Monte Carlo applications in experimental inertial confinement fusion studies

XXII Seminar on Software for Nuclear, Subnuclear and Applied Physics

10.06.2025

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The Intense Laser Irradiation Lab @ INO-CNR, Pisa

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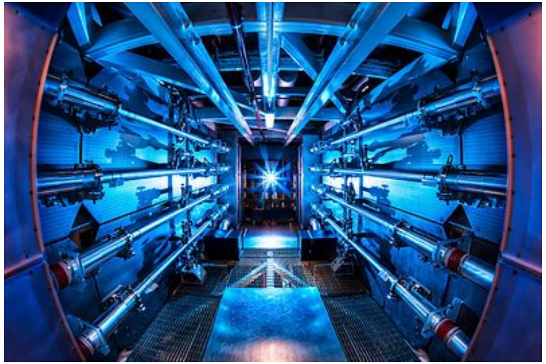
ILIL

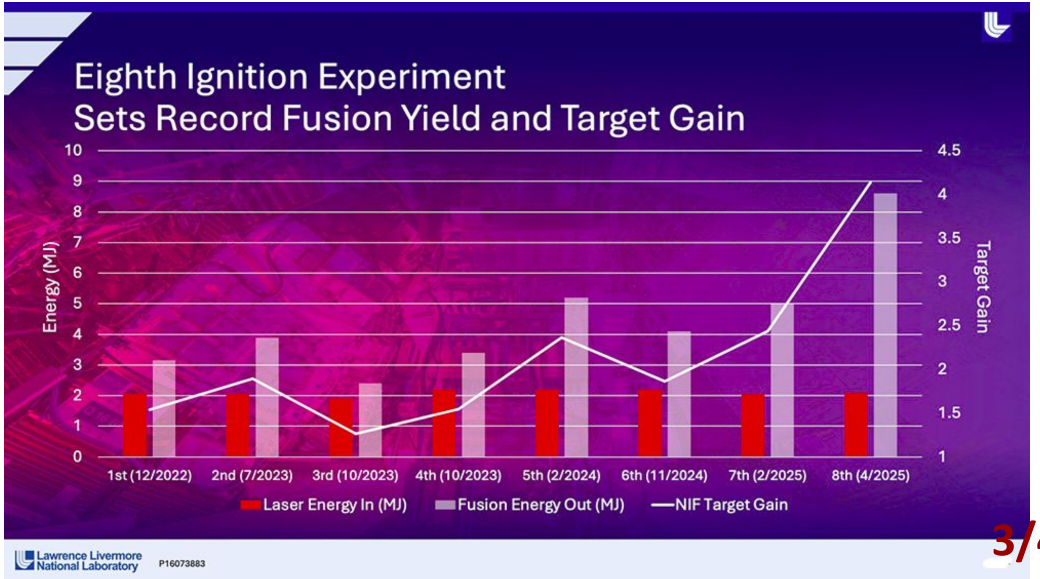
- ★ New laser sources and technology for ultra-intense lasers
- ★ Laser-plasma acceleration
- ★ Flash radiotherapy research
- ★ **Laser-plasma interaction for direct drive schemes of ICF**

Laserlab Europe

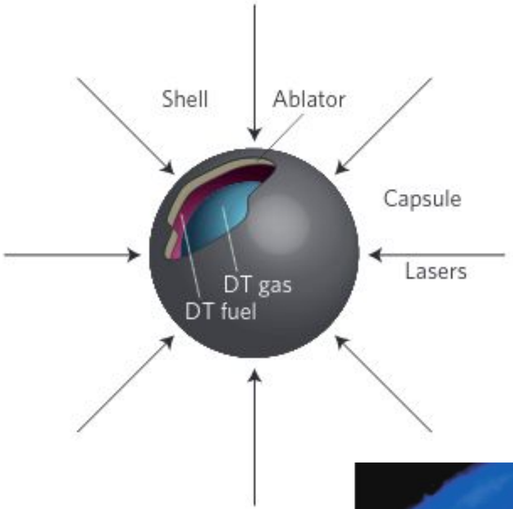
EUROfusion

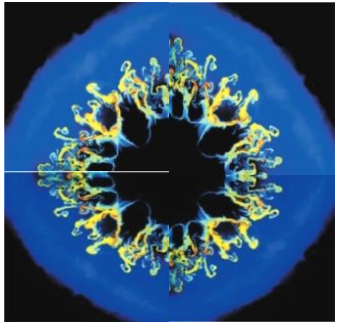
Inertial confinement fusion has been demonstrated to yield energy gain via indirect drive





In the next steps researchers are focusing on direct drive for fusion energy production





In this scheme the lasers will fire onto the fuel pellet **directly**

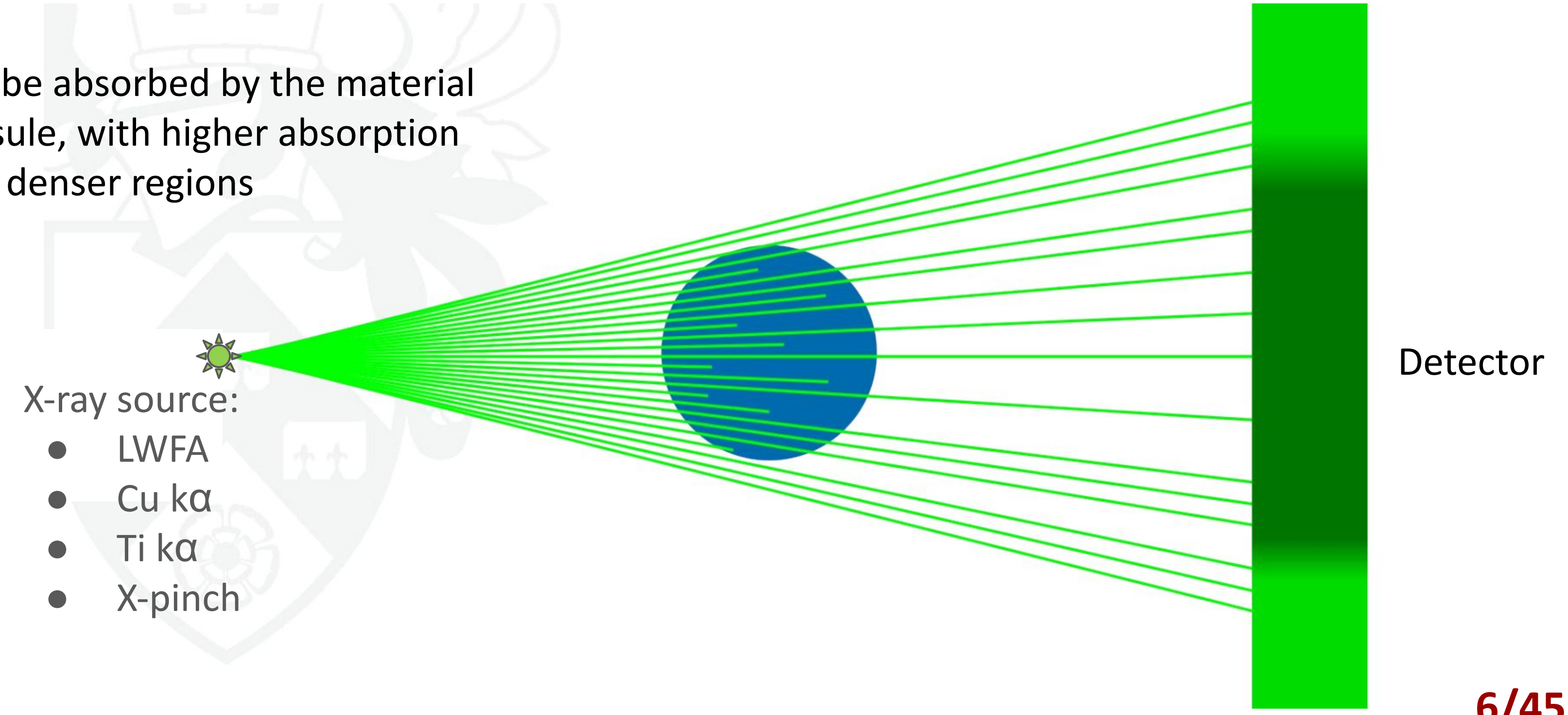
- ✅ Higher laser-target coupling efficiency
- ✅ Simpler targets (no gold hohlraum!)
- ❌ Prone to hydrodynamic instabilities
- ❌ Could require higher laser intensity
  → stronger growth of parametric instabilities

In this seminar we will cover three examples of how GEANT4 is used in ICF-relevant experiments

X-Ray Radiography and Phase Contrast Imaging

X-ray radiography techniques can be used to probe the interior of the imploding fuel capsule

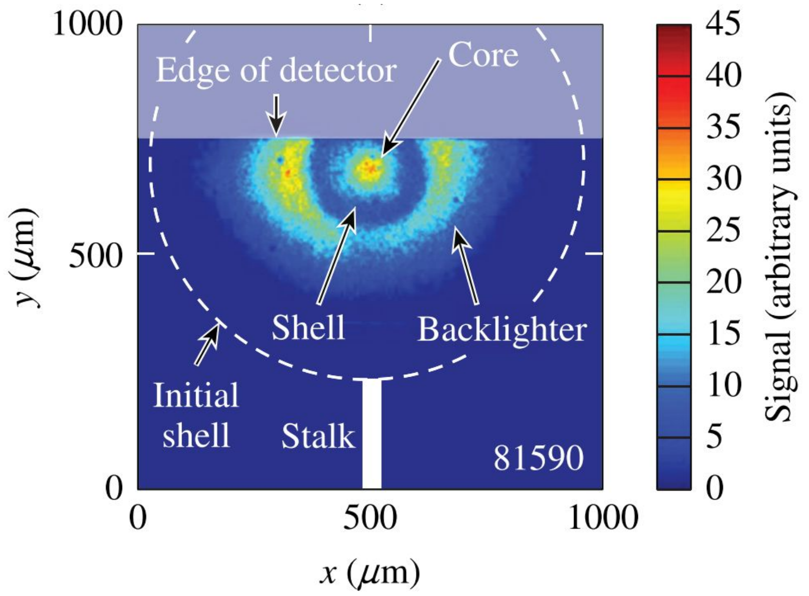
X-rays will be absorbed by the material in the capsule, with higher absorption realised in denser regions



X-ray radiography techniques can be used to probe the interior of the imploding fuel capsule

