Highly efficient X-ray generation in high intensity laser-solid simulations

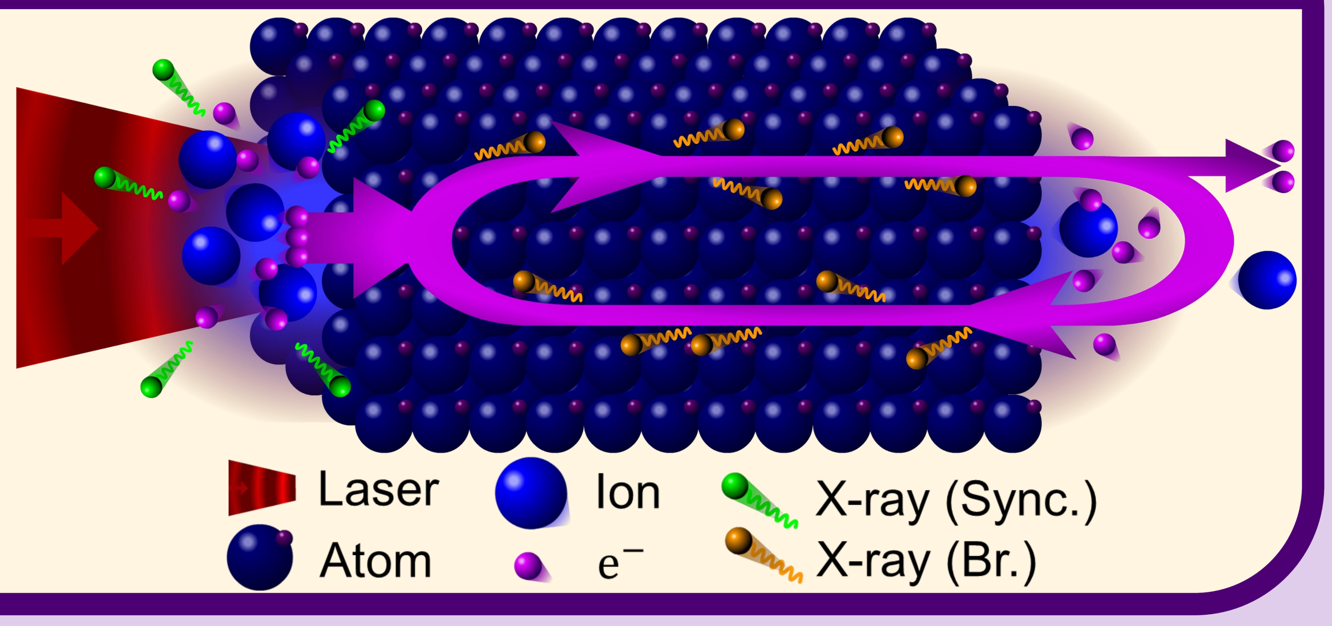
S. Morris (sjm630@york.ac.uk), C. Ridgers

University of York

Full talk

Introduction

- X-rays can be used to scan for special nuclear materials, and can also transmute nuclear waste into medical isotopes.
- When a petawatt-class laser strikes a solid, the surface is heated into a plasma and hot electrons (e⁻) are injected into the target, where they produce X-rays (bremsstrahlung).
- Finding the e⁻ energy to X-ray conversion efficiency $\eta_{e\to\gamma}$ is complicated by competing energy-loss mechanisms. **What fraction of injected e⁻ energy becomes hard X-rays?**



