Multi-group Eulerian Radiation Transport, Nuclear Burn with α Particle Transport, and new diagnostic features for First Light's multi-physics ICF code – **B2**

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Introduction

First Light Fusion is researching methods for achieving projectile-driven inertial fusion energy. Our multi-physics fixed-grid Eulerian code – ***B2*** – has been developed in-house in order to predict the outcome of ICF experiments, and the behaviour of projectiles driven by pulsed-power machines. B2 includes the following features (with those in **bold** recently implemented by the authors of this poster):

- Multi-material, two-temperature hydrodynamics with a VOF scheme for interfaces
- Thermal conduction
- Particle photonics (for e.g. laser ICF drivers)
- **Multi-group Eulerian Radiation Transport ($P_{1/3}$ closure)**
- **Nuclear burning of Deuterium-Tritium mixtures, with depletion of fuel material density and advection of fuel/ash species**
- **Single-group Eulerian α particle transport[1]**
- **Diagnostics: tracer particles, and pseudo-Lagrangian mass-packet reconstruction**

Radiation Transport

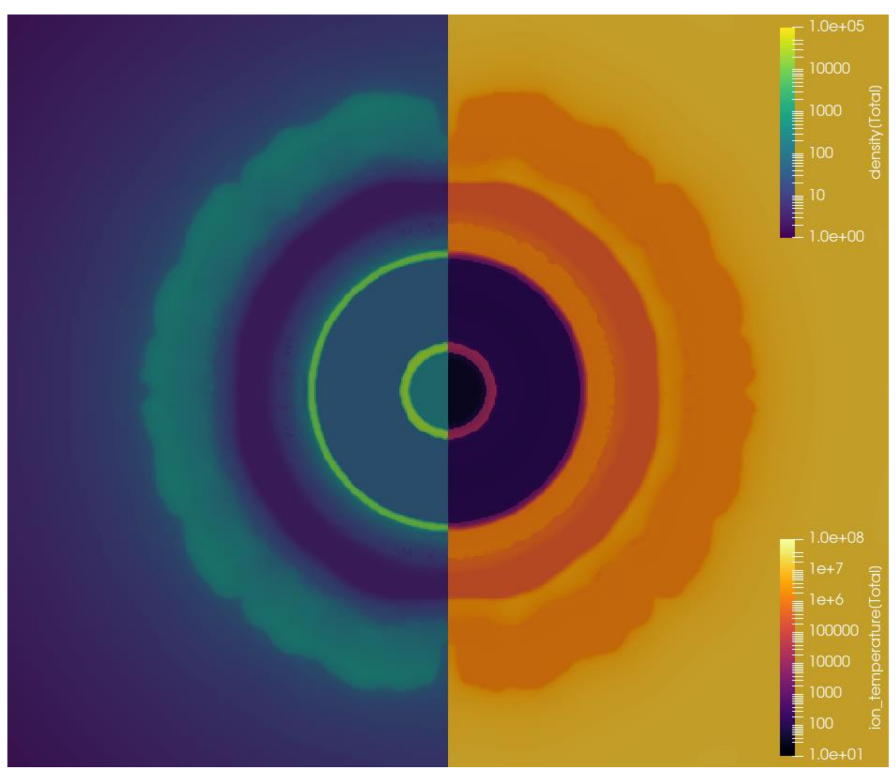
In high temperature plasma, a significant fraction of the total energy is carried by the radiation field. Tracking this radiation is critical to predicting behaviour accurately in high energy density systems. We have implemented an Eulerian (moment-closure) scheme for transporting our radiation on the same grid as the hydrodynamics, in which the energy density in each group (a slice of the photon energy spectrum) obeys

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \boldsymbol{q}_\nu = 4\pi j_\nu - c\chi_\nu E_\nu$$

which is a set of conservation laws (coupled indirectly through interactions with the medium – with emissivity j and opacity χ) that we can solve using a similar finite-volume method to that used for the equations of hydrodynamics. Under the $P_{1/3}$ closure, the flux $\boldsymbol{q}_g$ obeys

$$\frac{\partial \boldsymbol{q}_g}{\partial t} + 3c\chi_g \boldsymbol{q}_g = -c^2 \nabla E_g, \qquad g = 1, \ldots, N.$$

