Potential of the radiation-hydrodynamics code FLASH for laser-plasma acceleration studies

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Outline

- ➔ Hydrodynamic codes for plasmas
  - ➔ Solved equations
  - ➔ Different ways to solve equation
- ➔ Presentation of FLASH
  - ➔ Structure and Physical Modules
- ➔ Use of hydrodynamique codes
  - ➔ Different uses of hydrodynamic codes
  - ➔ Knowing the state of the plasma
  - ➔ Preliminary studies
- ➔ Conclusions

Hydrodynamic codes for plasmas

Hydrodynamic equations

- $\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$
- $\rho(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}) + \nabla p = 0$
- $\frac{\partial}{\partial t}(\rho \epsilon + \frac{\rho u^2}{2}) + \nabla \cdot (\rho \mathbf{u}(\epsilon + \frac{u^2}{2}) + p\mathbf{u}) = 0$

Where $\mathbf{u}$, ρ and p are the velocity, density and pressure and ϵ the specific internal energy.

To complete those equations an equation of state must be chosen, analytically (perfect gas) or tabulated (SESAME for example). Other equations may be necessary, to add MHD or radiative effects

Hydrodynamic codes for plasmas

- The system is projected on a mesh
- Equation solved using the finite volume method

Two different approaches

↙ ↘

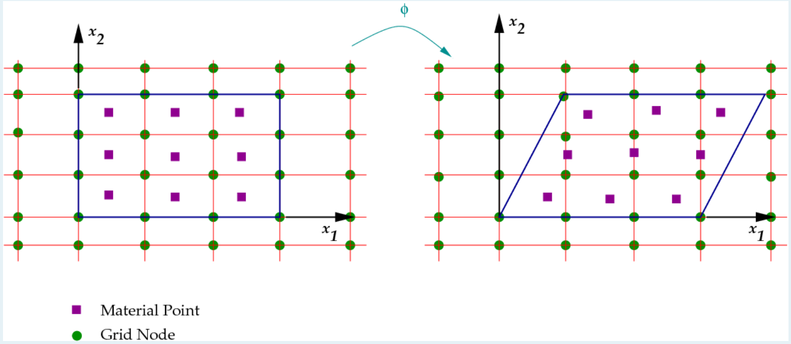
Eulerian Lagrangian

There are a lot of hydro codes, TROLL, RAMSES, Impact3D, FLASH, GORGON, HYADES, MULTI but only a few are open-access.

Hydrodynamic codes for plasmas

Eulerian Code

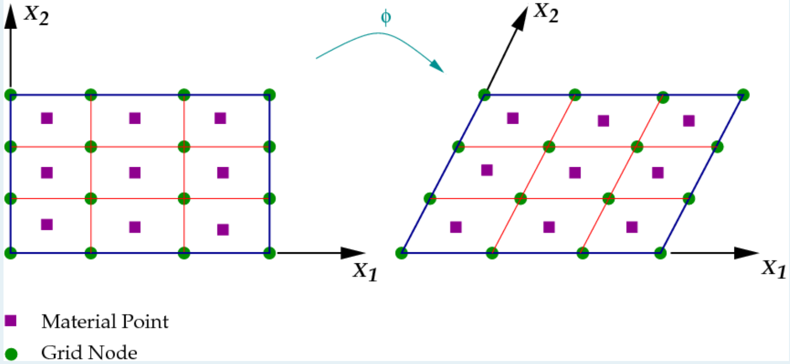
Fixed mesh and the quantities inside change ⇒ naturally more diffusive



Problem with gradients → Adaptative Mesh Rafinement

Lagrangian Code

Mesh deforms with the quantities



Problem with vorticity → Arbitrary Lagrangian Eulerian ⇒ really expensive and hard to parallelize

