

Simulations of sub-relativistic ion beam-plasma interactions

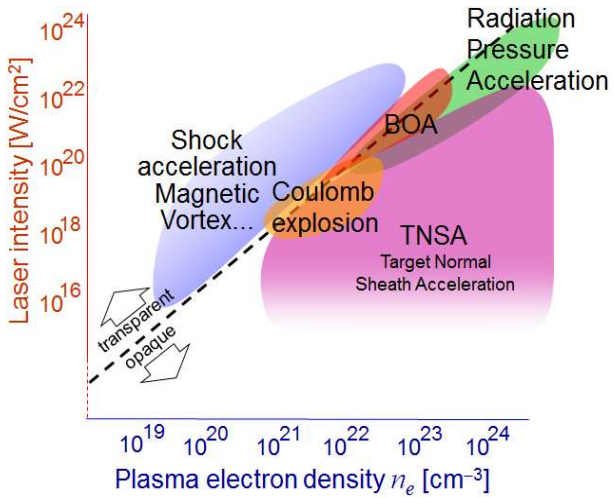
Martin King

Outline

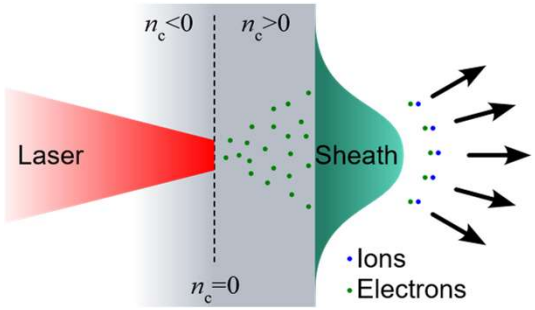
1. Ion acceleration mechanisms
2. Hydrodynamic simulations
3. Particle-in-cell simulations
4. Post-acceleration modelling
5. Machine learning
6. Challenges
7. Summary

Ion acceleration mechanisms

- Target normal sheath acceleration (TNSA)
- Radiation pressure acceleration
- Relativistic self-induced transparency

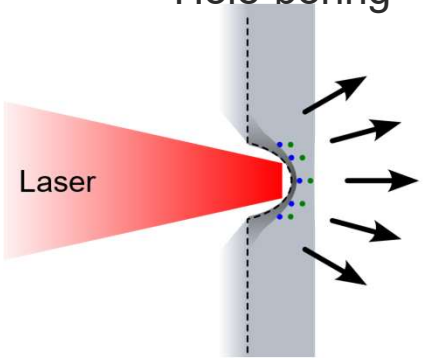


Sheath (surface) acceleration: (in μm-thick targets) TNSA

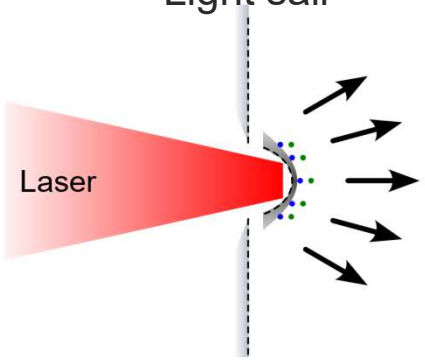


Radiation pressure Acceleration (RPA)