Self emission from hot core can be seen on the X-ray detector which is not related to the imaging

The ring-shaped shadow is from X-ray absorption in the dense compressed shell



We need better resolution to observe finer features around the shock

[1] C. Stoeckl *et al.*, *Phys. Plasmas* **24**, 056304 (2017)

X-rays will also experience refractive effects at density interfaces

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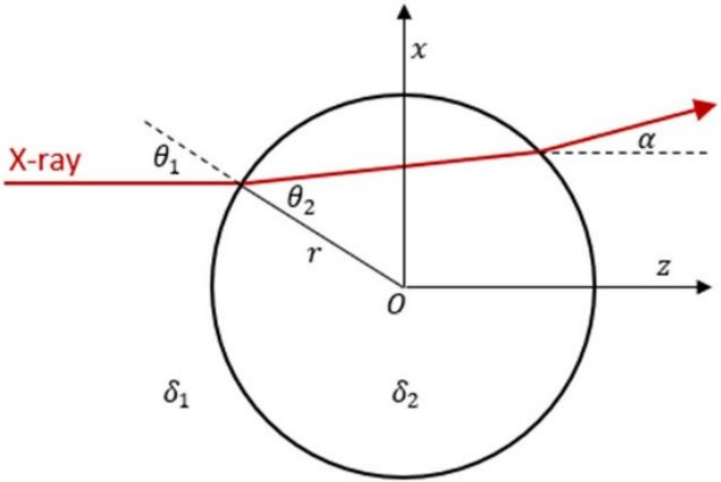
As the X-rays propagate through the target they also undergo **refraction** according to the refractive index,

$$n = 1 - \delta + i\beta$$

where the real part, $1 - \delta$, accounts for **phase shift** effects by the object, and the imaginary part β accounts for absorption by the object*

We can exploit these refractive effects to improve the **contrast** of the image

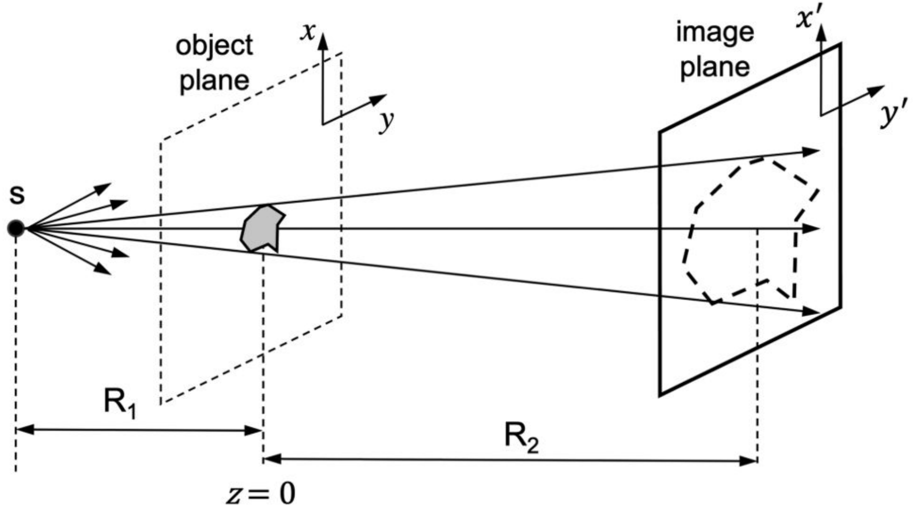


*δ is often the dominant term in ICF-relevant regimes

[1] L. Brombal *et al.*, *J. Phys. D: Appl. Phys.* **55**, 045102 (2022)

X-ray phase contrast imaging can be realised by placing the source and detector at appropriate distances

Optimal distance between the X-ray source and the object, R1, should be ≈ $s^2/2\lambda$ to allow good resolution at the image plane



[1] D. S. Montgomery, *Rev. Sci. Instrum.* **94**, 021103 (2023)

X-ray phase contrast imaging can be realised by placing the source and detector at appropriate distances

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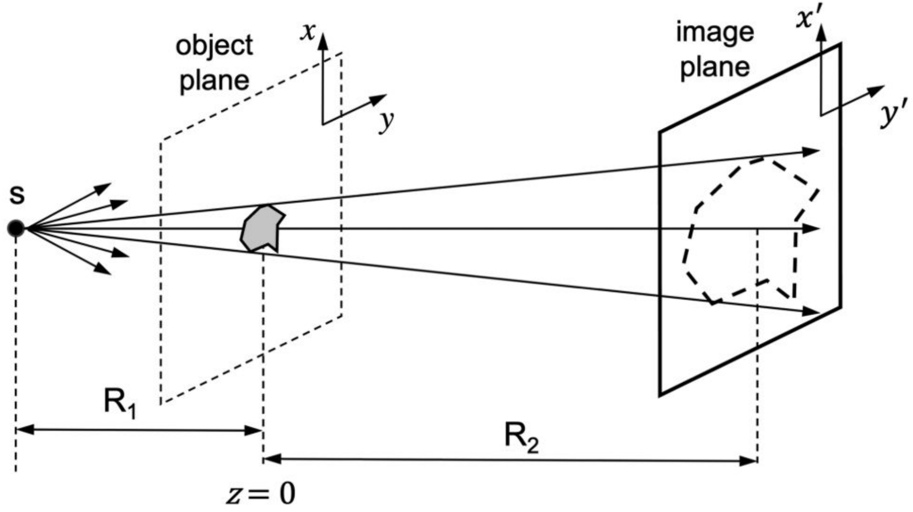
Detector should be placed at a distance R2 to satisfy

$$N_F = \frac{a^2}{\lambda}\left(\frac{R_1 + R_2}{R_1 R_2}\right) \gg 1$$

This distance is larger than that needed for X-ray absorption radiography

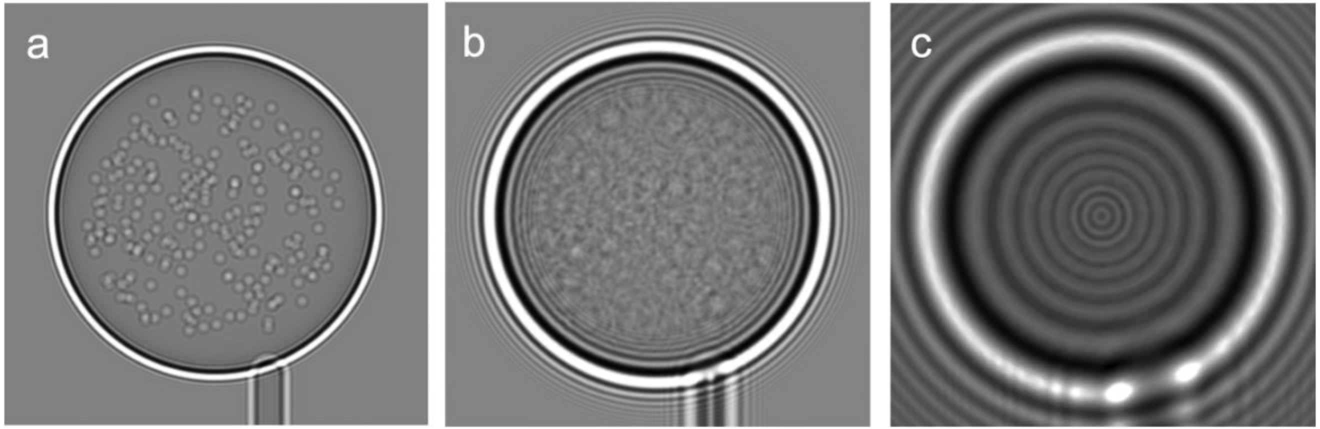


[1] D. S. Montgomery, *Rev. Sci. Instrum.* **94**, 021103 (2023)

X-ray phase contrast imaging regimes

$$N_F = \frac{a^2}{\lambda}\left(\frac{R_1 + R_2}{R_1 R_2}\right) \gg 1$$

$N_F >> 1$	$N_F \sim 1$	$N_F << 1$
Near-field Fresnel regime	Fresnel regime	far-field or Fraunhofer regime



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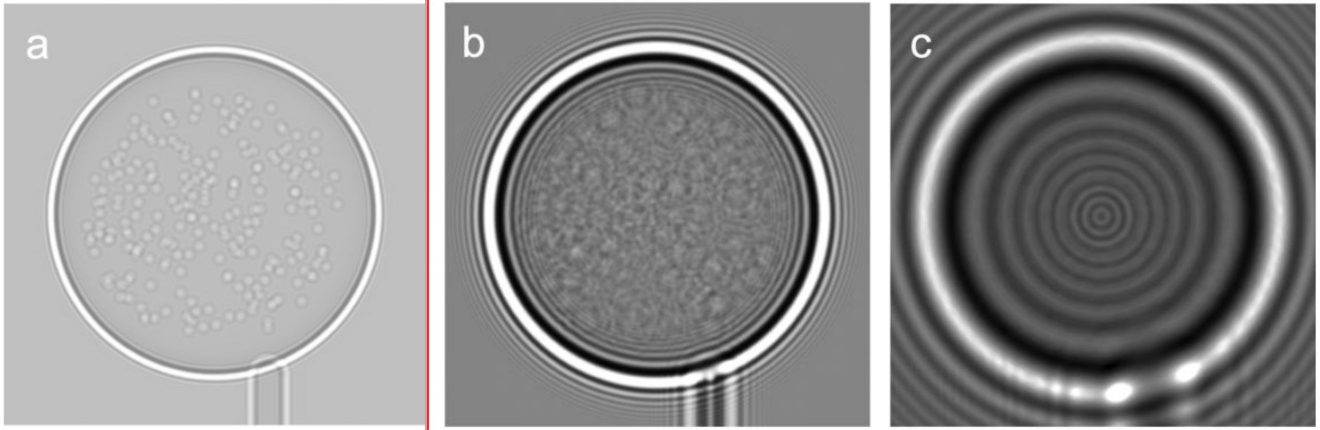

Diffractive effects are important and wave-solvers needed to reconstruct the density maps

[1] D. S. Montgomery, *Rev. Sci. Instrum.* **94**, 021103 (2023)

