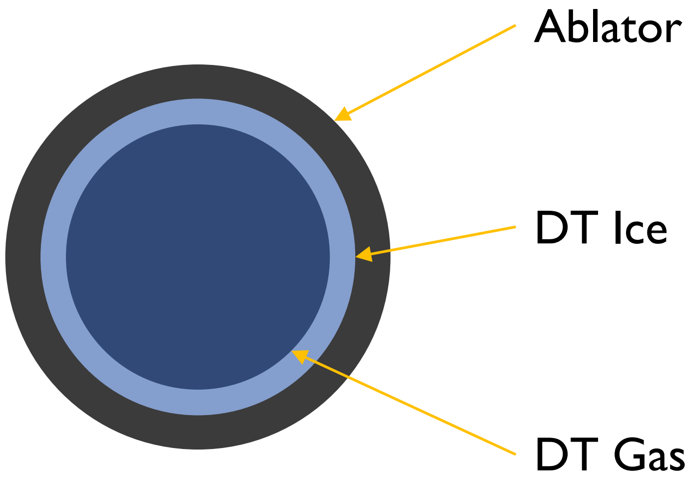
SYNTHETIC RAY DIAGNOSTICS FOR LASER-FUSION SIMULATIONS

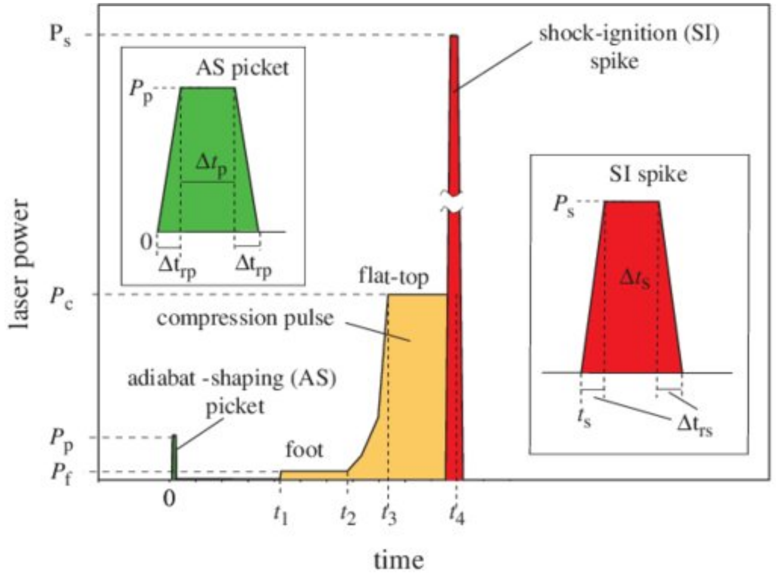
CFSA SEMINAR 15TH APRIL

ALUN REES

1. MOTIVATION

- UK heavily invested in pursuing ICF through the Shock-Ignition scheme
- ICF capsules are around a 0.6-2 mm in diameter (size of a pinhead or ball bearing)

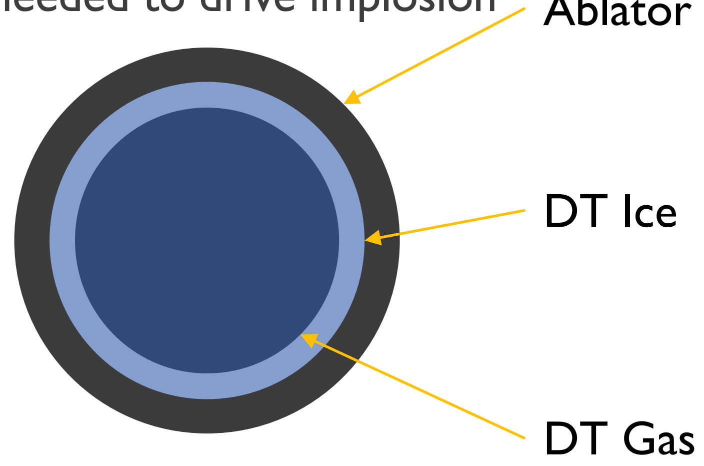




[1] Atzeni, S. et al. (2013). Energy and wavelength scaling of shock-ignited inertial fusion targets. New Journal of Physics. 15. 045004. 10.1088/1367-2630/15/4/045004.