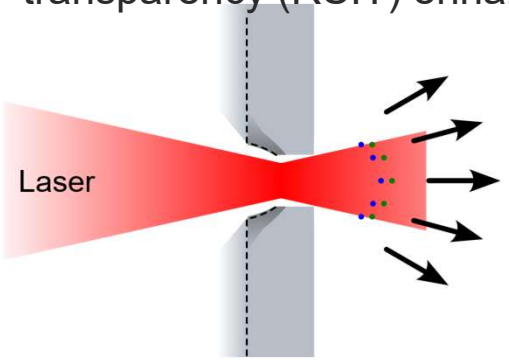
Hole-boring



Light sail



Relativistic self-induced transparency (RSIT) enhanced



Simulations of ion acceleration

Pre-expansion

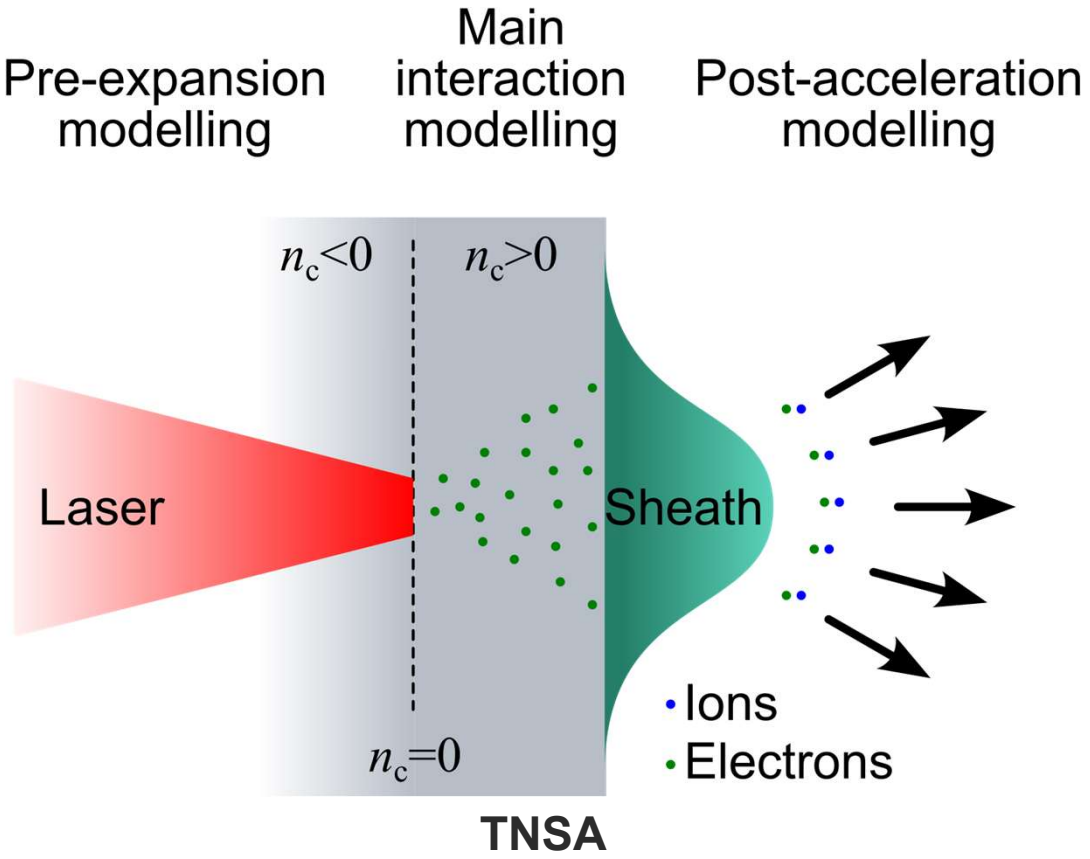
- Pico- to nano-second time-scales
- 1D/2D/3D hydrodynamics modelling (Helios, FLASH)

Main interaction

- Femto- to pico-second time-scales
- 2D/3D particle-in-cell modelling (EPOCH, WarpX)

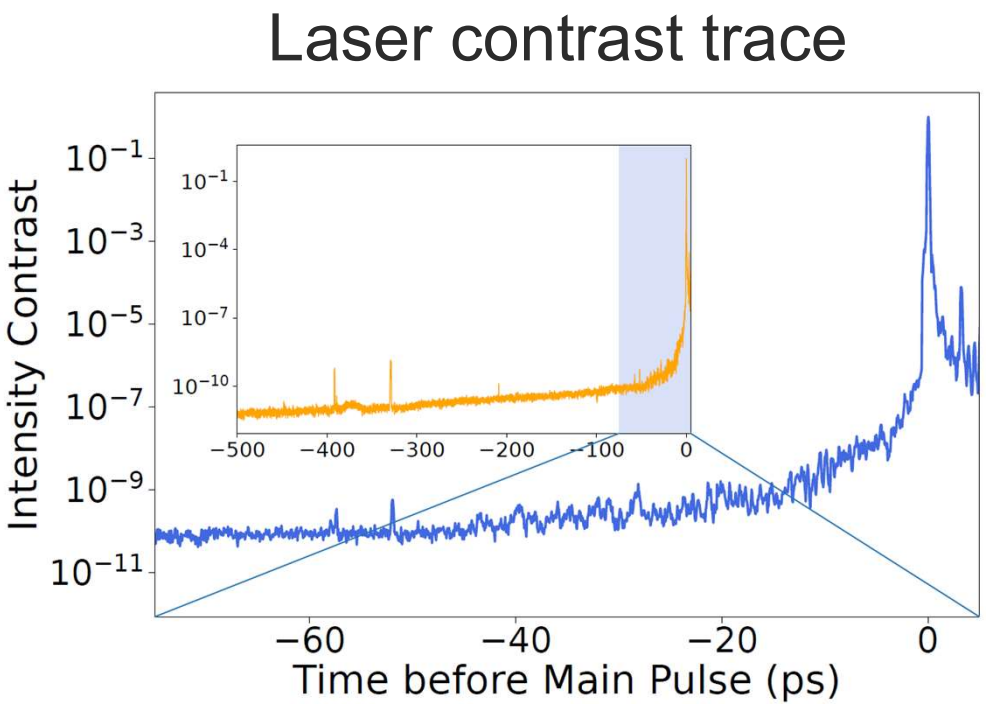
Post-acceleration

- Ray tracing through static fields
- Secondary interactions



Pre-expansion - Hydrodynamic modelling

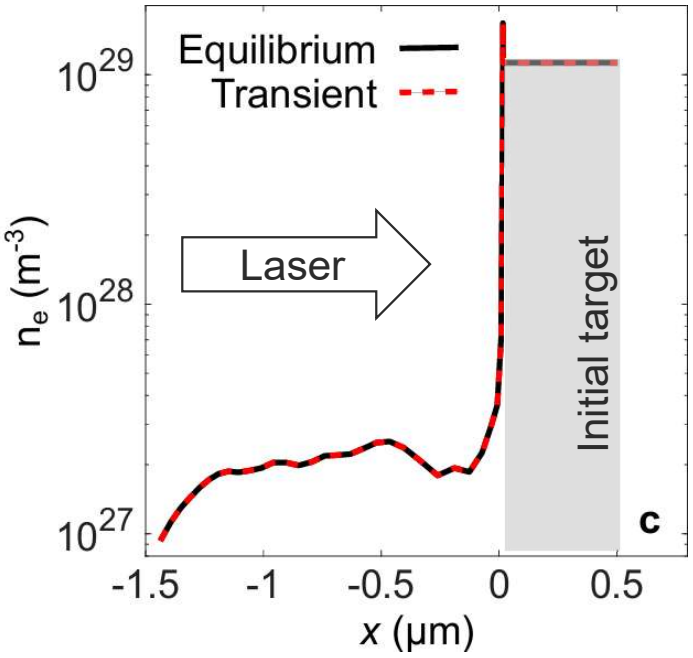
- Hydrodynamics codes
  - Compressible Radiation-MHD Framework
  - Ray-Traced Laser Heating
  - Tabulated Equations of State
  - Coupled Heat/Radiation Transport
- Inputs
  - Modelled/Sampled laser trace intensity trace
  - Target geometry and material composition



