Simulating Deuteron Diagnostics for ICF

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1.1 What is ICF?

An equal mix of Deuterium and Tritium fuel is spherically compressed achieving thermonuclear temperature and pressure in the central region of the compressed fuel, the hotspot, where fusion then occurs. At bang time, the point of peak neutron production, the compressed fuel is a plasma and is momentarily contained by the surrounding cold fuel's inertia.

1.2 Compression

High energy lasers ablate the outer layer of the assembly, the ablator. Compression is then driven by the reaction force of the the material moving outwards.

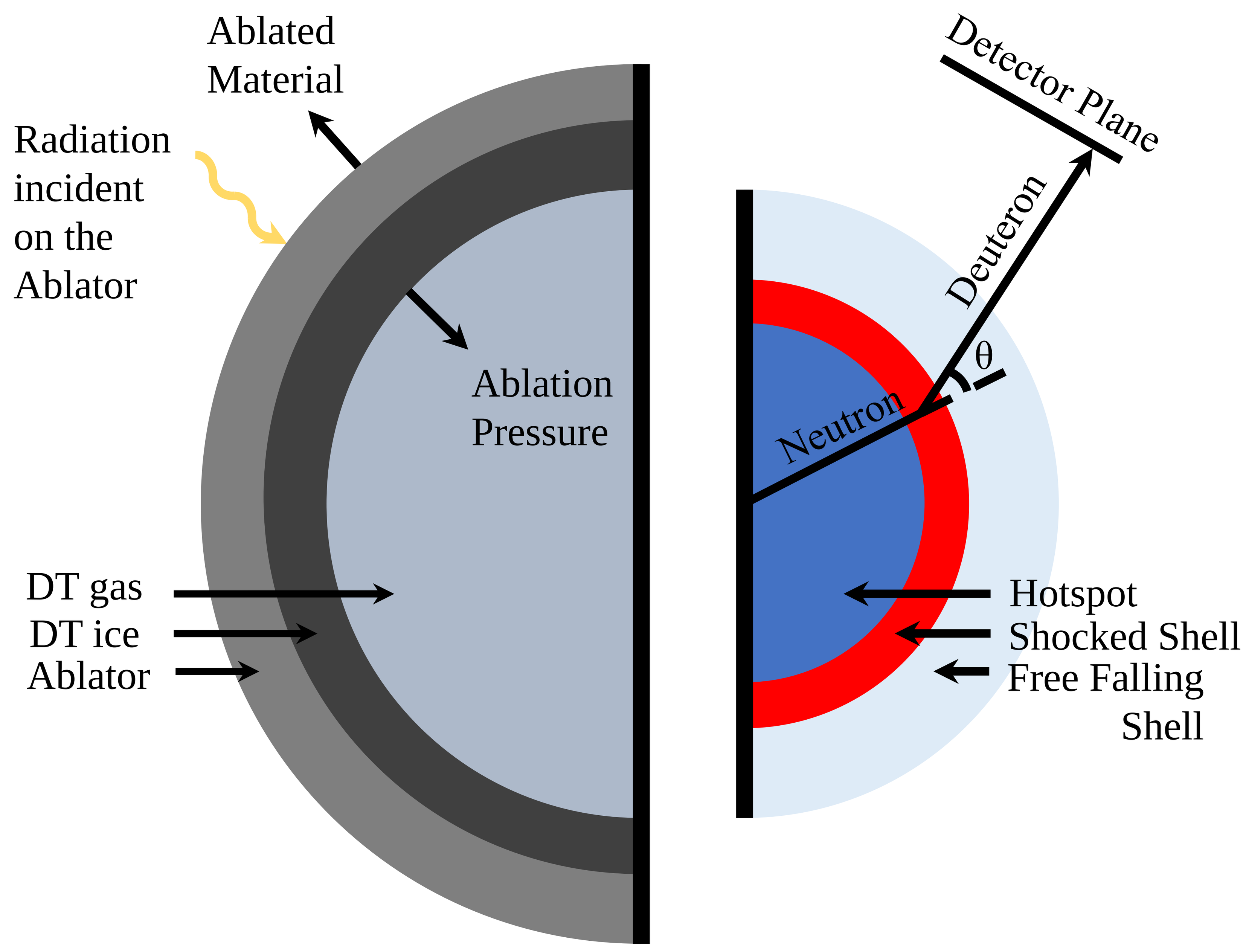

Figure 1.1 – The left hand side shows an ICF fuel assembly in the compression stage. The right hand side shows the same fuel assembly at bang time at which point, all regions are plasma with the shocked shell region being significantly denser than the hotspot and free falling shell.