1. MOTIVATION

- UK heavily invested in pursuing ICF through the Shock-Ignition scheme
- ICF capsules are around a 0.6-2 mm in diameter (size of a pinhead or ball bearing)
- Ablator needed to drive implosion



$$v_{shell} = v_e \ln \frac{m_0}{m_f} \qquad (1)$$

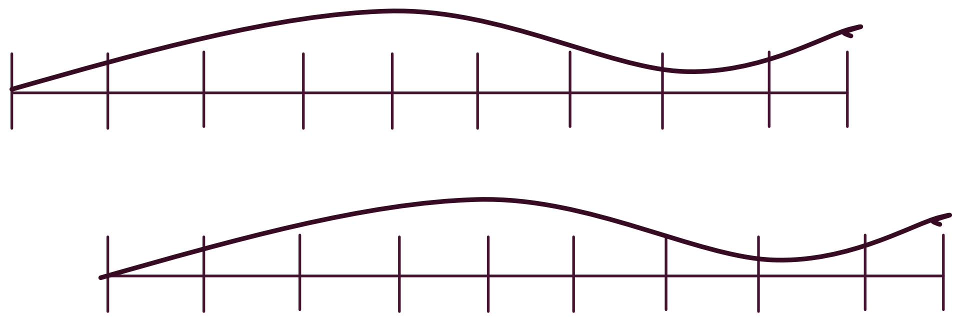
1. MOTIVATION

- UK heavily invested in pursuing ICF through the Shock-Ignition scheme (Direct-Drive)
- Experiments conducted at Omega laser facility in USA
- Very limited experimental time so need to optimise usage
- Therefore perform simulations to guide experiments
- Synthetic diagnostics can find optimal parameters for experimental diagnostics:
  - Position
  - Timing
  - Energy
  - Filters

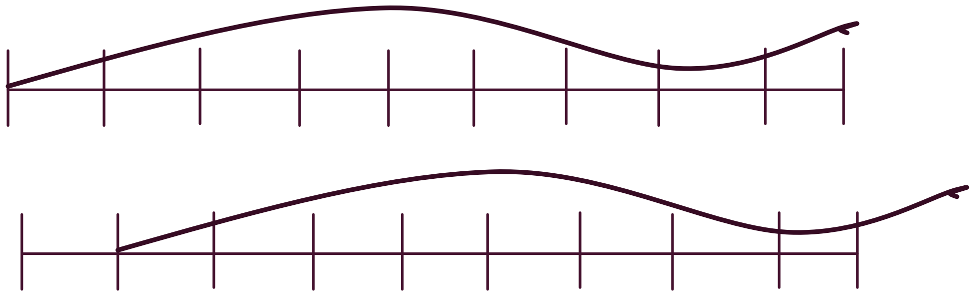
2. THE ODIN GRID

- 2D uses R-Z geometry (but can do X-Y)
- ALE code:
  - Starts off as Lagrangian
  - Remaps and locks out once sufficiently distorted
  - Eulerian scheme from then on

Lagrangian:



Eulerian:



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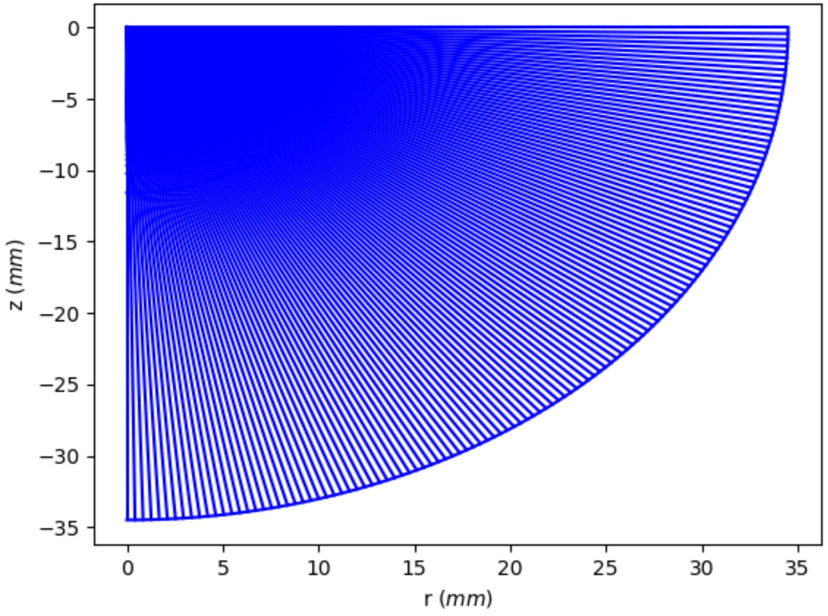
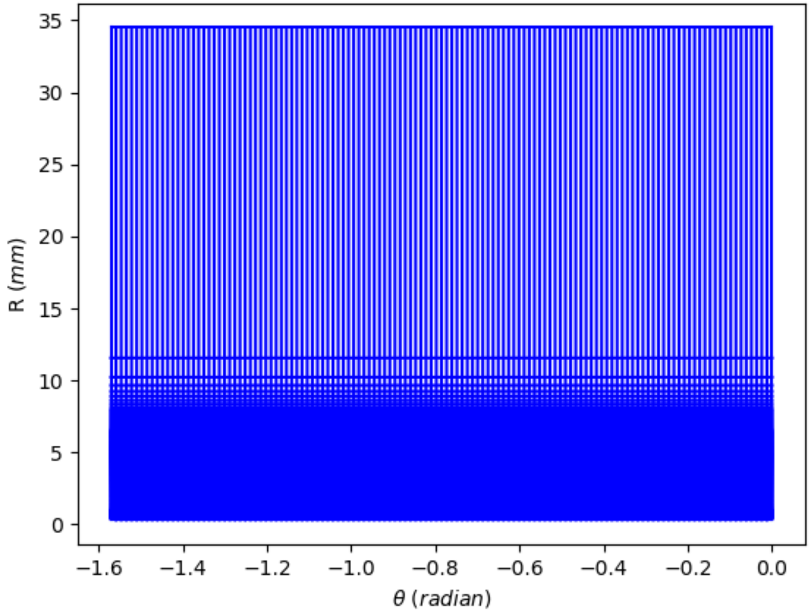
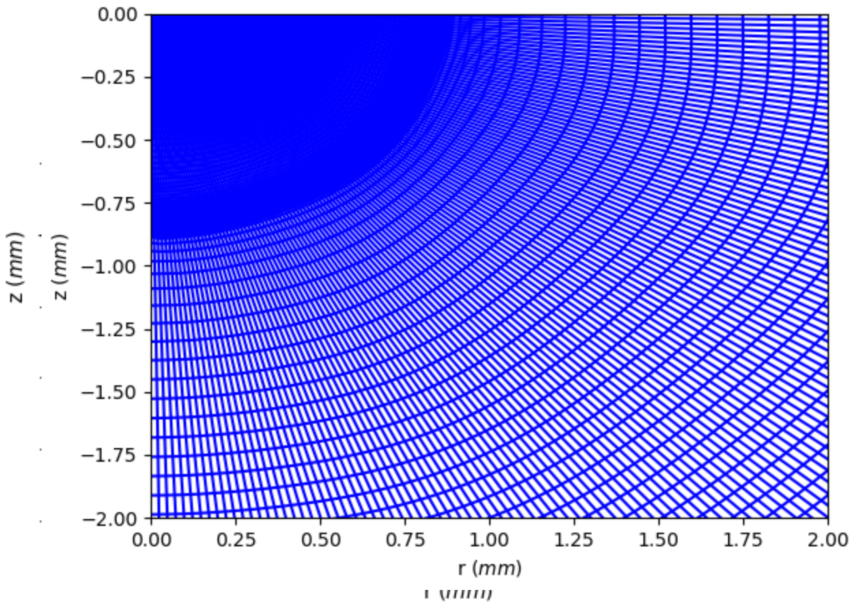


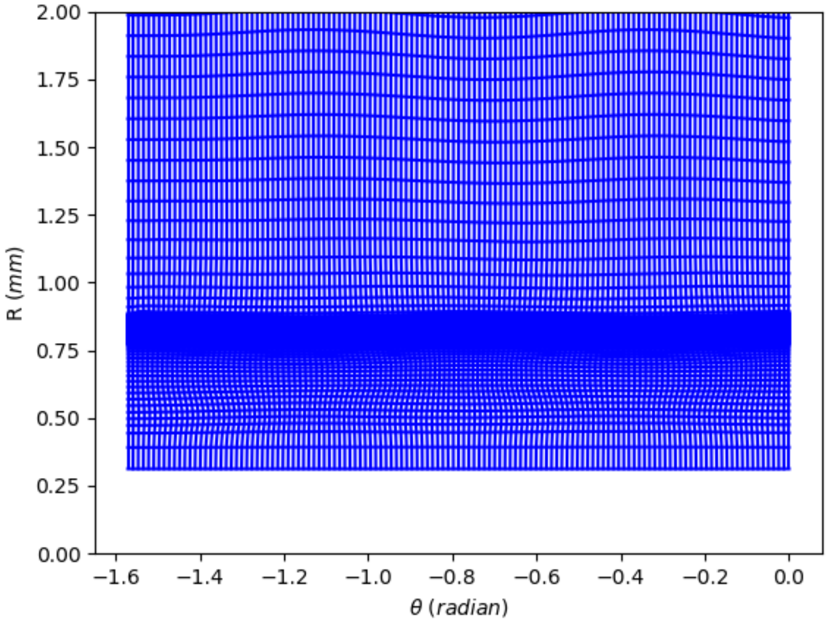


Full Domain

2. THE ODIN GRID

- 2D uses R-Z geometry (but can do X-Y)





