NuSec Collaboration Grant 2022
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Neutron and X-ray imaging in extreme environments

Christopher D Murphy
York Plasma Institute
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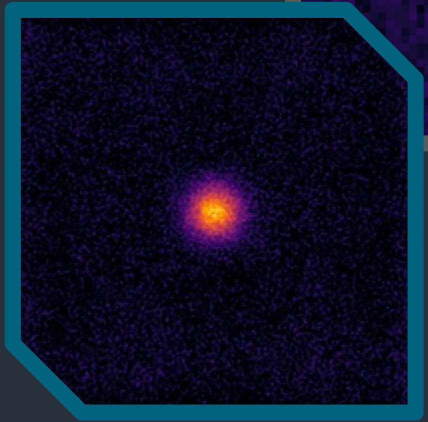

Contributors

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University of Michigan, USA

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- D. N. Fittinghoff

Los Alamos National Labs, USA

- P. L. Volegov

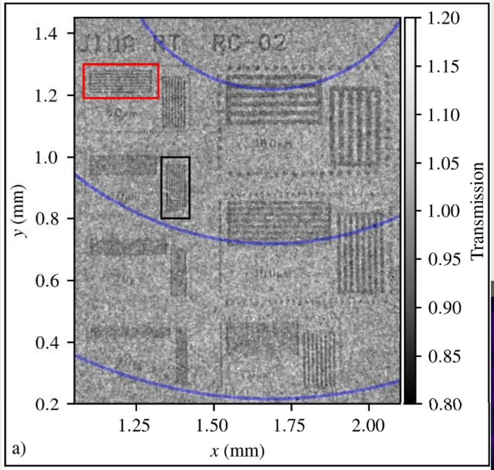
Scitech Precision, UK

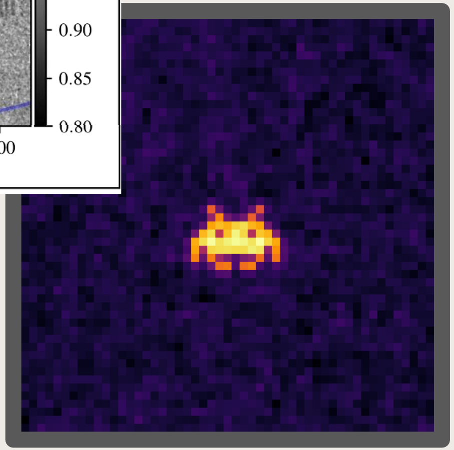
- C. Spindloe

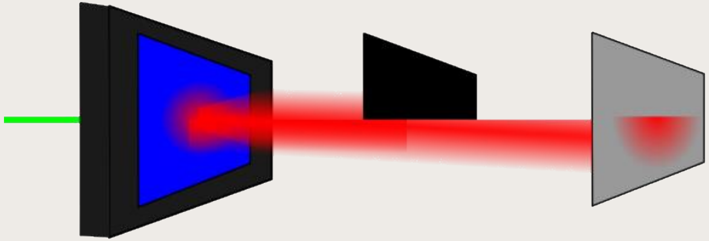
**: Now at LLNL

Talk will cover two main topics:

- Generation of laser-based x-ray sources…
  - …and how to image them: the 'CASPA'
- Extension to fusion neutrons
  - The NuSec Grant

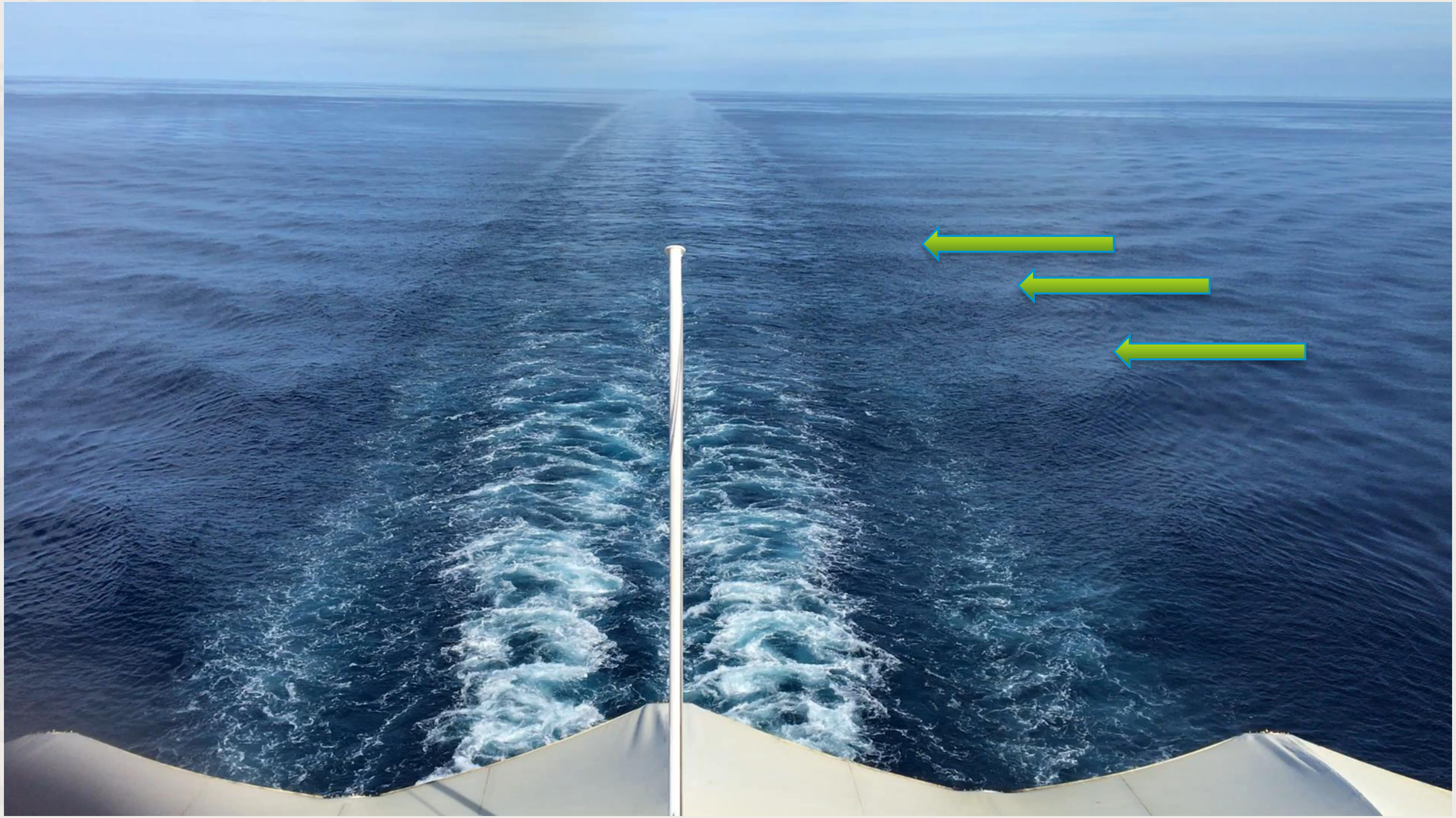




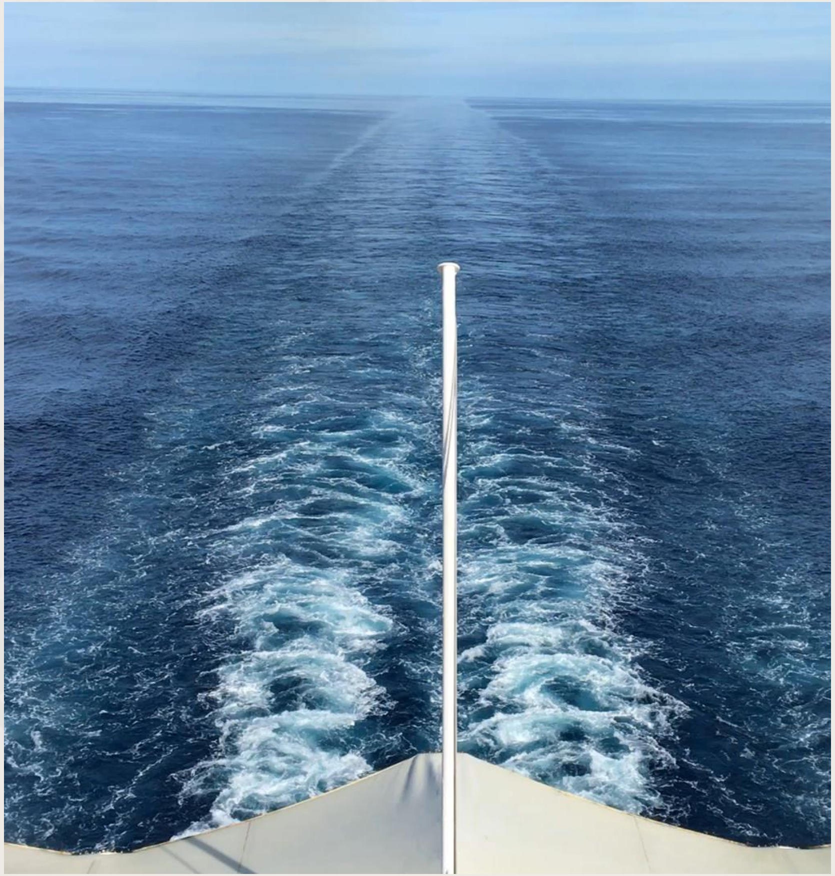


What has laser-plasma physics got to do with NuSec?

Wakefields

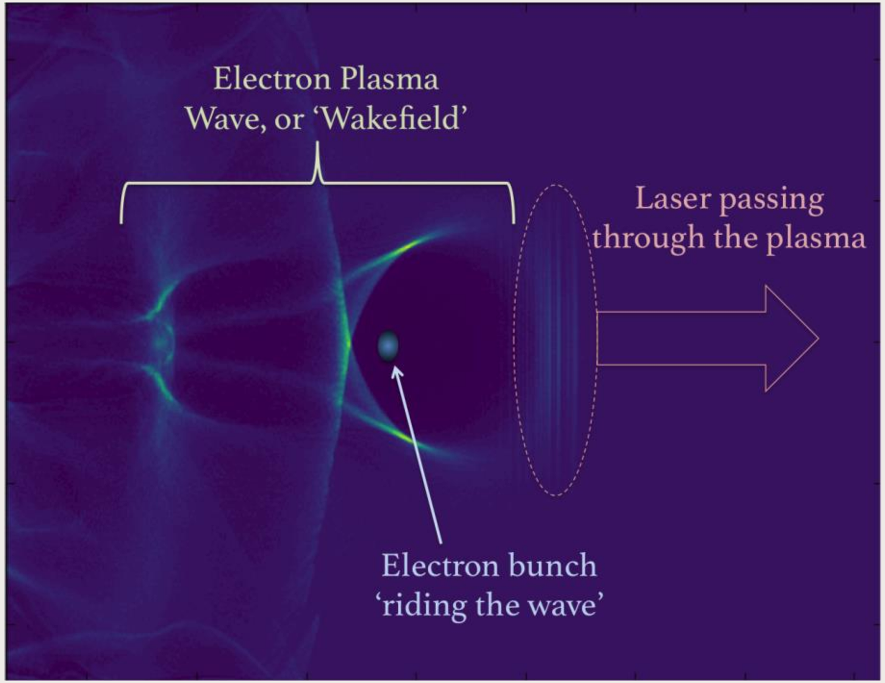


Laser Plasma Wakefields



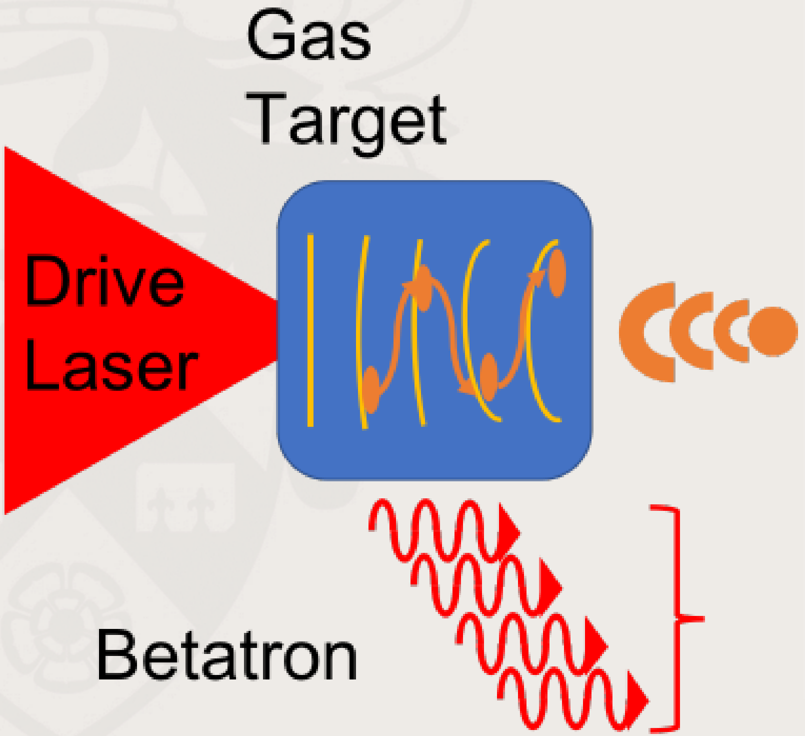
Laser Wakefield Accelerators (LWFA): why would you want to…

- No breakdown limit:
  - High Fields = small accelerator.
- Spatial scale comparable to the laser focus:
  - Micrometer-scale beams.
- Temporal scale comparable to the laser:
  - fs bunches.

