Synthetic Diagnostics for Laser-Fusion Simulations

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Motivation

With carbon emissions increasing and global temperatures rising to dangerous levels, the need for renewable energy has never been greater. One renewable energy solution that could meet the high demands that are currently being met by coal and oil is **Fusion energy**. Nuclear fusion is one of the highest energy density sources on Earth, has an abundant supply, and releases no greenhouse gases in the process. The most popular reaction being investigated is the Deuterium-Tritium (**DT**) reaction given by:

$$^2_1H + ^3_1H \rightarrow ^4_2He + ^1_1H + 18.3MeV \quad (1)$$

One avenue of achieving fusion is called **ICF** (Inertial Confinement Fusion). These experiments are subject to many challenges and, by running simulations, such as those done by the **Odin** code, we can gain invaluable insights. Alongside simulations, synthetic diagnostics can be used to design successful experiments. Odin can also be used to simulate other High Energy Density Physics, such as planetary cores and astrophysical plasmas.

1) Direct Drive ICF

- One of two branches of Inertial Confinement Fusion: Direct and Indirect drive
- A driver (laser) interacts directly with the DT capsule
- Capsule has an out layer, called an ablator that is needed to drive implosion
- Works using the same principles as rockets: by shedding mass, then it accelerates the implosion

$$\Delta v_{imp} = v_e ln\left(\frac{m_0}{m_f}\right) \quad (2)$$

- Typical capsule shown in Figure below [1]:

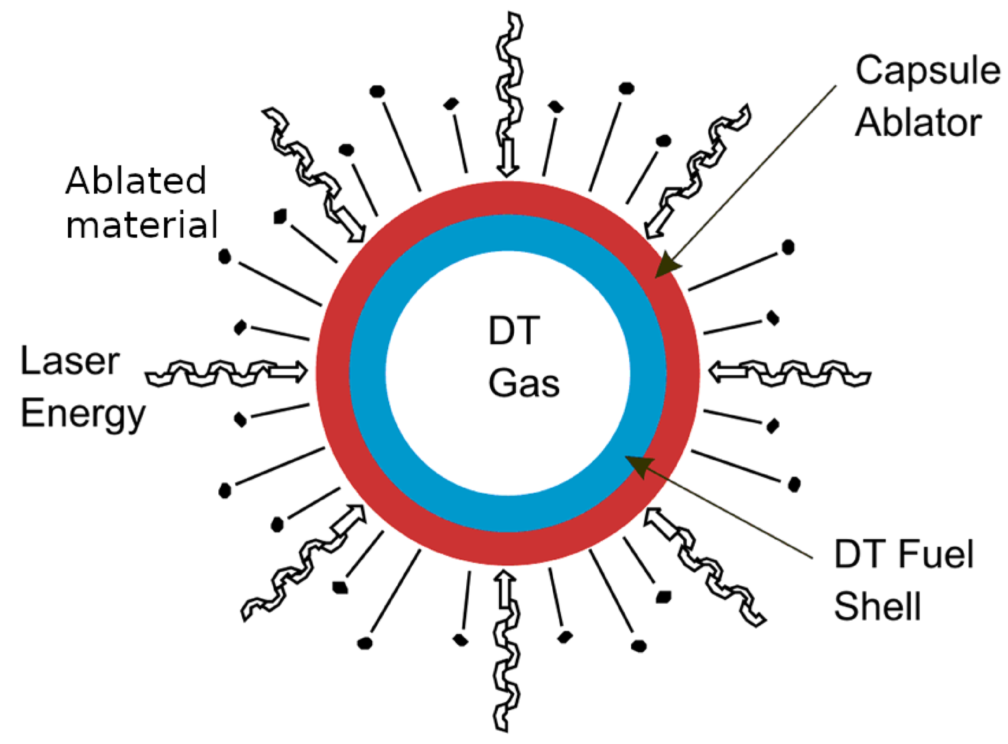

Figure 1: Typical ICF capsule with 3 distinct layers. Diagram depicts effect of laser on ablator.