Zoomed in

3. RAYTRACING METHOD

- Simplistic raytracing
- From Odin density grid, then calculate refractive index grid using:

$$\eta = \sqrt{1 - \frac{n_e}{n_{crit}}} \qquad (2)$$

- Where,

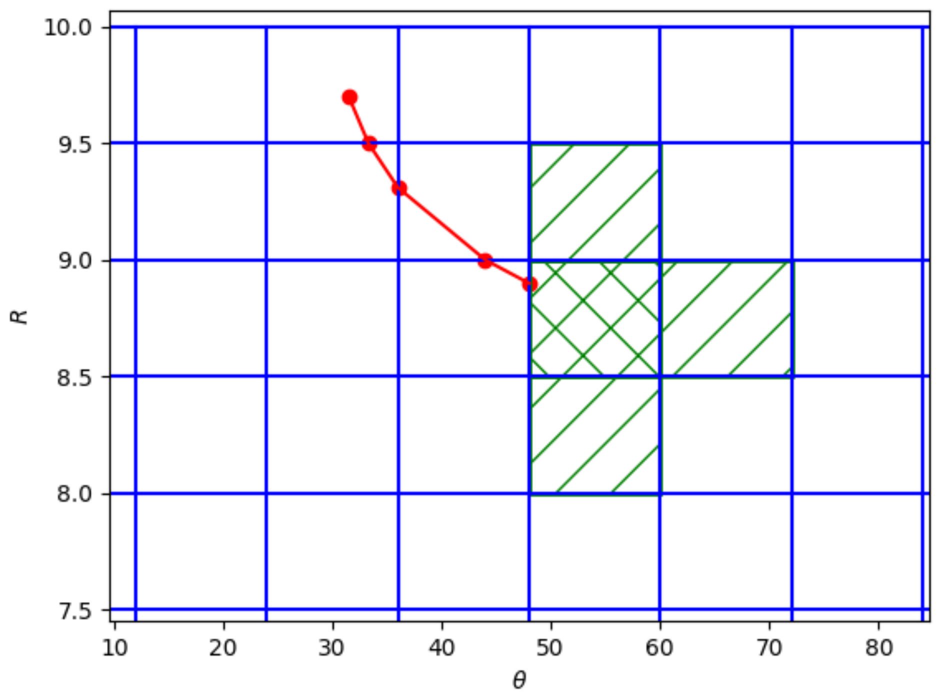
$$n_{crit} = \frac{\varepsilon_0 m_e \omega^2}{e^2} \qquad (3)$$

i.e each refractive index grid is wavelength dependant

- Update angle of trajectory at cell interfaces (Snell's law):

$$\theta_2 = \sin^{-1}\left(\frac{\eta_1}{\eta_2}\sin\theta_1\right) \qquad (4)$$

