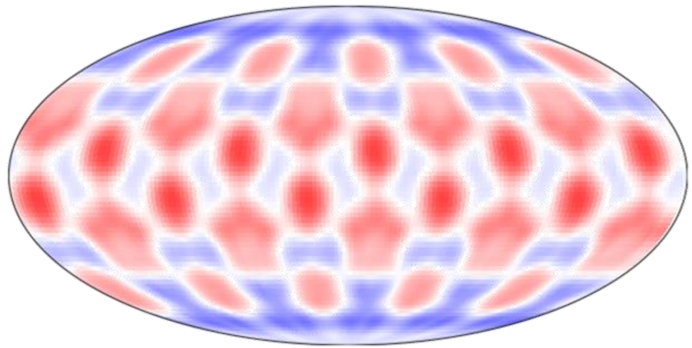
HEDP modelling capabilities



Jeremy Chittenden

Centre for Inertial Fusion Studies, Imperial College

IFE Network meeting March 23rd 2024

HEDP modelling capabilities

Gorgon / Chimera capabilities and recent updates

Spectroscopy and synthetic diagnostic tools

Neutron transport and diagnostic tools

Other rad-hydro & HEDP tools available

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CIFS

Gorgon Code

- 3D Cartesian, Cylindrical & Spherical Eulerian (1D Lagrangian)
- Extended MHD Generalized Ohm's Law -Biermann battery, Nernst, cross-Nernst, electron inertia & Hall term (different solver)
- Anisotropic magnetised heat flow (3D super-stepping or 1D implicit),
- Righi-Leduc, Ettinghausen. Spitzer/Braginskii conductivity models or Lee-More-Desjarlais / Sesame table interface
- Two temperature (electrons and ions) Equation of State
  - FEoS/Sesame file interface or inline Thomas-Fermi model
- 3D Laser ray tracing
- Multi-group radiation loss with probability of escape model.
  - Radiation and atomic data from in house CRE, DCA code 'Spk'.
- SLIC, level-set and Young's model interface tackers, etc.
- CAD file import, external circuit models,

Chimera Variant

- Multi-group explicit $P_{1/3}$ automatic flux limited or variable Eddington factor radiation transport.
  - Radiation and atomic data from in house CRE, DCA code 'Spk'.
- 3D advanced laser ray tracing, inverse projection, Cross-Beam Energy Transfer.
- Magnetised Monte Carlo fast particle and alpha-burn package with different stopping models (Spitzer, Maynard-Deutsch-Zimmerman) and dynamic population management.
- Full stress tensor & Johnson Cook material strength model

Recent additions or under developement

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Gorgon/Chimera Code

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla (p_e + p_i) + \vec{j} \times \vec{B}$$

$$\frac{\partial U_i}{\partial t} + \vec{u} \cdot \nabla U_i = -p_i \nabla \cdot \vec{u} - \nabla \cdot \vec{q_i} - Q_{ei}$$

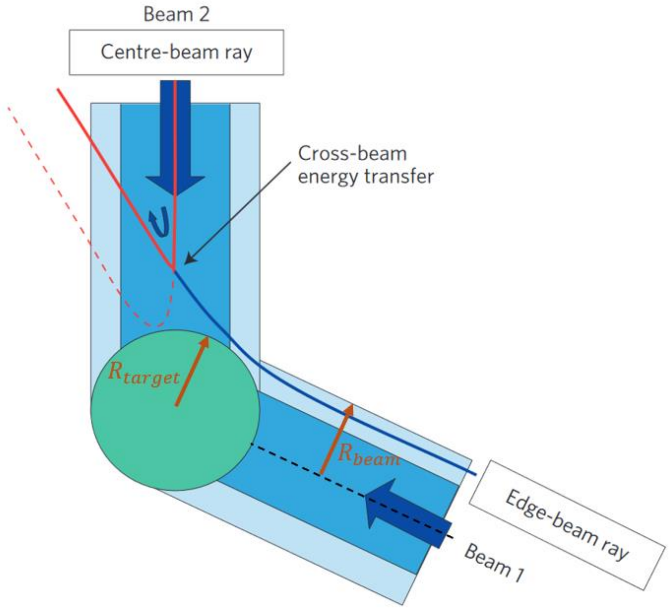
$$\frac{\partial U_e}{\partial t} + \vec{u}_e \cdot \nabla U_e = -p_e \nabla \cdot \vec{u}_e - \nabla \cdot \vec{q_e} + Q_{ei} + Q_{Ohmic} - Q_{Radiation} + Q_{Laser} + \ldots$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