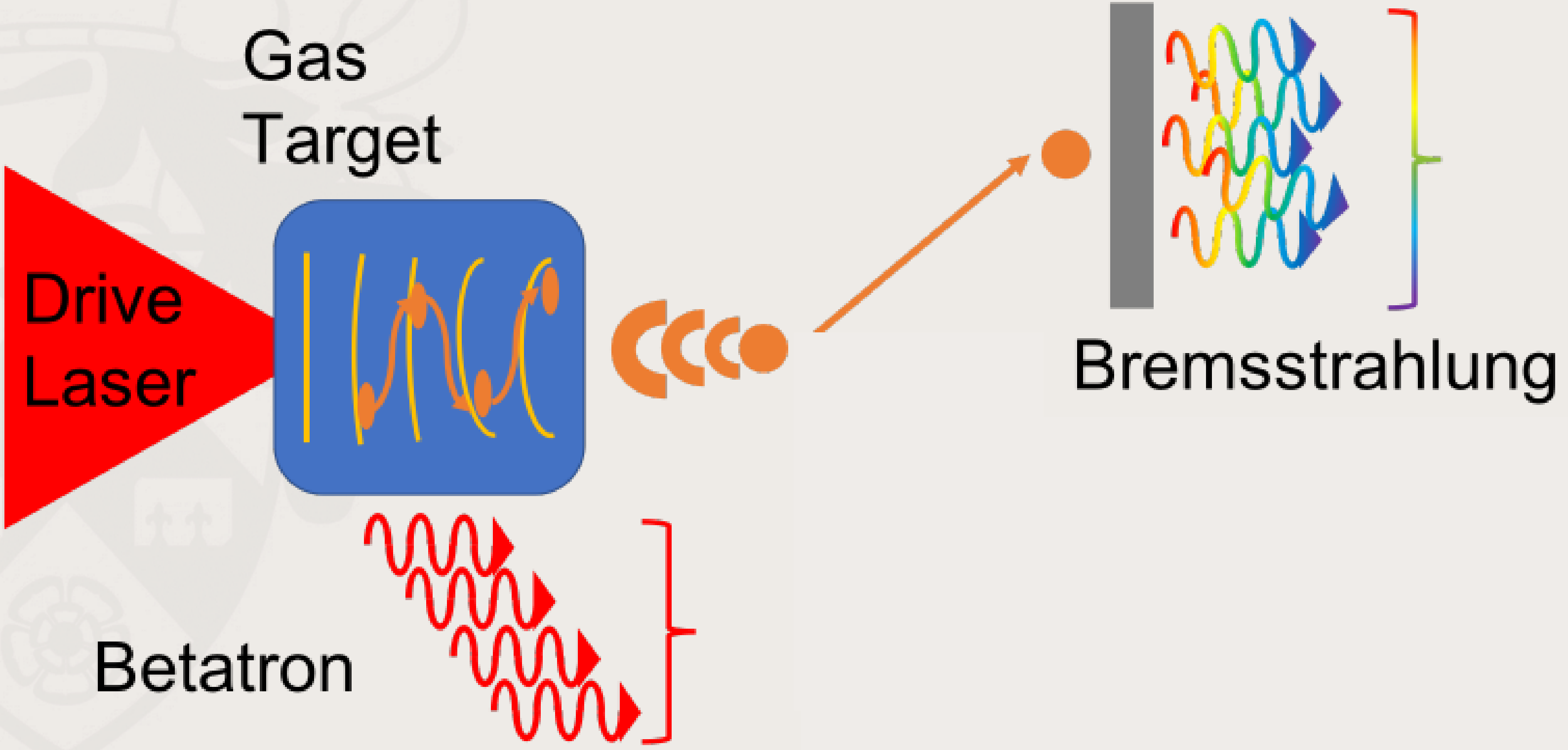


Since Tajima and Dawson,
Phys. Rev. Lett., **43**:267–270, (1979)

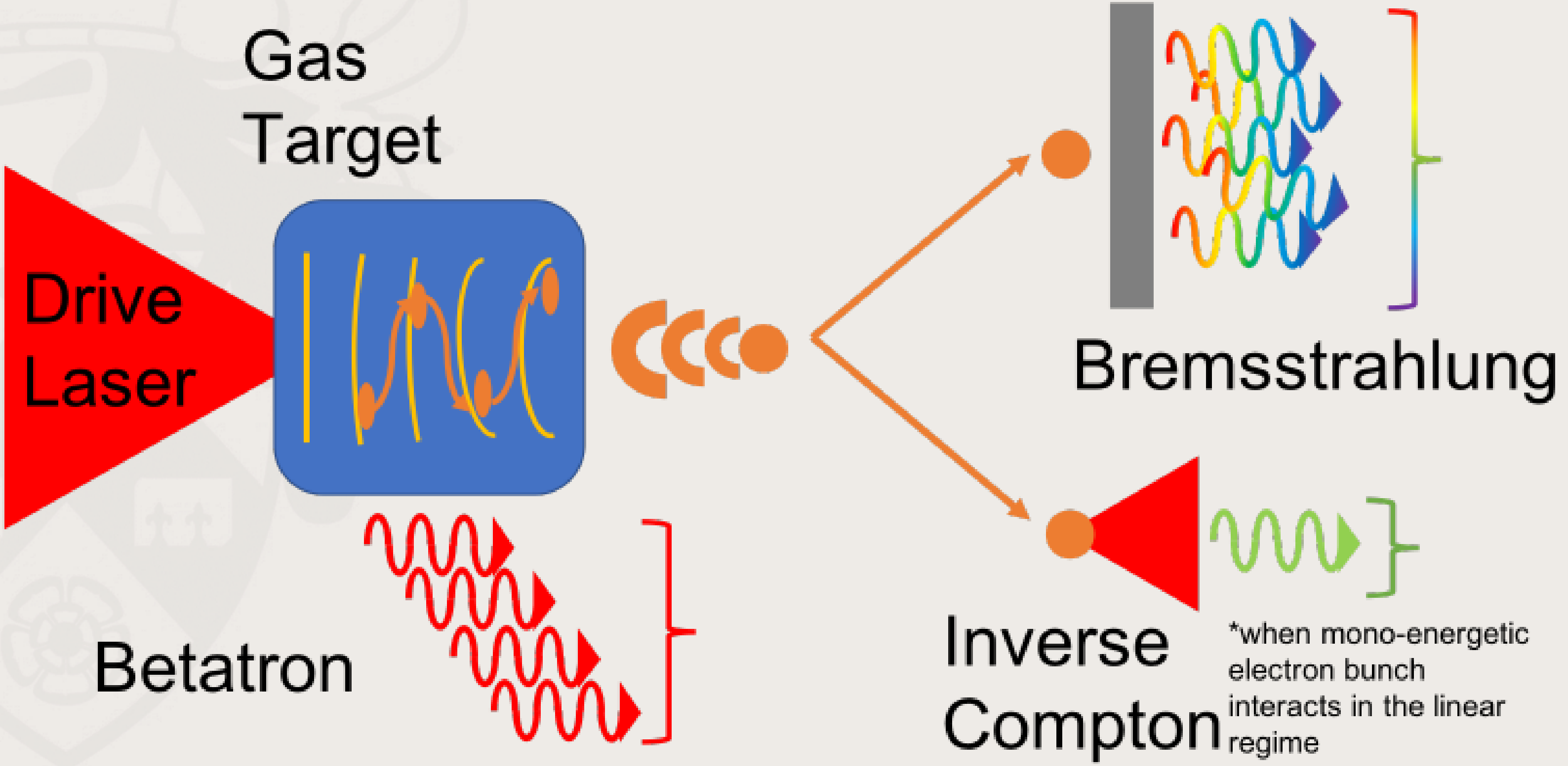
LWFA as an X-ray source



LWFA as an X-ray source

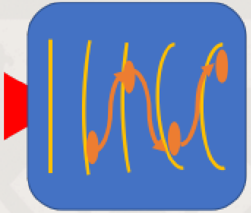


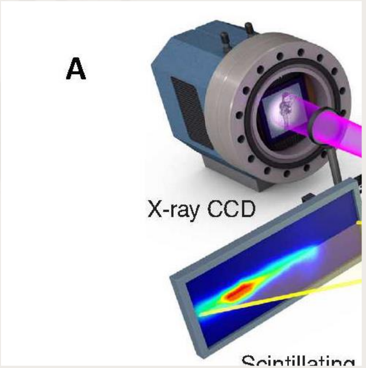
LWFA as an X-ray source



X-ray sources: Betatron and ICS

- Oscillations in the wakefield generate coherent keV x-rays.
- Source parameters:
    - Source size: few microns
    - Photon energy: 1 – 10 keV
    - Flux: 10^7 - 10^9





Kneip *et al.* Appl. Phys. Lett., **99** 093701 (2011).

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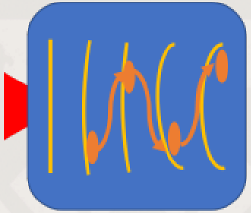
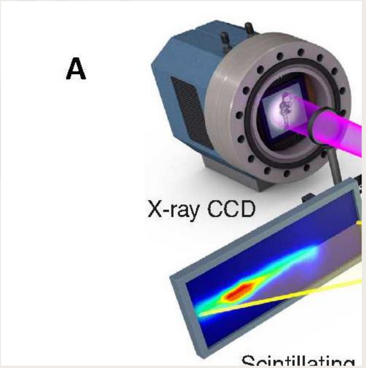
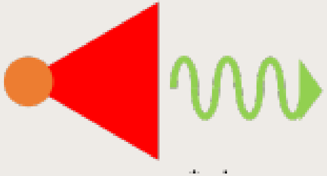
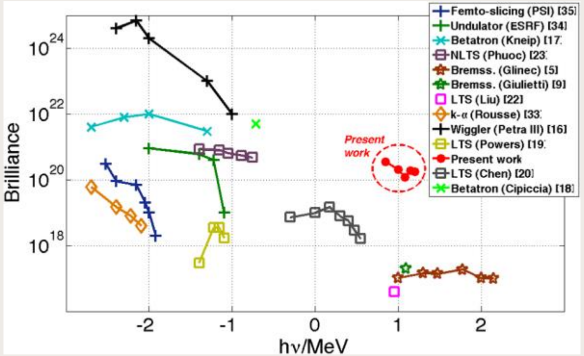




Kneip *et al.* Appl. Phys. Lett., **99** 093701 (2011).

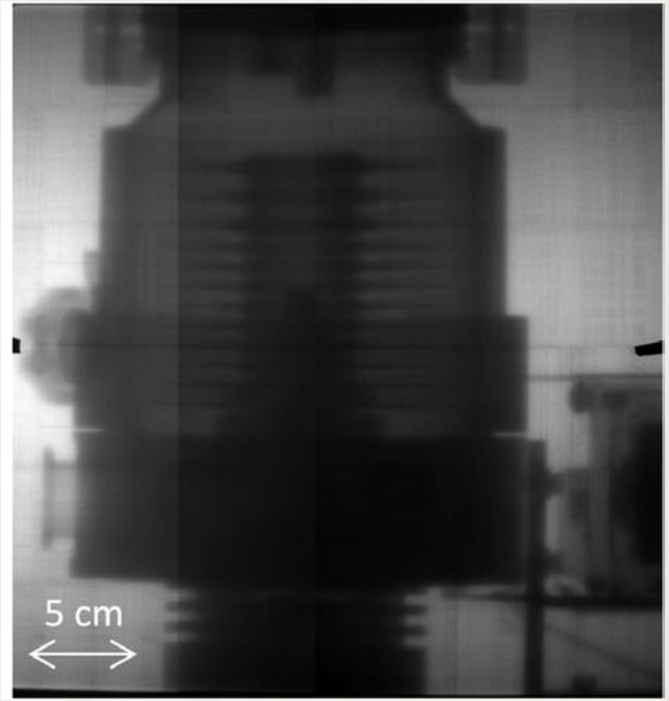
- Quasi-monoenergetic x-ray source from ICS
- Source parameters:
  - Source size: microns
  - Photon energy: keV - MeV
  - Flux: ~ 10^7





Sarri *et al.* Phys. Rev. Lett., **113**, 224801 (2014)

X-ray sources: Bremsstrahhlung



- Either LWFA acceleration followed by a foil, or direct laser irradiation of a foil generates MeV bremsstrahlung
- Source parameters
  - Source size: 0.01 – 1 mm
  - Photon energy: 100s keV - GeV
  - Flux: 10^6 – 10^{11} per shot

C M Brenner *et al.* 2016 *Plasma Phys. Control. Fusion* **58** 014039

Overview of radiography sources

Everything from damselflies to vacuum pumps…

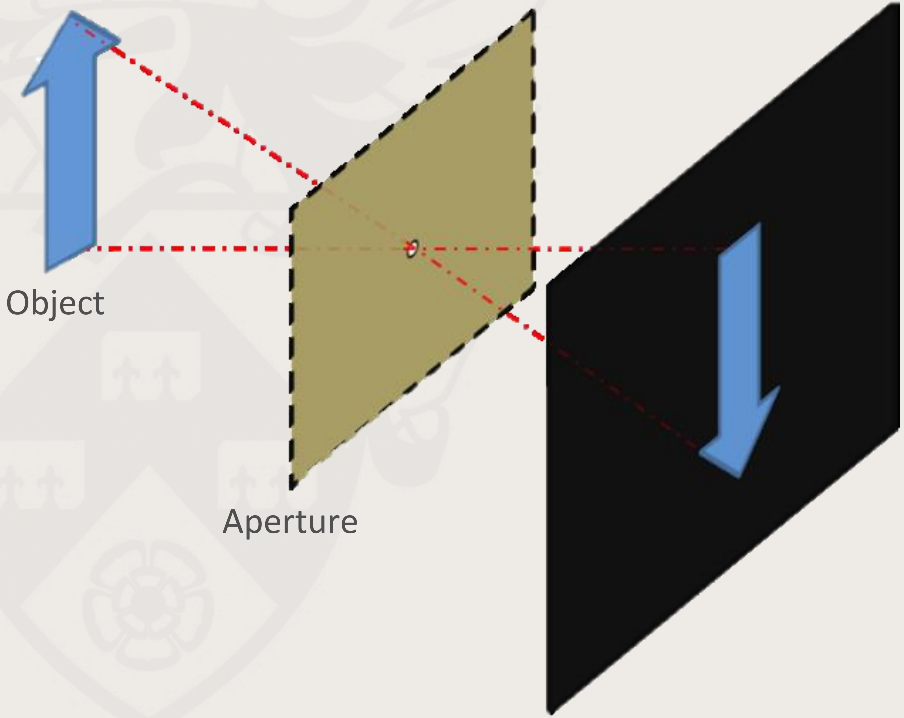
- A wealth of work exists on various LWFA radiation sources and imaging examples
- Important that the source matches the application in terms of source size, photon energy and flux (and repetition rate)
- Parameter space is expanding but requires optimisation

Diagnostics needed for source size at ever-increasing photon energy

How to measure hard x-ray sources:

Limitations of pinhole imaging.