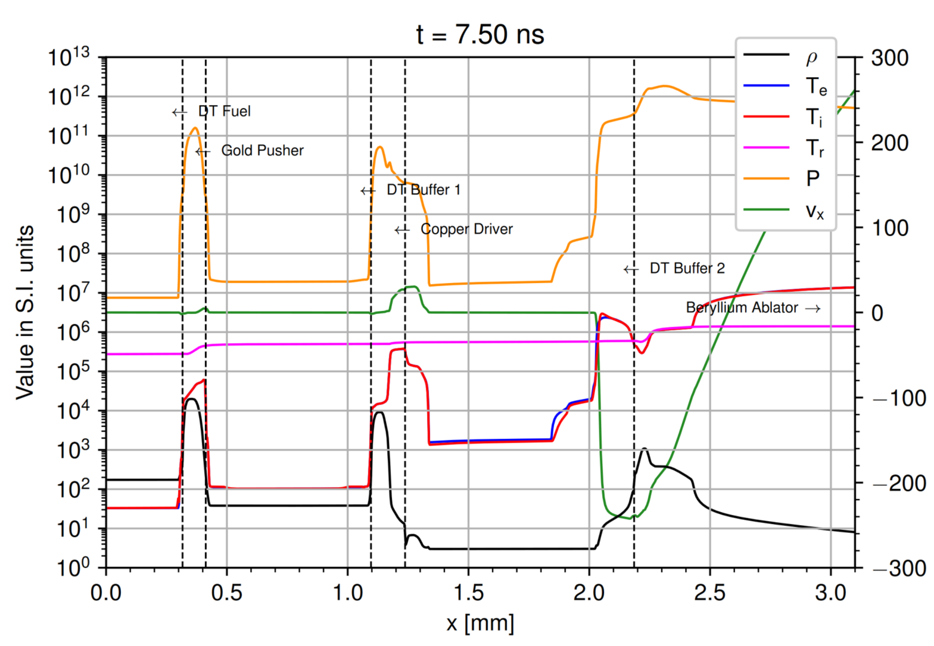
Compared to the commonly used diffusion approximation (in which the flux is not a separately evolving field), $P_{1/3}$ closure better resolves behaviour in the optically-thin limit, notably with the correct wave speed c.

