A simulation pipeline for short-pulse laser-driven hydrodynamics

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1. Project Aims

- Create a coupling layer between two plasma physics software packages that operate in different physical regimes:
  - HYADES [1], a radiation-hydrodynamics (RHD) code
  - EPOCH [2], a particle-in-cell (PIC) code
- Provide simulation support for short-pulse laser-solid interaction experiments

2. Experimental Context

- Laser pulses of 20 fs – 1 ps duration, and 10^{18} – 10^{20} W cm^{-2} peak intensity, interacting with solid targets
- By reproducing experimental data, simulations can provide insight into the processes driving the observed hydrodynamics

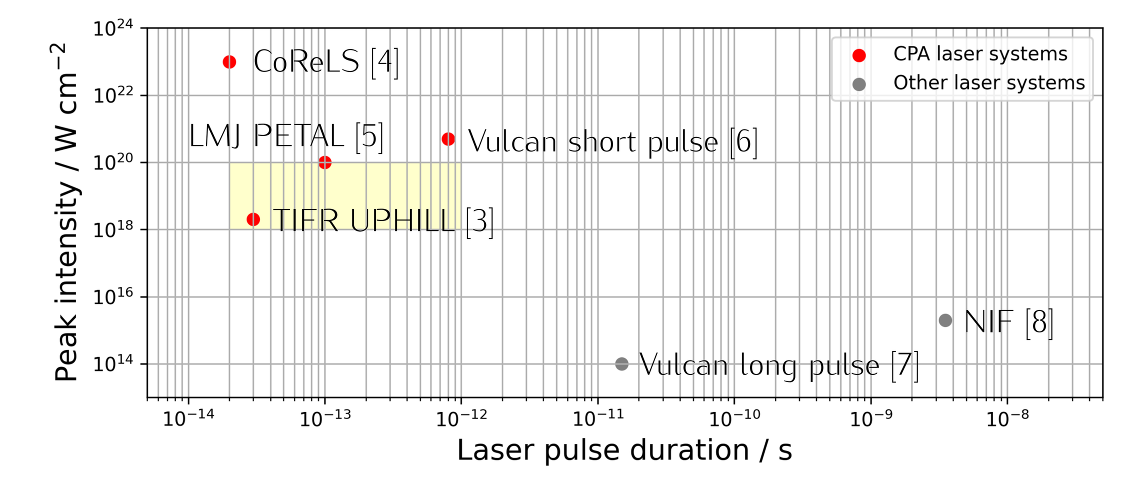

Figure 1: A selection of pulsed laser experiments arranged according to the laser pulse intensity (vertical axis) and duration (horizontal axis). The highlighted region corresponds to the domain of interest.