$$\vec{q_e} = \frac{n_e T_e \tau_e}{m_e} \underline{\underline{\kappa}} \cdot \nabla T_e - \frac{1}{e} T_e \left(\underline{\underline{\beta}} + \frac{5}{2} \underline{\underline{1}} \right) \cdot \vec{j}$$

$$\vec{E} = -\vec{u} \times \vec{B} + \frac{\vec{j} \times \vec{B}}{e n_e} - \frac{\nabla \cdot P_e}{e n_e} + \frac{m_e}{e^2 n_e \tau_e} \underline{\underline{\alpha}} \cdot \vec{j} - \frac{1}{e} \underline{\underline{\beta}} \cdot \nabla T_e$$

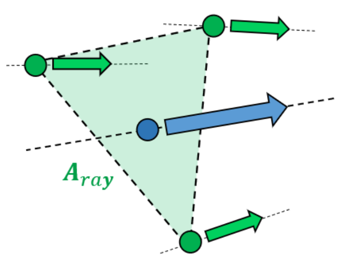
Cross-Beam Energy Transfer in Chimera



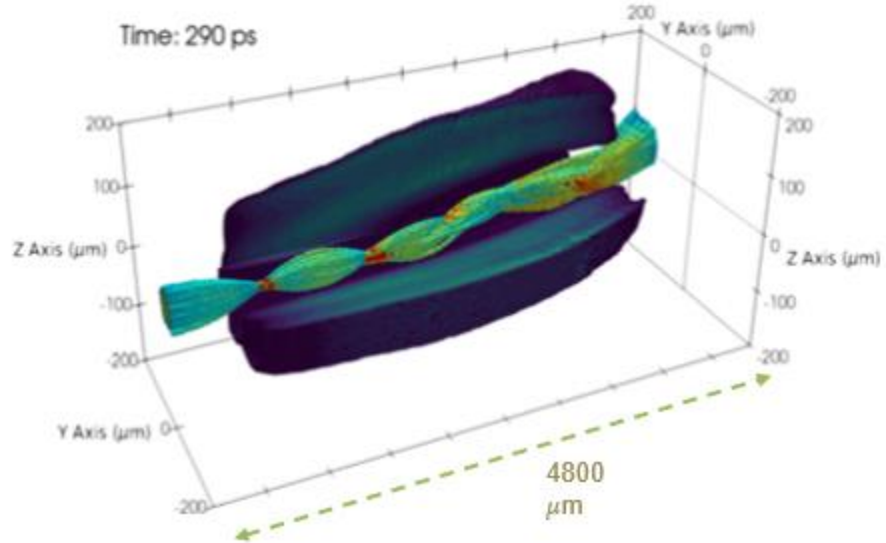
R. Betti *et al.*, Nat. Phys. **12**, 435–448 (2016)

$$E_{ray} = \frac{E_0}{\epsilon^{-1/4}} \frac{A_0}{A_{ray}}$$

R. K. Follet *et al.*, PoP **29**, 113902 (2022)



Non-linear self focusing in gas target on Vulcan



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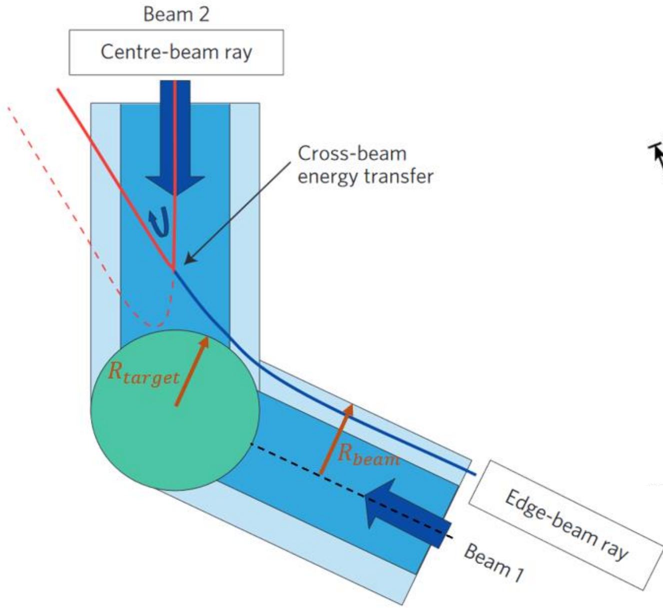
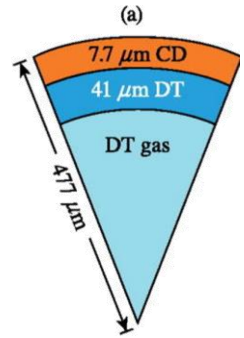
Cross-Beam Energy Transfer in Chimera