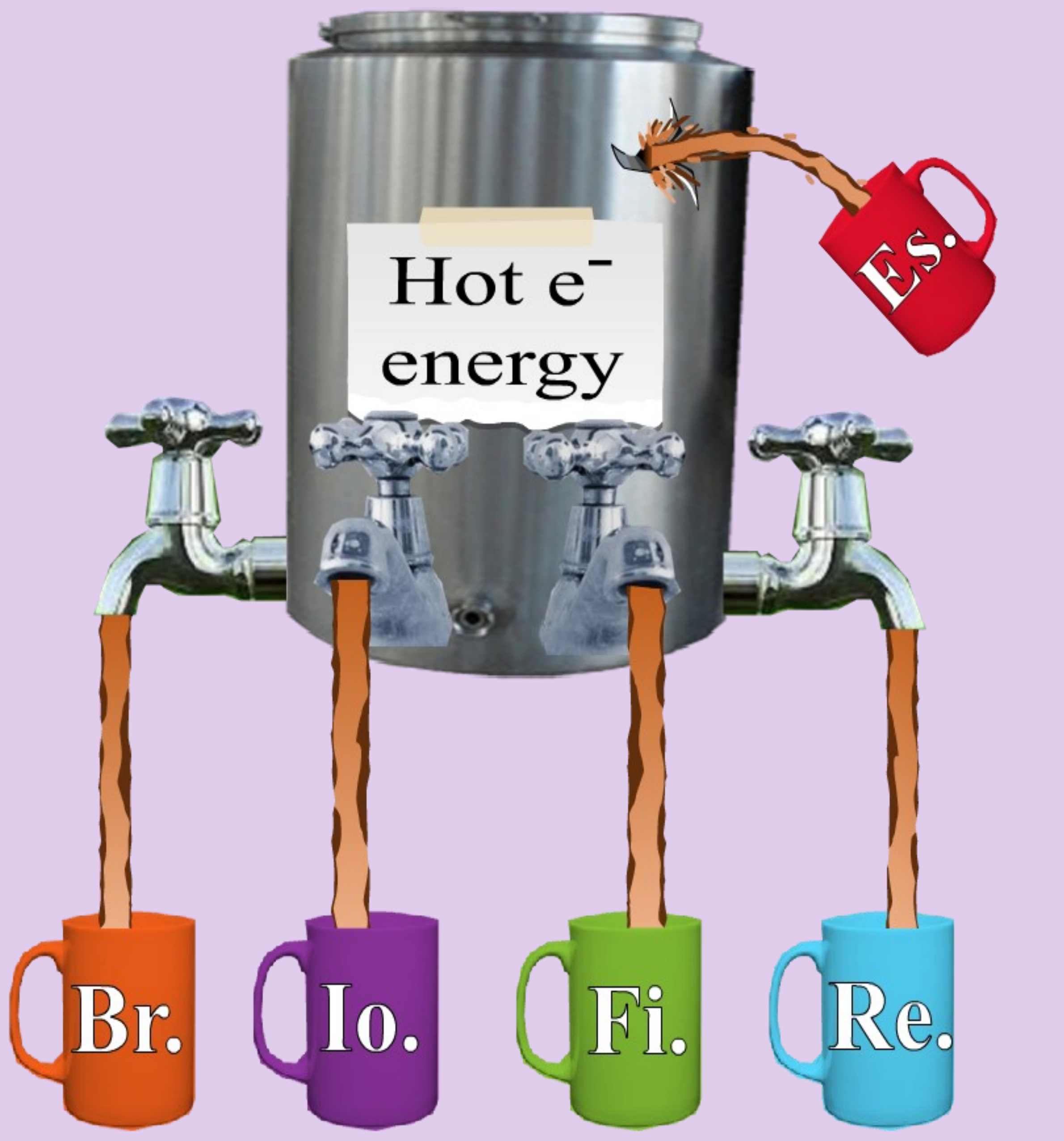


Fig. 1. Many processes compete for the same hot e⁻ energy. The bremsstrahlung (*Br.*) efficiency also depends on the energy lost to: ionisation (*Io.*), fields (*Fi.*), refluxing (*Re.*) and escaping (*Es.*) e⁻. Here *Es.* is different, as only the highest energy e⁻ escape. The rest are trapped by sheath fields, losing energy to the other processes until all energy is lost.

Bremsstrahlung (Br.)

- e⁻ accelerating in the electric fields of the target nuclei can lose energy through X-ray emission
- Stopping power (SI units):

$$\frac{dE}{dx} \approx -0.3 m_e n_i Z^2 E \ln\left(\frac{192}{Z^{1/3}}\right)$$

- Scales with atomic number squared Z^2, e⁻ energy E, and ion number density, n_i

Ionisation energy loss (Io.)

- e⁻ lose energy in non-radiative collisions with target atoms. Energy is transferred to heating the solid [1]
- Stopping power (SI units):

$$\frac{dE}{dx} \approx -10^{-26}\frac{Z n_i}{v^2}\left(\ln\left(\frac{E_k}{I_{ex}}\right) + f(\gamma)\right)$$

- Scales with e⁻ speed v, and target Z, n_i. Varies with the mean excitation energy, I_{ex}

Resistive fields (Fi.)