1.3 Fusion

At peak compression the hotspot is heated sufficiently by ram pressure that fusion occurs:
$D + T \rightarrow \alpha + n$ (14.1 MeV)

1.4 Scattering

Neutrons elastically scatter Deuterons. The energy of the deuteron E_D depends on the scattering angle θ and the neutron energy E_N:

$$E_D = 8/9\, E_N \cos^2\theta$$

1.5 Stopping Power

Scattered deuterons experience a plasma stopping power approximately proportional to the plasma density. Energy lost is proportional to the line integrated density along the path

2.1 Deuteron Imaging as a Diagnostic

Scattered deuterons can be imaged and used as a diagnostic for implosion performance. They contain information about the shape of the fuel at bang time and the density due to the stopping power acting on deuterons.

2.2 Model

A deterministic ray trace model has been developed which is capable of synthesising deuteron images at arbitrary detector angles from 3D hydrodynamic profiles.

2.3 Implementation

For a given scattering site, neutron direction and detector position, E_D is fixed. The energies of scattered deuterons are tracked as they are slowed in the plasma by stopping power and those that reach the detector are tallied.

3.1 High Energy Deuteron Images as an Alternative to Neutron Images

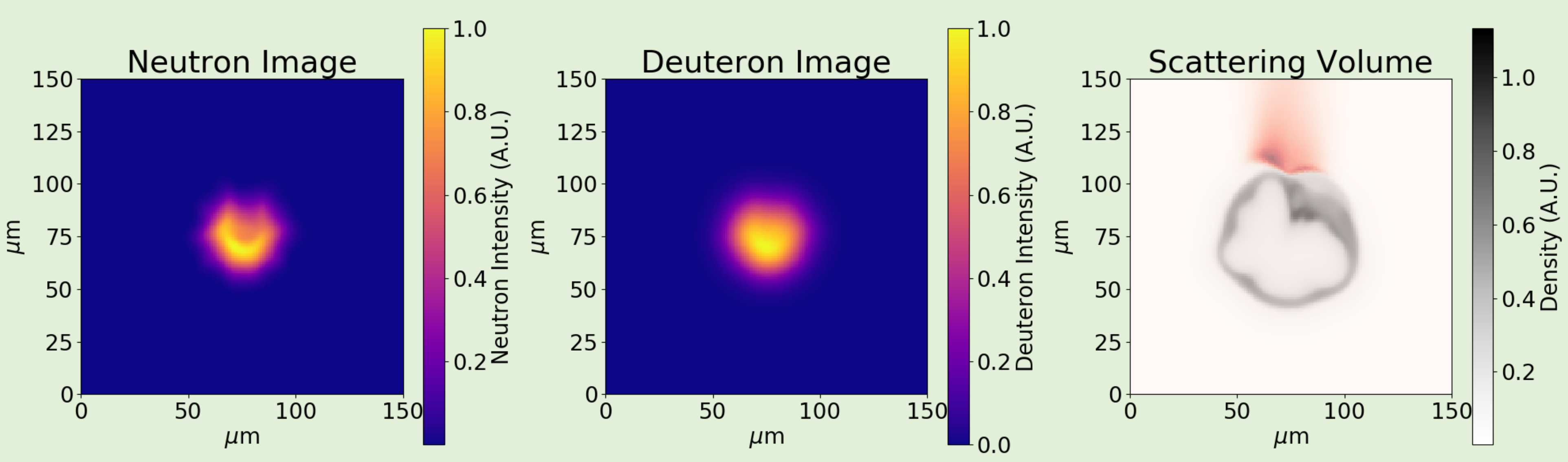

Figure 3.1 – The neutron image, deuteron image and scattering volume respectively for a perturbed implosion. Notice the deuteron image resembles the neutron image with blur. The scattering volume is the volume where deuterons were scattered from for this image.