Pre-expansion – 1D Hydrodynamic modelling - HELIOS

- 1D Lagrangian code (planar, cylindrical and spherical)
- 1D approximation is sufficient:
  - Minimal or symmetric expansion
  - Transverse expansion expected to be significantly larger than the main interaction

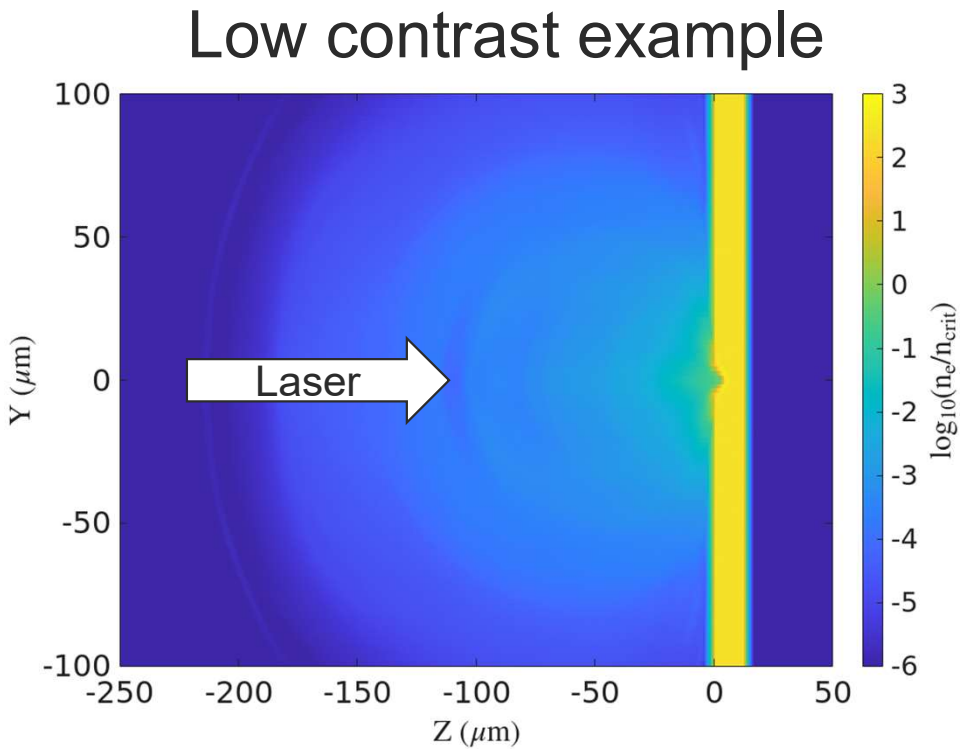
1D example with plasma mirror



Patel et al. Nature Photonics (accepted in principle)

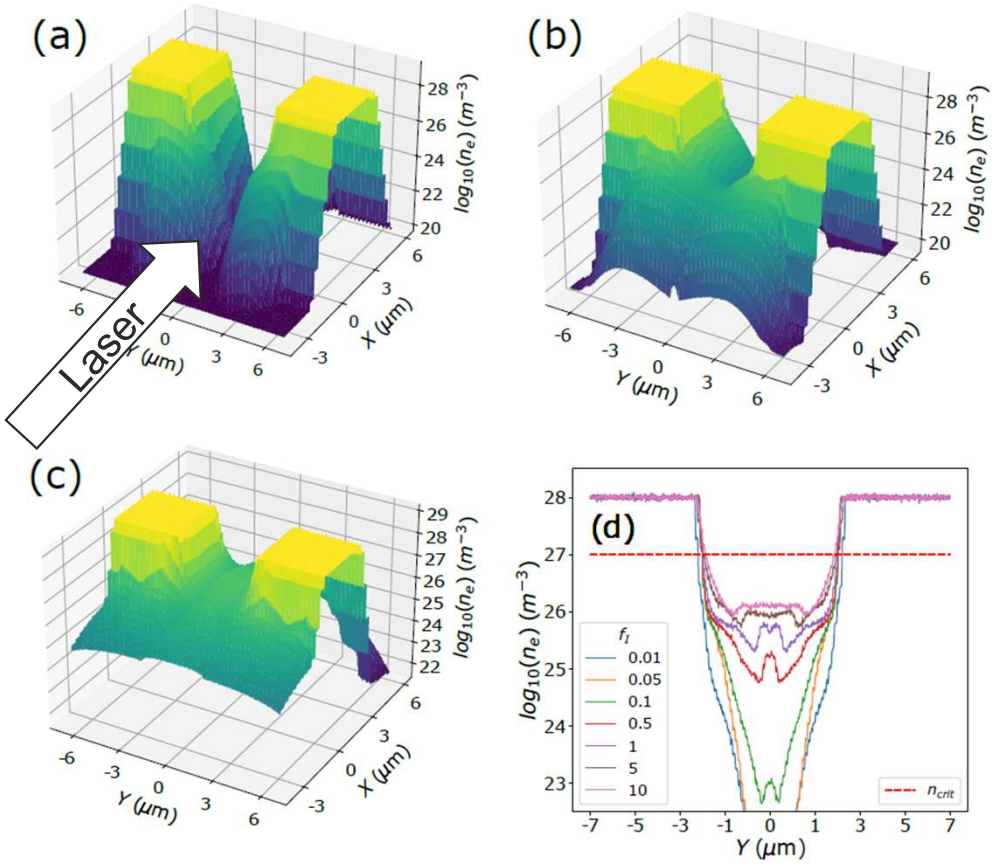
Pre-expansion – Hydrodynamic modelling - FLASH