Pinhole Imaging

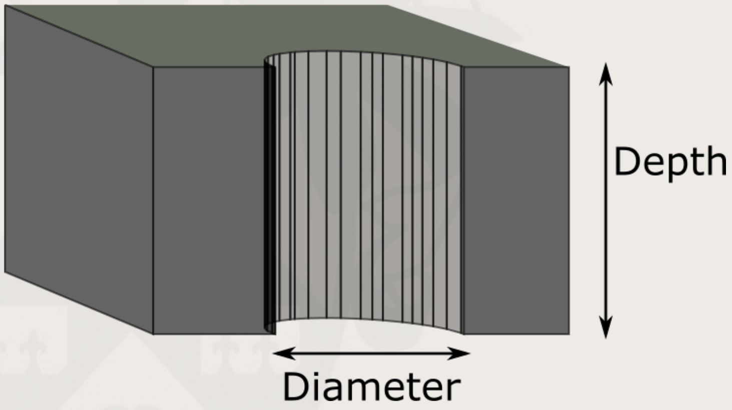


- Resolution inversely proportional to pinhole diameter.
- Inherent trade-off between signal strength and resolution.

What about an infinitely bright source?

High-Energy X-Rays

1 keV – 10 MeV



- Substrate need to be thick enough to attenuate almost all the radiation
- Need small pinholes and a thick substrate

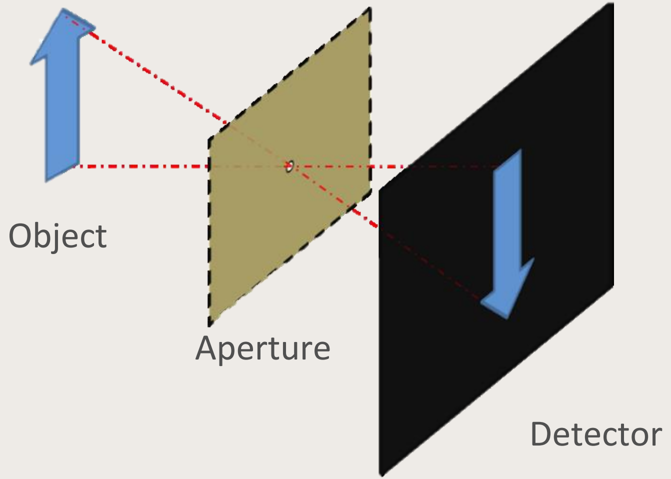
Maximum aspect ratio~ 50 [1]

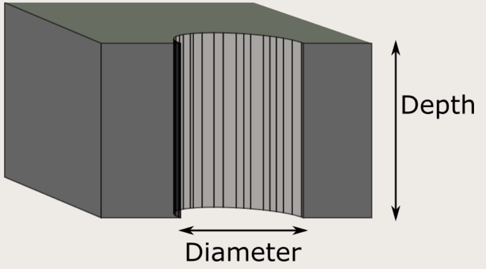
Moses. Nucl. Instrum. Methods Phys. Res. A., 648 (2011)

Optimisation requirements

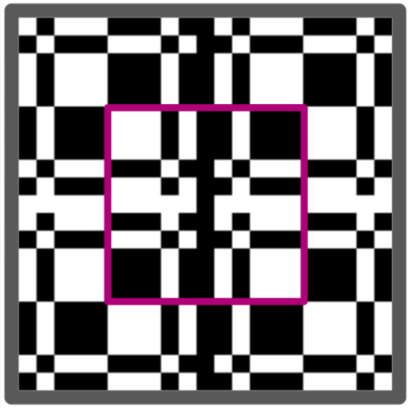
1 keV – 10 MeV

- Pinholes struggle when we need to be able to diagnose sources which are:
    - Relatively low flux
    - High photon energy
    - From a small source

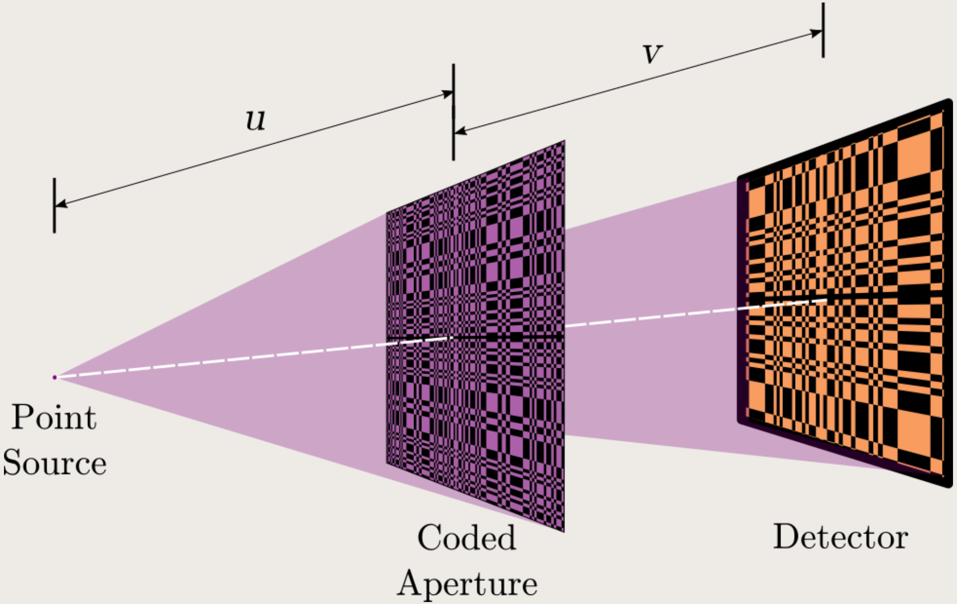




Coded Apertures



Example of a Coded Aperture:
Modified Uniformly Redundant Array[1]
11x11 base design

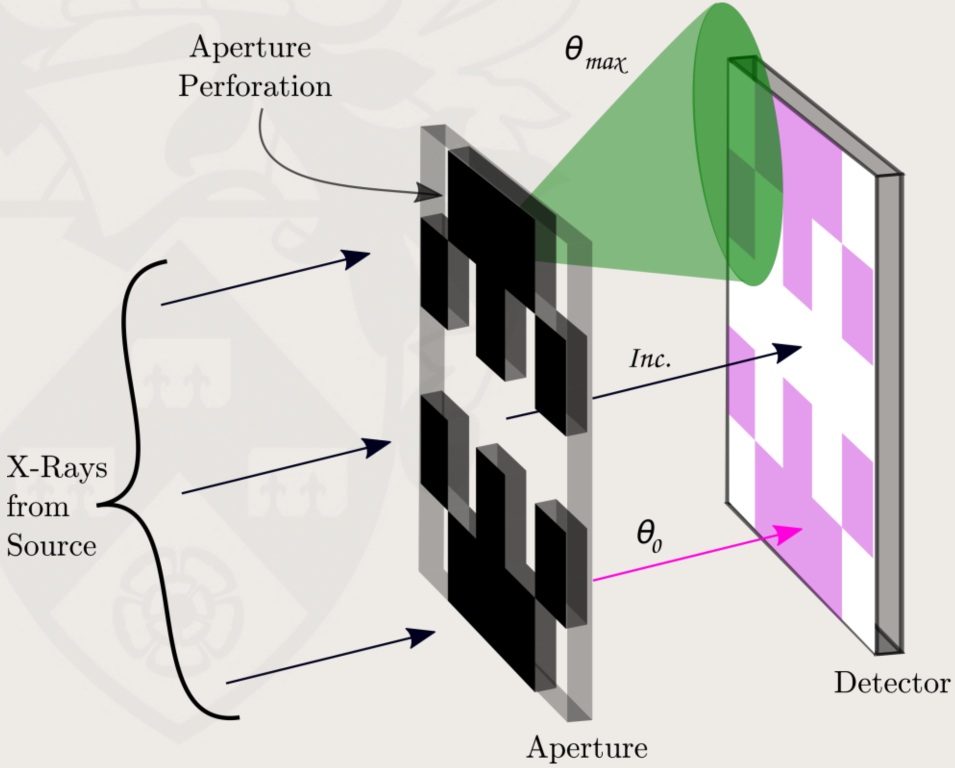


- Increased Signal
- No inherent signal to resolution trade-off
- Requires post-processing

[1] S R Gottesman and E E Fenimore., Appl. Opt., 1989.

CASPA

Coded Apertures with Scatter and Partial Attenuation

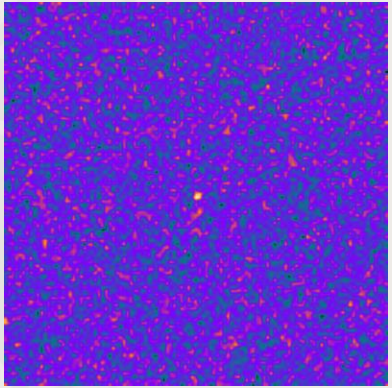


- Utilise inherent background subtraction CA decoding
- Data generated by ray tracing, and the simulation code Geant4
- Look at the effects of:
  - Partial Attenuation
  - Scattering
  - Both

CAPA

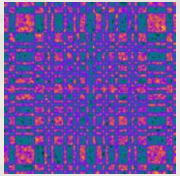
Coded Apertures with Partial Attenuation