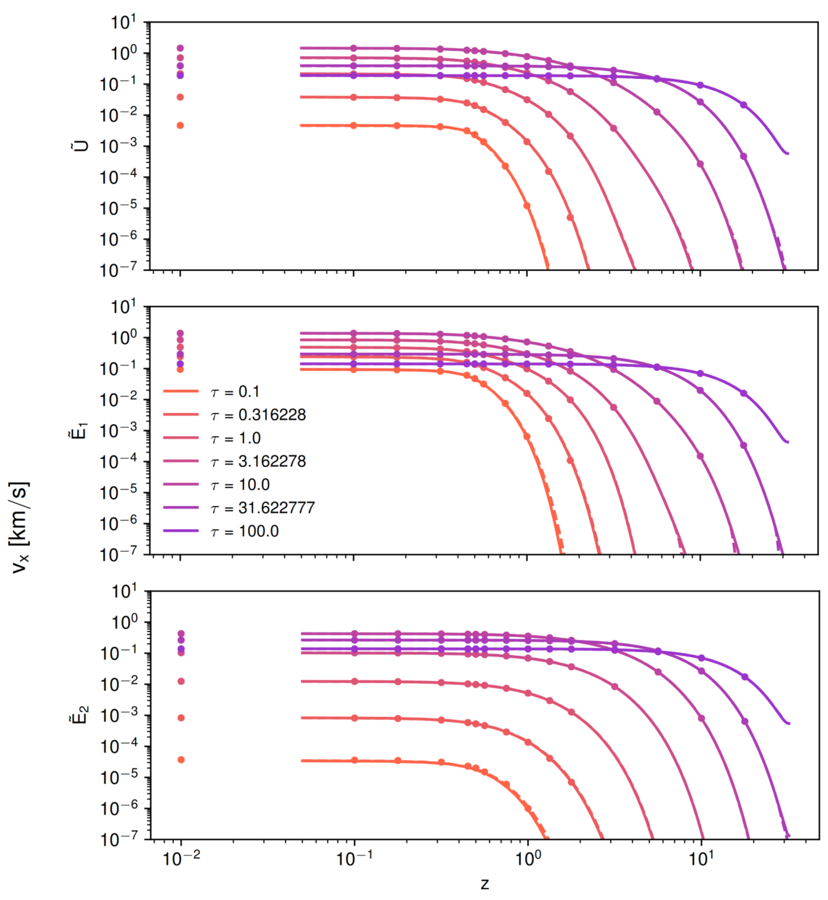


Top left: A temperature(left) / density(right) plot from a 2D simulation of the laser-driven *Revolver* ICF design[2] with 10-group $P_{1/3}$ radiation transport. The copper driver (middle layer) is being ablated by X-rays emitted by the laser-heated beryllium outer shell.

Bottom Left: A plot of multiple quantities in a 1D simulation of the same design at the same time, with each layer labelled. Ablation in the copper before the shock arrives is also clearly visible here.

Bottom Right: A plot of the radiation and material energy densities in an idealised 2-group Marshak Wave verification test case proposed by McClarren[3]. Our implementation (solid lines) agrees perfectly with the analytic result (dots, and dashed lines) at all times.





References

1. Atzeni & Caruso 1981 – *A diffusive model for alpha-particle energy transport in a laser plasma*
2. Molvig et al. 2016 – *Low Fuel Convergence Path to Direct-Drive Fusion Ignition*
3. McClarren 2022 – *Two-Group Radiative Transfer Benchmarks for the Non-Equilibrium Diffusion Model*

Nuclear Burn and α Particle Transport

In order to accurately predict the neutron yield from high burn-fraction ICF target designs, and self-consistently apply the heating due to charged particle products, we must consider the depletion of the fuel as it burns, which reduces the concentration of reactants and changes the hydrodynamic properties of the material containing the fuel. Thus, we now track and passively advect protium, deuterium, tritium, helium-3 and helium-4 densities, and solve the ODE system associated with nuclear burn in each cell in our simulation.

$$\frac{dn_D}{dt} = -R_{DD}$$
$$\frac{dn_T}{dt} = -R_{DT} + \frac{R_{DD}}{2}$$
$$\vdots$$

This is coupled to the hydrodynamics (via the total material density and internal energy) and the α particle transport solver (via a source term for each fusion reaction). We allow for either local α deposition and heating, or a proper transport model. In most ICF scenarios, the α stopping length is much larger than the hydrodynamic length scale of interest, so depositing charged products locally is unrealistic.

Thus, we have implemented a prototype transport model for the products of D-T fusion (the major self-heating channel in equimolar DT fuel). The D-T α particle products are transported according to the simple approximate scheme proposed by Atzeni & Caruso[1], in which we make the assumptions of quasi-equilibrium and isotropy, so that the distribution can by described solely by the energy density, which evolves according to

