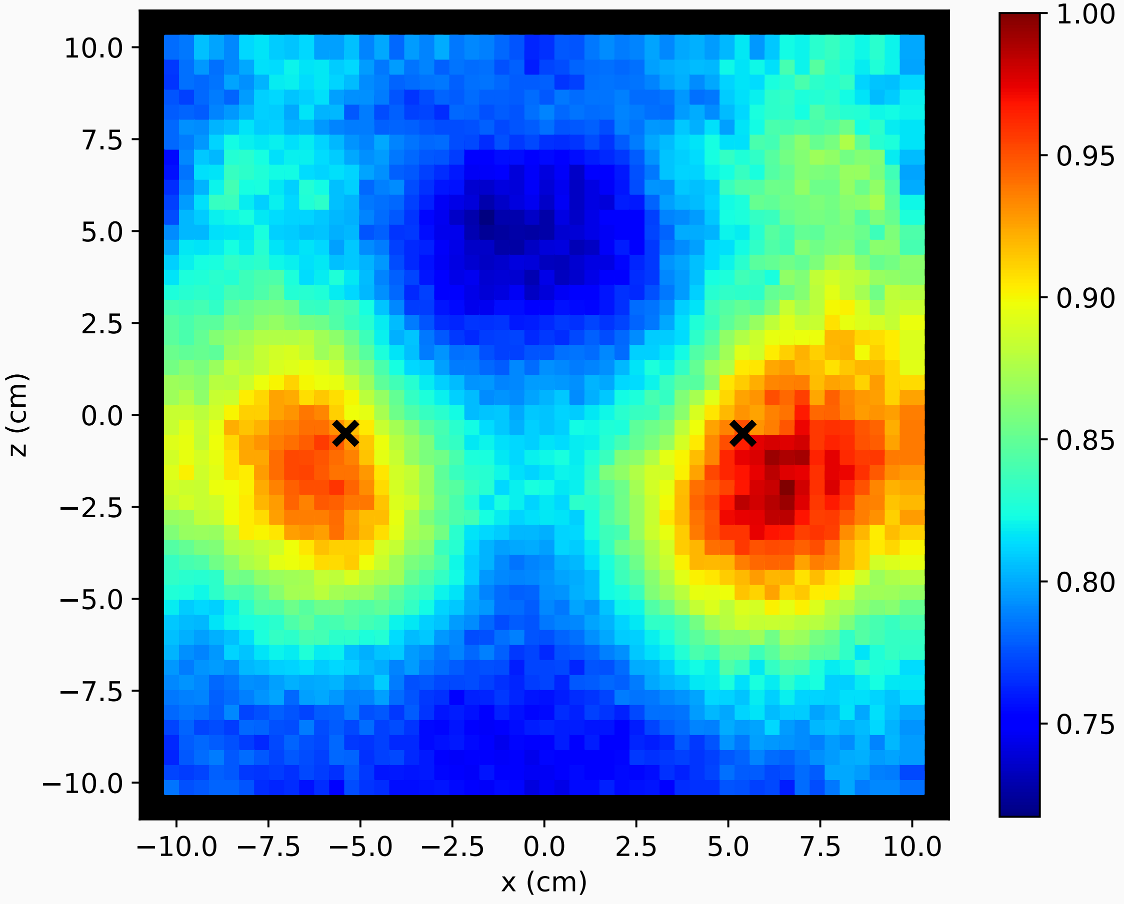

Fig 18. **Experimental image** of dual 662 keV point sources. Image displays the XZ plane at y = 0

Experiment vs. Simulation – Two Sources

- Again generally < 5% difference around the source locations

★ **Clear validation that the simulation behaves very similarly to the physical setup!**