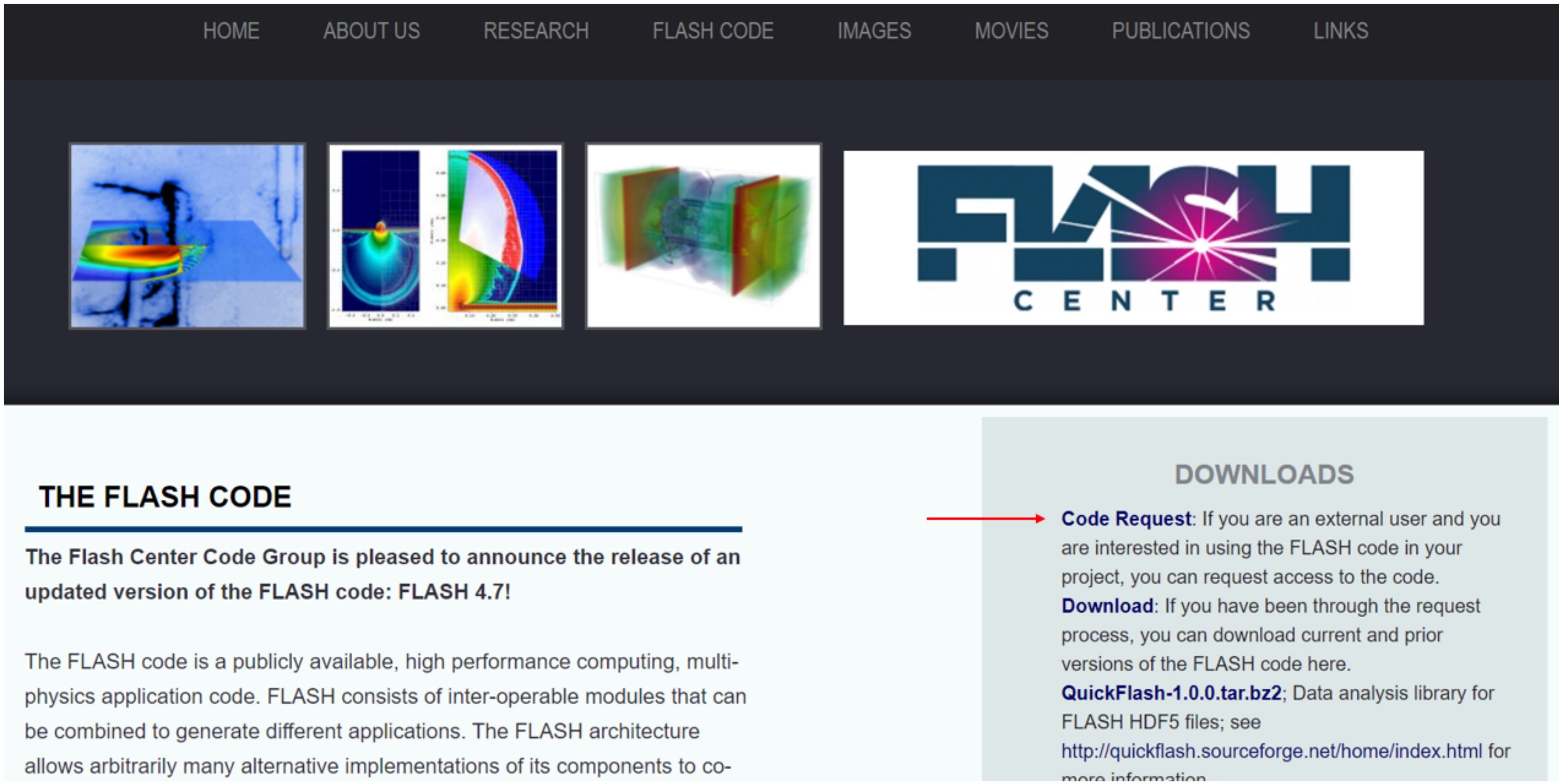
Each method tends to correct these defects by sticking to the other

Brief history of FLASH

- Developed in Rochester (previously in Chicago)
- First version in 2000
- Used by more 3500 people in the world
- First purpose was for astrophysical simulation but now a lot of physics can be simulated with FLASH

How to obtain the FLASH code ?

- To find FLASH https://flash.rochester.edu/site/



FLASH environment

User environment

- User guide
- Mailing list
- A lot of test problems
- Adapted to massively parallel computing

Conputational requirement

- Can run on personal laptop and super-computer
- Requires MPI, HDF5, HYPRE library
- VisIt is a usefull tool to analyse the results

Basic physics in FLASH

Basic physics

- 1D/2D/3D/Axisymmetric
- Adaptive Mesh Refinement (AMR)
- Radiative hydrodynamic/Multi-temperature
- Full Braginskii extended-MHD : Anisotropic conductivity, Hall effect, Nernst effect, Biermann-Battery ...
- Multi-species
- Laser deposition
- ...