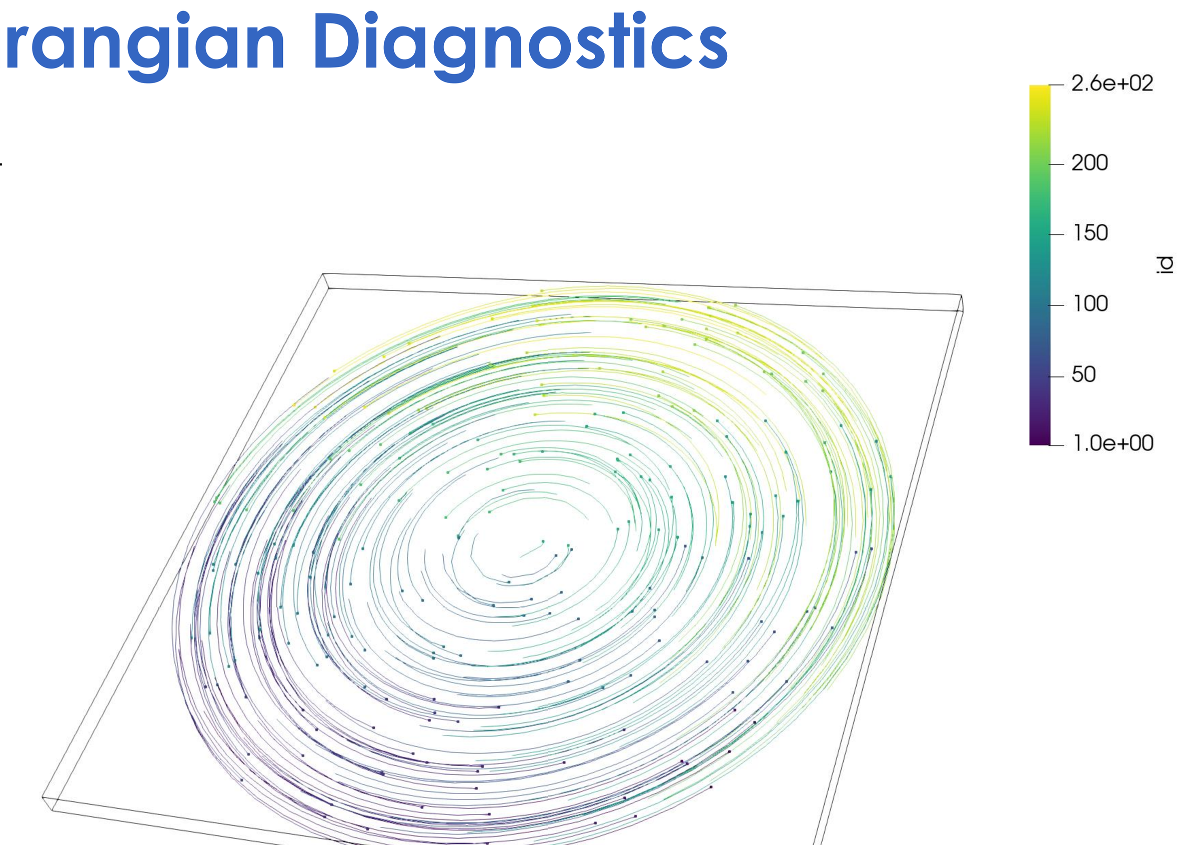
$$\frac{\partial \varepsilon}{\partial t} - \frac{v_0^2}{9} \nabla \cdot (\tau \nabla \varepsilon) = S - \frac{\varepsilon}{\tau}$$

where τ is the α particle stopping time and $S = R_{DT} + R_{DD}$. This exactly resembles the equation for diffusive radiation transport, and is easy to solve via the same method; indeed, the CFL condition is less strict than the one for RT, since $v_0 \sim 0.04c$ for D-T alphas!