2) The Odin Code

- An **ALE** (Arbitrary Lagrangian Eulerian) Radiation-Hydrodynamics code, called **Odin** [2], is being developed at the University of Warwick
- The code has all of the physics needed to simulate an ICF implosion and ALE scheme means that it is able to remap the grid during major distortions
- Odin is being used to design the UK's shock ignition experiments on the Omega EP laser facility, at the Laboratory of Laser Energetics at the University of Rochester, USA
- It has been successfully benchmarked against other codes and test cases [3]

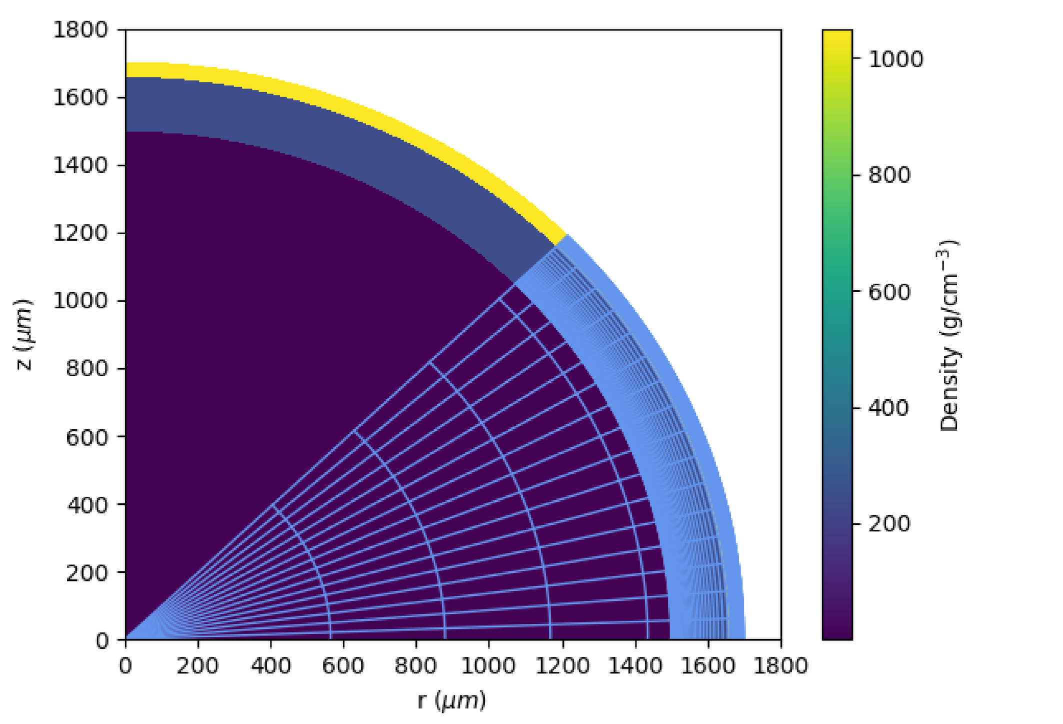

Figure 2: Initial conditions of an *Odin* simulation. The density is shown in color, and half of the simulation mesh has been revealed.