X-ray phase contrast imaging regimes

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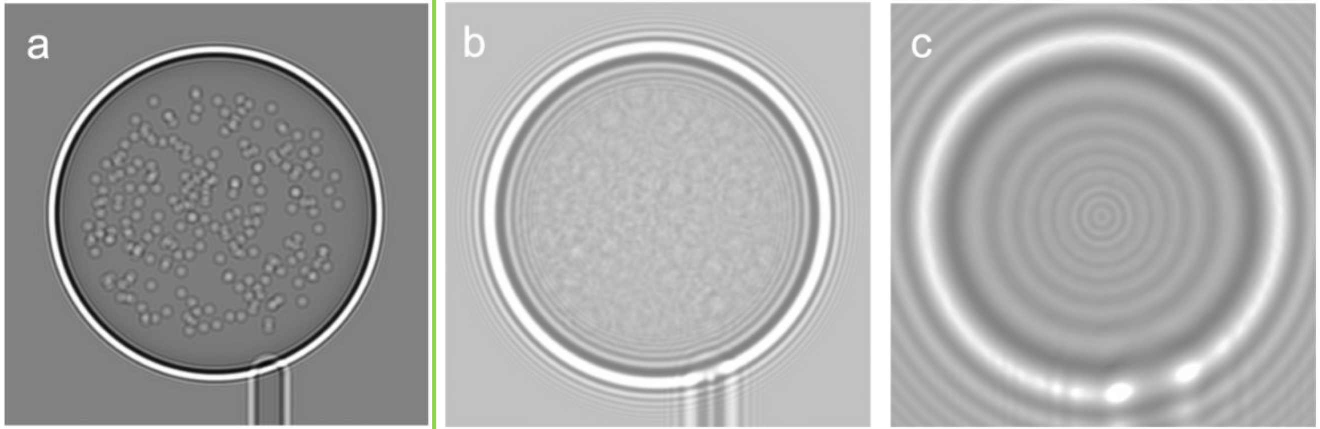
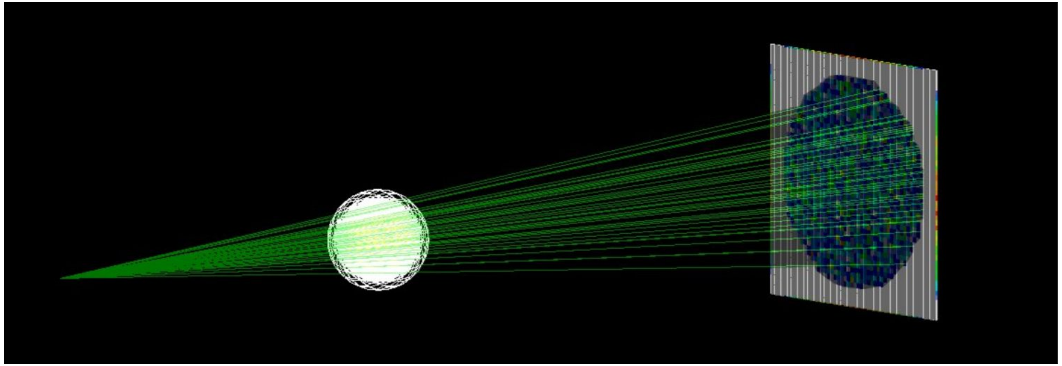


Refractive effects are dominant and physics can be reproduced using particle-tracing e.g. with GEANT4

Refractive models can be included in GEANT4

X-ray refraction process is integrated in GEANT4 through a dedicated physics list class (`G4XrayRefractionPhysics`) where the refraction process is made available to x-rays (i.e. `gamma` particles) [1]

Previous work [2] has shown this is sufficient to reproduce physics of XPCI in our regime

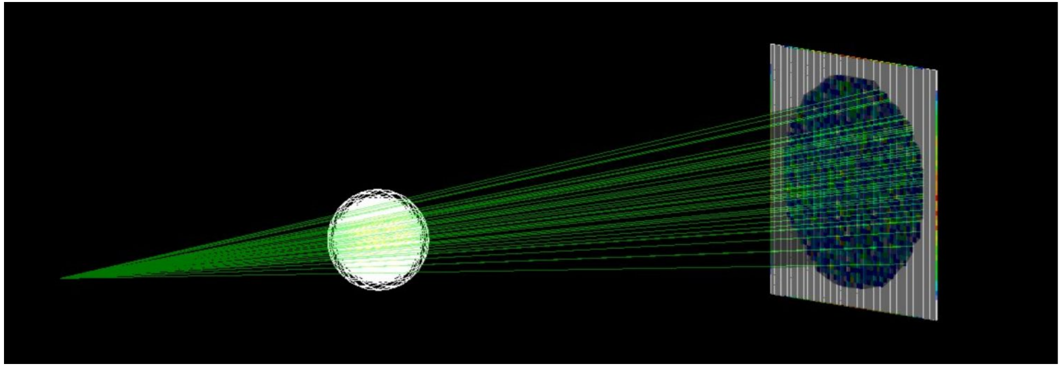


[1] L. Brombal *et al.*, *J. Phys. D: Appl. Phys.* **55**, 045102 (2022) **[2]** A. Peterzol *et al.*, Med. Phys. **32**, 3617 (2005)

Refractive models can be included in GEANT4

Refraction process is invoked at the end of each simulation step (`PostStep` point) where the material at the final position is compared with the material of the previous simulation step (`PreStep` point)

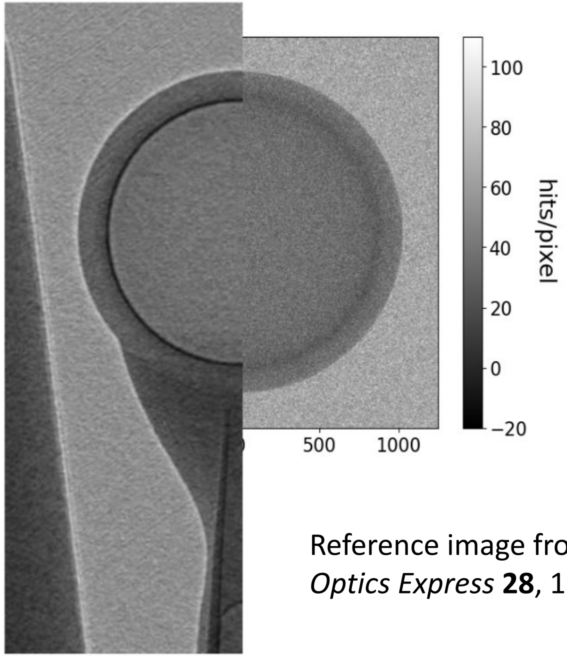
If the materials are different this indicates the X-ray has crossed an interface and the x-ray direction is updated following refraction according to Snell's Law



[1] L. Brombal *et al.*, *J. Phys. D: Appl. Phys.* **55**, 045102 (2022)

Example of image obtained by considering only absorption

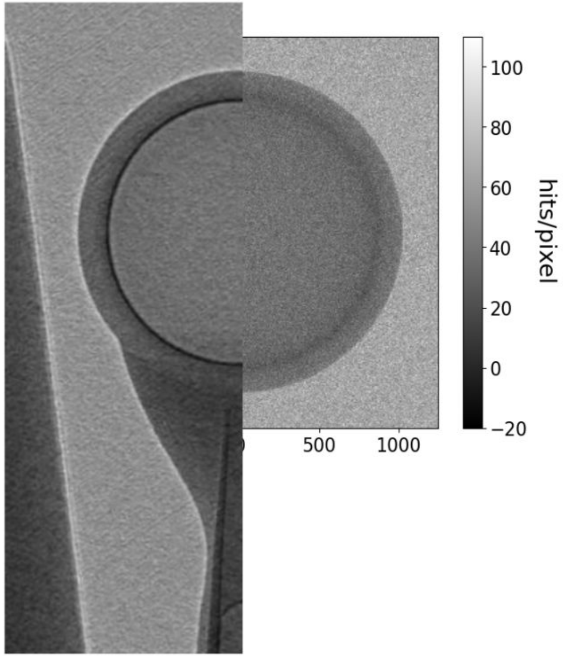
Absorption only



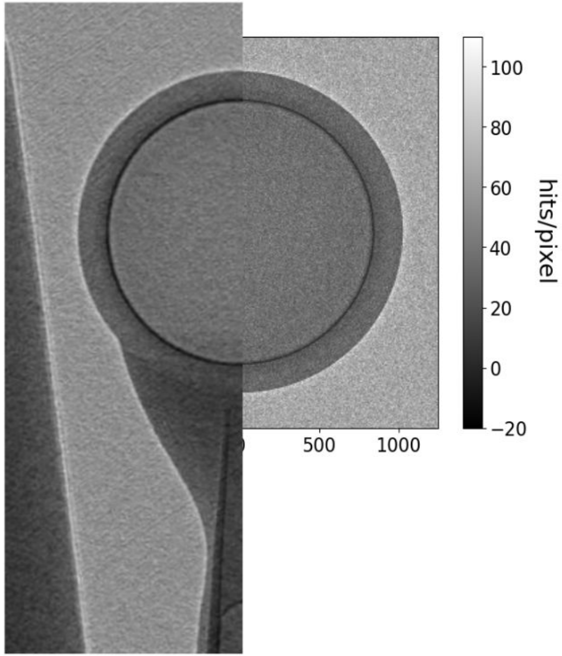
Reference image from S. Fourmaux *et al.*, *Optics Express* **28**, 13978 (2020)

Improvement in resolution is realised by including refractive effects

Absorption only



Absorption + refraction

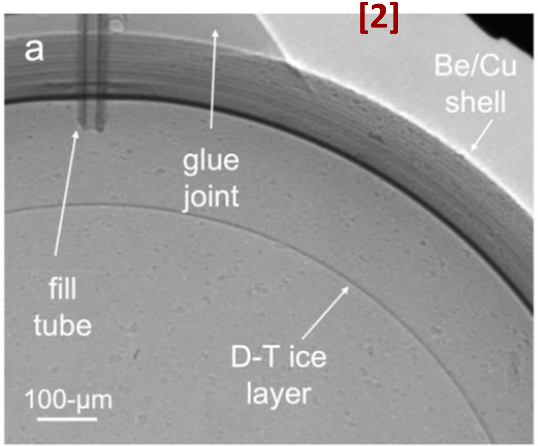


Next steps for XPCI modelling

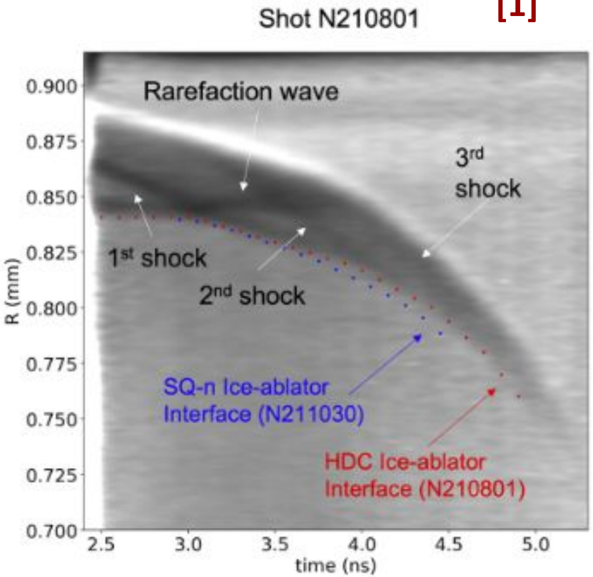
Initial experimental results of XPCI in ICF applications are promising