- 1D, 2D Cartesian/ Cylindrical/Spherical and 3D
- Higher dimensionality required for:
  - Larger expansions
  - Non-planar/complex geometry targets



Pre-expansion – 2D/3D Hydrodynamic modelling - FLASH

- Complex geometry
  - Hemi-spherical targets
  - Conical targets
  - Aperture targets
- Aperture example
  - Plasma expands outwards and into aperture
  - Can impact propagation and interaction physics



E. Bacon PhD Thesis 2026

Pre-expansion – Hydrodynamic modelling – Outputs as inputs

Hydrodynamic modelling outputs

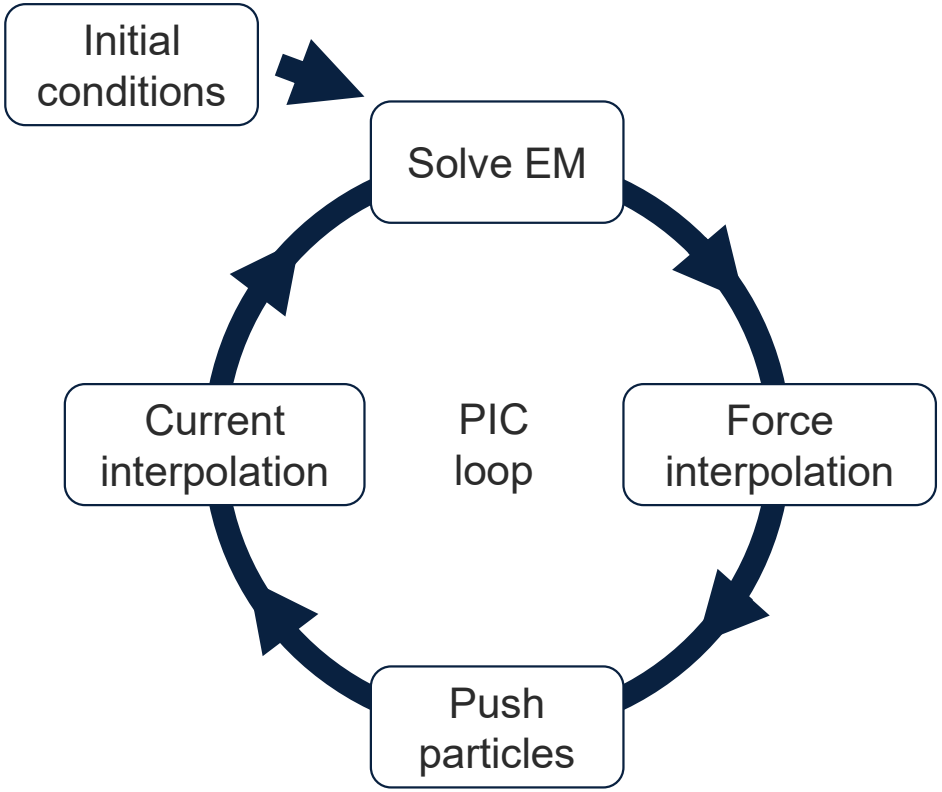
- Electron/ion densities
- Electron/ion temperatures
- Ionization states