The figures show the neutron image and the deuteron image in the 12-13 MeV (the energy with which deuterons reach detector) range for a 3D perturbed implosion. There are two important conclusions to note about high energy deuteron images:

3.1 Resemblance to Neutron Image

High energy deuterons are forward scattered and so their images resemble the size and shape of the neutron image.

3.2 Deuteron Image Blur

The deuteron image is subject to blur compared to the neutron image due to the non-zero scattering angle associated with the finite energy interval.

4.1 Mid Energy Deuteron Images for Shocked Shell Imaging

The figure shows a deuteron image with a 6-7 MeV interval with its scattering volume. A majority of the scattering occurs in the high density shocked shell indicating middling energy intervals image this region effectively.

The features seen in the image indicate hydrodynamic perturbations in the region of the shocked shell facing the detector.

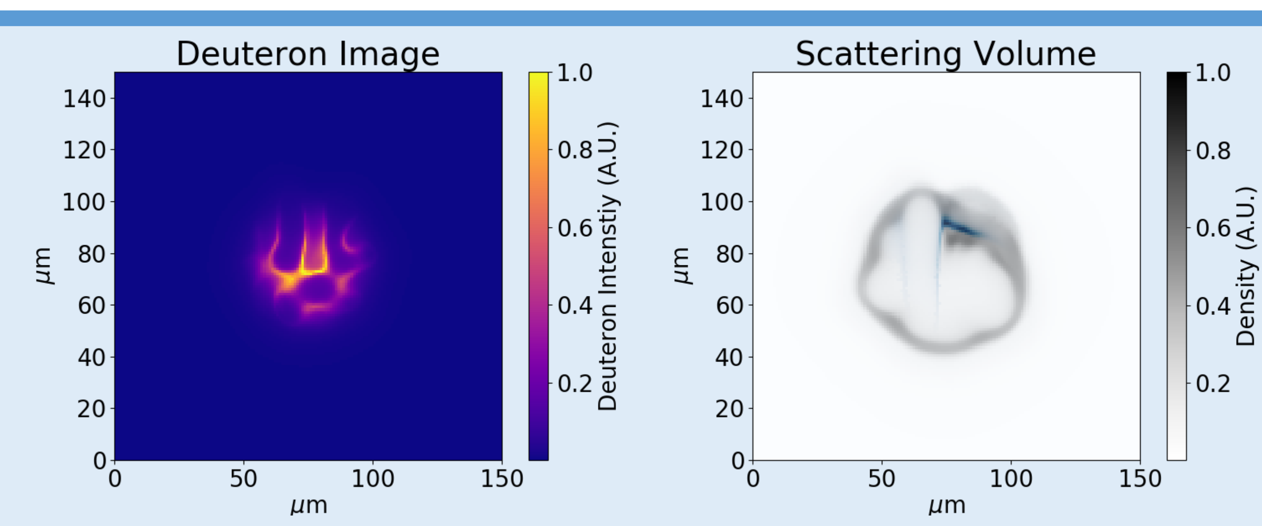

Figure 4.1 – Deuteron image (6-7 MeV) and corresponding scattering volume.