Producing more synthetic data can help with designing future XPCI setups and experiments

[2]



[1]



[1] A. Do *et al.*, PRL **129**, 215003 (2022)
[2] D. S. Montgomery *et al.* J. *Phys. IV France* **133**, 869 (2006)

Bremsstrahlung measurements of hot electrons

For the best chances of implosion we want the laser energy to be absorbed collisionally

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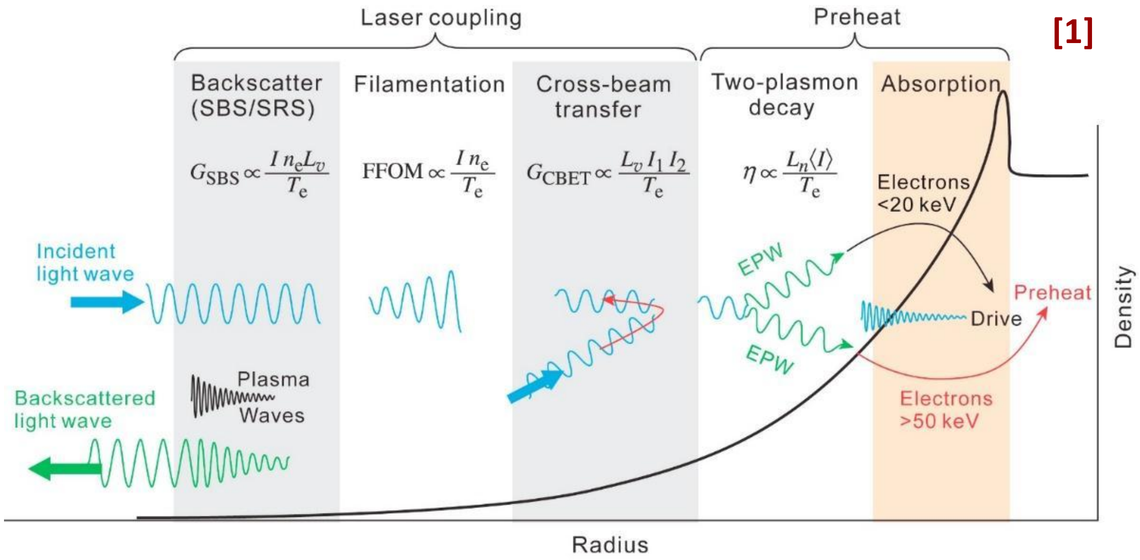
The laser is absorbed into the plasma via the **inverse Bremsstrahlung**, or **collisional absorption**, process

Many other processes can occur as the laser interacts with the plasma…

[1]



[1] D. H. Froula *et al.*, *PPCF* **54**, 124016 (2012)

Hot electrons can be created via the SRS and TPD processes

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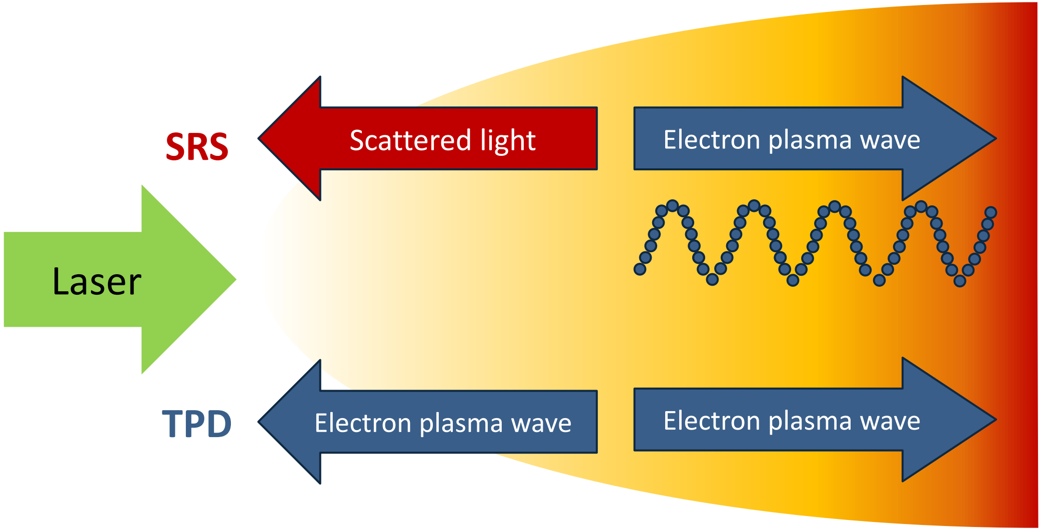
The **Stimulated Raman Scattering** (SRS) and **Two Plasmon Decay** (TPD) processes excite electron plasma waves

These waves can be damped to produce a population of suprathermal, **hot electrons**

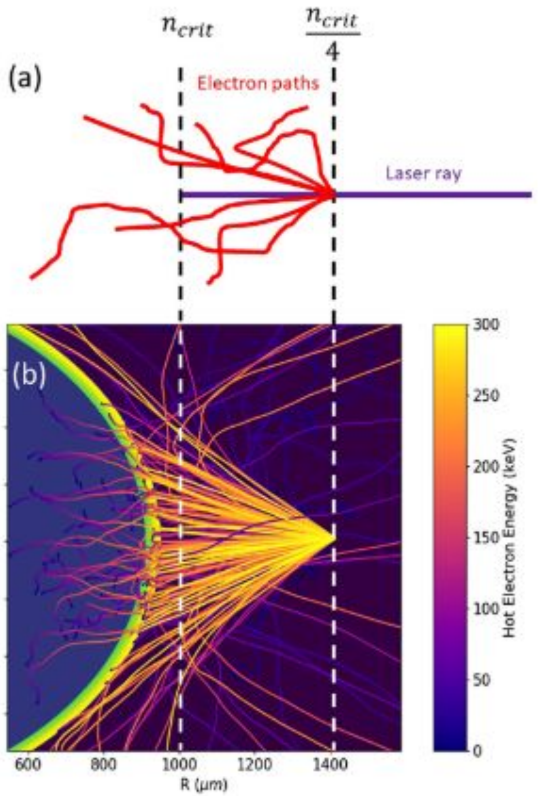


Implosion efficiency can be affected by these hot electrons

Less energy is required to compress fuel that is kept cold due to its higher compressibility

These hot electrons can travel ahead of the shock front and deposit their energy in the uncompressed fuel

This will heat the interior fuel and make it more difficult to compress (and ignite)

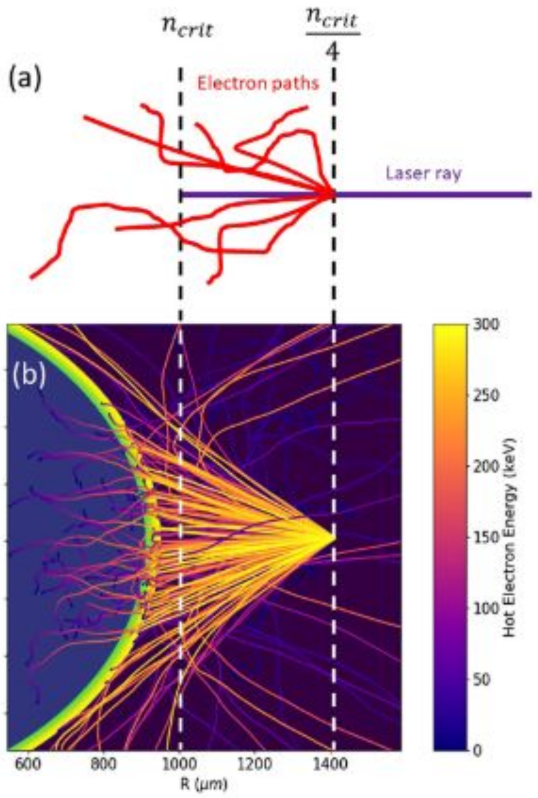


[1] D. Barlow *et al.*, *Phys. Plasmas* **29**, 082704 (2022)

Implosion efficiency can be affected by these hot electrons

Other work suggests under carefully controlled conditions, e.g. timing of the hot electron generation and energy spectrum of the electrons, they can be stopped in the dense plasma and actually aid the compression

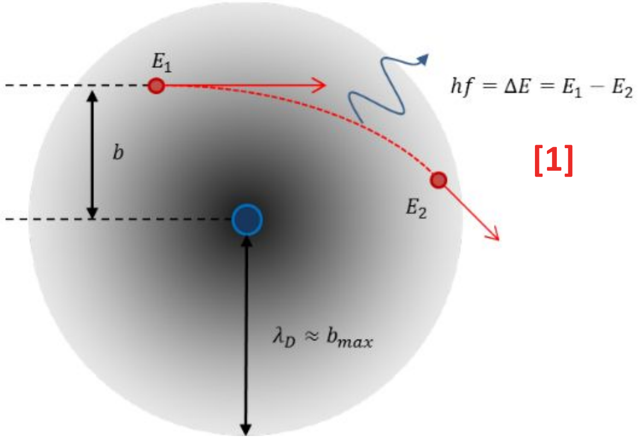
In the experimental conditions considered here, most of the hot electrons are stopped inside the target → how do we measure them?