3. RAYTRACING METHOD

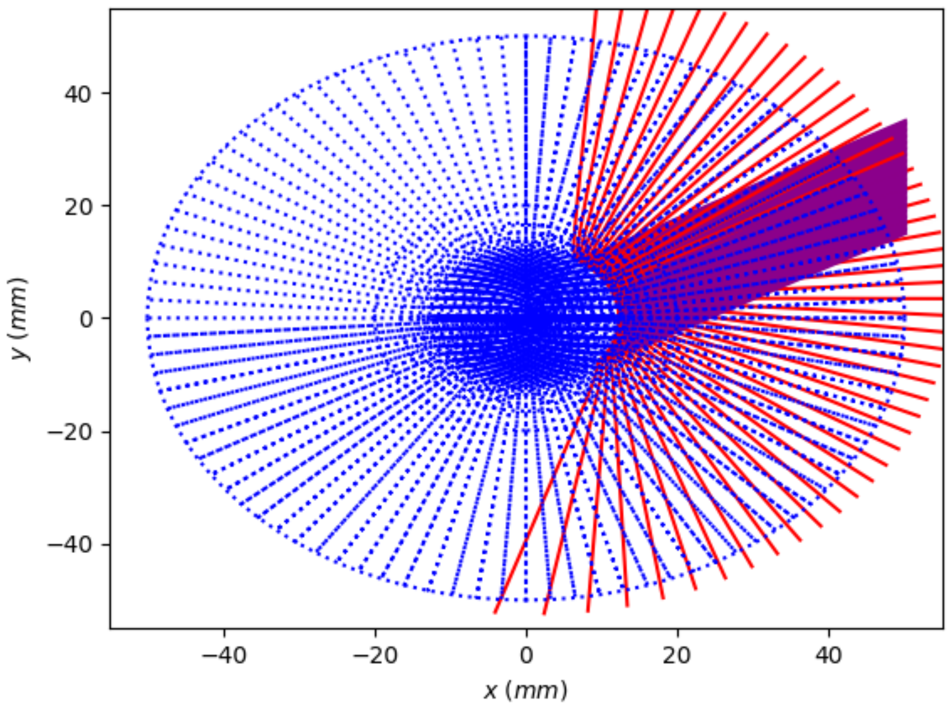


- Update angle of trajectory at cell interfaces:

$$\theta_2 = \sin^{-1}\left(\frac{\eta_1}{\eta_2}\sin\theta_1\right) \qquad (4)$$

- Jumps from cell edge to cell edge

3. RAYTRACING METHOD



- Update angle of trajectory at cell interfaces:

$$\theta_2 = \sin^{-1}\left(\frac{\eta_1}{\eta_2}\sin\theta_1\right)$$

- 50 rays
- 532nm - 2ω Nd:YAG
- Typical implosion simulation about ¼ way through
- Works in 3D

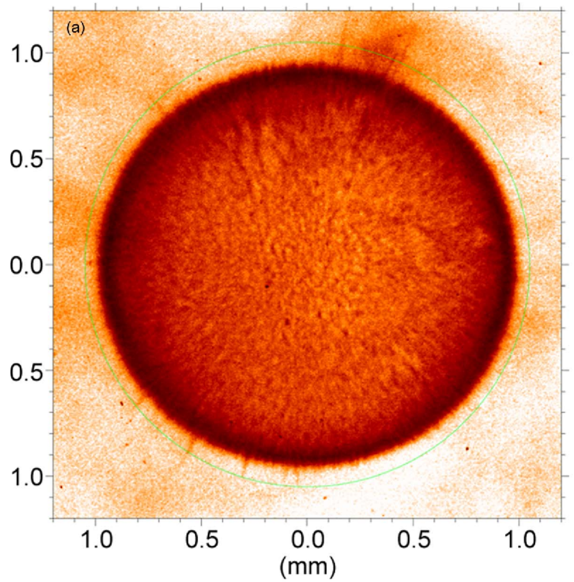
4. X-RAY RADIOGRAPHY BACKLIGHTER

- Due to their high energies, X-rays are highly probing
- Ideal as a diagnostic for ICF implosions
- X-rays attenuated as they pass through the plasma
- Spectral intensity given by:

$$\frac{dI_\nu}{ds} = -\kappa'_\nu I_\nu + \kappa'_\nu B_\nu \qquad (5)$$

- By ignoring self-emission then get the following equation for attenuation of x-ray:

$$I(s) = I_0 \exp(-\kappa_\nu n_e s) \qquad (6)$$



[2] Cuneo, M. E., Roger Alan Vesey, D. B. Sinars, Gena R. Bennett, Ian C. Smith, Briggs W. Atherton, James L. Porter and D. F. Wenger. "Monochromatic 6.151-keV Radiographs of a Highly Unstable Inertial Confinement Fusion Capsule Implosion." *IEEE Transactions on Plasma Science* 39 (2010): 2412-2413.