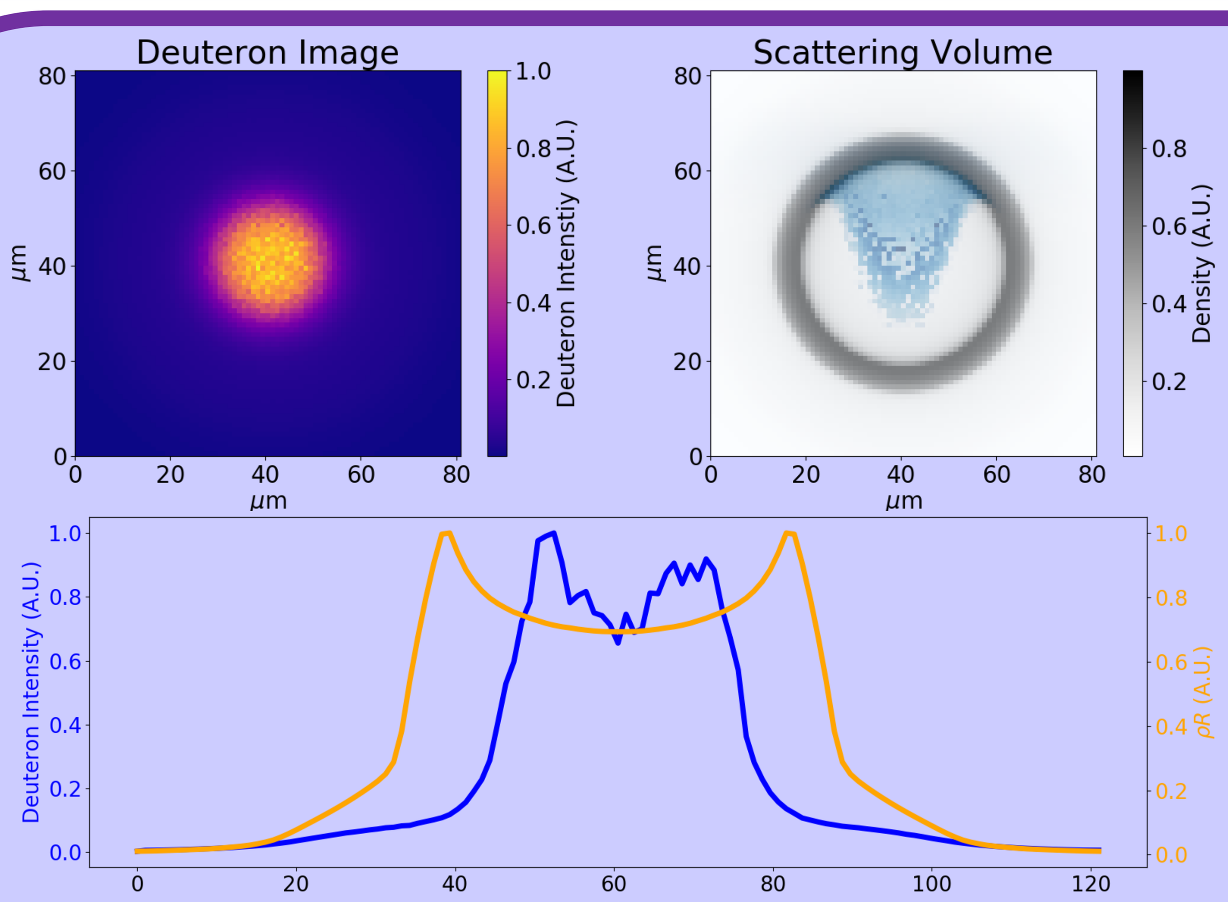

Figure 5.1 – Deuteron image (1-2 MeV) and corresponding scattering volume (above). Line-integrated density and deuteron image cross section (below).

5.1 Low Energy Deuteron Images for inferring Fuel region sizes

The figure shows a deuteron image in the 1-2 MeV interval with its scattering volume. Below is a cross section of the deuteron image (blue), and the line integrated density of the plasma in the direction perpendicular to the detector plane (yellow).

Looking at the line integrated density, three distinct regions can be seen. From $\approx 40 - 80\,\mu m$ is the hotspot. Then the regions on either side of the hotspot with steep gradients correspond to the high density shocked shell. Finally, the shallower regions at the edges of the plot correspond to the lower density free falling shell.

The deuteron image contour contains the same features (slightly narrowed due to the shape of the scattering volume) because the amount of scattering depends on the density in each region and for low energy images, deuterons can be scattered from all regions.