Raytracing for Laser-fusion simulations

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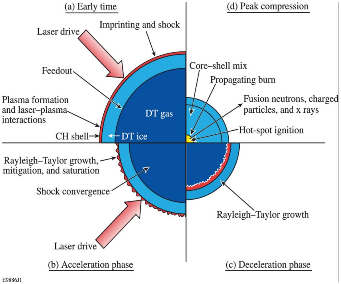
- **York**: Matthew Khan

Summary

Inertial Confinement Fusion

Here are the main stages of an ICF implosion[1]:



The Lawson criteria [2] must be fulfilled in order for fusion reactions to take place. It is commonly agreed that the Lawson criteria corresponds to an areal density of $\rho R \geq 3g/cm^2$.

[1] Craxton, R. et al., 2015. Direct-drive inertial confinement fusion: A review. Physics of Plasmas, 22(11), p.110501.
[2] Pfalzner, S., 2006. An introduction to inertial confinement fusion. New York: Taylor & Francis/CRC Press.

The Odin Code

Odin is a radiation-hydrodynamics ALE code[3] developed at Warwick and used for studying ICF. It has a number of advanced features such as:

- ALE: Computational grid moves with the fluid as long as possible, before remapping to a smother grid and restarts in Lagrangian mode.
- Multi-material with arbitrary EoS and opacity.
- Thermal conduction and multi-group radiation transport handled implicitly using PETSc.
- 3D laser ray-tracing and energy deposition.
- 3D hot-electron transport (Duncan Barlow).

[3] Goffrey, T. A cylindrical magnetohydrodynamic arbitrary ALE code. PhD thesis, University of Warwick.

Ray-Tracing routine

- A new feature that I have been working on alongside Keith Bennett is a refractive ray-tracing routine.
- Rays are refracted in 3D according to the vector form of Snell's law[4]:

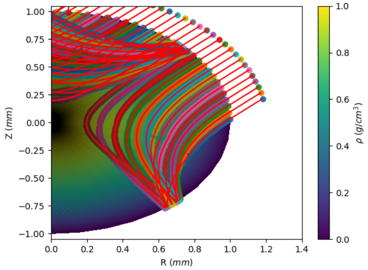
$$\vec{v}_{\text{refract}} = \left(\frac{n_1}{n_2}\right)\vec{l} + \left(\frac{n_1}{n_2}\cos\theta_1 - \cos\theta_2\right)\vec{n} \qquad (1)$$

- The rays deposit their energy via inverse bremsstrahlung [5] at, or prior to, the critical density:

$$k_{IB} = \frac{\overline{\nu_{el}(t)}}{c}\left(\frac{n}{n_c}\right)\left(1 - \frac{n}{n_c}\right)^{-\frac{1}{2}} \qquad (2)$$

[4] Glassner, A., 1991. An Introduction to ray tracing. London: Academic Press.
[5] Sharifian, M., Ghoveisi, F., Gholamzadeh, L. and Firouzi Farrashbandi, N., 2019. The inverse Bremsstrahlung absorption in the presence of Maxwellian and non-Maxwellian electrons. Chinese Physics B, 28(10), p.105202.

Ray-Tracing routine



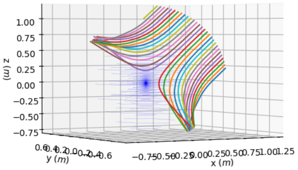


Figure 1: The paths of a small subset of the multiple beams entering a spherical capsule and being refracted due to a linear density profile in 2D (left) and 3D (right).

The OMEGA laser facility

- The OMEGA laser facility is the leading facility for direct-drive ICF. It has 60 beams operating with 3ω Nd:YAG lasers at 351 nm (UV light)
- Capable of delivering 40 kJ of energy, or 60 TW onto a target less than 1 mm in diameter.
- Due to experimental limitations, there is a difference in the amount of power requested and actually delivered by the lasers.
- There is also a large discrepancy between each beam's power. The average variation for the shot we are interested in is 10.1126 %

The OMEGA laser facility

- Here is the beam power discrepancy:

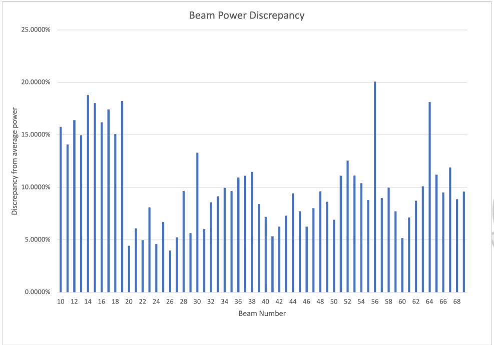


Figure 2: The beam power discrepancy of each of the 60 beams of OMEGA. Note that the average discrepancy is ≈10%.