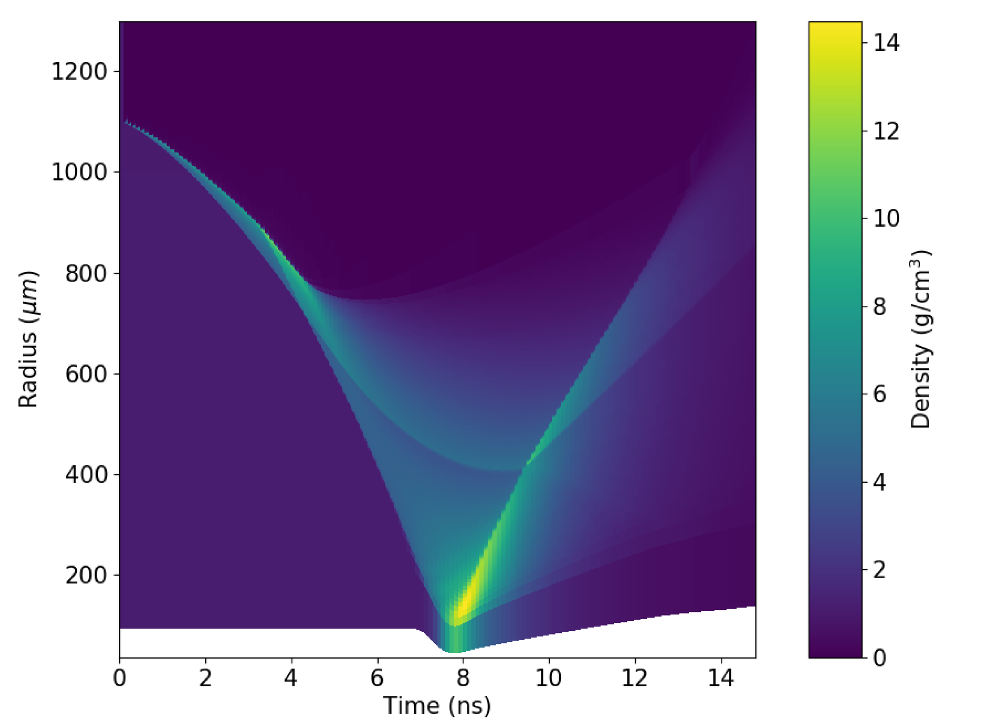

Figure 3: An R vs t plot from an Odin simulation. These are helpful for finding peak compression time.

3) Challenges

So far, ICF experiments have failed to ignite. To ignite, a capsule needs to meet the Lawson criteria [1]:

$$n \cdot R \geq \frac{(k_B T)^{3/2}}{\langle \sigma v \rangle} \quad (3)$$

- Main problem is laser-capsule energy coupling caused by:
  - Laser Plasma Instabilities (SRS, SBS, TPD, and CBET)
  - Hydrodynamic Instabilities (Rayleigh-Taylor, Kelvin-Helmholtz)
  - Implosion symmetry
  - Shock timing (shock-ignition)

4) Synthetic Diagnostics

- Methods of post-processing Odin output to recreate the measurements made by real-life diagnostics
- Provides direct comparison between experiment and simulation
- Can be used to position, filter, and provide idealised results of diagnostics
- Current diagnostics include a raytracing diagnostic to map ray trajectories, X-ray radiography, and spectroscopy