Pinhole

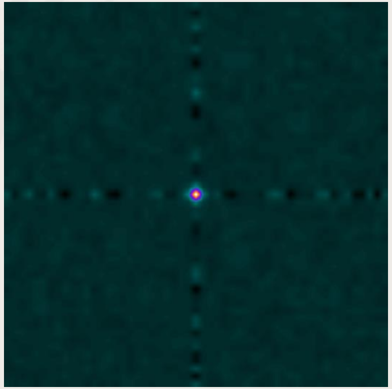


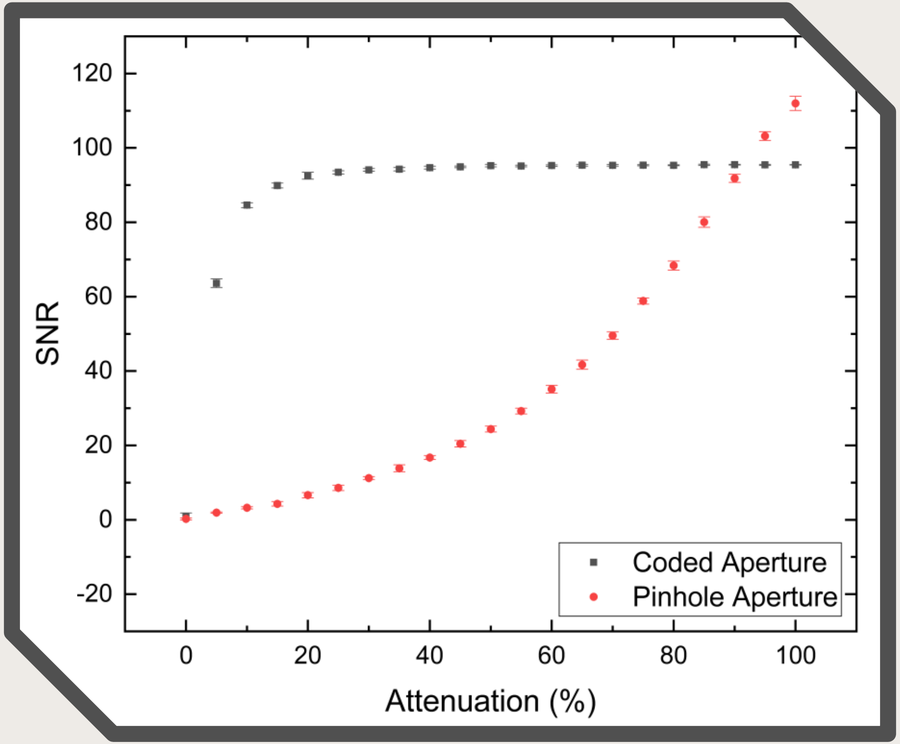
010%
Attenuation

Coded Aperture



Detector

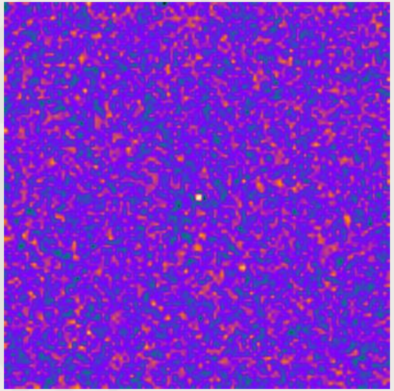




CASNA

Coded Apertures with Scatter and No Attenuation

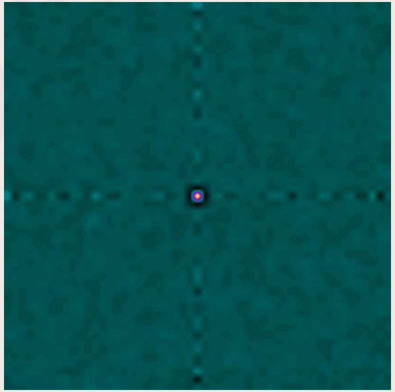
Pinhole

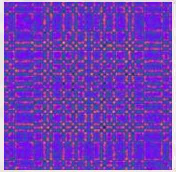


4^o

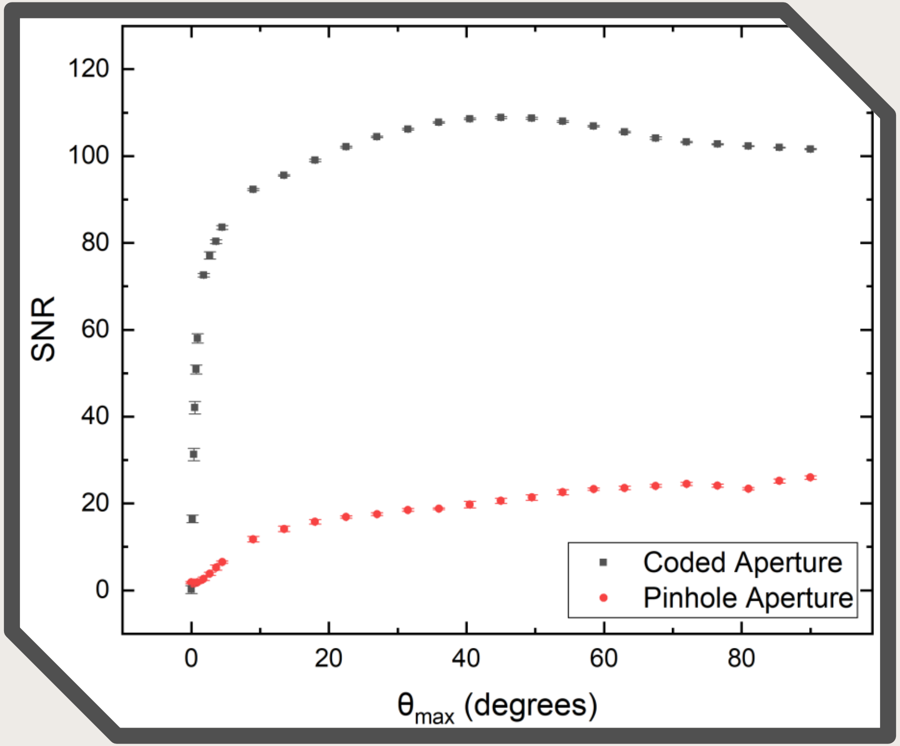
θ_{max}

Coded Aperture





Detector



CASPA Demonstration

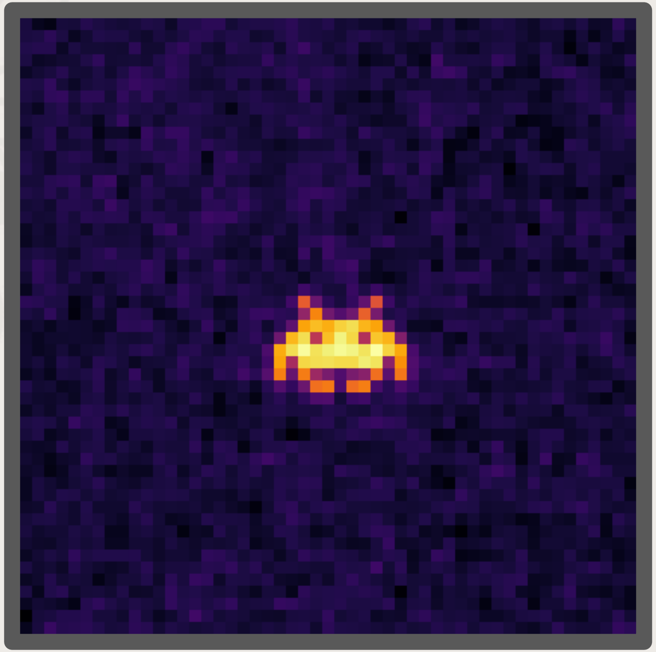
Extended Objects

Input Parameters

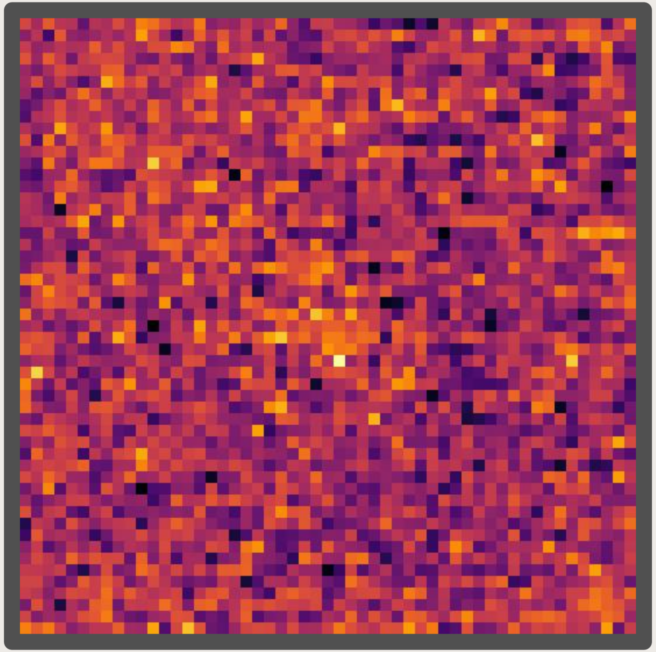
W aperture

511 keV photons

- CASPA thickness
  - 250 µm
- Thickness for full attenuation
  - 18 mm



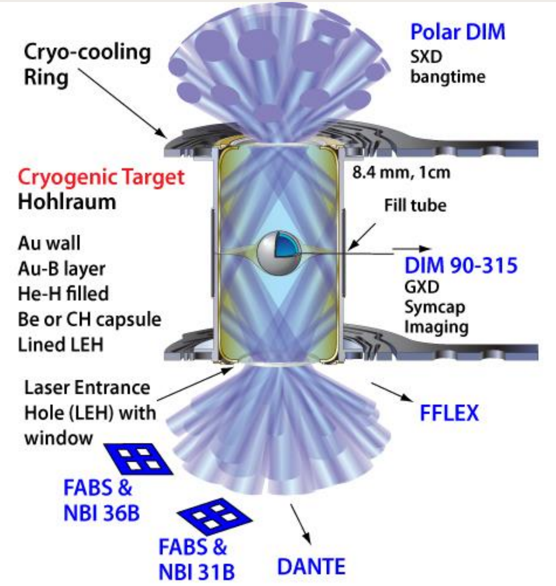
CASPA



Equivalent Pinhole

[1] M Selwood et al., Plasma Phys. Control. Fusion, 62(7), 2020

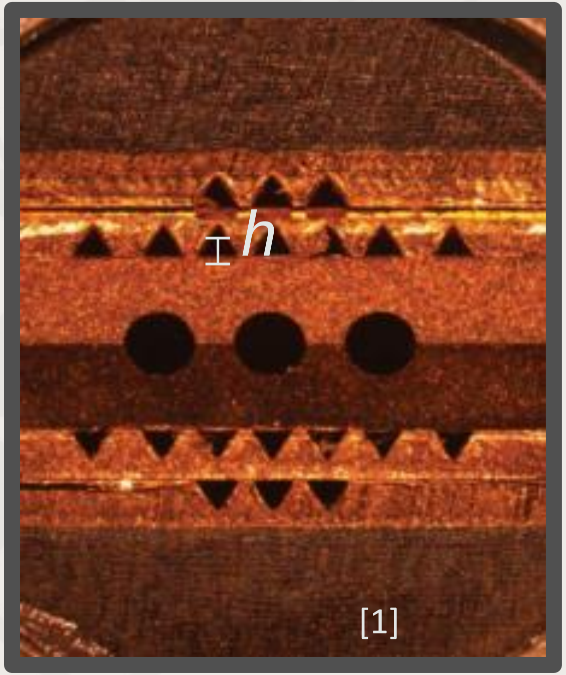
If these coded apertures work for highly penetrating x-rays, what about neutrons?



Lawrence Livermore National Laboratory

https://lasers.llnl.gov/for-users/experimental-capabilities/hohlraum-energetics

National Ignition Facility: neutron imaging

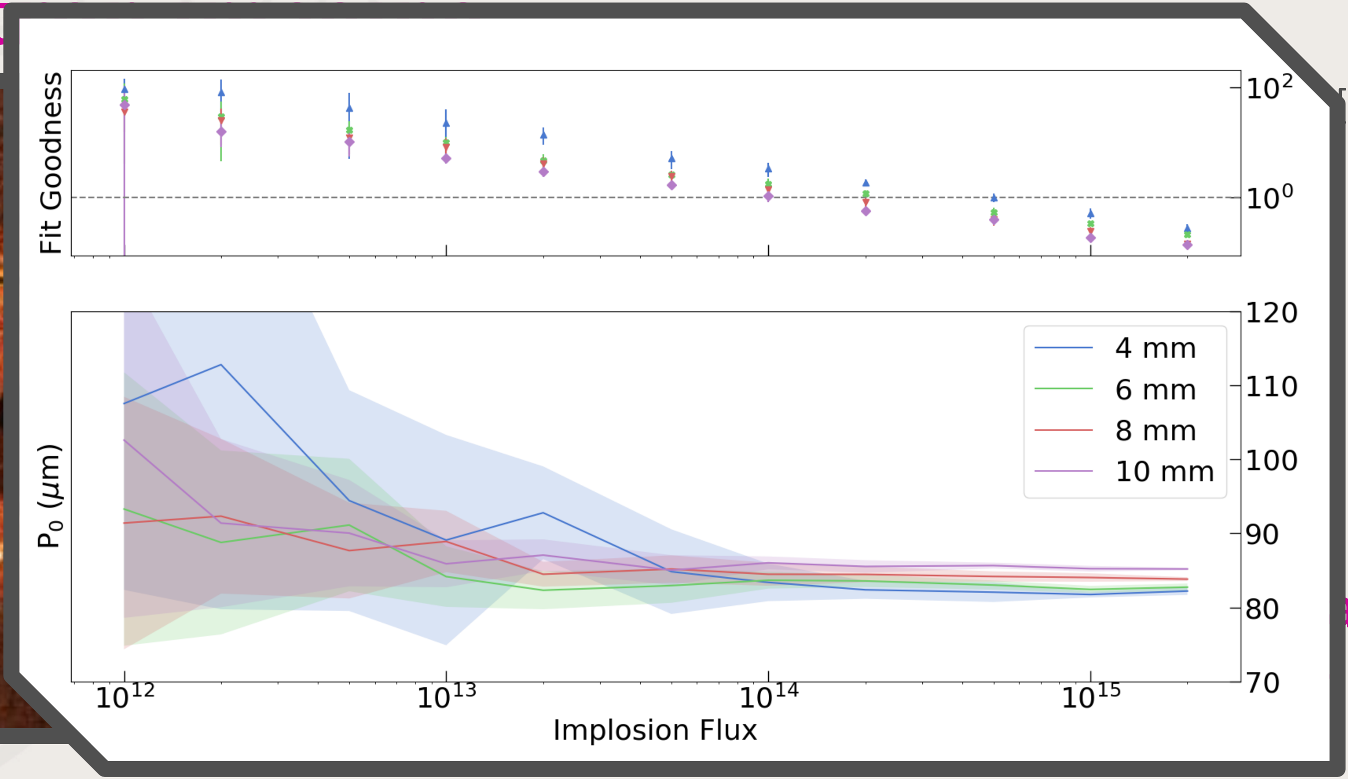


- 20 cm thick gold substrate [1]
- Small field of view
- Challenging to align
- Difficult and expensive to manufacture

Initial simulations imply that a CASPA of 10 – 12 mm would suffice.

[1] F E Merrill *et al.*, Rev. Sci. Instrum., 83, 2012.

National Ignition Facility: neut



[1]

a CASPA

ice.

[1] F E Merrill *et al.*, Rev. Sci. Instrum., 83, 2012.

NuSec Collaboration Project

- Looking to benchmark the neutron imaging simulations.
- Hoping to understand detector challenges.

[1]

- Also looking at maximum likelihood techniques for improving the final imaging quality.

NuSec Collaboration Project

- Trip to Michigan in May-June
  - Starting a new collaboration
  - Understanding overlaps in research interests
  - Sharing modelling and experimental capability

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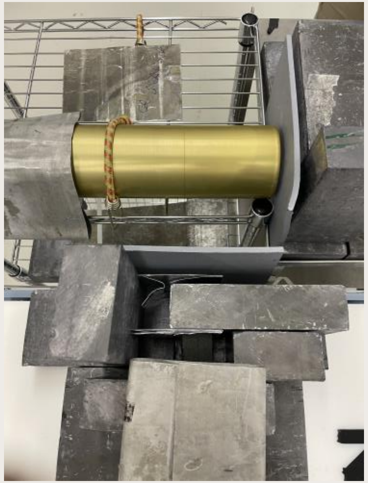
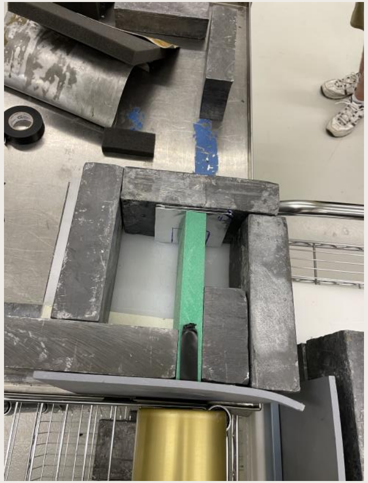
NuSec Collaboration Project

- Initial work on DT neutron detection
    - How do we differentiate between x-ray and neutron emission?
    - Can we use spatially resolving neutron detectors?
    - Can we enhance the neutron signal?





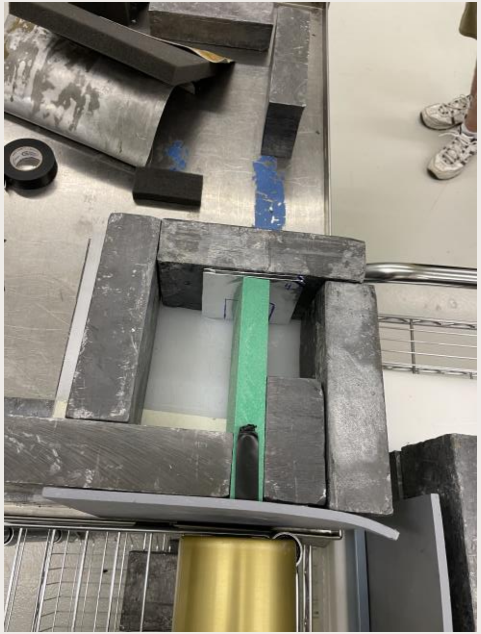
Consortium for Monitoring Technology and Verification

University of Michigan

University of York School of Physics, Engineering and Technology

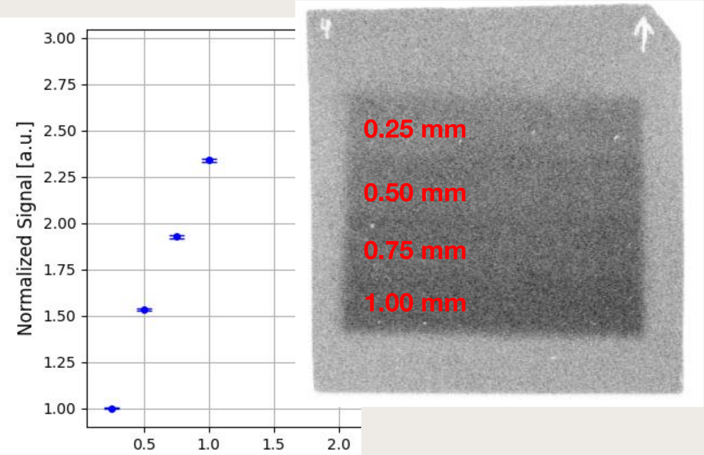
NuSec Collaboration Project

- Results
  - Differential filtering
  - Can we use spatially resolving neutron detectors?
  - Can we enhance the neutron signal?