- The hot e⁻ current draws a resistive return current. This generates electric fields which slow hot e⁻, and heat the target through Ohmic heating [1]
- Stopping power (SI units):

$$\frac{dE}{dx} \approx -e\eta J$$

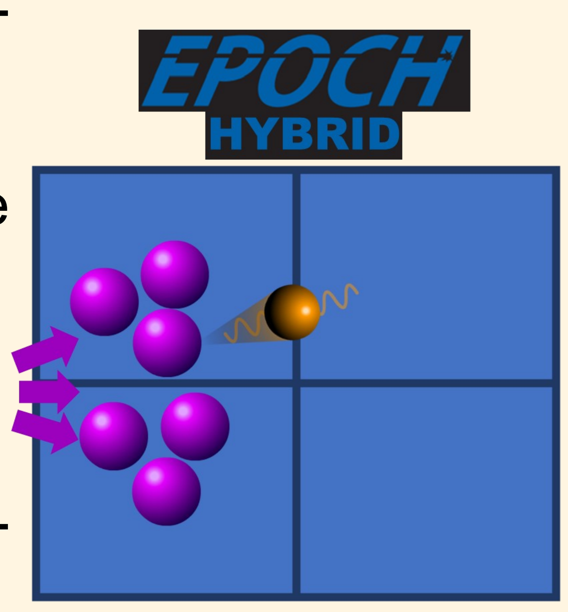
- Scales with resistivity η, and hot e⁻ current density J

Reflux and escape (Es. Re.)

- As e⁻ leave the solid, they set up sheath fields. High energy e⁻ escape, but the rest reflux with some energy loss and scatter
- Behaviour modelled in 2D-PIC (EPOCH) simulations, up to 700 fs simulation time:
  - Escape energy*: $2a_0 m_e c^2$
  - Mean reflux momentum loss: $0.0027 a_0 m_e c$
  - Mean reflux scatter range: 23°

Hybrid-PIC code

- Extension to EPOCH PIC code
- Macro-electrons based on laser parameters are injected into the solid
- The field solver assumes the presence of a resistive return current [1]
- e⁻ undergo *Br.* and *Io.* as they move
- Energy lost to the solid raises the temperature of the local cell, updating η
- Empirical reflux boundaries used



github.com/Status-Mirror/epoch

Simulation setup

- We ran 3D simulations for many target materials and laser intensities, I to find $\eta_{e\to\gamma}$
- Laser: 40 fs pulse, 5 μm spot size
- Run for 10-100 ps to capture the full emission