[1] D. Barlow *et al.*, *Phys. Plasmas* **29**, 082704 (2022)

Bremsstrahlung emission can be used to (indirectly) study hot electrons

As the hot electrons travel through the target they induce **Bremsstrahlung radiation**



[1]

[1] C. D. Armstrong, PhD thesis (2019)

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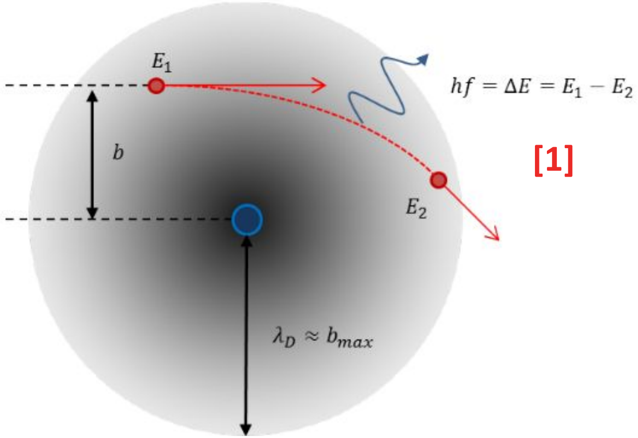
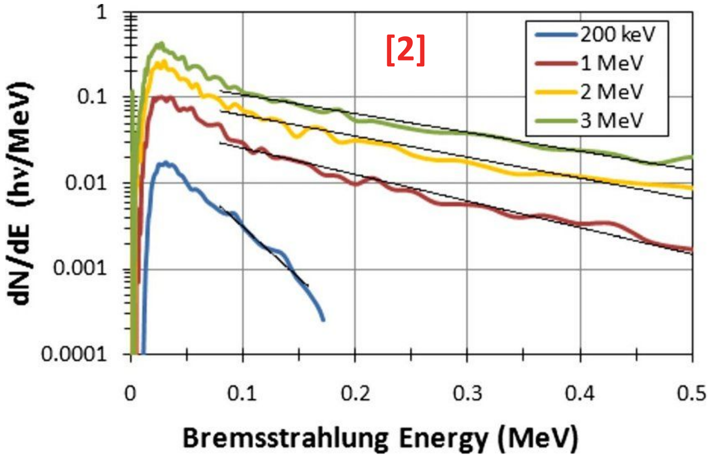


The resultant X-ray spectrum is dependent on the **temperature** of the electrons, which defines the electron energy spectrum



[1] C. D. Armstrong, PhD thesis (2019)
[2] C. D. Chen *et al.*, *Phys. Plasmas* **16**, 082705 (2009)

Filter-based detectors can be used to measure the emitted X-ray spectrum

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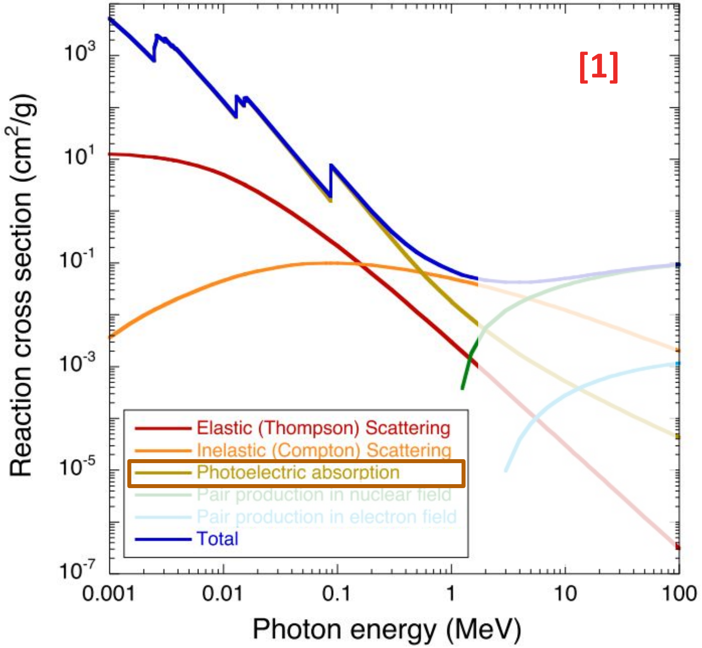
Emitted X-ray photons are attenuated as they propagate through a given filter

Lower energy photons undergo more collisions (and ultimately absorption) than higher energy photons



[1] R. H. H. Scott *et al*,. *Rev. Sci. Instrum.* **84**, 083505 (2013)

Filter-based detectors can be used to measure the emitted X-ray spectrum

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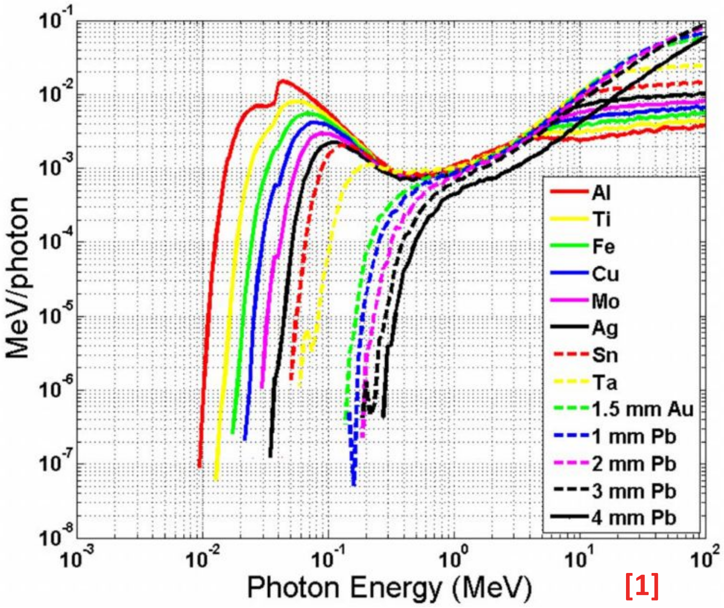
For increasing material **Z** and **thickness** the number of collisions increases

→ by tuning filters it is possible to cut-off a particular X-ray photon energy that can propagate through the filter

Measuring and comparing the photon number behind two different filters can inform how many X-ray photons are within that energy "bin"



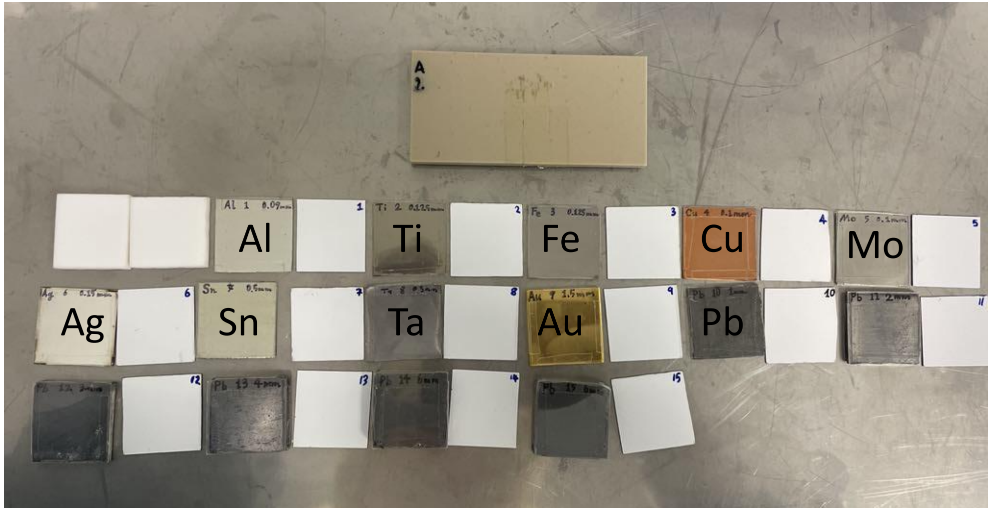
[1]

[1] C. D. Chen *et al.*, *Rev. Sci. Instrum.* **79**, 10E305 (2008)

Bremsstrahlung cannon detectors have been designed to measure the X-ray spectrum

Stack of filters of increasing attenuation

Image plate placed behind each one to measure the propagating X-ray photons

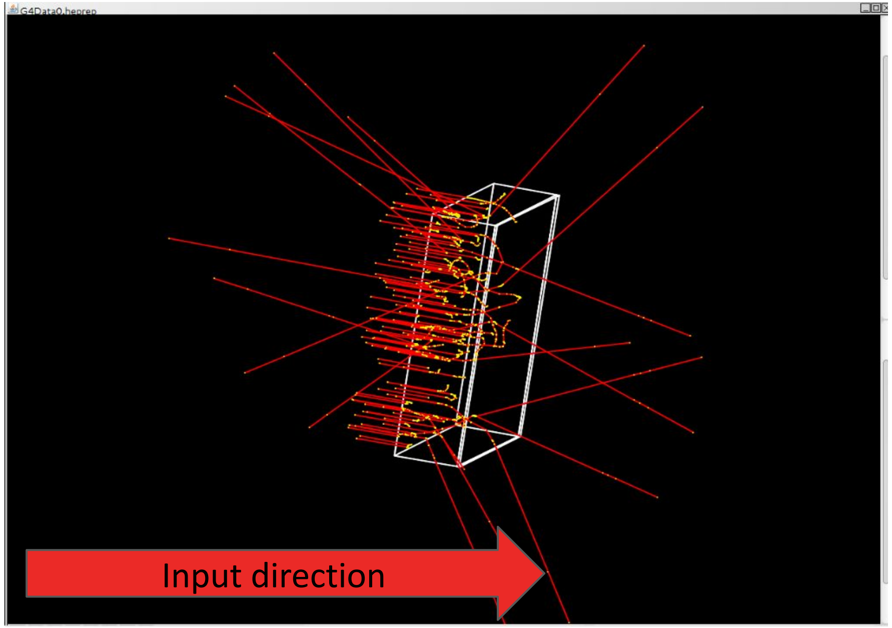


A sample hot electron population is modelled in GEANT4 and sent into the target

Electron energies are sub-MeV (~ 10's keV)

"`Low Energy Livermore Model`" physics package which includes:

- Scattering (Compton/Rayleigh)
- Absorption (photoelectric and others)
- Pair production
- Ionisation
- K-alpha production
- Bremsstrahlung emission