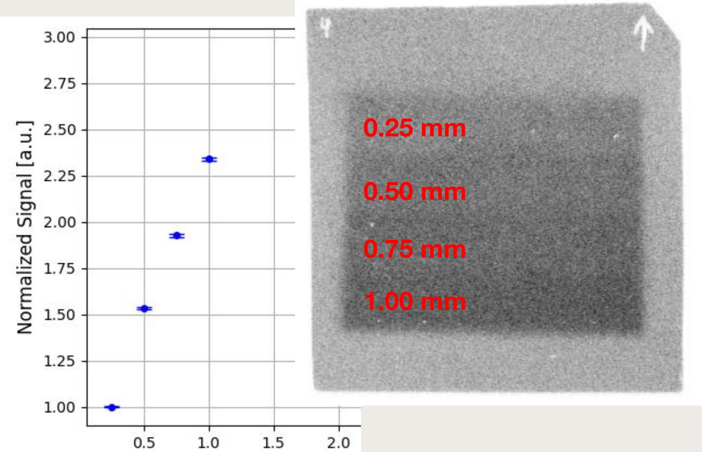
NuSec Collaboration Project

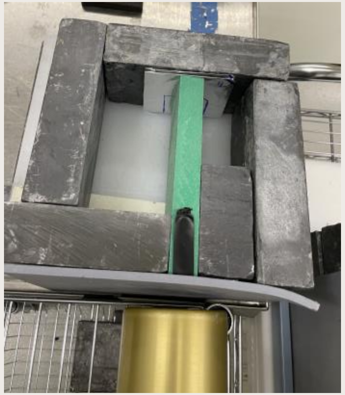
- Results: Neutron detection
  - Using Fujifilm BAS- ND for spatial resolution
    - Designed for thermal neutrons
  - Neutron signal enhanced by additional plastic coating

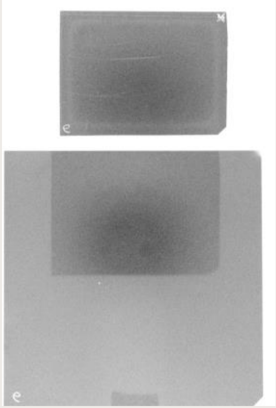


NuSec Collaboration Project

- Results: Neutron detection
  - Using Fujifilm BAS- ND for spatial resolution
    - Designed for thermal neutrons
  - Neutron signal enhanced by additional plastic coating
  - Selectively block x-rays and neutrons







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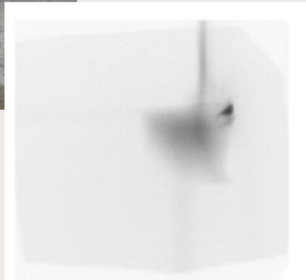
NuSec Collaboration Project

- Results: Imaging?
  - Built a pinhole from lead bricks
    - One clockwise, one anti-clockwise
  - Designed mainly to image x-ray source
    - Designed for thermal neutrons
  - Need more data!



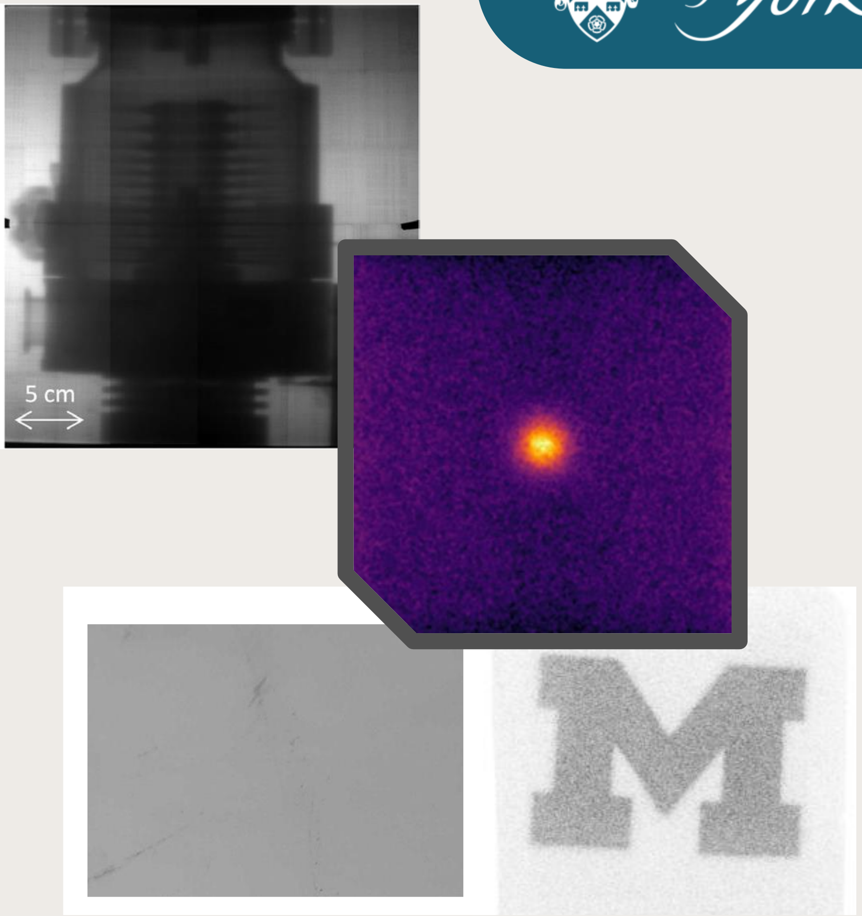
CONSORTIUM FOR MONITORING TECHNOLOGY AND VERIFICATION

UNIVERSITY OF MICHIGAN

UNIVERSITY of York
School of Physics, Engineering and Technology

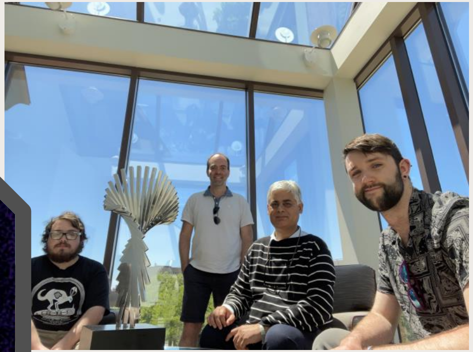
Conclusions

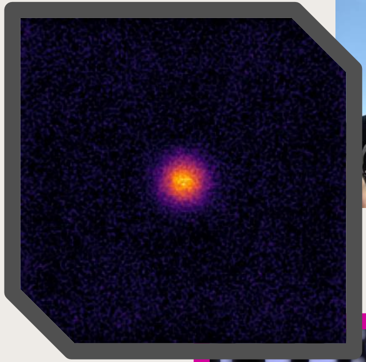
- Laser-based x-ray sources could provide additional research opportunities.
- Coded apertures show promise for x-ray and neutron imaging.
- A new collaboration is now underway and a paper is in preparation.

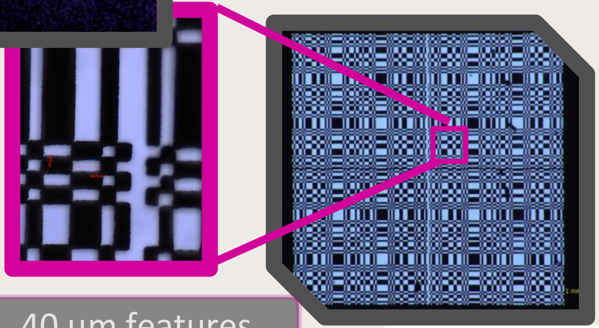


Further Work

- Hoping for a repeat trip to Michigan to further imaging technique
- Utilising Maximum Likelihood algorithms to improve the neutron imaging
- Advancing imaging of x-ray sources at York or Central Laser Facility







40 μm features

scitech precision
MICRO LASER TARGETS

Thank you… Questions?

University of York, UK
- Matthew P. Selwood**, Chris Underwood, and Chris Murphy

University of Michigan, USA
- Colton Graham, Jamil Mir, and Igor Jovanovic

LLNL, USA
- D. N Fittinghoff, J. Williams

Los Alamos National Lab, USA
- P. L. Volegov

SciTech Precision, UK
- C. Spindloe

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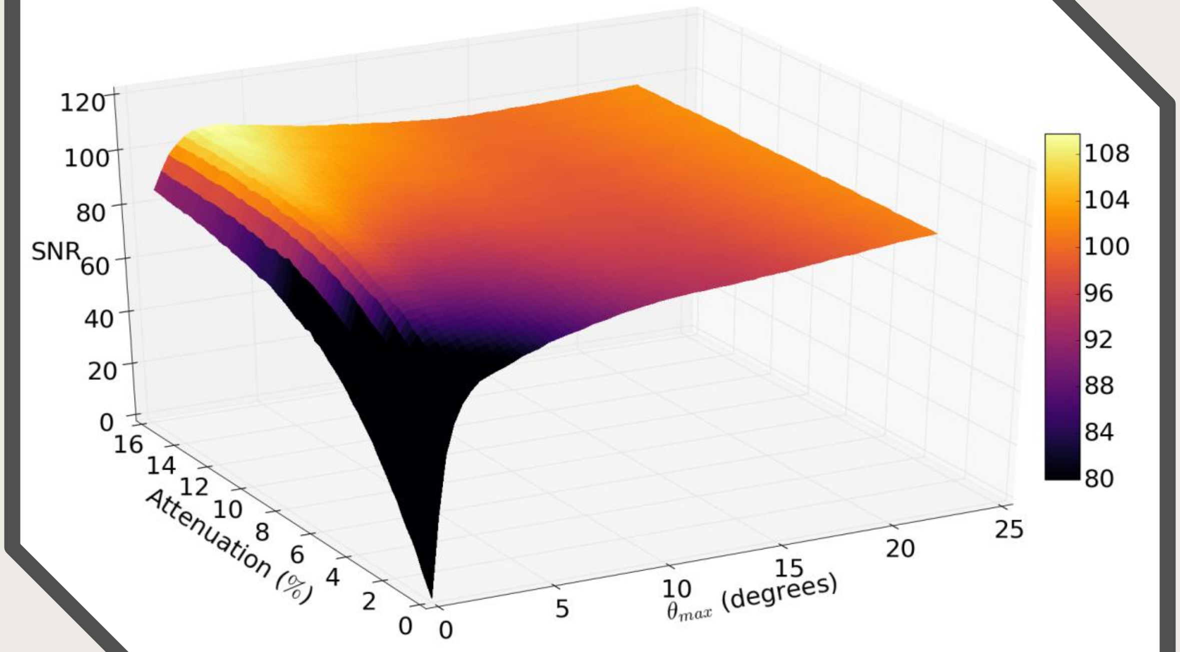
CASPA

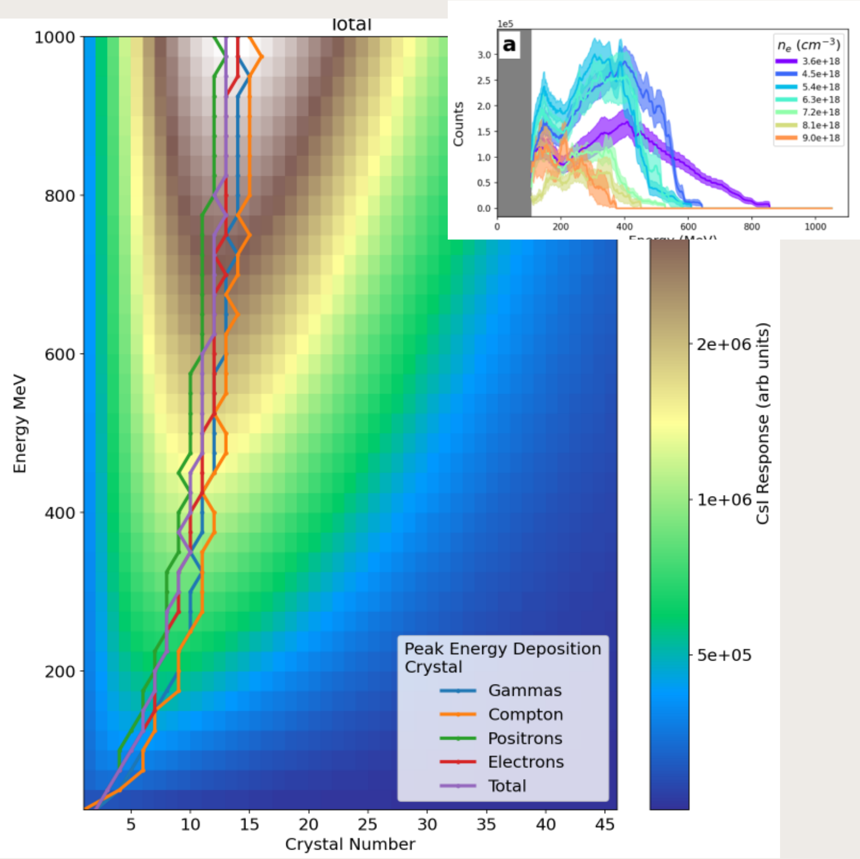
Coded Apertures with Scatter and Partial Attenuation

- For known x-ray source, good SNR achieved at low attenuation
- With known θ_{max} CASPA can be designed



LWFA-generated Bremsstrahlung

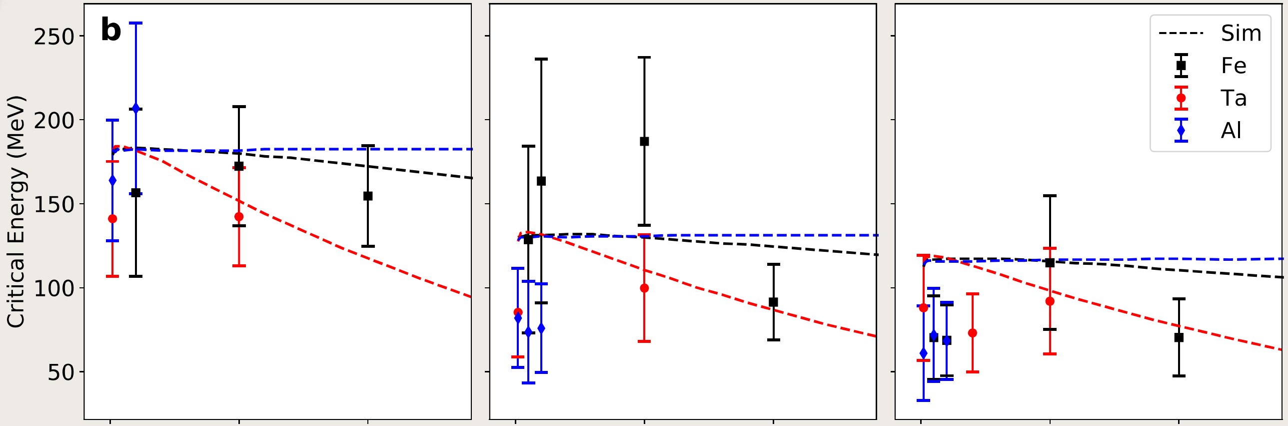
- Self-filtered CsI (Tl) scintillator stack
  - In principle, calibration is simple
    - Using Geant4, the response for a single electron energy is found and a response matrix is generated: $$R_{En}\gamma_E = C_n$$
  - In fact, the response at high photon energy is similar so an assumption about the spectrum is required
    - Use a standard bremsstrahlung response
  - Can find a 'critical energy'.