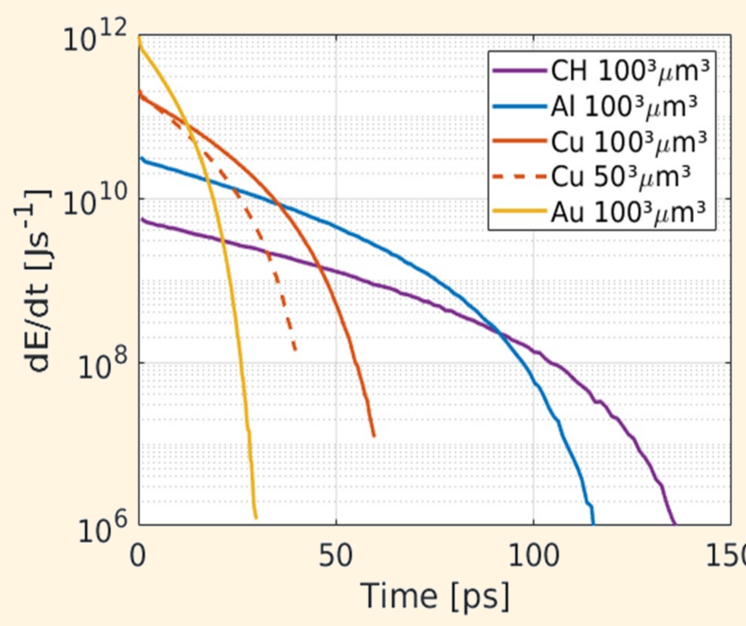


Fig. 2. X-ray emission rates

Results

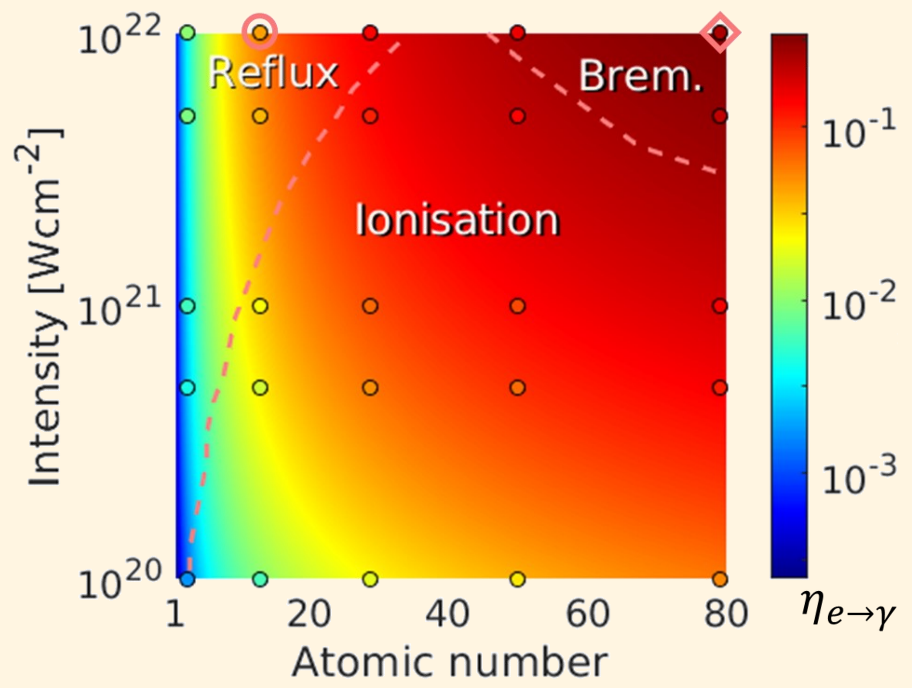


Fig. 3. Conversion efficiency of hot e⁻ energy into X-rays over 1 MeV

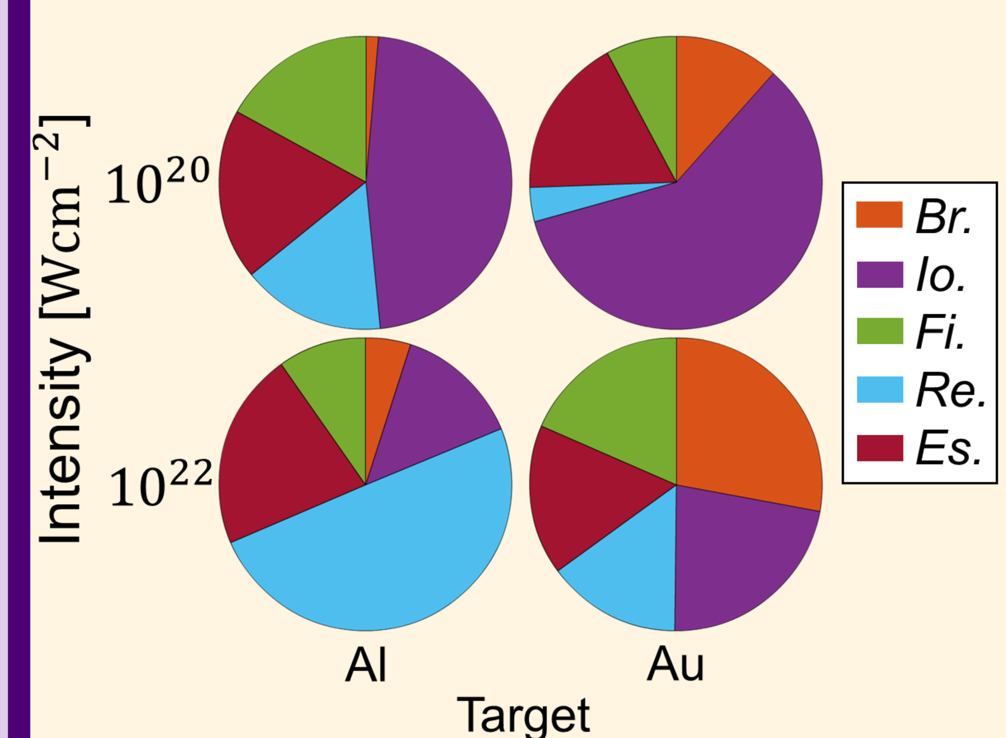


Fig. 4. Pie charts showing energy fraction lost to each process

- Pink diamond shows the peak electron efficiency: 25%
- Pink circle shows Al at 10^{22} Wcm^{-2}. We find laser to X-ray efficiency 0.014, while PIC simulations [2,3] suggest values between $(0.4\text{-}8)\times10^{-5}$
- PIC codes underestimate the emission as they simulate shorter time-scales
- *Br.* dominates high Z high I, *Io.* dominates most Z at low I
- Monte Carlo (MC) codes don't model *Re.* or *Fi.* losses, and will overestimate the emission
- At high I, low Z, *Br.* and *Io.* are too weak to slow e⁻, so e⁻ hit more boundaries and Re. dominates. MC codes would be very poor here.

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References:
[1] Davies, J.R., 2002. *Phys. Rev. E*, *65*(2), p.026407.
[2] Vyskočil, J., 2018. *PPCF*, 60(5), p.054013.
[3] Wan, F., 2017. *Eur. Phys. J. D*, 71(9), pp.1-8.