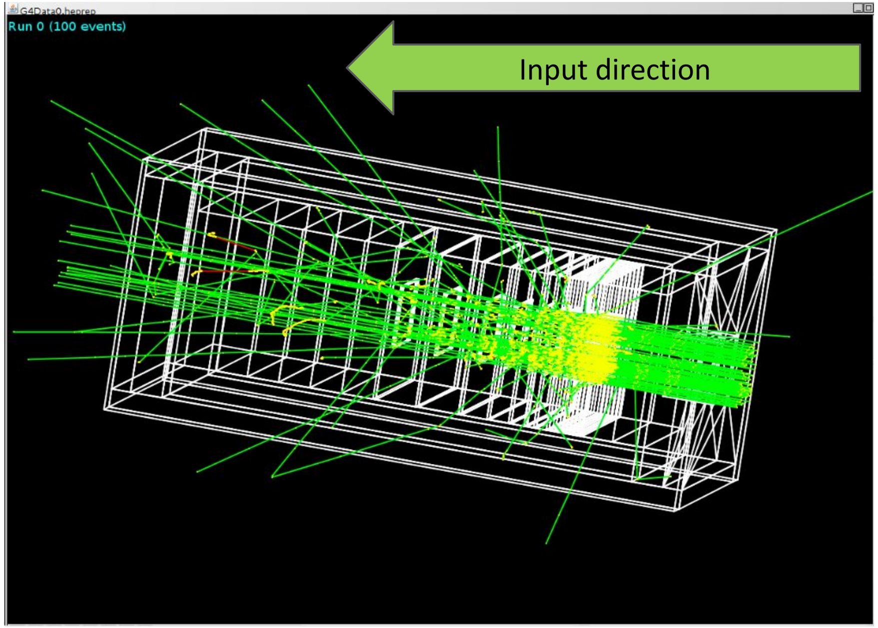


Propagation of the photon distribution through the detector is also modelled in GEANT4

Resulting X-ray photon distribution (predominantly bremsstrahlung emission) is retrieved

Photon distributions are parameterized and used separately as input to GEANT4 simulations of the bremsstrahlung filter set

Deposited energy per simulated photon in each image plate active layer is measured in these simulations



Parameter scan is performed to infer the hot electron spectrum

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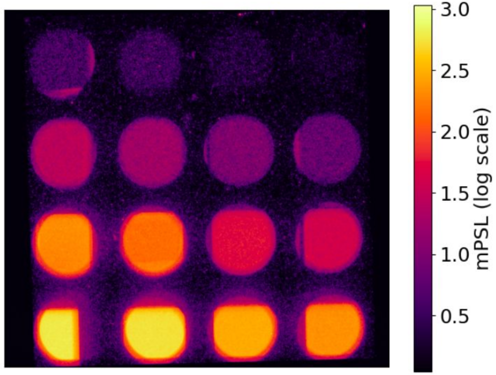
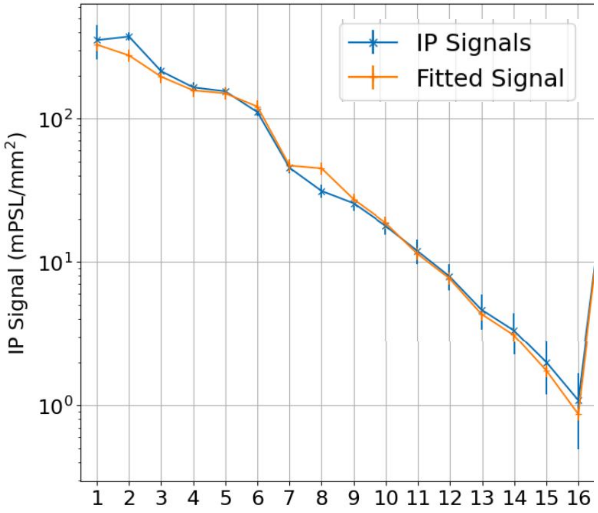
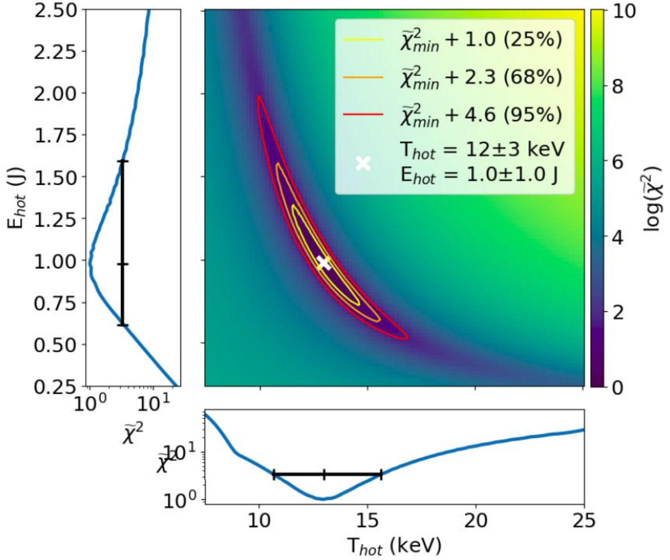
Signal recorded on image plates



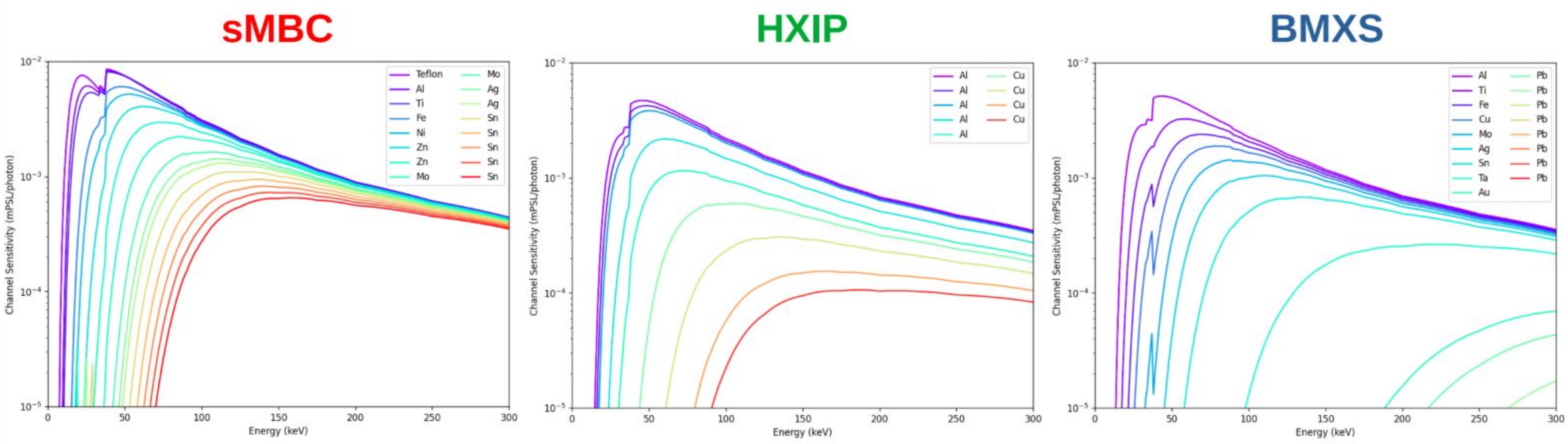


Parameter scan of electron temperature and energies



M. Khan, talk at DDFIW (2024)

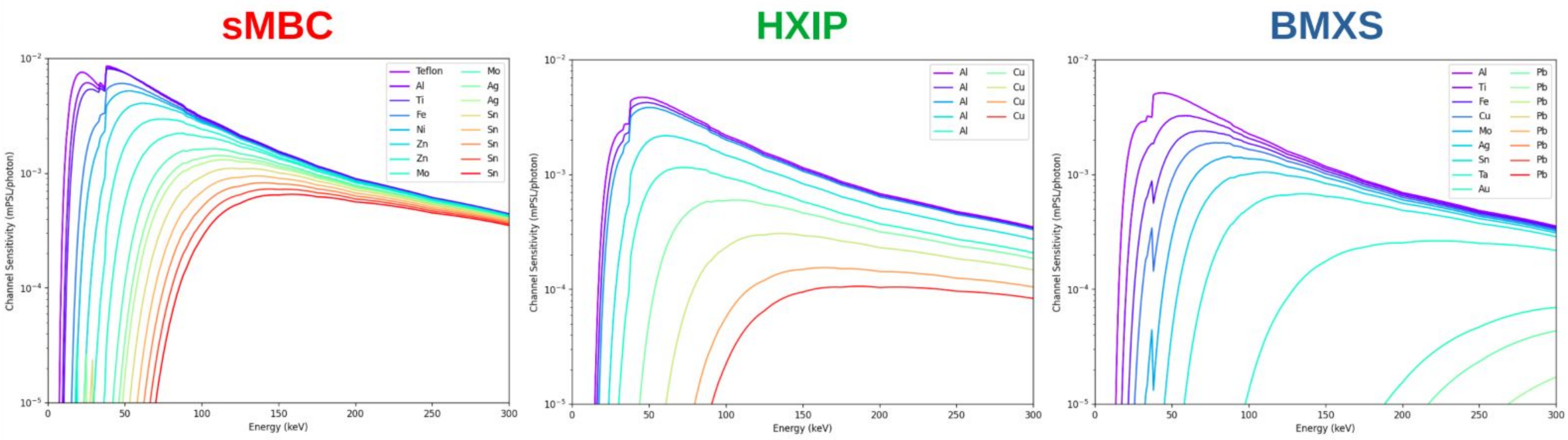
GEANT4 is also used for designing the bremsstrahlung detectors



Response functions of channels is a combination of filter attenuation and IP sensitivity

M. Khan, talk at DDFIW (2024)

GEANT4 is also used for designing the bremsstrahlung detectors

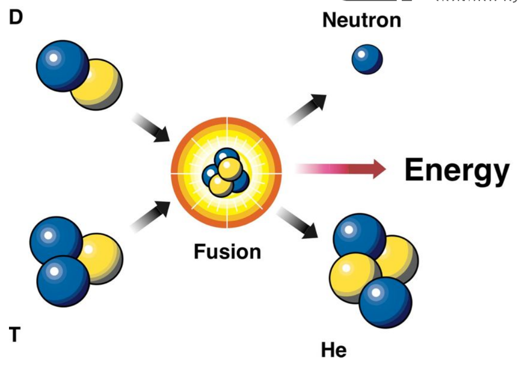


Simulations are utilised to design an optimal filter set for resolving a chosen energy range (for us < 150 keV photons for ~ 10 keV electrons)

M. Khan, talk at DDFIW (2024)

Neutron Time-of-Flight Detectors

Fusion-generated neutrons exit the fuel pellet with a spectrum of energies



Neutrons are generated within the fusing plasma and **scatter** while exiting through the dense fuel layer