4. X-RAY RADIOGRAPHY BACKLIGHTER

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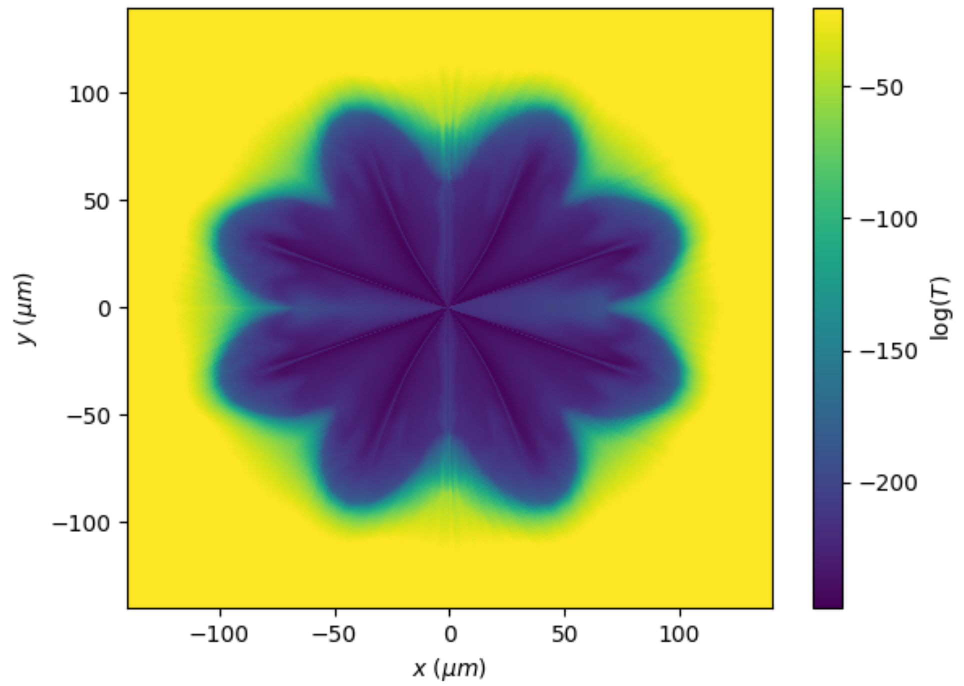
$$I(s) = I_0 \exp(-\kappa_\nu n_e s) \qquad (6)$$

- This particular result used $\lambda = 0.1nm$
- Experimentally:
  - $\lambda \approx (1nm - 0.1pm)$
  - $\tau_{pulse} = 10ns$
  - $\Delta t_{shot} = 700ns$



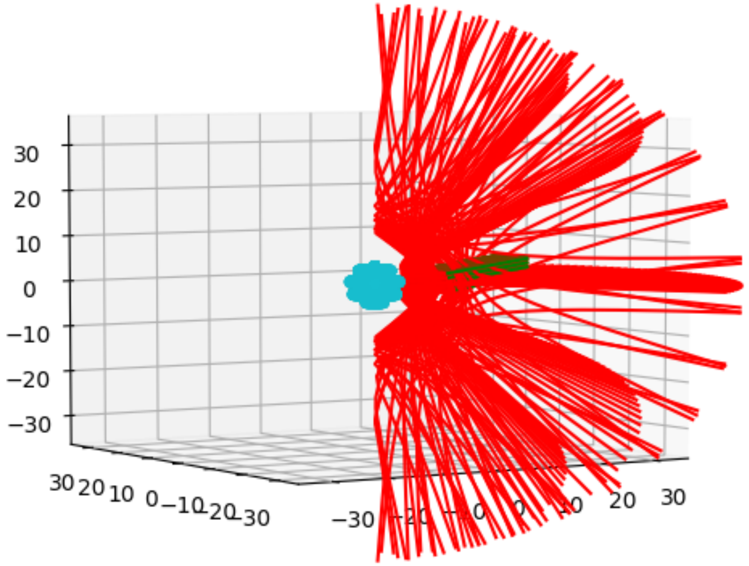
5. FUTURE DIAGNOSTICS

- Simulation/Experiment dependant
- X-ray spectroscopy
  - Can analyse self-emission from target
  - Need to solve the radiation transport equation
- Phase Contrast Imaging
  - Relatively new plasma diagnostic being utilised
  - Able to clearly see steep density gradients – ideal for ICF

QUESTIONS?

Thanks for listening!