The OMEGA laser facility

- Here is a histogram of the energy delivered by each of the laser beams of OMEGA:

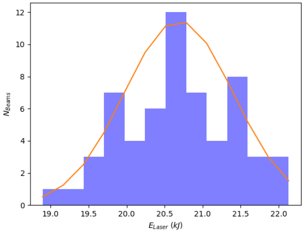


Figure 3: A histogram showing the energy delivered by the 60 beams of Omega during shot 93303.

- The Gaussian distribution fitted to the histogram has a mean value of 20.686 kJ and a standard deviation of 0.720 kJ.
- The aim of our simulation study is to investigate the effect of laser-power asymmetry on this OMEGA experiment and on ICF implosions in general.

Results

- Having developed the refractive ray-tracing routine, we set about running simulations of an OMEGA experiment: 93303.
- Initial simulations are simplified 2D with radial rays.
- A snapshot of one of the simulations is shown below:

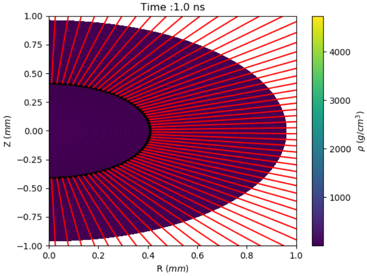


Figure 4: A snapshot of an OMEGA 93303 simulation at 1ns, which shows the rays passing through the ablated plasma and depositing their energy at the critical surface.

Results

- The main focus of our current simulations is to see what impacts the peak areal density ρR_{Max} value.
- Since we applied a single beam per simulation, these results give an exaggerated outcome of different laser power profiles.
- They will fail to highlight the asymmetric implosion that results, and the hydrodynamic instabilities that this can cause.
- Below is the time evolution of the capsule and its density:

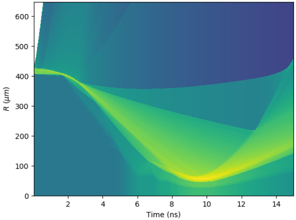


Figure 5: A snapshot of an OMEGA 93303 simulation at 1ns, which shows the rays passing through the ablated plasma and depositing their energy at the critical surface.

Results

As mentioned previously, one of the best parameters for measuring the success of an ICF implosion is the areal density, ρR. The following plot, shows the development of the implosion relative to the timescale of the laser profile:

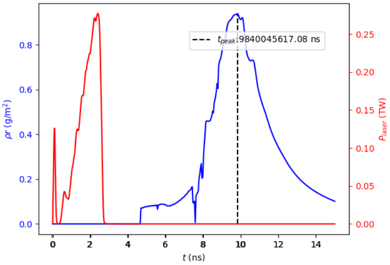


Figure 6: The ρR value of the capsule is shown in blue alongside the laser power profile (in TW) shown in red. Note that both parameters share a scale on the time axis.

Results

Of the 25 simulations that have been run, here is how their maximum areal density compares as a function of the energy per beam.

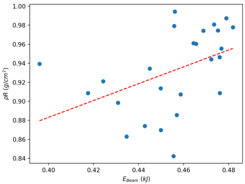


Figure 7: The maximum ρR value from each of the 25 simulations plotted against the energy per beam used from the laser power profile.

Note that the data shows a linear positive correlation between the maximum areal density given by:

$$\rho R_{Max} = 0.887 E_{Beam} + 0.528 \quad (3)$$

Future Work

With some preliminary results completed, the aim of our study is to:

- Run full 3D simulations using the experimental beam positions and laser power profiles.
- Include a basic LPI model to account for hot electron generation and CBET.
- Fine-tune these laser loss mechanisms by comparing to experimental data.
- Perform post-processing analysis on the data using software such as *SPECT3D*.
- A more accurate LPI model is being developed by Andrew Angus.

Summary

- We have successfully developed a refractive ray-tracing routine for the *Odin* ALE code.
- We are in the process of running simulations of experiments were undertaken at the *OMEGA* laser facility.
- The focus of our study is to investigate the effect of laser-power asymmetry on target implosion.
- This could set limitations on the power delivery needed by experimental lasers at Direct-drive laser facilities.