Particle-in-cell code inputs

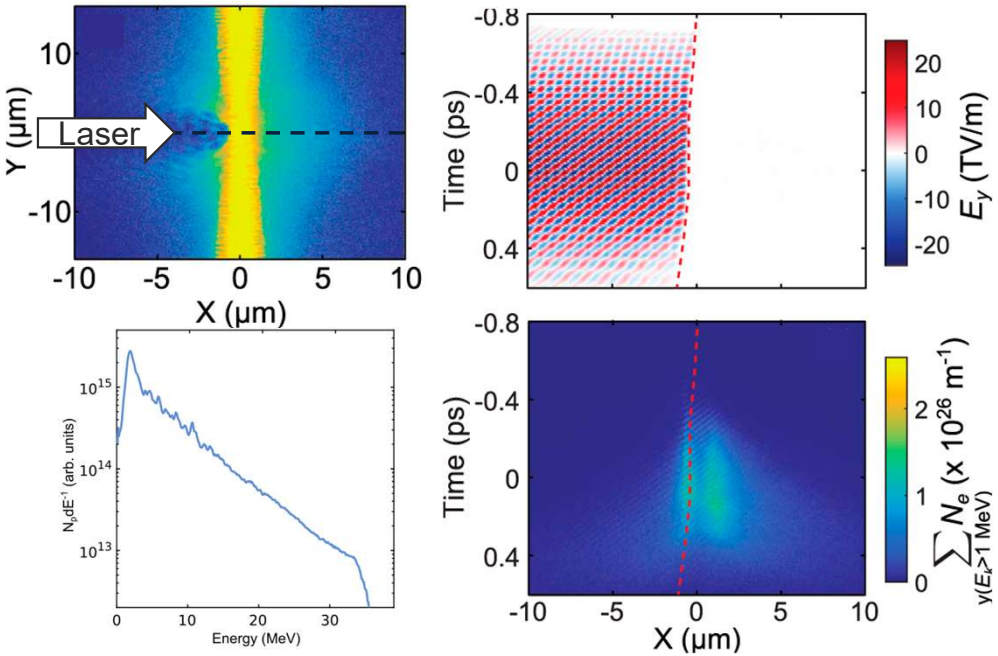
Main interaction - Particle-in-cell (PIC) modelling

- Finite-difference time-domain (FDTD) EM solver
- Simulation volume defined by a regular grid 1D/2D/3D
- Unbound macroparticle populations define the plasma
- Lorentz particle-pusher
- Computationally expensive



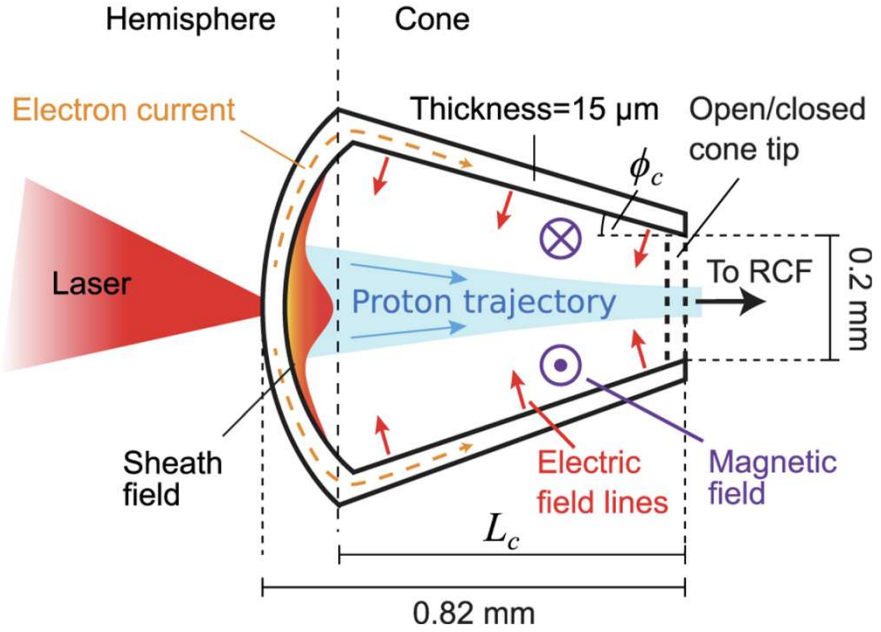
Main interaction - Particle-in-cell (PIC) modelling – TNSA example

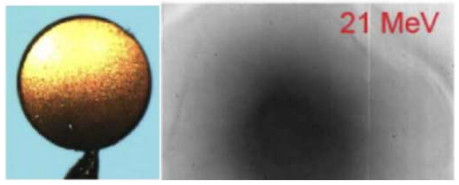
- Observe the evolving field and particle properties in space and time
- Elucidate the underpinning physical behaviour
- Tune and optimise generated ion beam properties

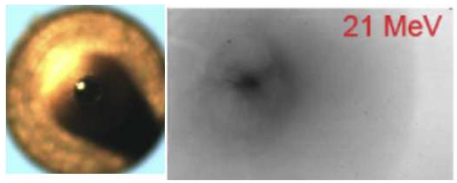


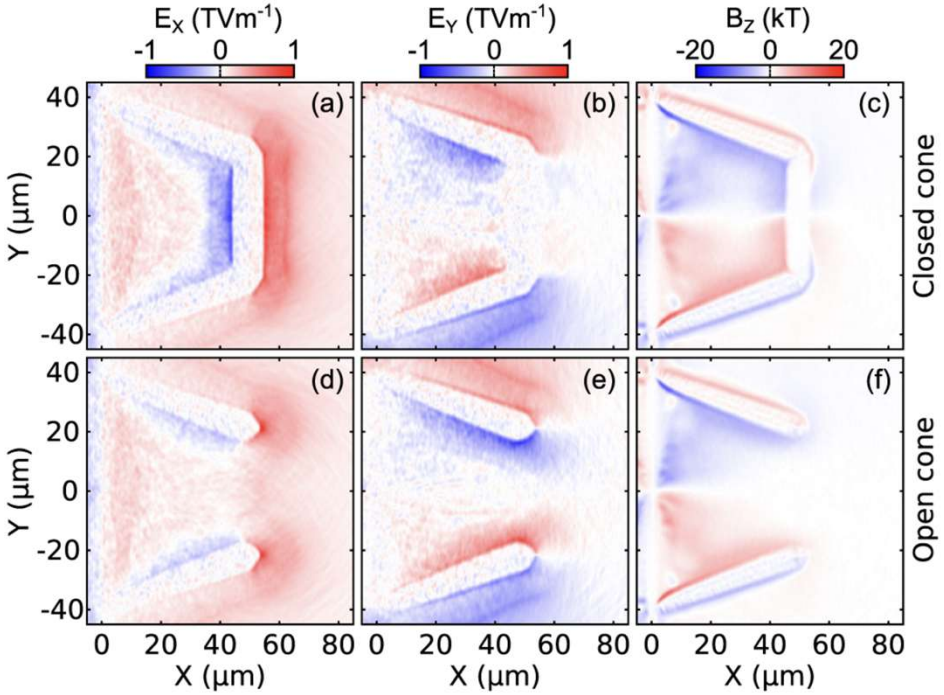
Williamson et al. New J. Phys. 22.5, 053044 (2020)