LWFA-generated Bremsstrahlung

Scaling of flux with converter thickness

- 3 plasma densities
- 3 converters
- Converter thickness
    - 0.05 – 15 mm



- Characterising the critical energy shows that the energy drops as the converter thickness increases
    - This can be considered an effect of the electron spectrum 'softening' as it radiates.
    - Better matches at thicker targets (unmeasured low energy population)

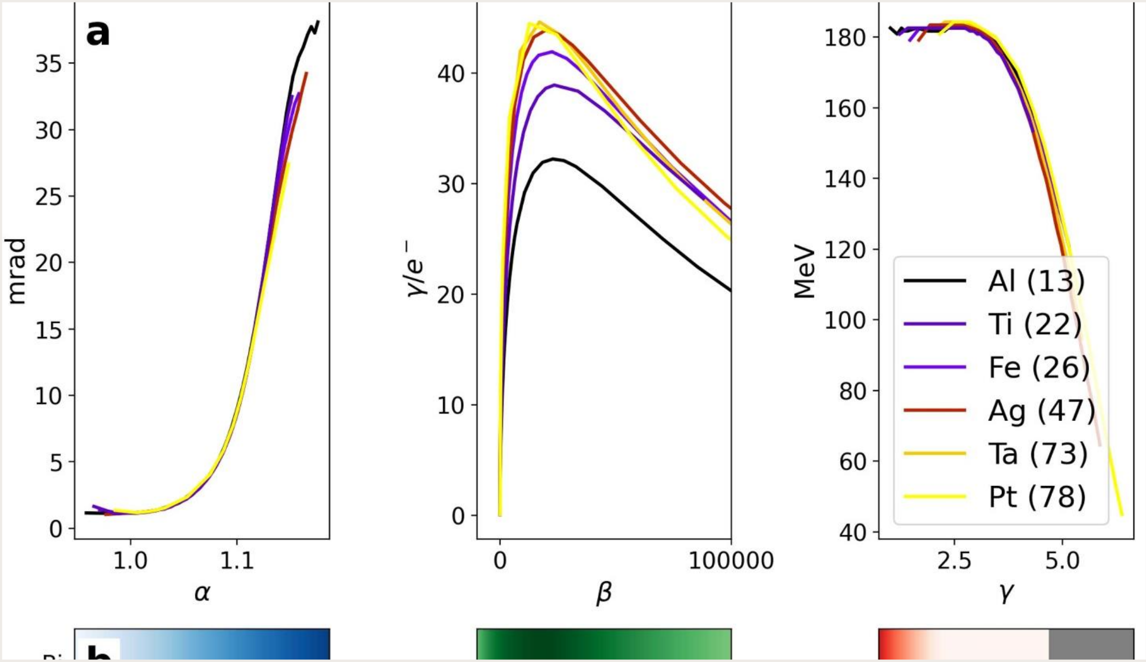
LWFA-generated Bremsstrahlung

Independence of the scalings

$$\alpha = R^{0.03\pm0.01}\rho^{0.008\pm0.004}Z^{0.01\pm0.003}$$

$$\beta = R^{1.63\pm0.02}\rho^{1.07\pm0.04}Z^{1.16\pm0.03}$$

$$\gamma = R^{0.20\pm0.004}\rho^{0.29\pm0.002}Z^{0.08\pm0.001}$$



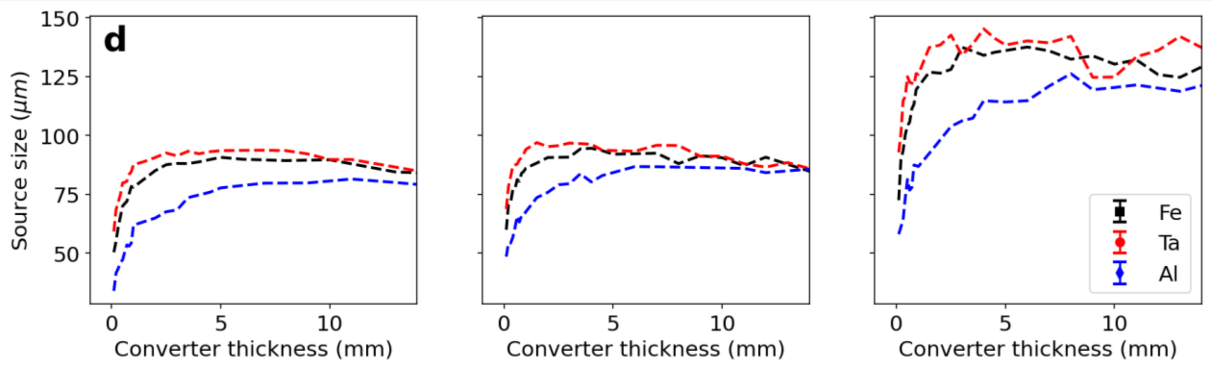
Can empirically fit all the converter materials to parameters which depend on thickness, density and Z

- For example, for a higher flux but a lower E_{crit} we aim for low beta and high gamma.

LWFA-generated Bremsstrahlung

An interesting result: Source size or resolution?

- For thin targets, increasing thickness results in an increase of the source size
- But this does not continue



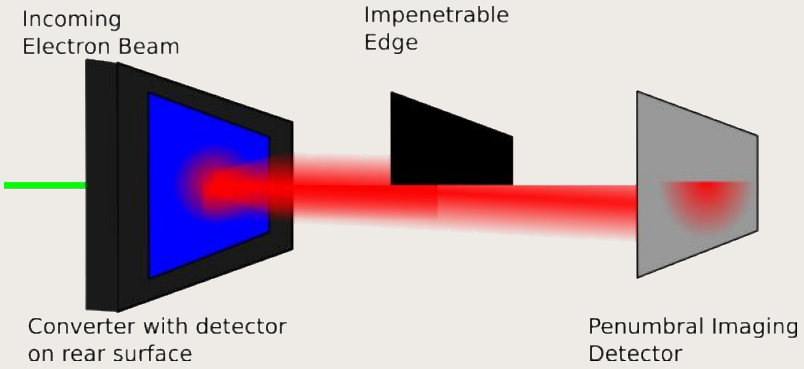
- Increasing the thickness of the converter only increases the measured source size up to a point.
  - Must consider the method of measurement here.

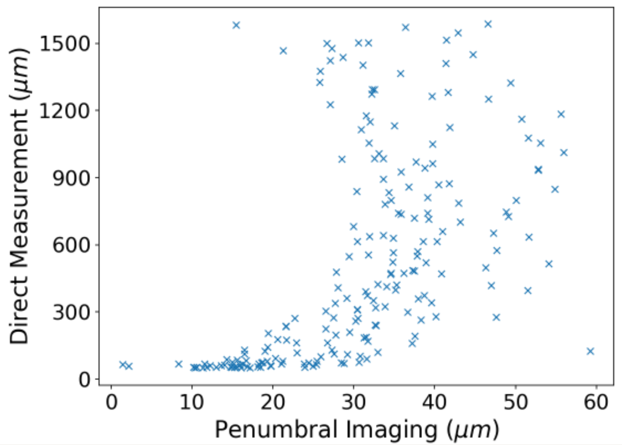
LWFA-generated Bremsstrahlung

An interesting result: Source size or resolution?

- The methodology of the measurement is simulation of penumbral imaging.
- A further simulation is run to look at the source at the rear of the converter AND the penumbral imaging measurement.

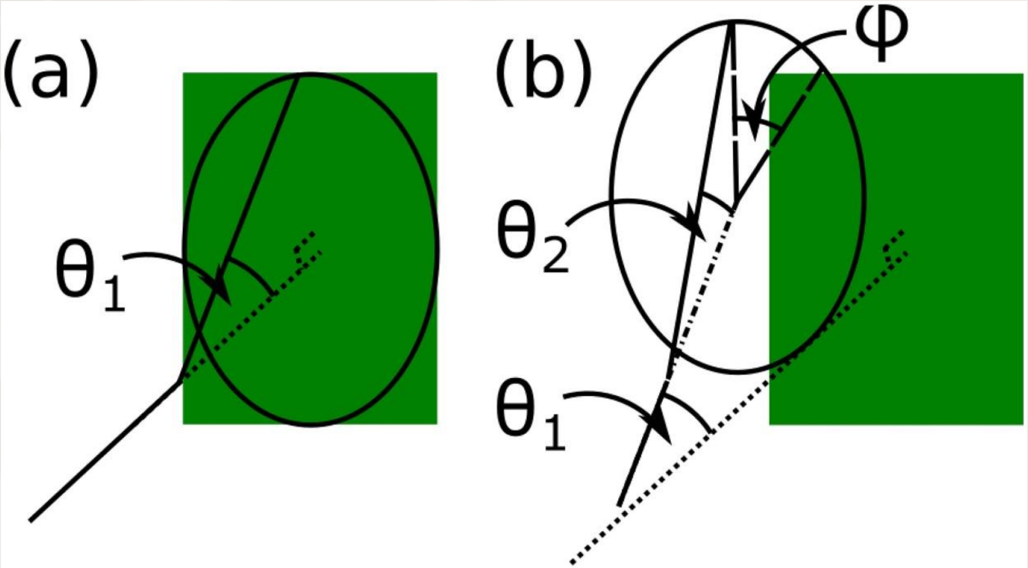
- Now we see that the source goes up but the measurement plateaus.
    - What is the physics?





LWFA-generated Bremsstrahlung

An interesting result: Source size or resolution?



- The increase in the source size becomes dominated by secondary scattering.
- Secondary scattering event are unlikely to contribute to the penumbral signal
- Open Question:

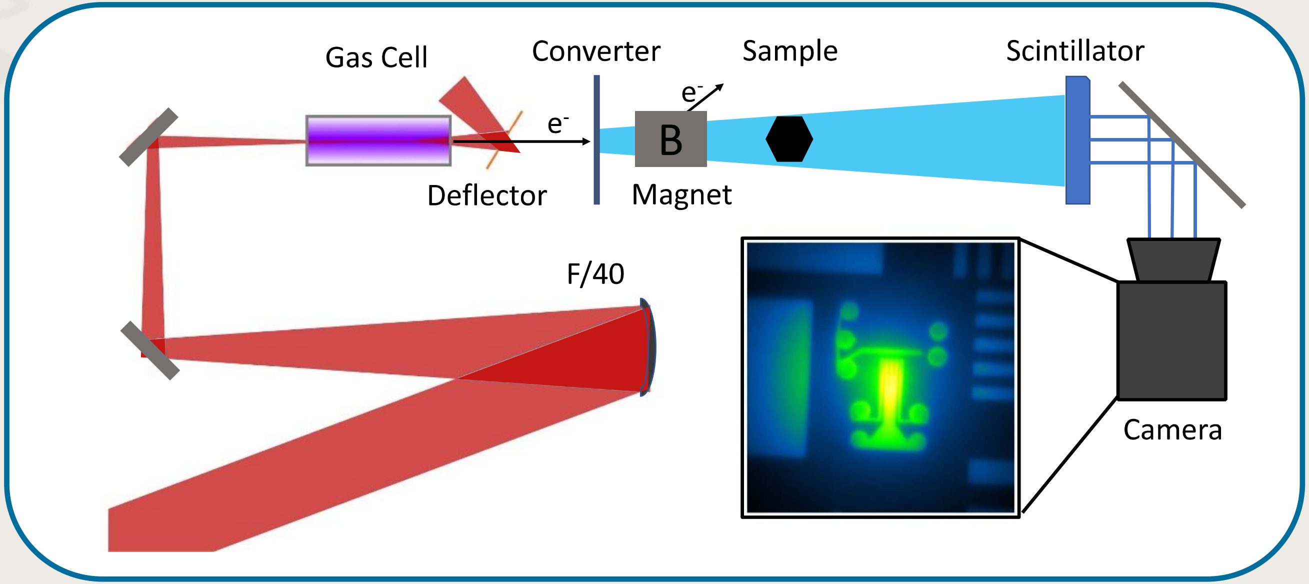
Do we care?

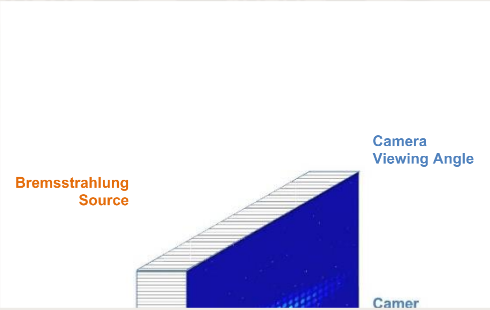
LWFA-generated Bremsstrahlung

Can we control flux, energy and source size independently?