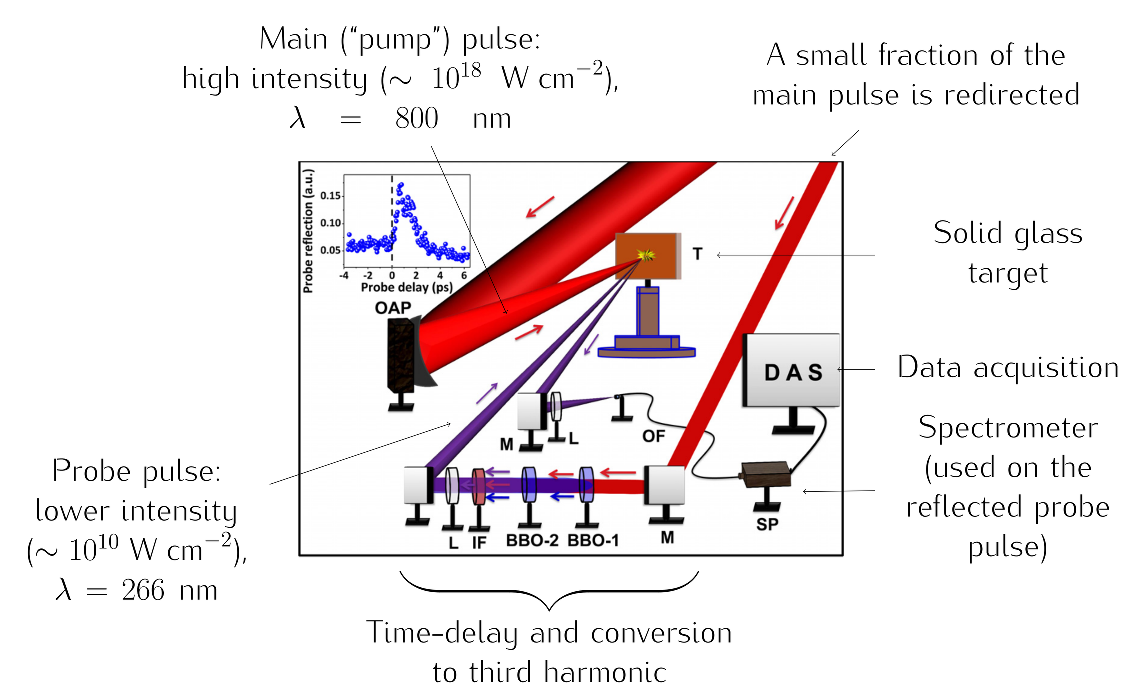

Figure 2: Experimental setup for pump-probe Doppler spectrometry. [3]

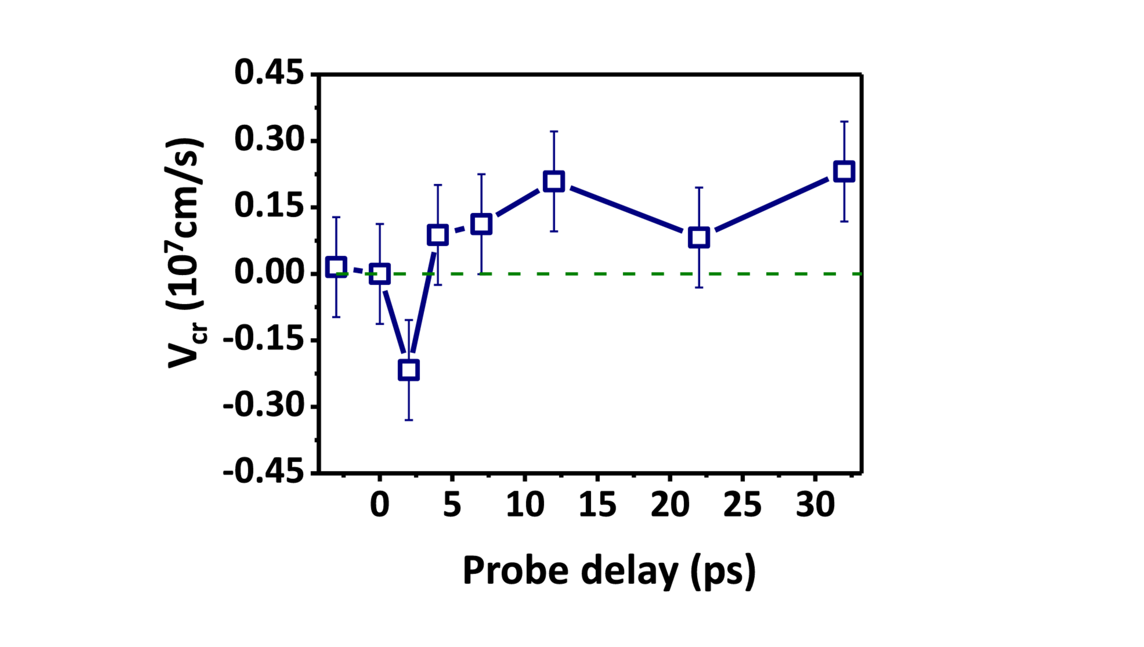

Figure 3: Results from a Doppler spectrometry experiment [3]. The velocity of the material at the probe critical surface is inferred from the Doppler shift of the reflected probe pulse. Successive probe pulses are used to track the hydrodynamic motion of this layer of material.