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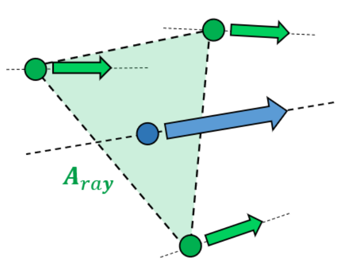
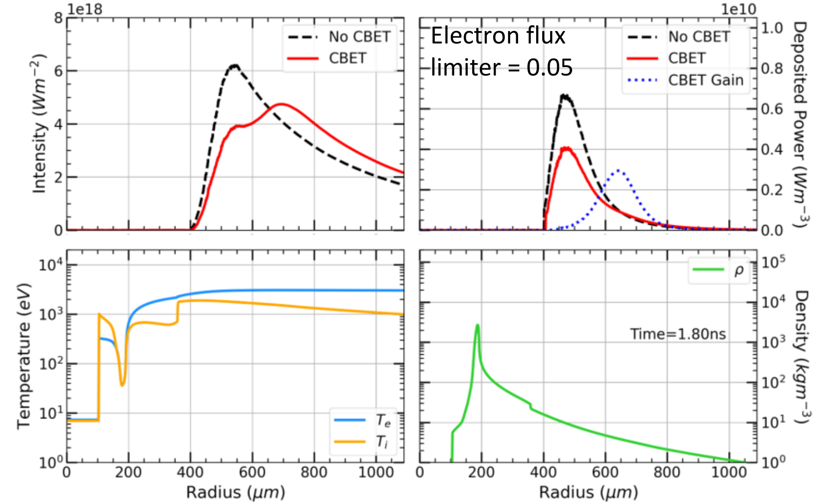
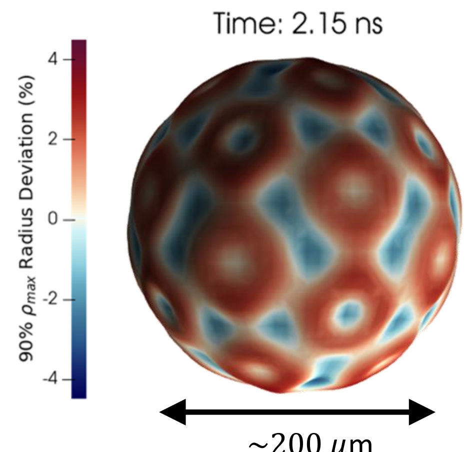


1D hydro + 3D ray trace shows drive deficit





Density contour plot at $CR = 5$ shows that significant low-mode asymmetries imprinted

Anisotropic Radiation Transport using Variable Eddington Factor

$$\frac{\partial E_\upsilon}{\partial t} + \nabla . \vec{F}_\upsilon = - \kappa_\upsilon c E_\upsilon + 4\pi j_\upsilon$$

$$\frac{\partial \vec{F}_\upsilon}{\partial t} = -c^2 \nabla . \bar{\bar{P}} - \kappa c \vec{F}_\upsilon$$

$$P_\nu^{ij} = \frac{3p-1}{2} P_{\text{thin}}^{ij} + \frac{3(1-p)}{2} P_{\text{thick}}^{ij},$$