Gemini Laser

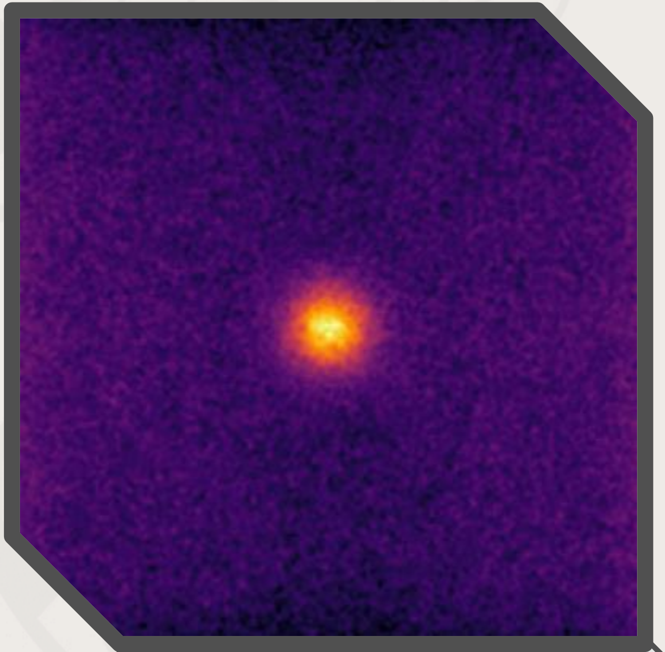
- 6J in 50 fs
- 3 x 10^{18} Wcm^{-2}
- 11.8 mm gas cell





CASPA Correction

Thickness Compensation

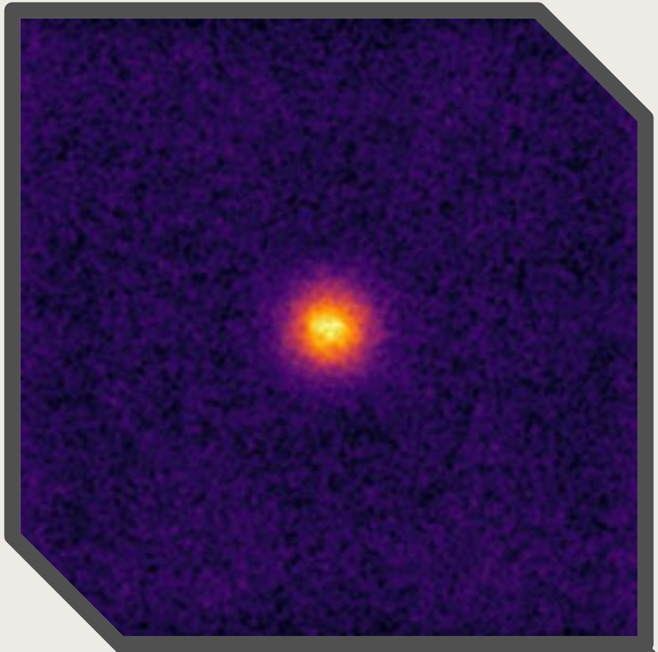


No additional correction

$$\cos(n\vartheta)$$

n scales with aperture thickness

Can be found empirically



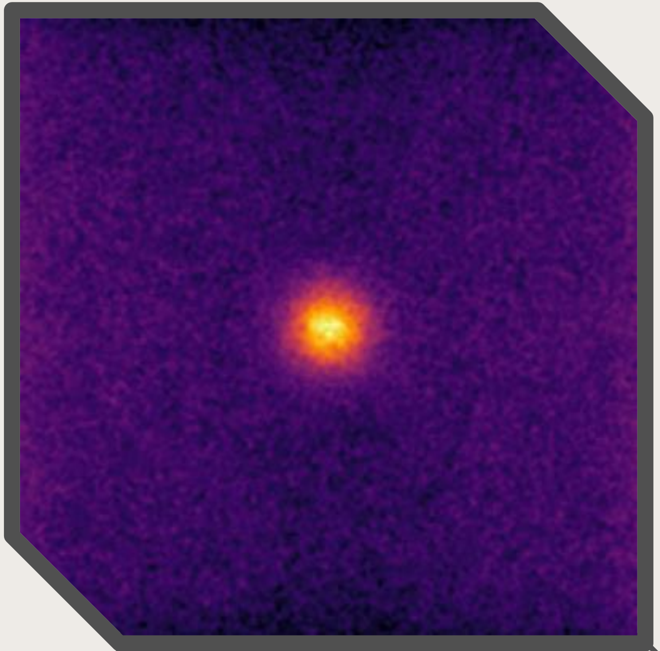
n = 30 correction

Thickness Correction

Mu & Liu, 2006

- Coded aperture corrections:

1. Near-field
   - $\cos^3(\vartheta)$
2. Aspect Ratio
   - Substrate thickness
   - Perforation size
   - Aperture Design
   - ϑ



$\times10^{14}$ total yield Geant4 simulation, 10 mm W p97 aperture, of a P_0 = 80 µm gaussian profile

[1] Mu and Liu, in *IEEE Transactions on Medical Imaging*, vol. 25, no. 6, June 2006 pp. 701-711

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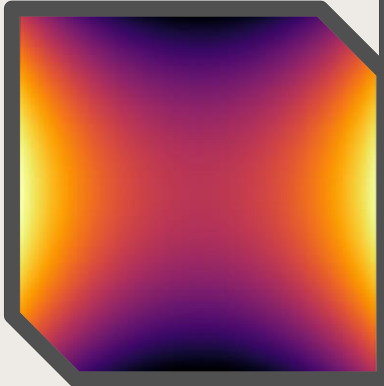
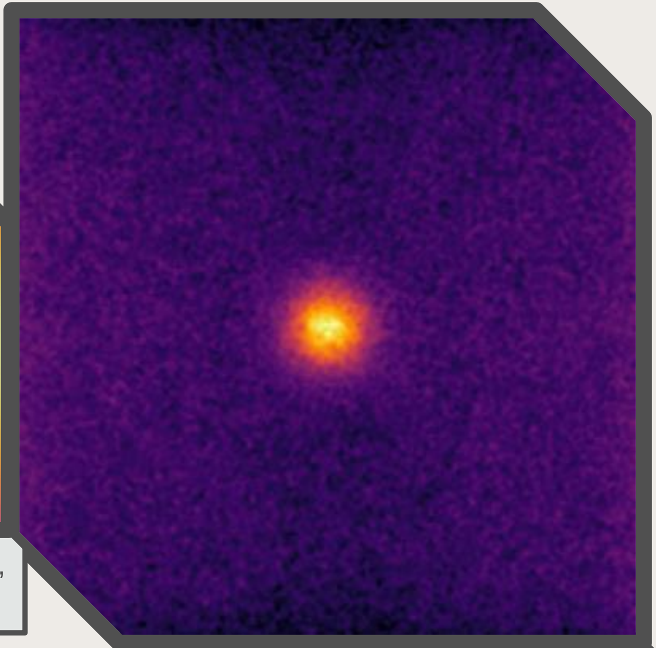


$\cos(\vartheta)$ on the detector, post decoding



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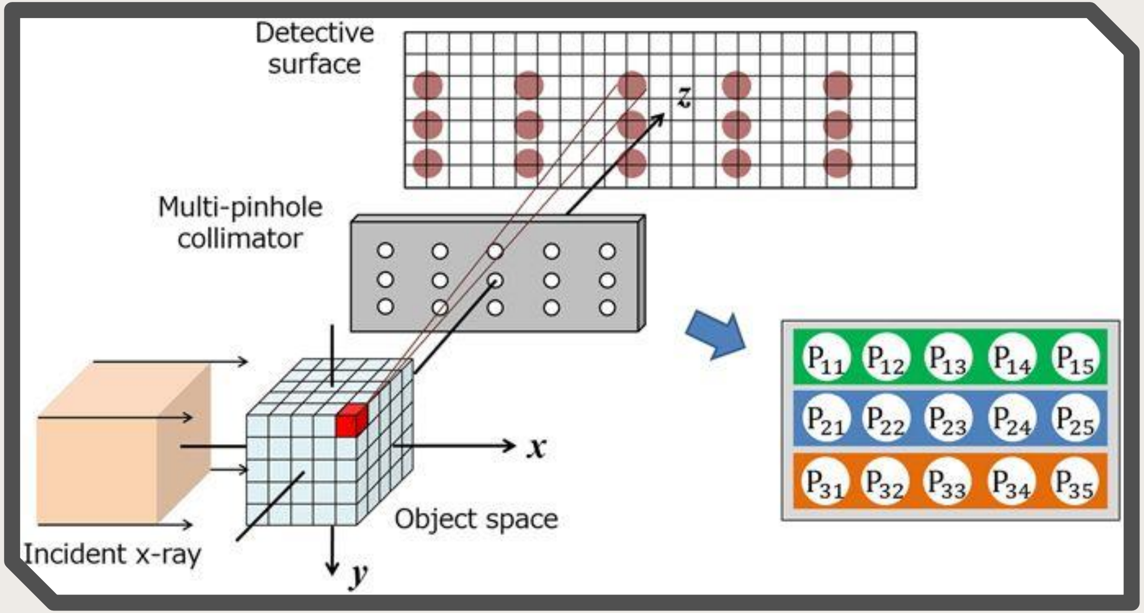
[1] Mu and Liu, in *IEEE Transactions on Medical Imaging*, vol. 25, no. 6, June 2006 pp. 701-711

Pinhole Array

- Higher signal
- Requires minimal post-processing to combine images
- Requires large detector
    - $$$

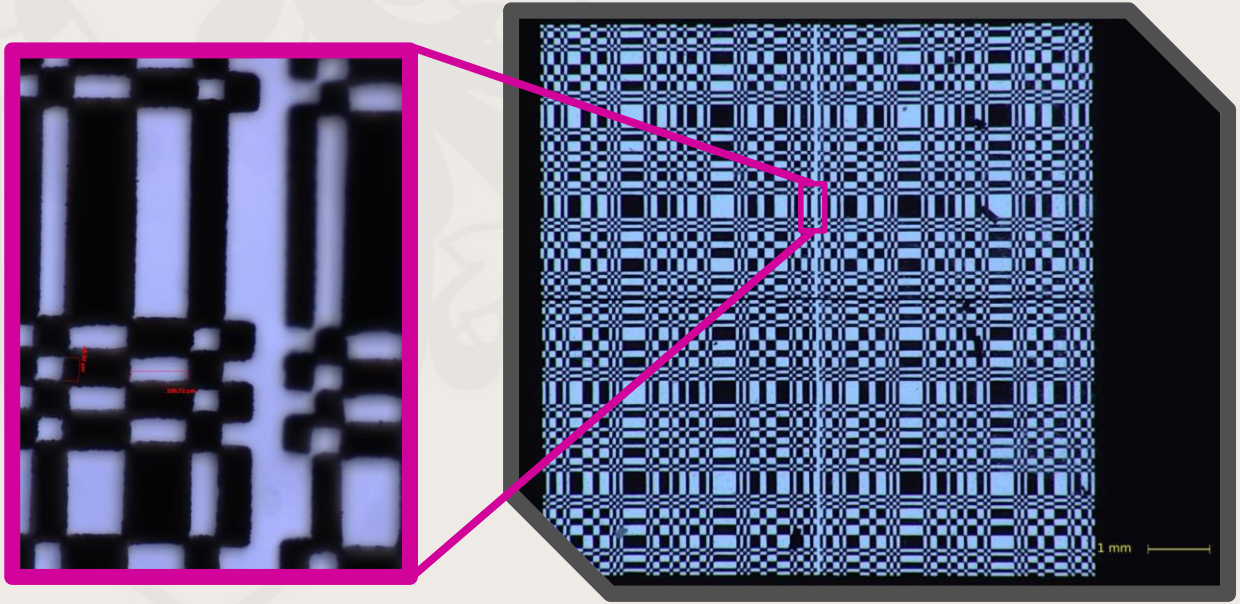


[1] Sasaya, T., Sunaguchi, N., Hyodo, K. et al., Sci Rep 7, 2017.

Gemini Experiment

Higginbotham, Jan 2020

- Manufacture required rounded corners

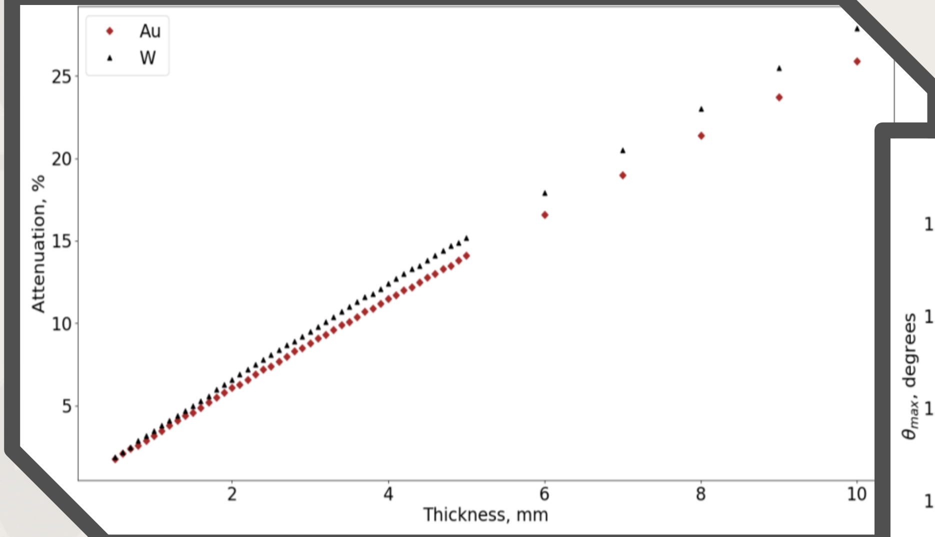


- No images
- Will try again!

Material Choice

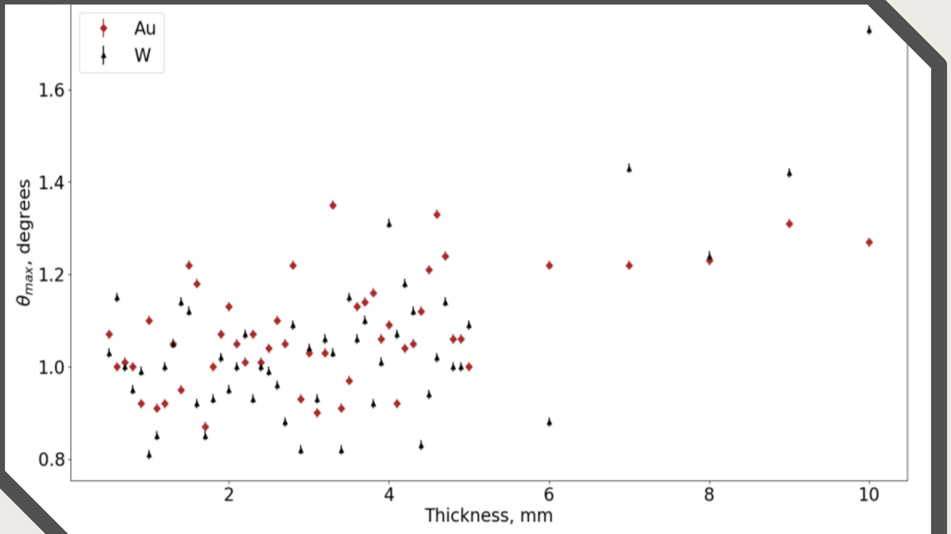
Attenuation or Scatter dominated

DT neutrons



- Not so clear scatter correlation
  - Au better for thinner sheets?