Main interaction - Particle-in-cell (PIC) modelling – Cone targetry example



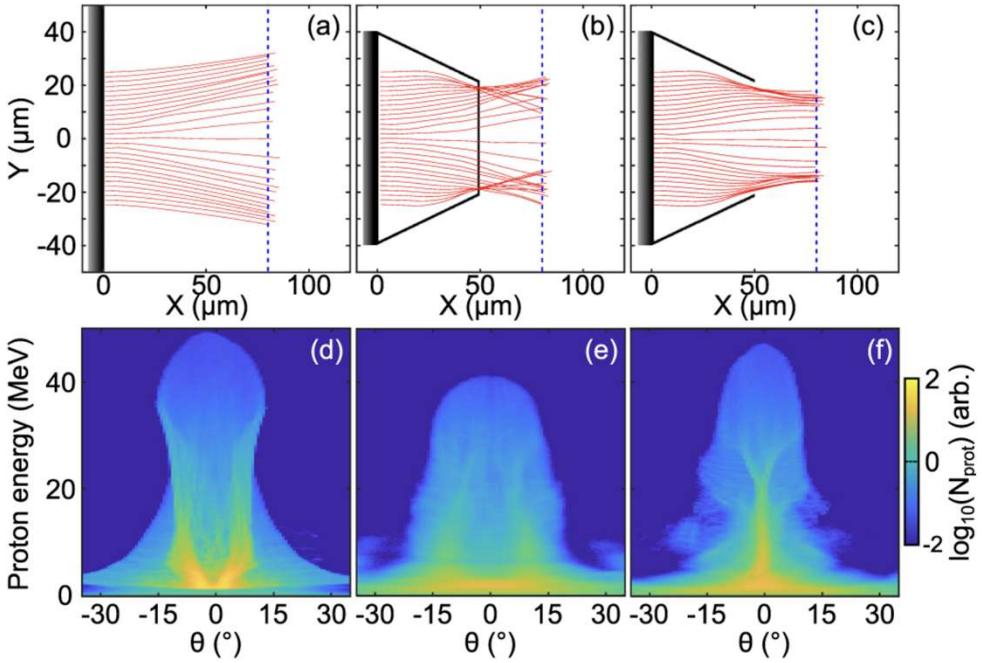


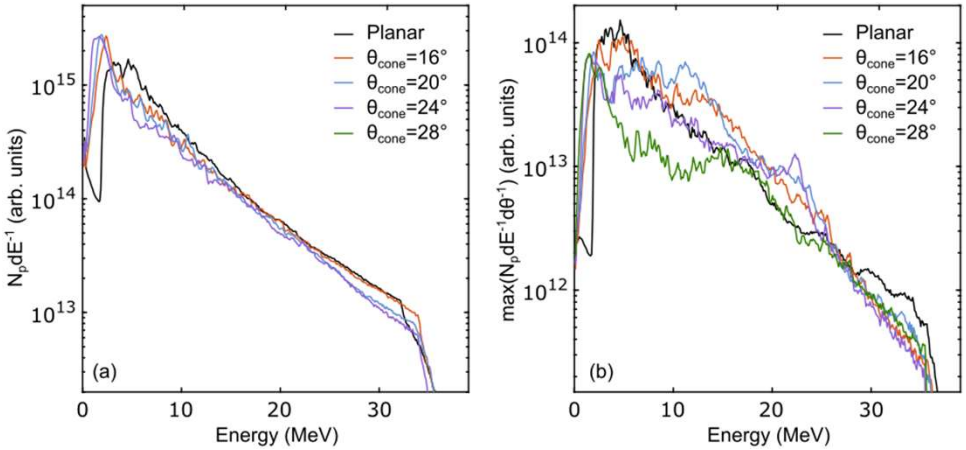




King et al. Plasma Phys. Control. Fusion 66 015001 (2023)