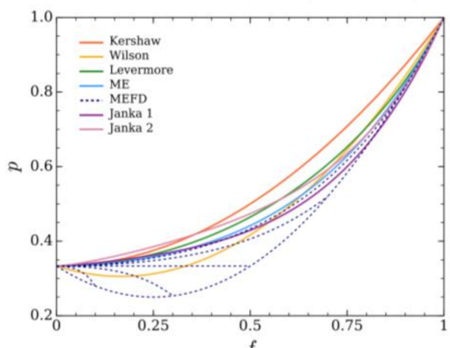
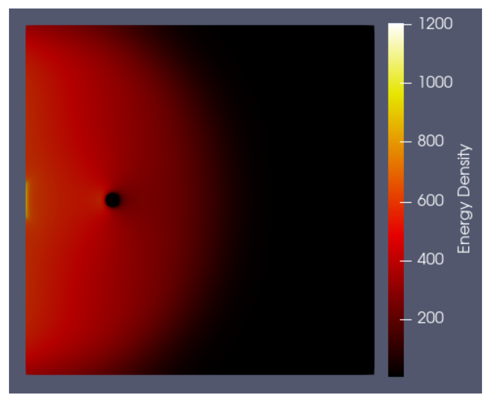


Figure 1. The closure relations for the Eddington factor $p = P_\nu^{xx}/E_\nu$ as the function of flux factor $f = F_\nu^x/E_\nu$. The MEFD closure is a two parameter function and is represented by series of curves for $e = 0.1, 0.2, 0.3, 0.5, 0.7$ and 0.9. The bottom curve is the limit of maximal packing. In the limit $e \to 0$, the MEFD closure reduces to its classical limit, the ME closure, represented by the solid sky blue line (see Section 3.4).

Constant 1000eV source, travelling only in $\hat{x}$

Vacuum medium, Purely absorbing obstacle

P1 Closure

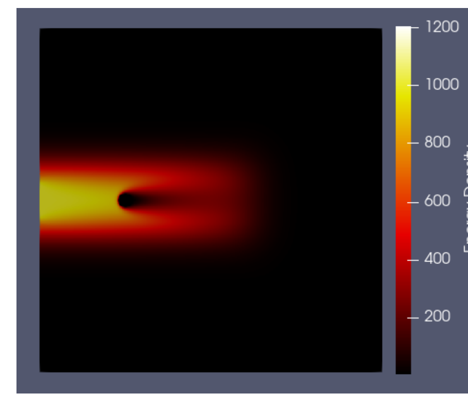


Flux is in the direction of ∇E

Isotropic propagation

No shadow

Kershaw Closure



Radiation propagates in $\hat{x}$

Casts shadow

Numerical diffusion present

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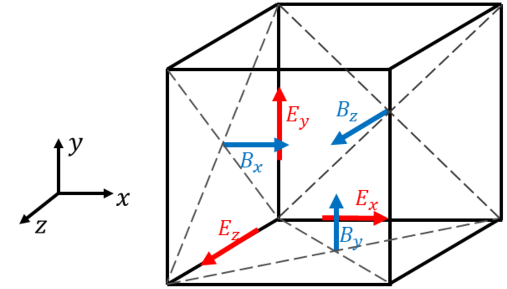
Extended MHD in Chimera



Magnetic field from induction equation

Electric field either from:

- Ampere's Law: circuit coupling with transmission line models
- Generalised Ohm's Law

Solved with a leapfrog scheme on a staggered Yee grid

Hall: field advected with electrons on small scales

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \frac{\alpha}{e^2 n_e^2} \cdot \mathbf{j} + \frac{\beta}{e} \cdot \nabla T_e + \frac{\mathbf{j} \times \mathbf{B}}{e n_e} - \frac{m_e}{e^2 n_e} \frac{\partial \mathbf{j}}{\partial t}$$

Frozen-in-flow: 'field moves with fluid flow'

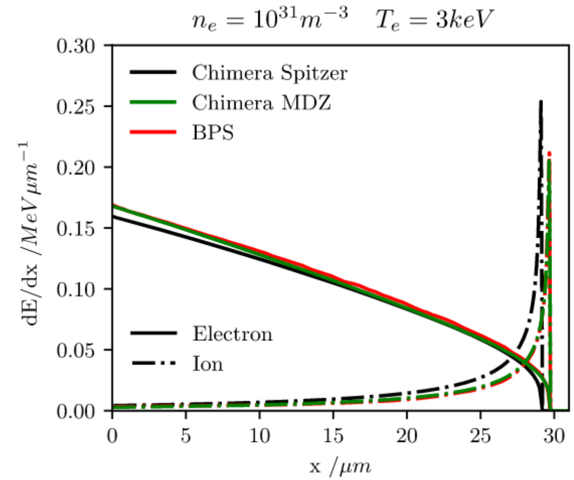
Resistive diffusion: field diffuses into resistive plasma