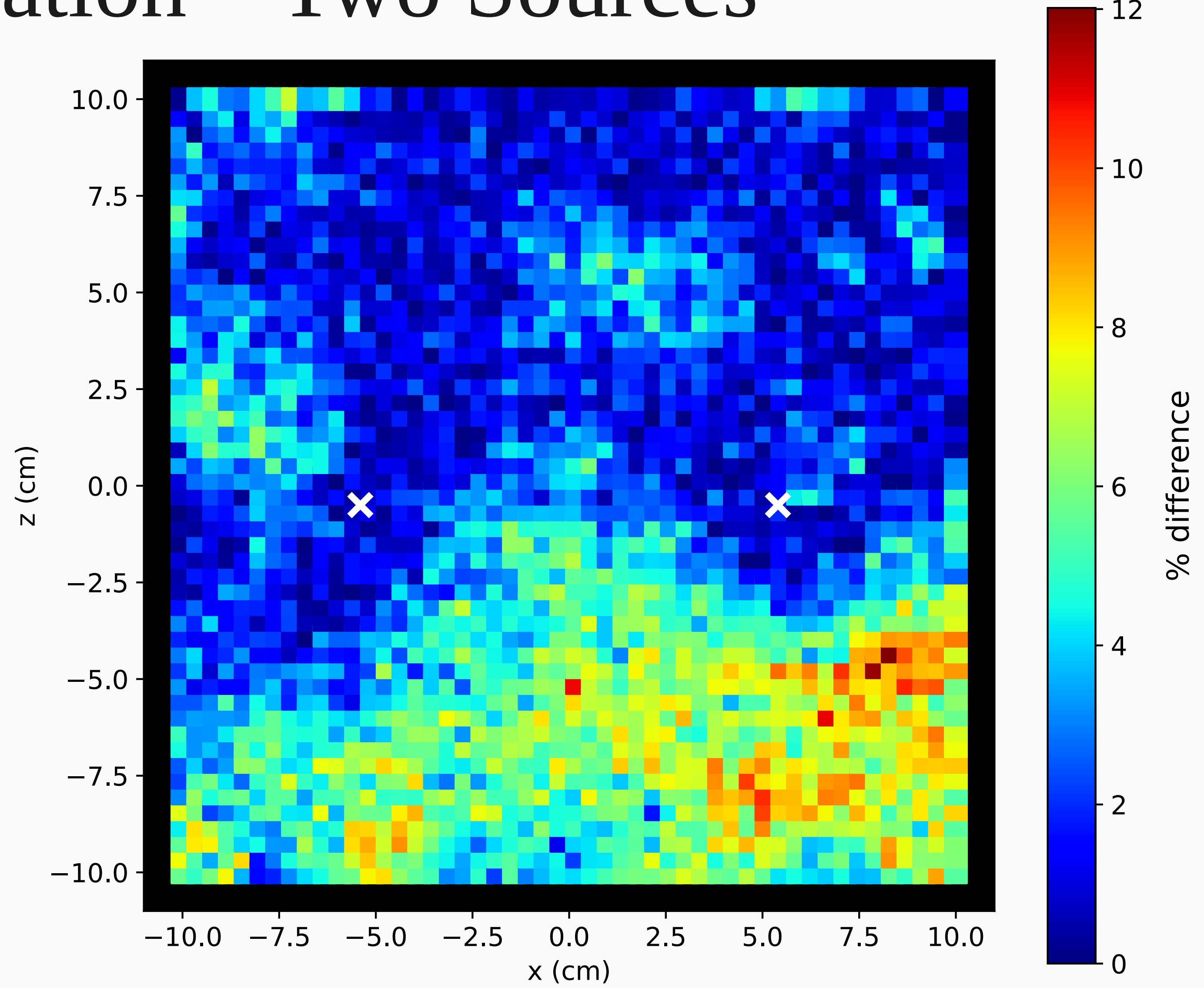

Fig 19. The **percentage difference** between the simulated and experimental images of **the dual sources** for each pixel in the plane.

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Summary

- BNCT provides alternative cancer therapy with both biological and physical targeting of the tumour
- Dosimetry is challenging, but prompt gamma imaging could offer an online method

- **Simulation study using Geant4 showed feasibility of using a modified Compton camera design for prompt gamma imaging during BNCT**

- **Experimental work to validate the simulated camera performance demonstrated a very good agreement between simulation and experiment**