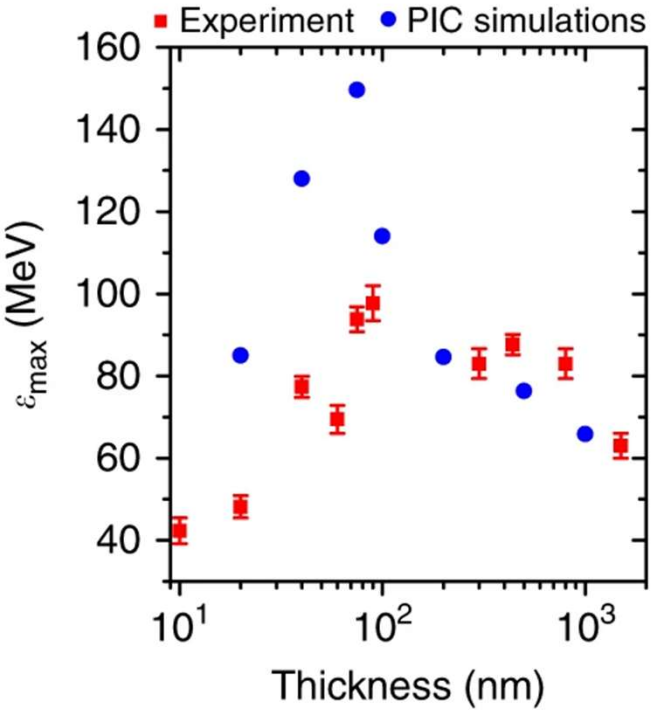
Main interaction - Particle-in-cell (PIC) modelling – Cone targetry example

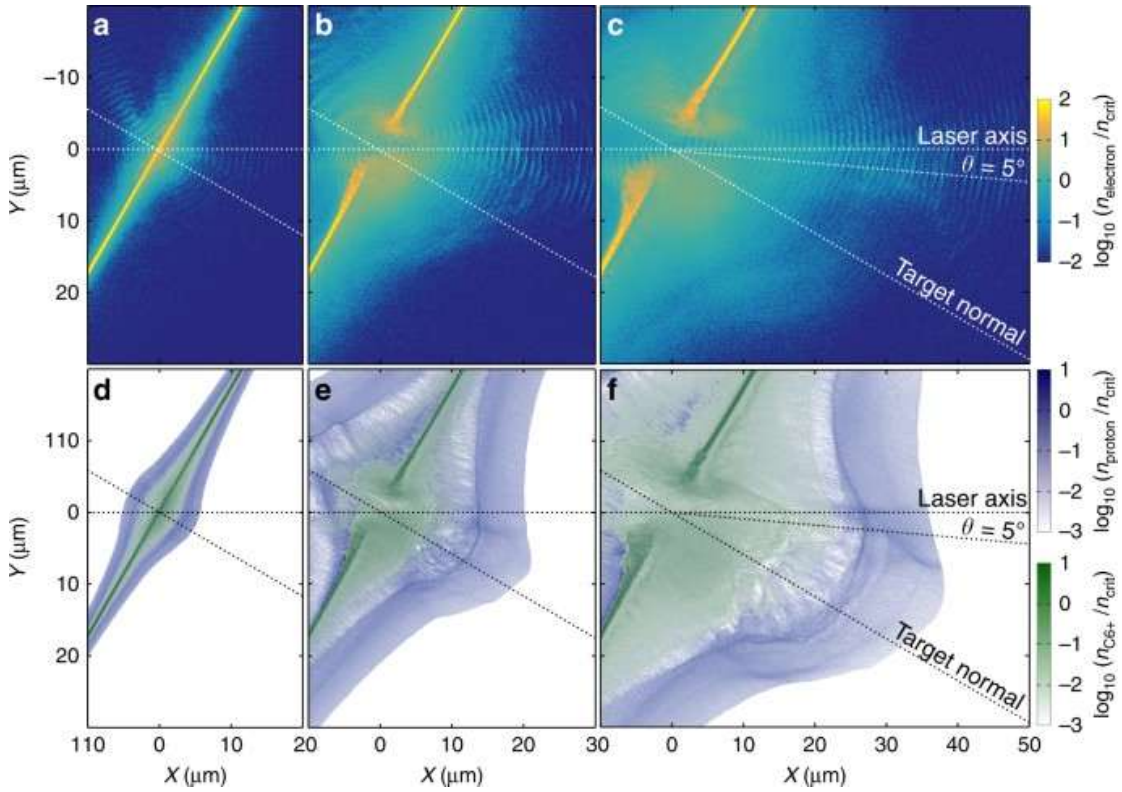




King et al. Plasma Phys. Control. Fusion 66 015001 (2023)