Electrothermal effects: esp. Nernst, field advected down temperature gradients

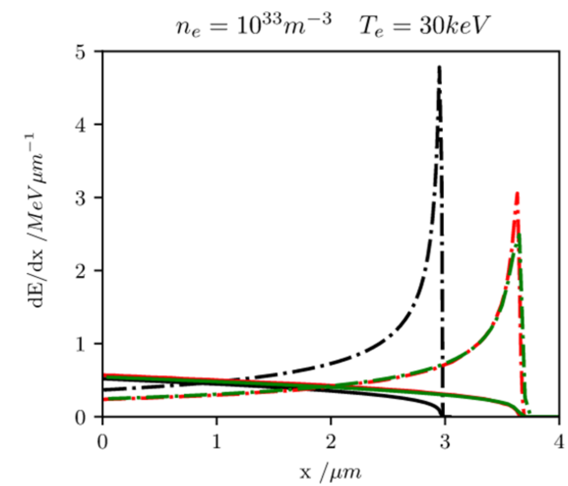
Electron inertia: determines current on smallest scales

Alpha transport and burn package

- In-line model for primary DT fusion α particle heating
- Fast charged particle push including magnetized trajectories
- Monte Carlo stopping model [M. Sherlock, *J. Comp. Phys*., 227, 4 (2008)
- Stopping powers from Spitzer or Maynard-Deutsch (weak coupling, quantum scattering and long-range collective oscillations in an arbitrarily degenerate plasma)
- Dynamic population management with linked list memory structure



Friction $$\frac{\partial v_{\alpha\parallel}}{\partial t} = -A(1 + m_\alpha/m_\beta)\frac{G(x)}{v_\beta^2}$$



Diffusion $$\frac{\partial v^2_{\alpha\parallel}}{\partial t} = AG(x)/v_\alpha$$

$$\frac{\partial v^2_{\alpha\perp}}{\partial t} = A\frac{\mathrm{erf}(x) - G(x)}{v_\alpha}$$

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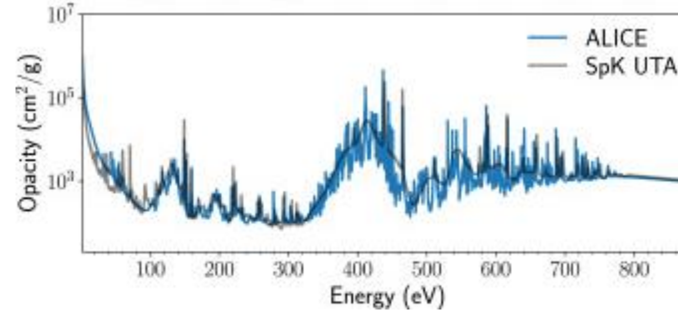
SpK Atomic Physics Code

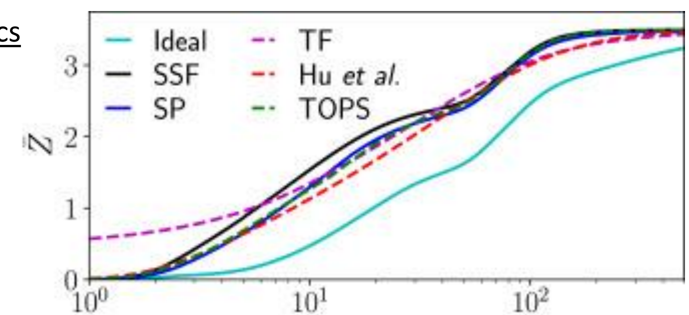
Detailed configuration accounting microphysics code for ionisation, opacities and EoS

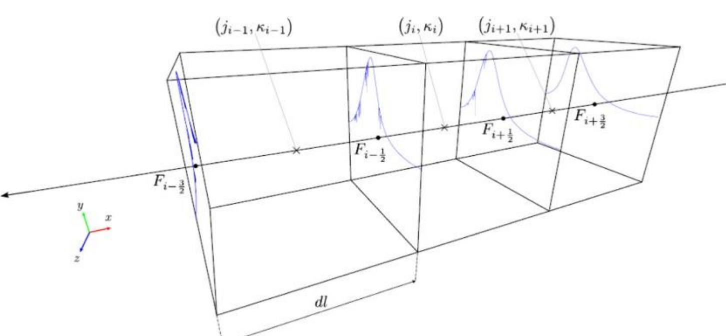
Key features:

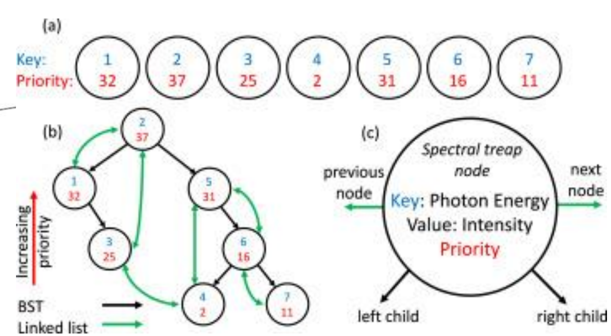
- Analytic atomic model (SHM+NIST)
- Effective temperature CRE
- Unresolved transition arrays
- IPD models including Stewart-Pyatt and Lin-Roepke
- Treap-based data structure for spectra

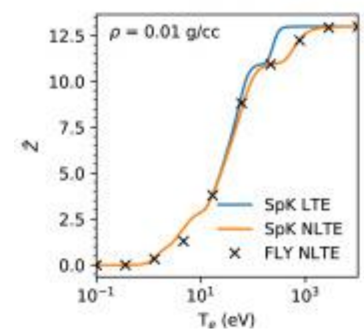
High Energy Density Physics **48,** 101053 (2023).











Synthetic Diagnostic Codes

X-ray & XUV

X-ray filtered imaging and spectra

Including self emission and absorption using either opacity groups or detailed spectral modelling (SpK)

X-ray backlighting

laser

shadowgraphy, Schlieren, interferometry, Faraday rotation, Thomson scattering, refractometer

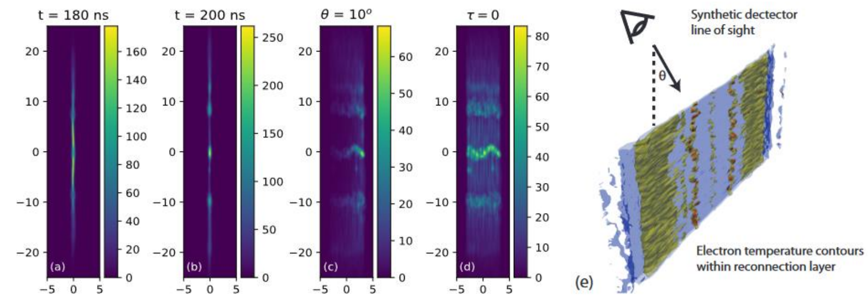
other

proton deflectometry,

charged particle imaging

neutron imaging and spectra including downscatter and backscatter

beam-target and thermonuclear neutrons



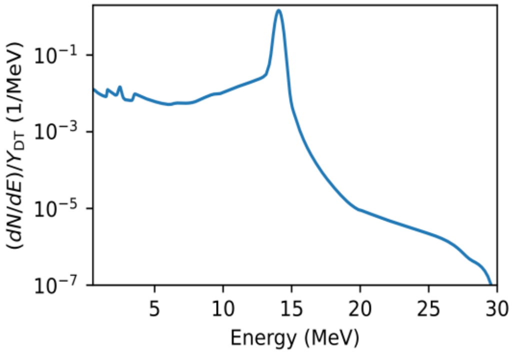
Synthetic time-resolved X-ray images filtered by 2µm of Mylar from different viewing angles in a magnetic reconnection experiment on Z using SpK NLTE emissivity and opacity tables.