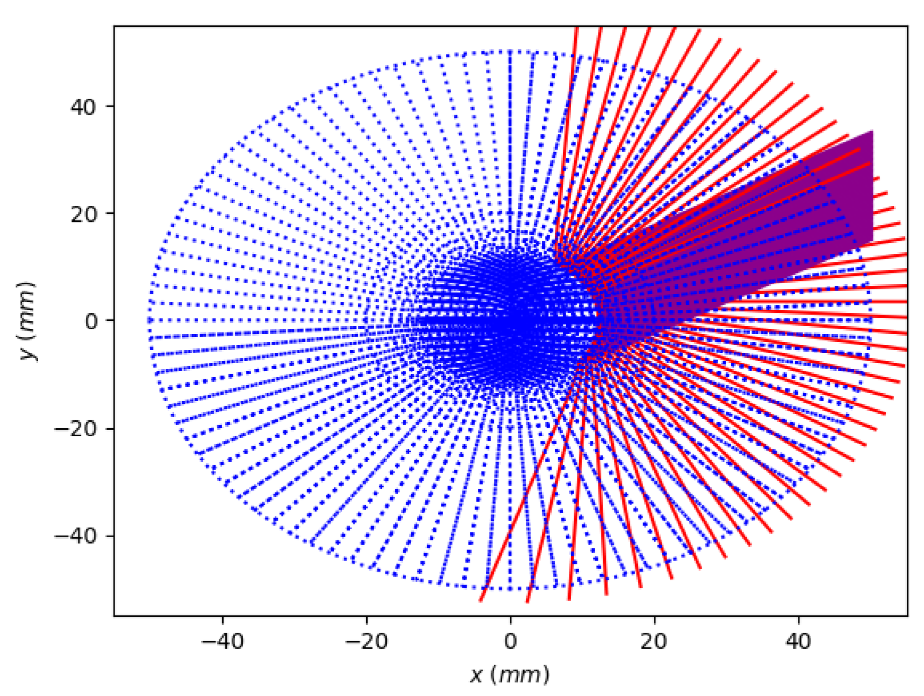

Figure 4: The visual output of the 2D raytracing algorithm. Rays are refracted according to Snell's law.

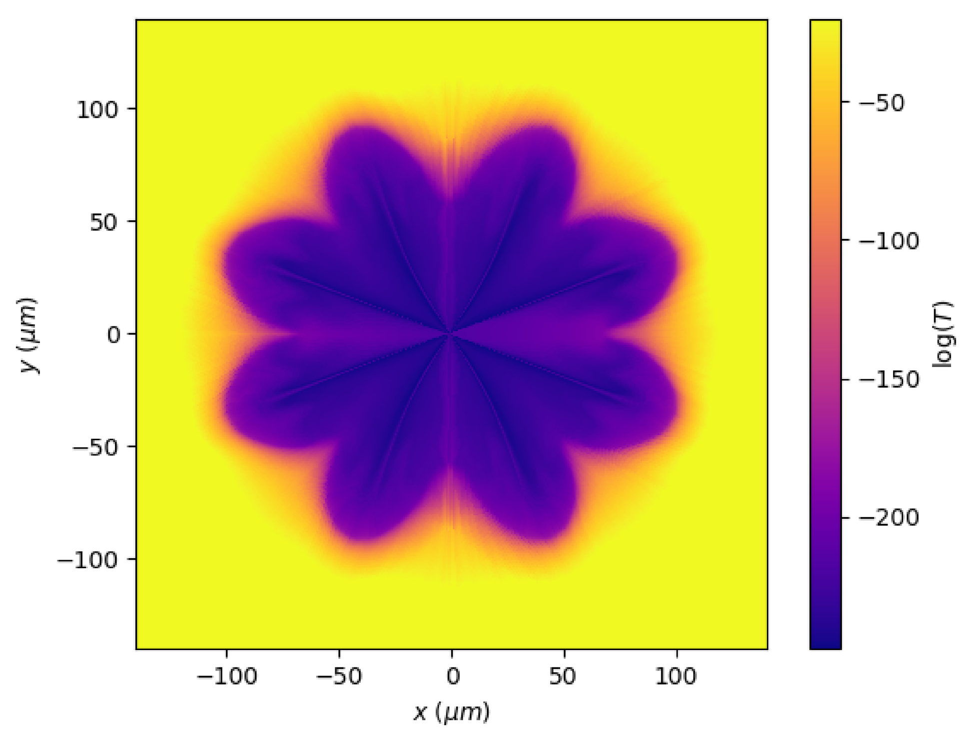

Figure 5: Radiograph of Odin capsule using X-rays of 200 keV. Note that the z axis shows Transmittance.

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References

[1] Stefano Atzeni. *ICF with Advanced Ignition Schemes: Fast Ignition and Shock Ignition*, pages 243–277. Springer International Publishing, Heidelberg, 2013.

[2] T. Goffrey. *A cylindrical magnetohydrodynamic arbitrary Lagrangian Eulerian code.* PhD thesis, University of Warwick, 2014.

[3] I. V. Igumenshchev et al. Three-dimensional modeling of direct-drive cryogenic implosions on omega. *Physics of Plasmas*, 23(5), 5 2016.