3. Three stages of laser interaction

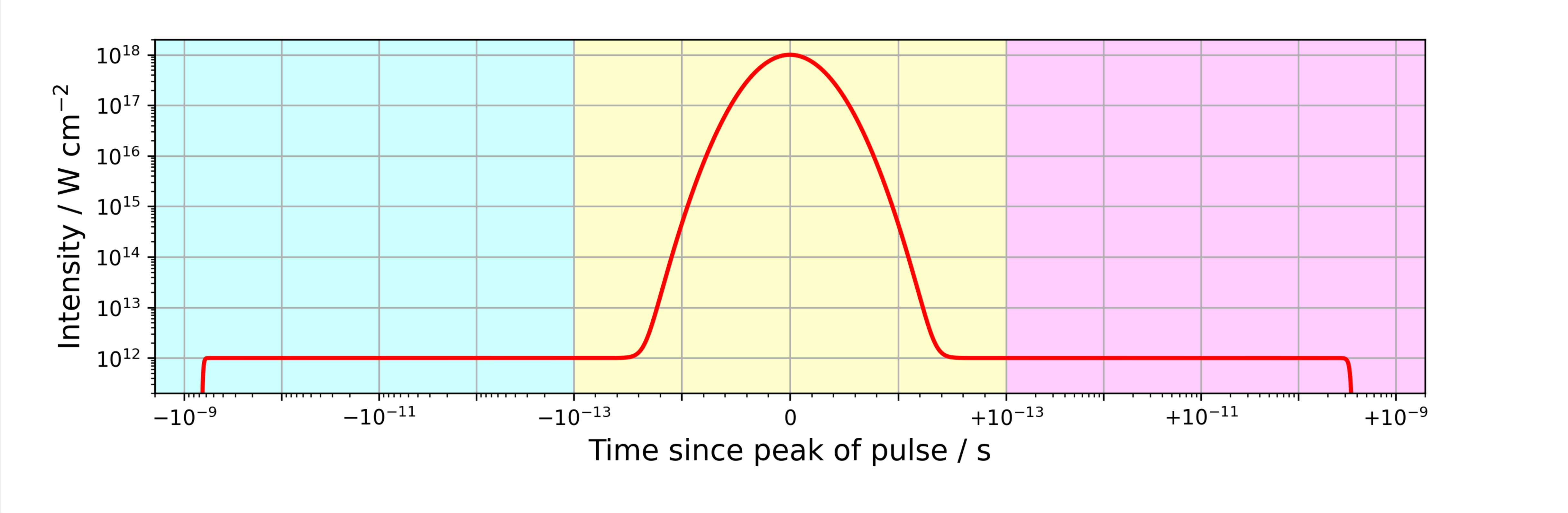

Figure 4: Illustration of a laser pulse produced via chirped-pulse amplification. Due to the wide range of time scales involved, different simulation strategies are required to capture the key physical processes at each stage of the interaction.

1. Pre-pulse

- Target surface ionises when intensity exceeds 10^{10} W cm^{-2}
- The ionised material expands and forms a pre-plasma
- **Simulated with RHD code**

2. Main pulse

- High-energy electrons are launched past the critical surface
- These electrons drive return currents and deposit energy as heat
- **Simulated with PIC code**

3. Post-pulse

- Heating creates pressure gradients in the target
- Pressure gradients drive hydrodynamic motion
- **Simulated with RHD code**

4. Transferring from RHD to PIC

- Select narrow region near critical density
- Separate ion distribution into distinct particle species
- Discretise physical quantities over a regular grid