3D RAYTRACING

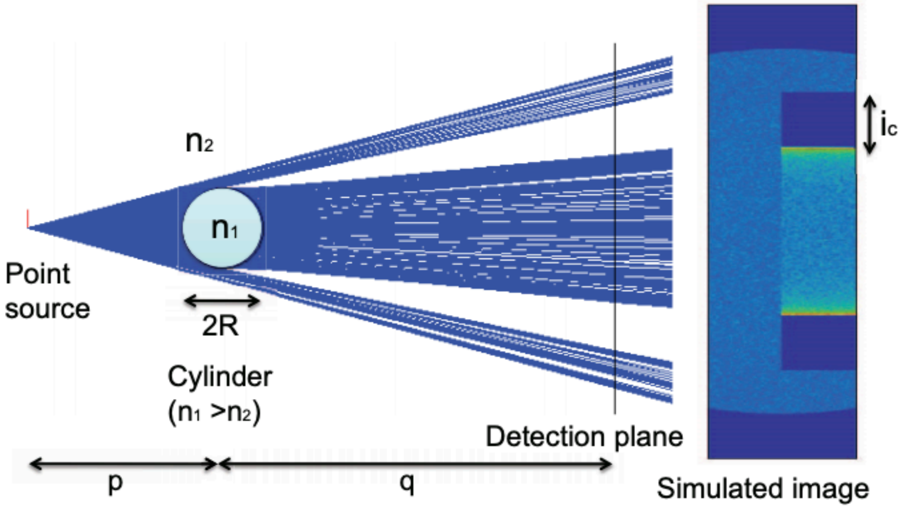


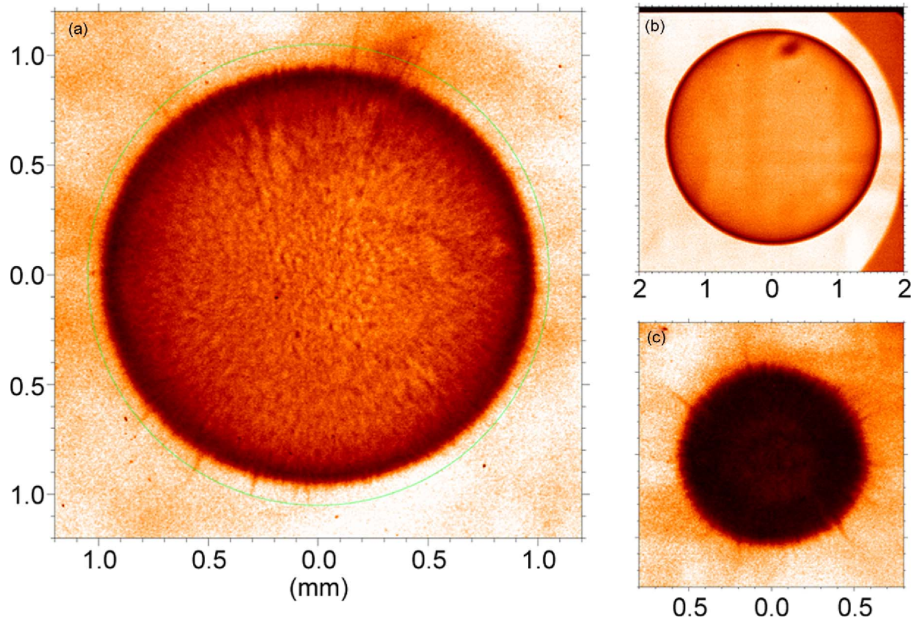
THE OMEGA LASER FACILITY

- LLE – Laboratory of Laser Energetics
- University of Rochester, New York
- 60 beam 3ω Nd:YAG laser system
- Omega EP includes 4 additional beams for X-ray backlighter
- Capable of delivering 40kJ at up to 60TW onto a target less than a millimetre
- Maximum fusion yield is 10^{14} neutrons (once held the world record)

X-RAY RADIOGRAPHY

- Typical set up for a backlighter used for radiography:





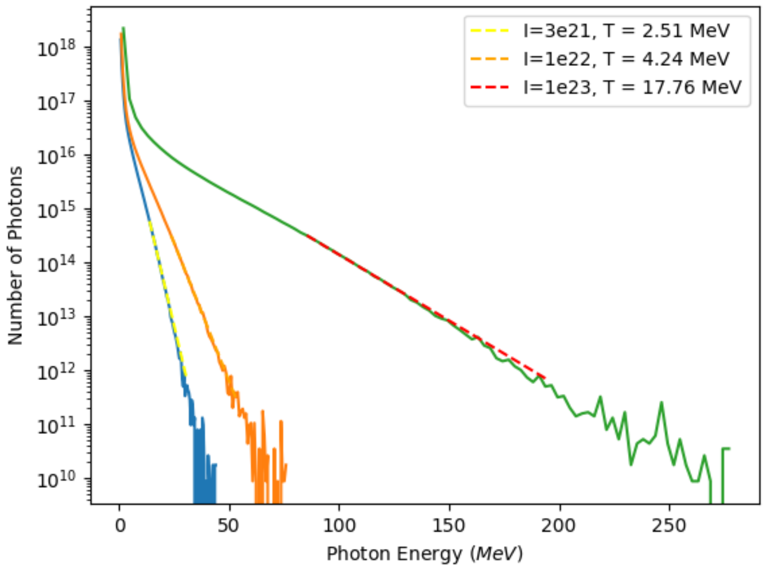
[3] Ping, Y., Landen, O. L., Hicks, D. G., Koch, J. A., Wallace, R., Sorce, C., Hammel, B. A., and Collins, G. W. *Refraction-enhanced x-ray radiography for density profile measurements at CH/Be interface*. United States: N. p., 2011. Web. doi:10.1088/1748-0221/6/09/P09004.