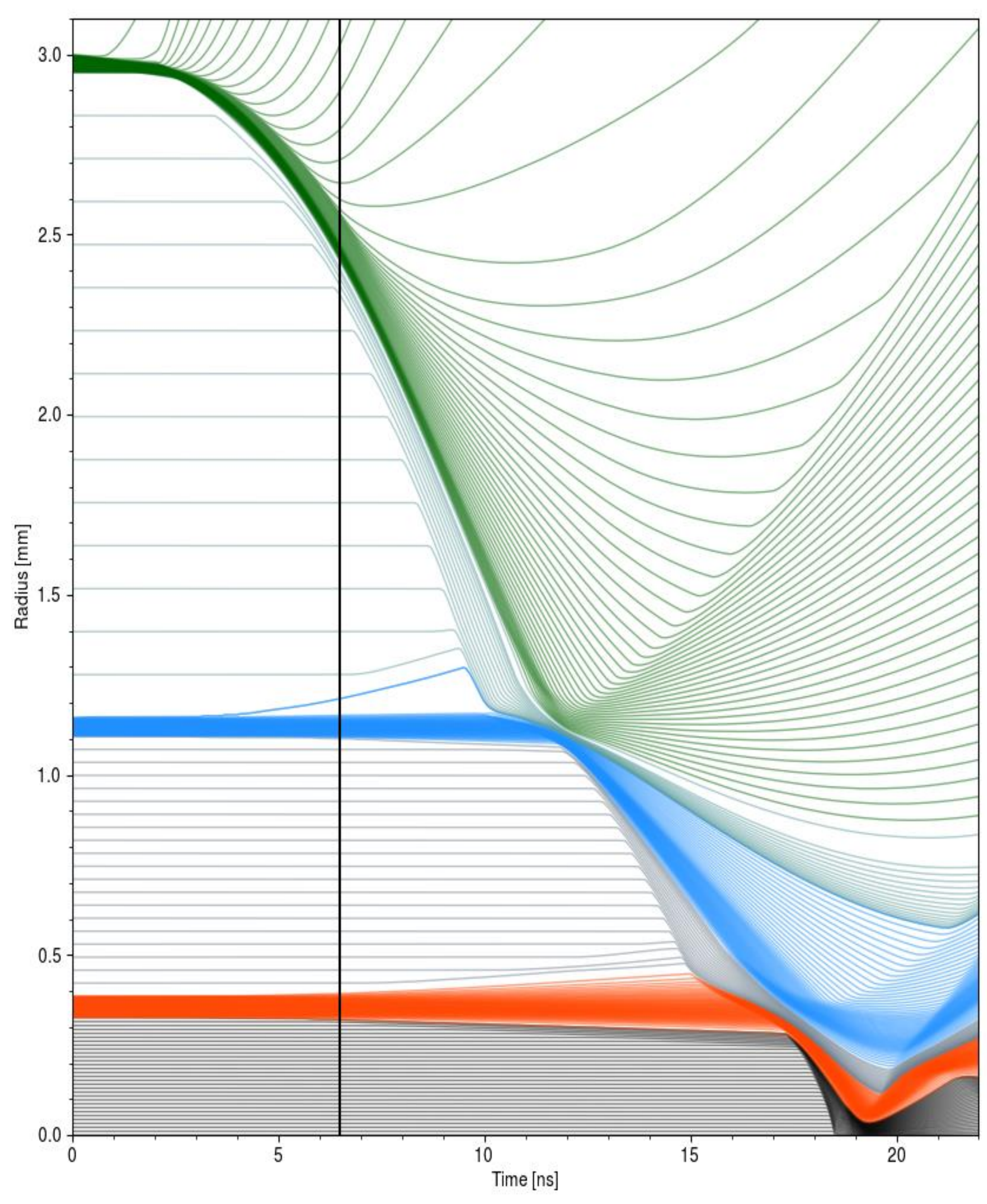
Lagrangian Diagnostics

It is often useful to have *Lagrangian* information about material in a simulation: '*what was the path of a given packet of material through time and space?*'. This question can be difficult to answer in Eulerian codes, as they deal only with the bulk properties of static regions of space. However, we can extract the Lagrangian representation of the fluid by evolving *tracer particles* using the Eulerian flow field $\boldsymbol{u}(\boldsymbol{x}, t)$. Each of these simply obeys

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{u}(\boldsymbol{x}, t).$$



Right: Paths of tracer particles in a circular flow test case. Different colours are associated with different particle IDs.



These make use of our new parallel particle API for B2, which will eventually also be used for new Lagrangian physics operators. We have additionally implemented a method to track mass-packets in a 1D Eulerian simulation. By integrating over the density field we can separate it into bins of constant mass, associated with the same fluid element throughout the simulation (like a particle in a Lagrangian code). We can output this information more frequently than snapshots of the whole grid, as there is less data to store per time step.

Left: Mass-packet position vs. time in a *Revolver* simulation with RT enabled. We can see ablation in the driver and pusher ahead of the main shock due to X-rays radiating from hot post-shock material. We do not perfectly match the HYDRA simulation's behaviour[2], but qualitatively see similar features. A notable difference is that we see earlier/greater ablation in the inner layers, possibly because our average intensity-weighted opacity (over the 10 groups) may be too low due to the coarse discretisation of the spectrum, allowing X-rays to penetrate too far inwards.