The **primary** unscattered neutron energy spectrum contains information on the state of the fusing hot spot from which they were generated

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He}^4\,(3.53\ \mathrm{MeV}) + \mathrm{n}\,(14.06\ \mathrm{MeV})\,.$$

The **scattered** neutron spectrum contains information about the dense fuel layer [1]

$$\mathrm{n} + \mathrm{D} \rightarrow \mathrm{n}'\,(1.56 - 14.06\ \mathrm{MeV}) + \mathrm{D}'\,(<12.50\ \mathrm{MeV})\,,$$
$$\mathrm{n} + \mathrm{T} \rightarrow \mathrm{n}'\,(3.53 - 14.06\ \mathrm{MeV}) + \mathrm{T}'\,(<10.53\ \mathrm{MeV})\,.$$

[1] O.M. Mannion *et al.*, *Nuclear Inst. and Methods in Physics Research, A* **964**, 163774 (2020)

Analysis of the neutron energy spectrum components gives insight into the fusion physics

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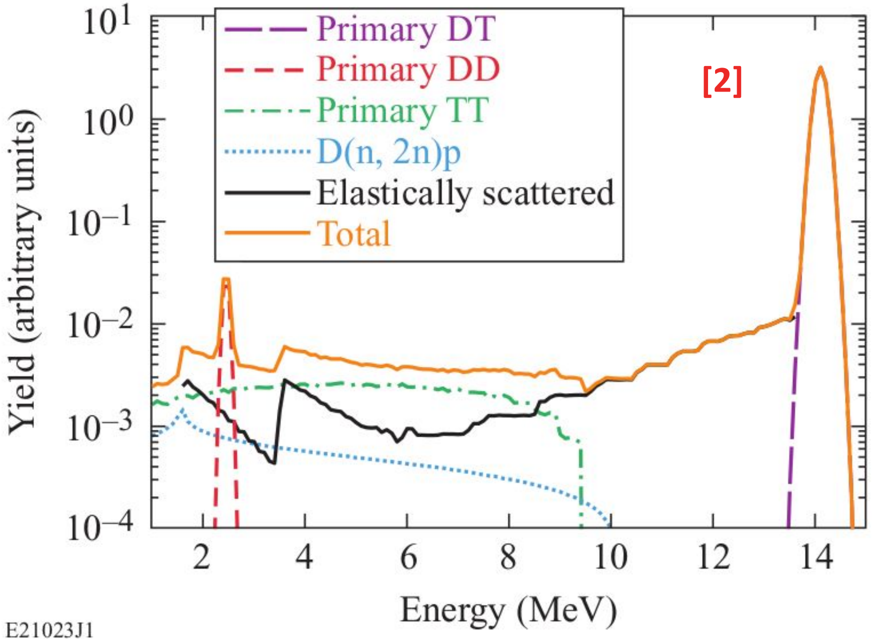
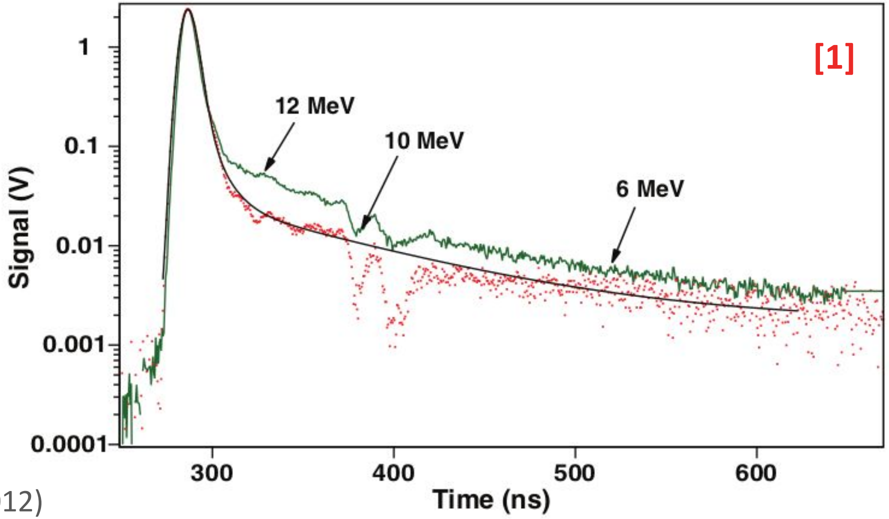
- ★ Hot spot velocity
- ★ Yield
- ★ "Apparent" ion temperature (Tion) from analysis of the variance of the neutron kinetic energy distribution
- ★ Compressed fuel, ρr, through measurement of the downscatter ratio (DSR), which compares the integral between 10 - 12 MeV with the integral between 13 - 15 MeV [1]



[1] A. S. Moore *et al.*, *Rev. Sci. Instrum.* **92**, 023516 (2021)
[2] C. J. Forrest *et al.*, *Rev. Sci. Instrum.* **83**, 10D919 (2012)

Principle of a neutron time-of-flight (nTOF) detector

The arrival time of the neutrons (**time of flight**) to a detector at a given distance d is a function of its velocity (thus, kinetic energy) and the distance to the detector



[1] M. Gatu Johnson *et al.*, *Rev. Sci. Instrum.* **83**, 10D308 (2012)

Principle of a neutron time-of-flight (nTOF) detector

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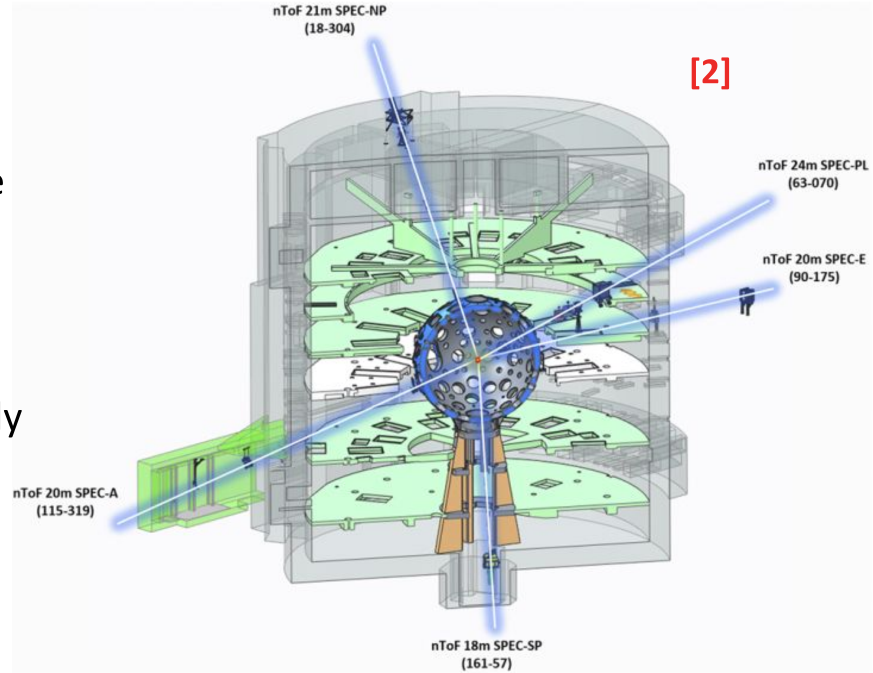
Assumes an **instantaneous point-source** of neutrons which is satisfied for a detector placed at a sufficiently large distance (10-20 m)

Neutrons are detected using a **scintillating material**



[2] A. S. Moore *et al.*, *Rev. Sci. Instrum.* **92**, 023516 (2021)

Understanding the time-of-flight detector signal

$$S(t) = \left[\frac{dN}{dE} T(E) L(E) \frac{dE}{dt}\right] \otimes IRF(t) + bcg(t)$$

Transmission term to account for attenuation through air

Neutron energy-dependent **light output** of the scintillator

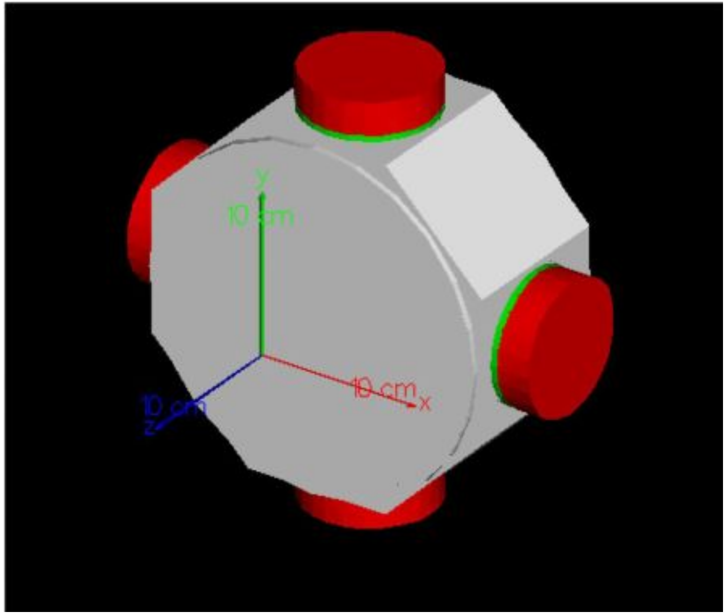
Instrument response function:

1. Scintillation decay time
2. Broadening introduced by the finite scintillation photon travel times before detection
3. Broadening introduced by the finite transit time of the incident neutrons

Background from neutrons scattering e.g. inside target chamber

[1] D. Patel *et al.*, *J. Appl. Phys*. **137**, 165903 (2025)

Modelling of the nTOF detectors



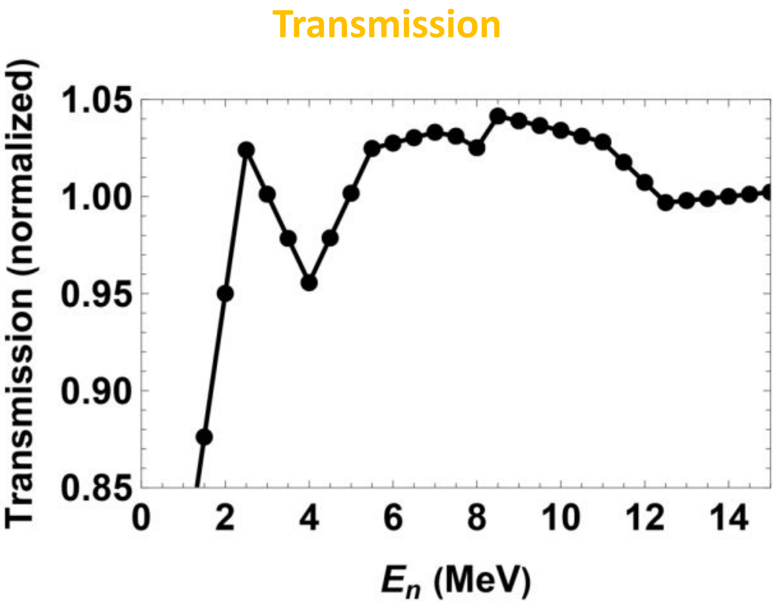
`QGSP-BIC-HP` physics model for modelling high-precision neutron scattering/transport