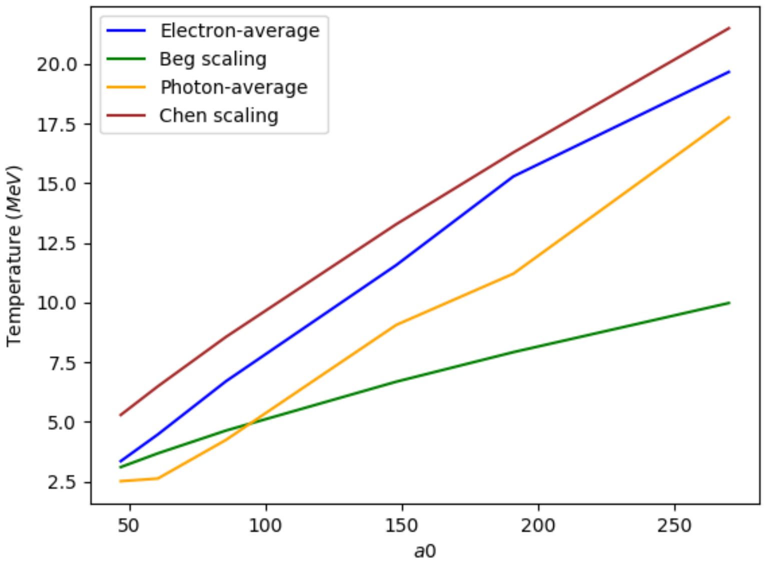
X-RAY RADIOGRAPHY

- The backlighter is a X-ray source
- Usually use Laser metal interaction
- Metal foil is ideal (typically Aluminium, Gold or Silver)
- Majority of X-rays created by Bremsstrahlung
- X-rays typically span 1keV-5 MeV (1nm-0.1pm)
- Can model this using *EPOCH*

X-RAY RADIOGRAPHY – EPOCH RESULTS

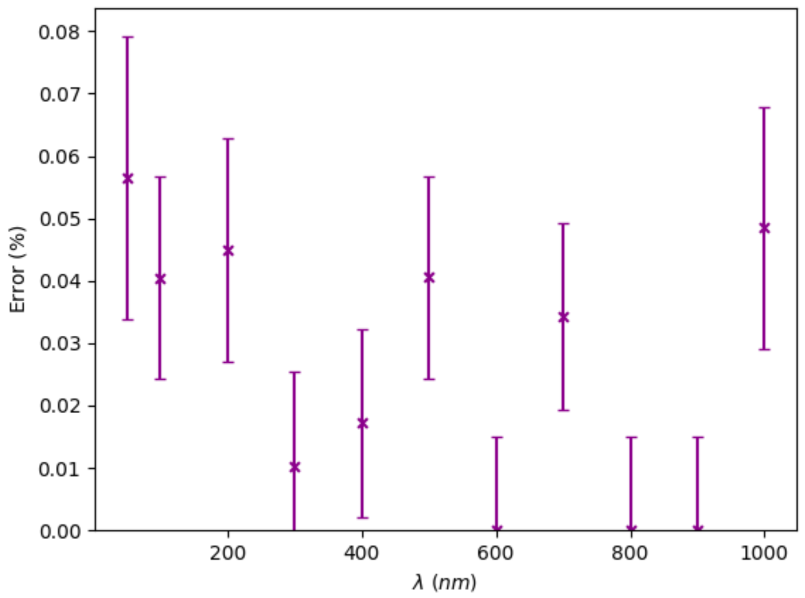
- Can model this using *EPOCH*





RAYTRACING METHOD ERROR

- Able to find critical surface very well



PHASE CONTRAST IMAGING

- Refractive index has real and imaginary components:

$$\underline{\eta} = 1 - \delta - i\beta$$

- κ is mass attenuation coefficient,

$$\kappa = \frac{4\pi\beta}{\lambda}$$

- Scalar wavefunction within a medium is given by:

$$\psi(z) = E_0 e^{i\eta k z} = E_0 e^{i(1-\delta)\kappa z} e^{-i\beta k z}$$

- Phase shift is given by:

$$\phi = \frac{2\pi}{\lambda} \int \delta(z) dz$$

RADIATION TRANSPORT EQUATION

$$\frac{1}{c}\frac{\partial}{\partial t}I_\nu + \hat{\Omega}\cdot\nabla I_\nu + (k_{\nu,s} + k_{\nu,a})I_\nu = j_\nu + \frac{1}{4\pi}k_{\nu,s}\int_\Omega I_\nu d\Omega$$