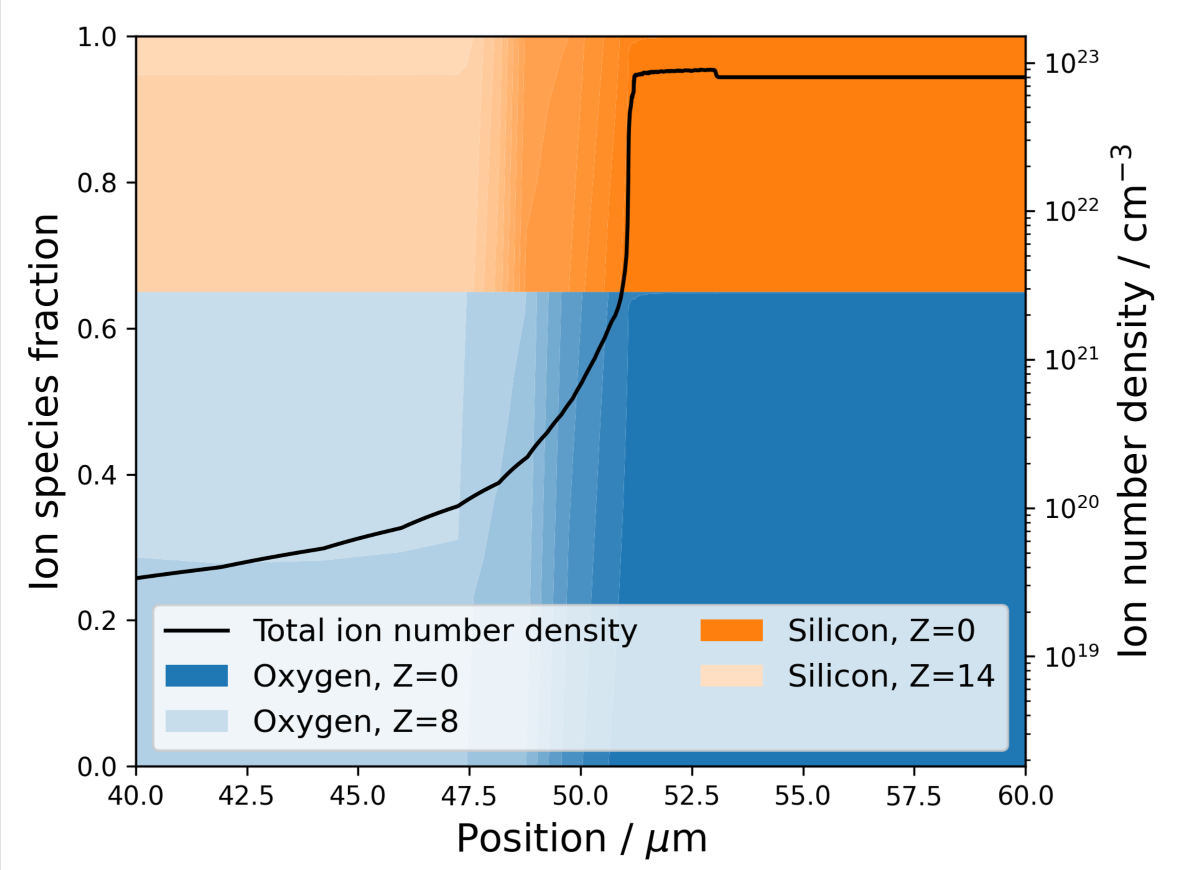

Figure 5: Ion species distribution and number density profile after the pre-pulse interaction. EPOCH requires individual number density profiles for each ionisation state of each element.

5. Transferring from PIC to RHD

- Apply smoothing to noisy PIC outputs
- Generate fluid mesh geometry and interpolate the smoothed profiles over the mesh
- Superimpose the PIC-simulated region onto the RHD pre-pulse conditions