DT neutrons



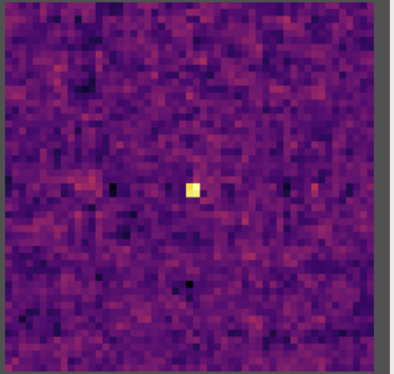
- Clear trend in attenuation
  - W better

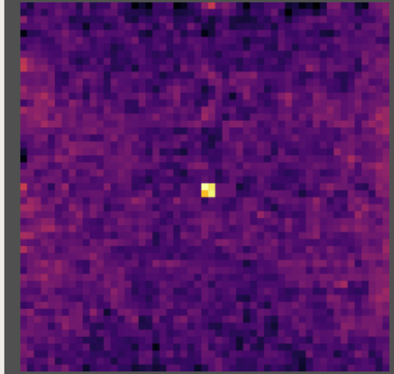
RTM vs. Geant4

Flux: 5.33×10^6

Events: 1.33×10^6

SNR: 47 ± 3





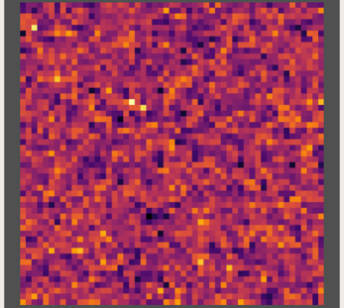
Flux: 2^{32-1} $(\sim 10^9)$

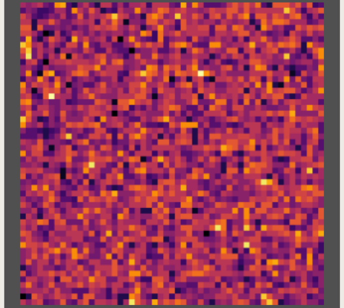
Events: 1.34×10^6

SNR: 43

Run Time: 3 seconds

Ray Tracing Model

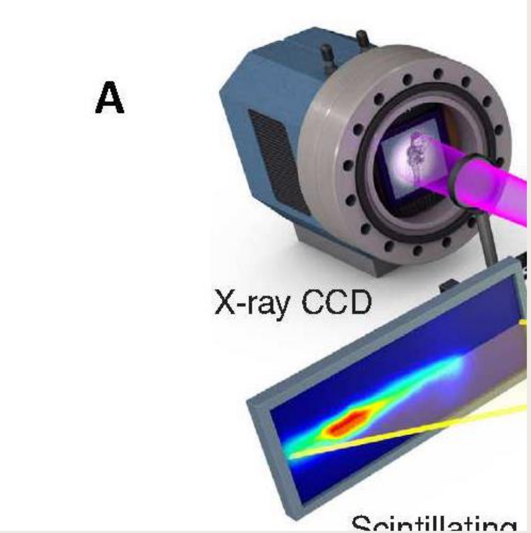


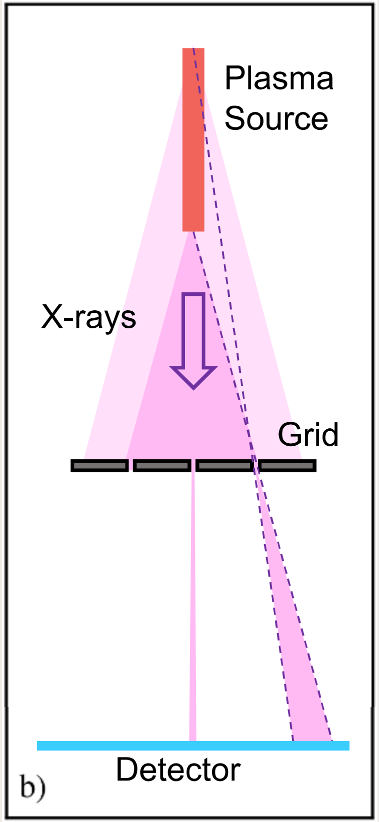


Run Time: 22 hours

Radiation from betatron oscillations

- Some excellent results
- Can vary flux, maximum energy, spectral quality...
  - But maybe not always at the same time!





O J Finlay et al., Plasma Phys. Control. Fusion 63 (2021) 084010

Detection

- Too high energy for standard CCD
- Could potentially use plastic as a scintillator
- Potentially spectrally-selective architecture to be explored

[1]

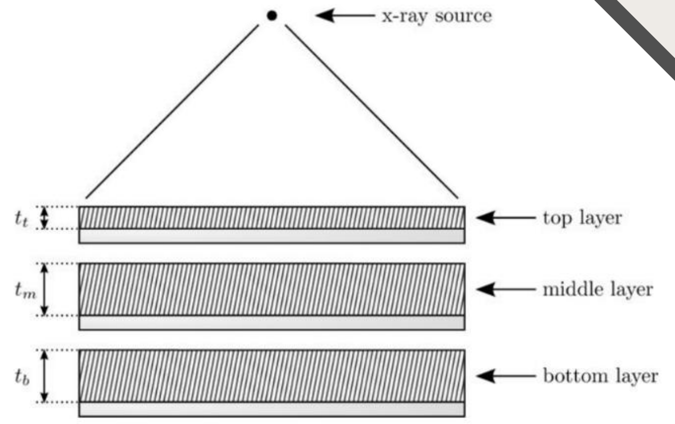
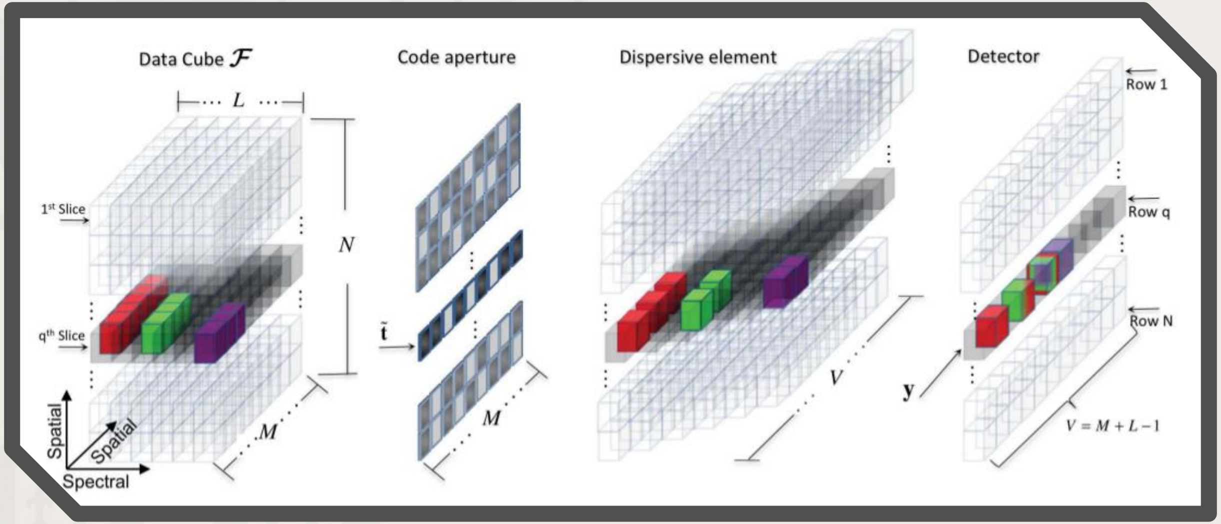


Fig 1.
Diagram depicting the three-layer design of the proposed detector, where each layer is composed of a scintillator layer of thicknesses t_t, t_m and t_b respectively coupled to a flat-panel sensor.

[1] Maurino. Proc SPIE Int Soc Opt Eng., 9783, 2016

Spectral Selectivity

Ideas



- Different photon energies will have different CASPA absorptions

[1] H. Arguello and G. R. Arce, IEEE Trans. on Img. Process., 2013.

CASPAs Resolution

Theoretical

- 511 KeV, W aperture
- Assuming aspect ratio of 50
- Magnification of 1*
- No additional noise in simulation, yet

	Pinhole (Traditional method)	**Coded Aperture** (CASPA method)
Attenuation (%)	99	6.3
Thickness (µm)	18,000	250
Resolution Max.* (µm)	720	10

High-Z radiography

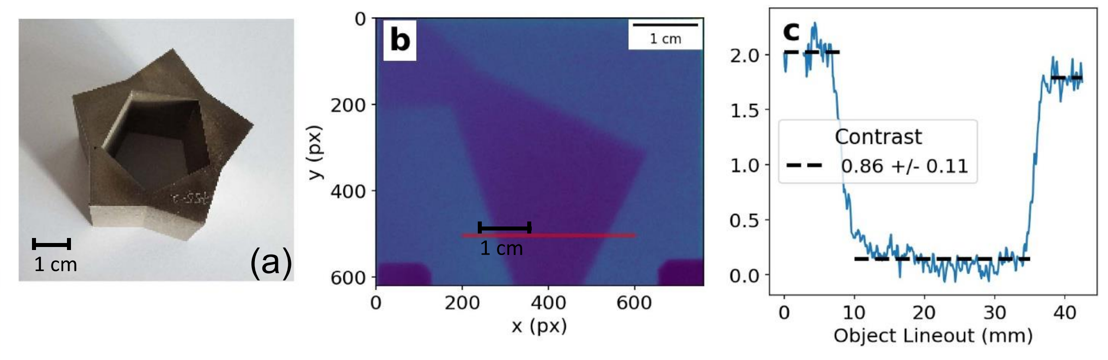
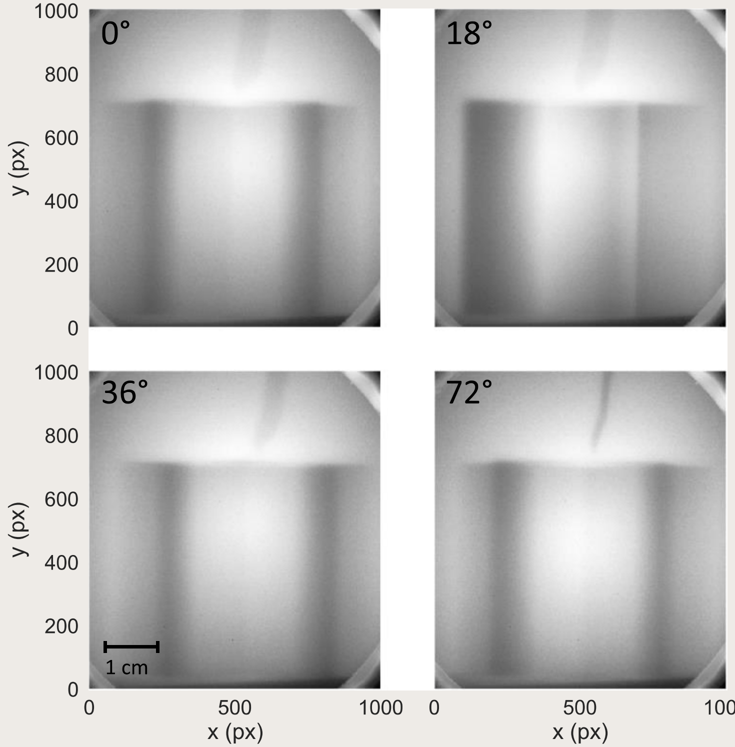
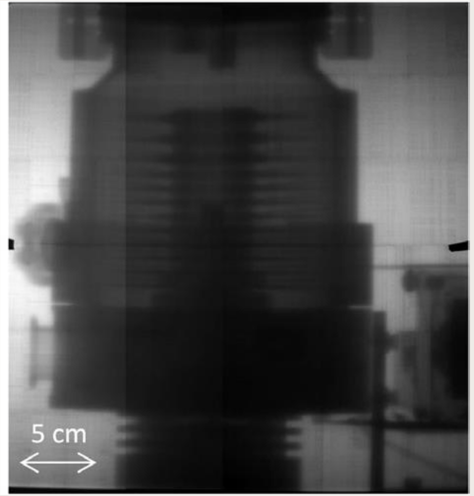


Figure 9. (a) Photograph of Inconel star object. (b) 2 mm LYSO image of star. The x-ray beam profile has been removed, and the image is the result of a pixel-wise median of 10 shots. (c) Contrast of 0.9 ± 0.1 of Inconel star object measured on the 2 mm LYSO for lineout marked on (b).

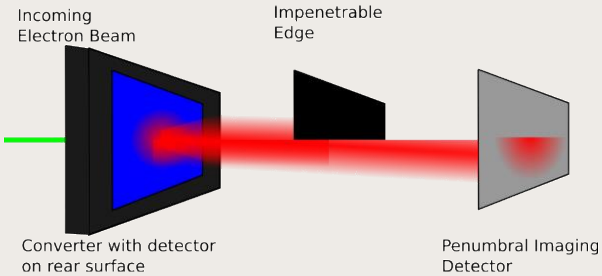


Previous Work

- Laser-plasma accelerators are able to generate MeV – GeV electrons in millimetres
- While challenging to control, they are generally:
    - femtosecond duration
    - microns in extent
- Potential for MeV photon sources for micron-resolution radiography

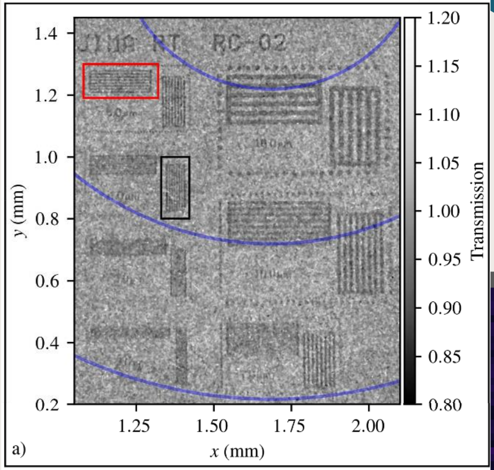


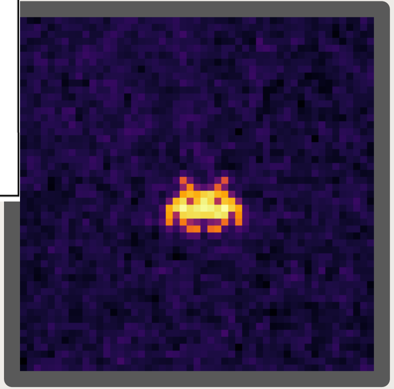
C M Brenner *et al.* 2016 *Plasma Phys. Control. Fusion* **58** 014039

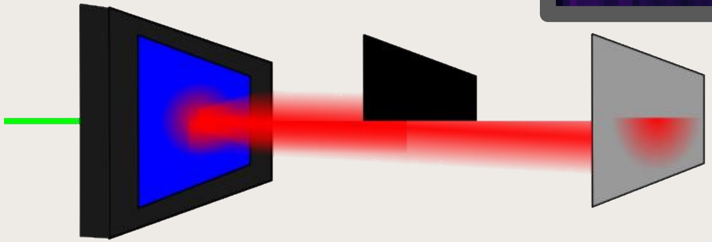


Overview

1. Laser Wakefield Acceleration
2. LWFA as a source
3. Bremsstrahlung sources
4. Imaging x-rays – the 'CASPA'
5. Extension to fusion neutrons
6. Conclusion







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