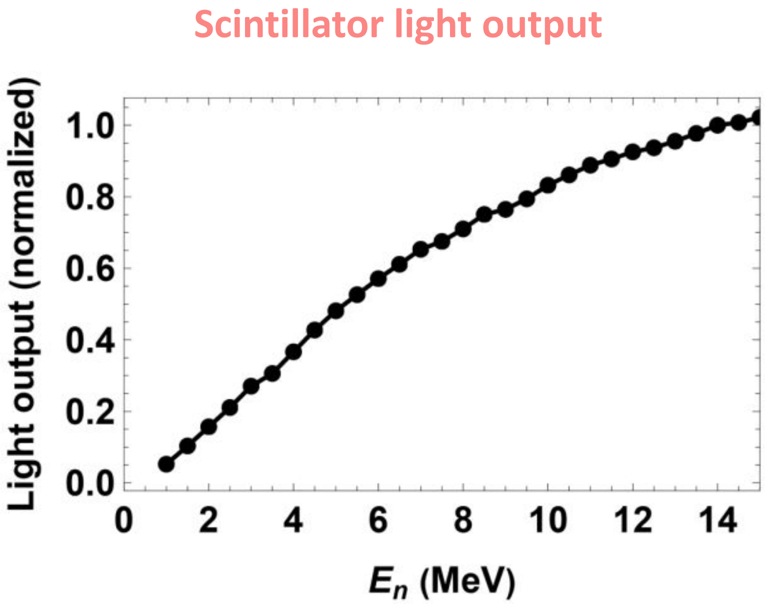
Includes:

- Cherenkov effect
- Scintillation
- Absorption
- Rayleigh scattering
- Boundary scattering
- Mie scattering

[1] D. Patel *et al.*, *J. Appl. Phys*. **137**, 165903 (2025)

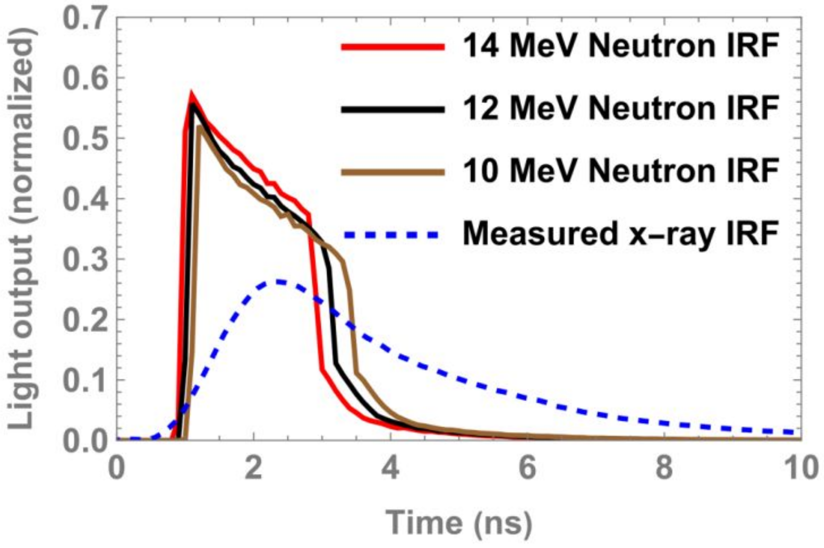
GEANT4 simulations to help deconvolve the measured nTOF signal





[1] D. Patel *et al.*, *J. Appl. Phys*. **137**, 165903 (2025)

Instrument response function



Measurement of ps X-ray source:

1. Scintillation decay time
2. Broadening introduced by the finite scintillation photon travel times before detection

GEANT4 simulations:

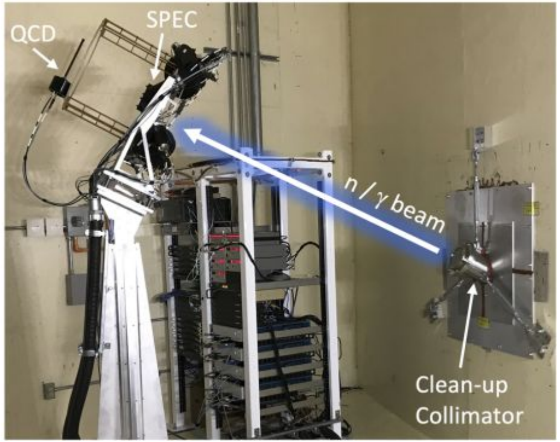
3. Broadening introduced by the finite transit time of the incident neutrons

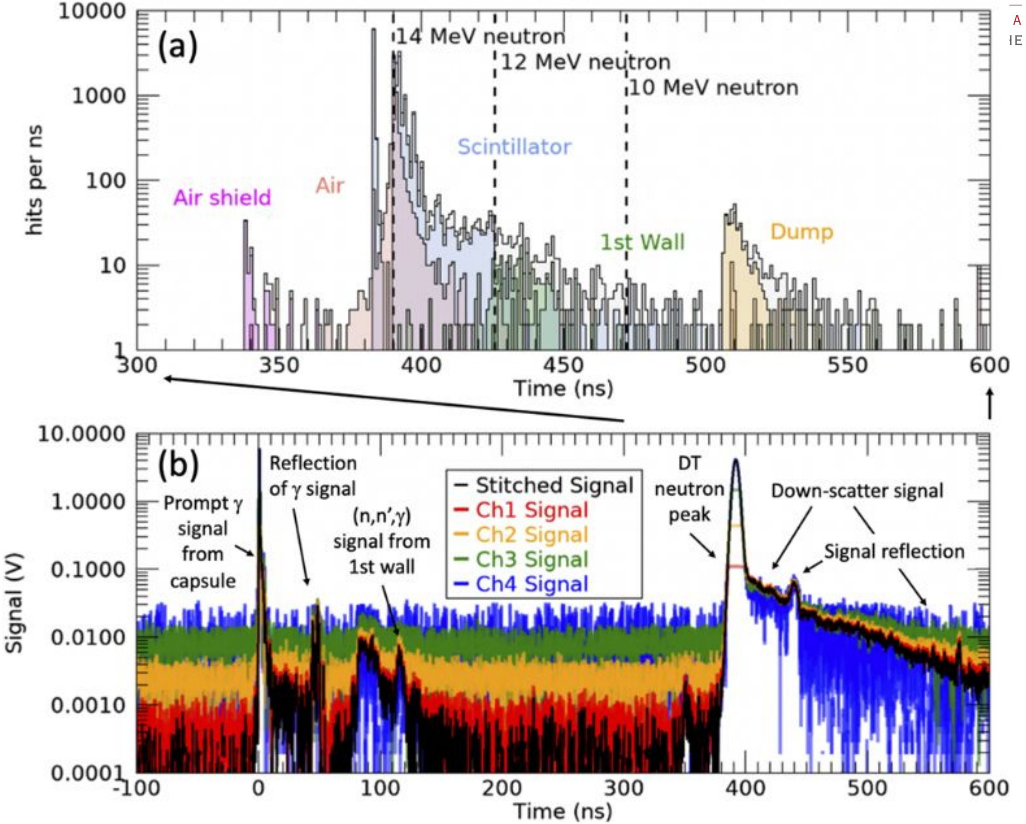
Here the simulations demonstrated the first 2 terms dominate the signal broadening

[1] D. Patel *et al.*, *J. Appl. Phys*. **137**, 165903 (2025)

Background signal

Detector needs to be designed to reduce background contributions, for example by adding a collimator





[1] A. S. Moore *et al.*, *Rev. Sci. Instrum.* **92**, 023516 (2021)

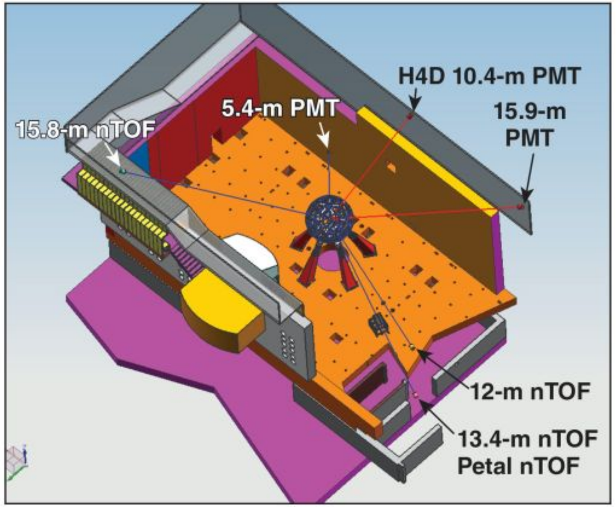
Next steps for nTOF detection?

Measurements of neutron spectra form an integral part of ICF implosion measurements

Improvements are ongoing to push the diagnostics capabilities [1]:

- Increase the dynamic range and precision of typical nToF measurements
- Develop time-resolved neutron measurements resolved in time through the duration of the burn
- Develop detectors optimized for other energy ranges in the neutron spectrum

[1] A. S. Moore *et al.*, *Rev. Sci. Instrum.* **94**, 061102 (2023)



Monte Carlo simulations will remain important for helping define active medium choices and detector placement and shielding

Summary

We discussed three examples of where GEANT4 simulations are applied in ICF research:

- ★ X-ray Phase Contrast Imaging of imploding capsules
- ★ Measurements of hot electron temperature via Bremsstrahlung detectors
- ★ Neutron time-of-flight detectors to obtain neutron spectra and information on fusion performance

ICF experiments (in particular implosions) do not occur very often and we need to be assured these diagnostics will work!

Monte Carlo simulations are a powerful tool for designing ICF diagnostics and interpreting data

Thanks to:

Calum Freeman:
XPCI

Matt Khan:
BSC detector

And to you for your attention!