Main interaction - Particle-in-cell (PIC) modelling – RSIT example

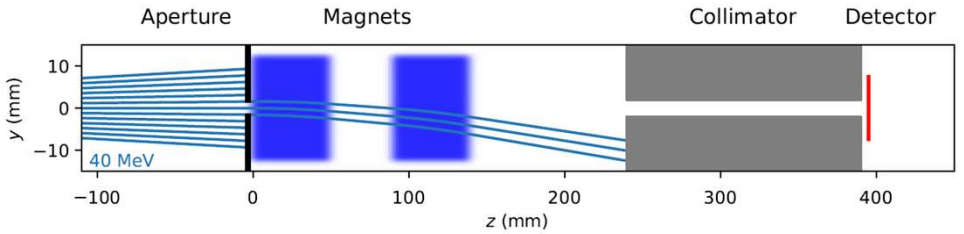


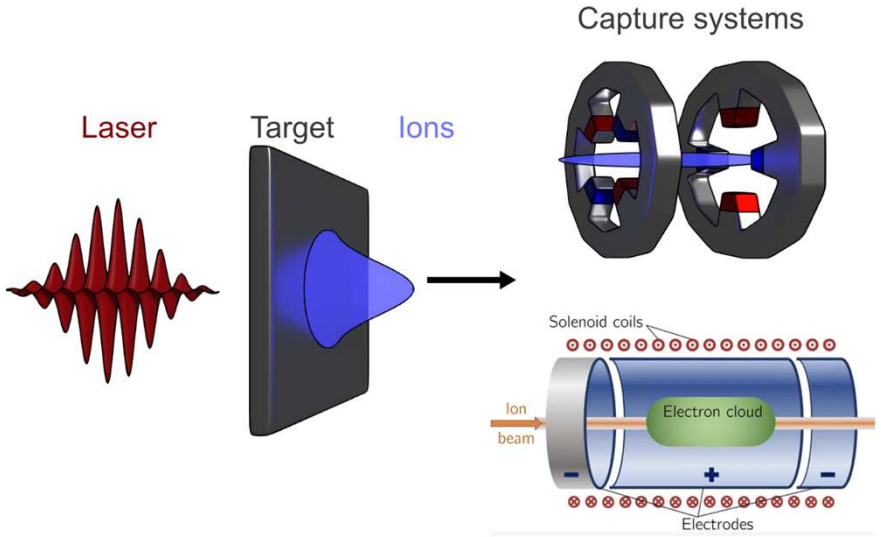


Higginson et al. Nat. Commun. 9(1) 724 (2018

Main interaction - Particle-in-cell (PIC) modelling – Post-acceleration

- Output from PIC
  - Direct ion (and associated electrons) position and momentums
  - Determined beam divergence
- Input into further models
  - Track through static fields
  - Simulate beam capture systems (BDSIM etc.)
  - Reinject into secondary hydro/PIC simulations

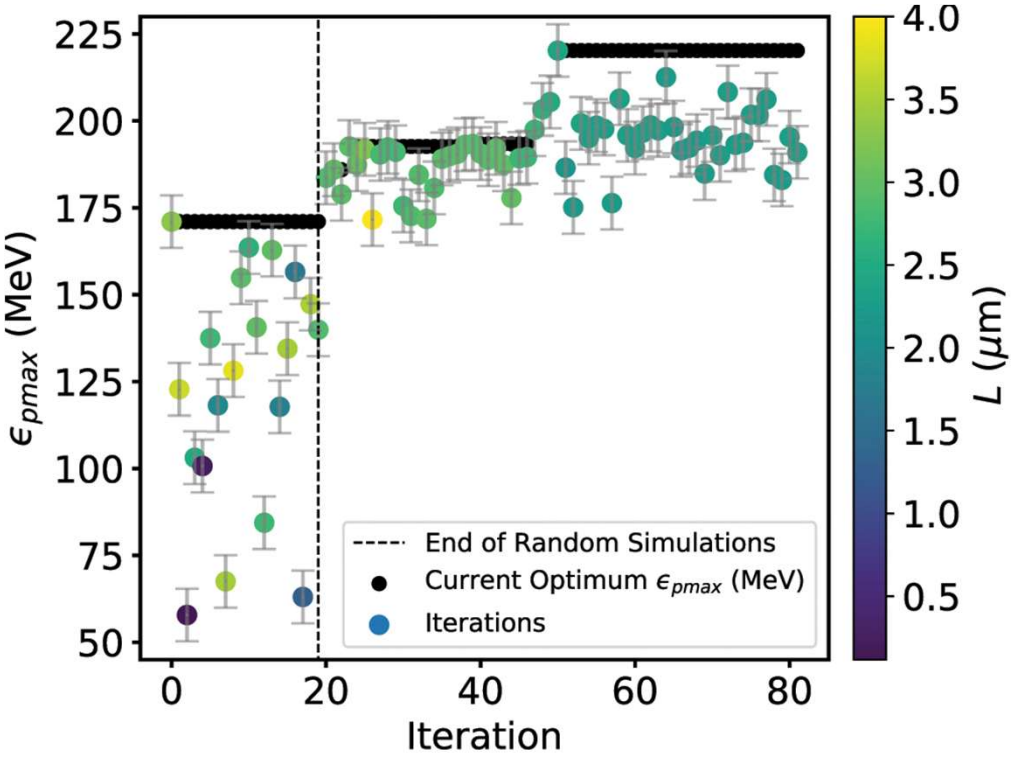




Aymar et al. Front. Phys. 8:567738 (2020)

Machine learning techniques

- Bayesian optimisation of PIC simulations
  - Optimise over large parameter spaces
  - E.g. Target thickness, scale-length, pulse duration and energy
- Combined simulations
  - Can extend this technique to incorporate hydrodynamic simulations and/or post-acceleration simulations



Dolier New J. Phys. 24.7 073025 (2022)

Challenges

- Experimental verification
  - Front surface expansion measurements near the critical density, shot-to-shot variation etc.
  - Characterisation of the heavy ion beam divergence

- Computational resources
  - High resolution 2D and full 3D PIC simulations are resource intensive
  - Porting PIC from CPU based systems to GPU (EPOCH development, WarpX)

Summary

- Different stages of the ion acceleration process require different simulation codes
- Hydrodynamic modelling for long-time scale pre-expansion dynamics
- Particle-in-cell modelling for the main high intensity interaction
- Post-acceleration codes can be used to model beam capture and further modify the beam
- Each modelling technique can be input to the next and can be iterated on with machine learning techniques

Acknowledgments

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University of
Strathclyde
Glasgow