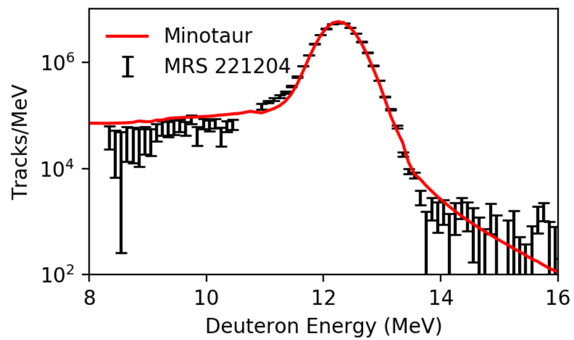
Neutron transport diagnostic codes

Minotaur:

Spherical 1D, time-independent, discrete ordinates

Can post-process Chimera 1D simulations

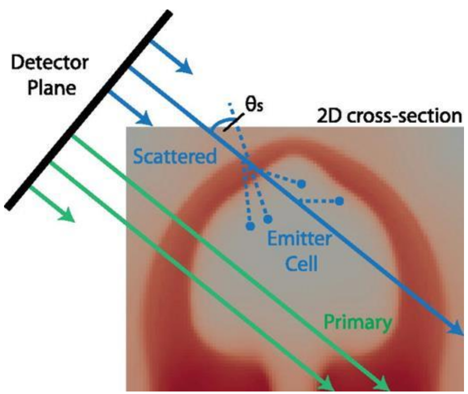


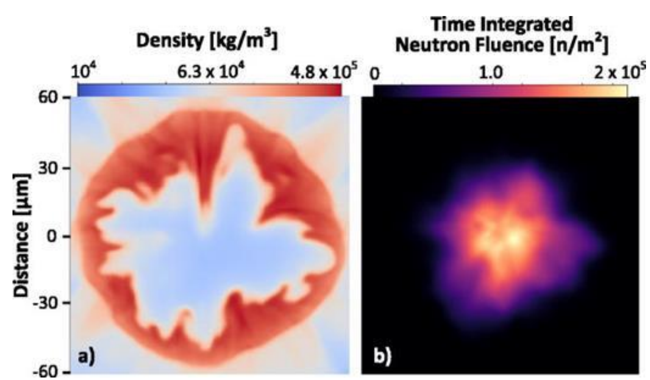


Inverse ray trace (AKED):

3D, time-independent, single scatter neutron transport

Can post-process Chimera 3D simulations

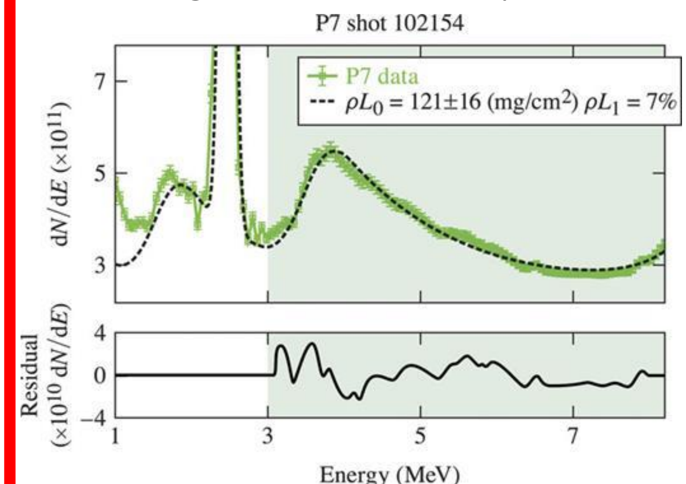




Open source

NeSST (github.com/aidancrilly/nesst)

0D single scatter neutron spectra



DRESS (github.com/jacob-eri/pydress)

MCF 0D primary neutron spectra

iFP fusion product spectral model

Other rad-hydro & HEDP tools available

Other academic rad-hydro codes available in the UK

Odin 2D Arbitrary Lagrangian-Eulerian with laser ray tracing and ideal MHD

HELIOS, Medusa, Hyades 1D Lagrangian

Other academic rad-hydro codes non-UK (non exhaustive)

FLASH 3D Eulerian AMR available from the FLASH center at the University of Rochester

Dued – 2D rad MHD Stefano Atzeni, Rome

MULTI-3D 3D rad hydro Rafael Ramis, Madrid

2D radiation hydrodynamic code SARA – Javier Honrubia

CRASH - an extension to BATS-R-US with multi-group radiation transfer, heat conduction and equation-of-state.

Non rad-hydro HEDP codes (non exhaustive)

Epoch 3D Particle-in-cell with fields

IMPACT 2-D magnetised VFP code

CTC+ (classical transport code) extended MHD transport and hydrodynamics

HEDP modelling capabilities

Gorgon / Chimera capabilities and recent updates

Spectroscopy and synthetic diagnostic tools

Neutron transport and diagnostic tools

Other rad-hydro & HEDP tools available