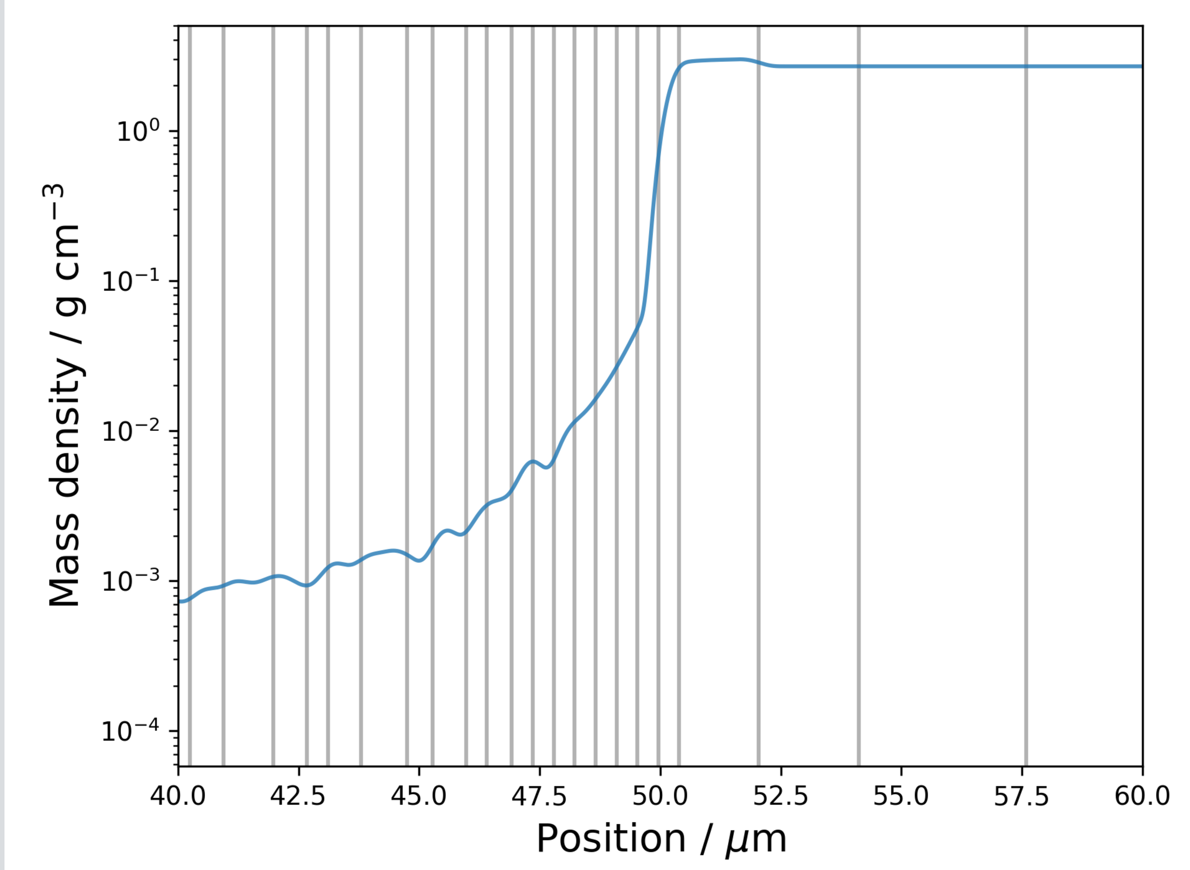

Figure 6: A mass density profile used to generate the layout of a post-pulse fluid mesh in the simulation pipeline. There are five fluid elements between each successive pair of vertical bars.

References

[1] Jon T. Larsen and Stephen M. Lane. "HYADES—A plasma hydrodynamics code for dense plasma studies". In: *Journal of Quantitative Spectroscopy and Radiative Transfer* 51.1 (1994). Special Issue Radiative Properties of Hot Dense Matter, pp. 179–186. ISSN: 0022-4073. DOI: https://doi.org/10.1016/0022-4073(94)90078-7. URL: https://www.sciencedirect.com/science/article/pii/0022407394900787.

[2] T D Arber et al. "Contemporary particle-in-cell approach to laser-plasma modelling". In: *Plasma Physics and Controlled Fusion* 57.11 (Nov. 2015), pp. 1–26.

[3] Amitava Adak et al. "Ultrafast dynamics of a near-solid-density layer in an intense femtosecond laser-excited plasma". In: *Physics of Plasmas* 21.6 (2014), p. 062704. DOI: 10.1063/1.4882675. eprint: https://doi.org/10.1063/1.4882675. URL: https://doi.org/10.1063/1.4882675.

[4] Jin Woo Yoon et al. "Realization of laser intensity over 10 23 W/cm 2". In: *Optica* 8.5 (2021), pp. 630–635.

[5] A Casner et al. "LMJ/PETAL laser facility: Overview and opportunities for laboratory astrophysics". In: *High Energy Density Physics* 17 (2015), pp. 2–11.

[6] K. U. Akli et al. "Laser Heating of Solid Matter by Light-Pressure-Driven Shocks at Ultrarelativistic Intensities". In: *Phys. Rev. Lett.* 100 (16 Apr. 2008), p. 165002. DOI: 10.1103/PhysRevLett.100.165002. URL: https://link.aps.org/doi/10.1103/PhysRevLett.100.165002.

[7] D Jung et al. "Experimental characterization of picosecond laser interaction with solid targets". In: *Physical Review E* 77.5 (2008), p. 056403.

[8] SH Glenzer et al. "Progress in long scale length laser–plasma interactions". In: *Nuclear Fusion* 44.12 (2004), S185.

6. Future Work

- Extend to 2D simulations
  - This will enable a much wider range of experiments to be simulated
- Introduce additional simulation code modules