Physics not included

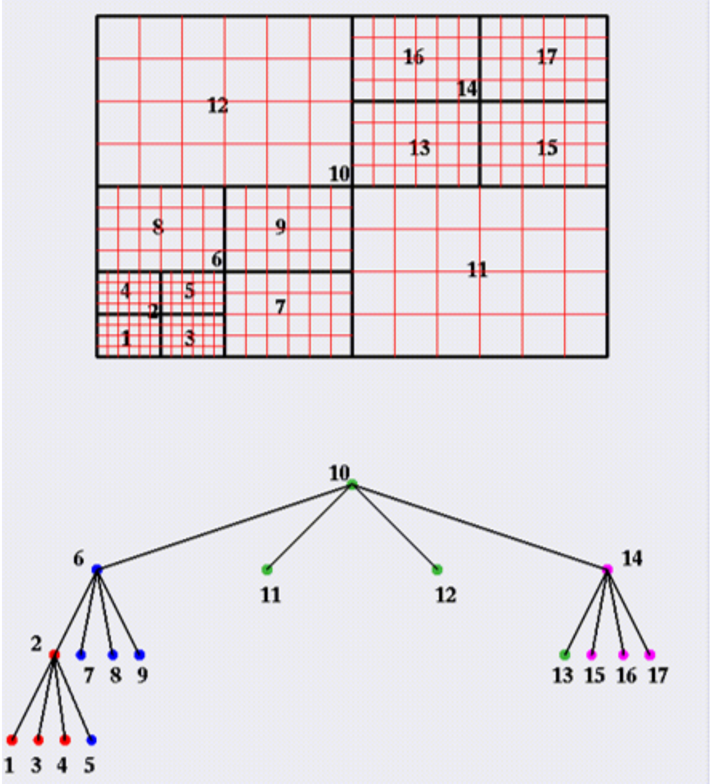
- Void medium
- Must add external equation of state/opacity for more realistic physics

Adaptive mesh refinement (AMR)

- For a better description of sharp gradients some codes use Adaptative Mesh Refinement
- When the gradient is too sharp (determined by the user) the mesh is refined
- No default refinement variables

- Blocks are put in a tree structure:parent at the root and children in the branches
- Three rules govern the establishment of refined child blocks

Helps to reduce simulation time

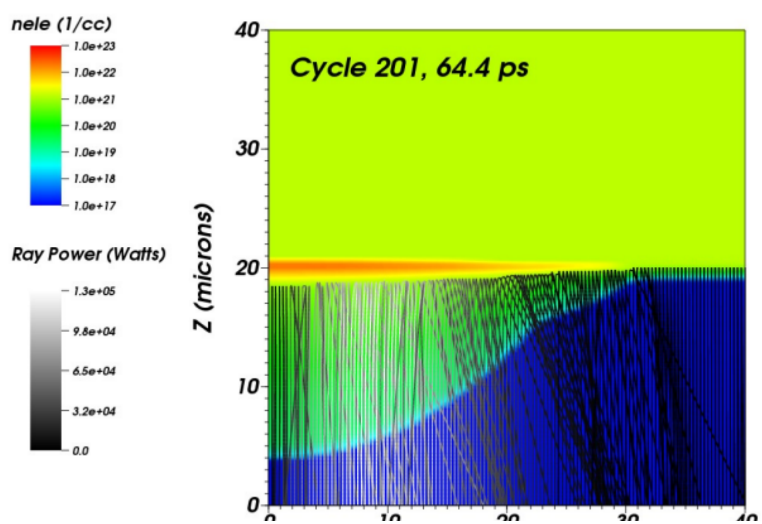


Laser deposition

- Laser beams are treated in the geometric optics approximation $\rightarrow$ beams are made of a number of rays
- The refraction can be treated in 2D and 3D
- Laser energy power deposition is calculated by inverse Bremsstrahlung

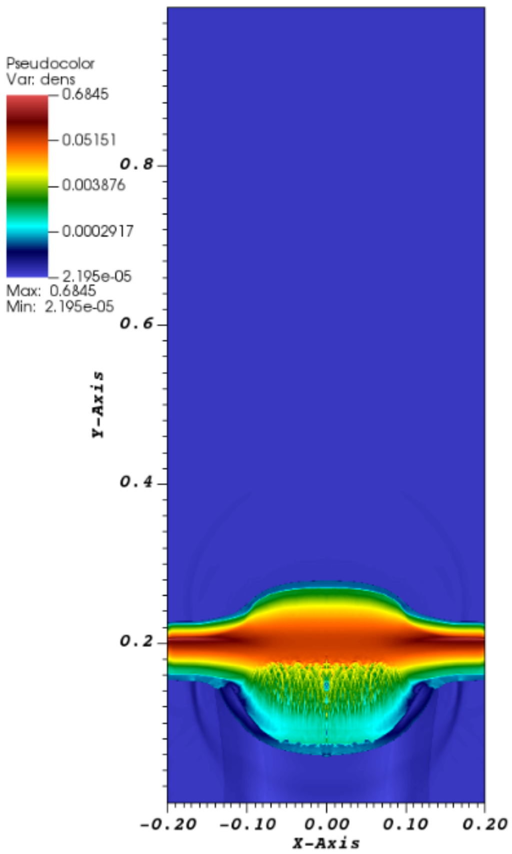
Inverse Bremsstrahlung

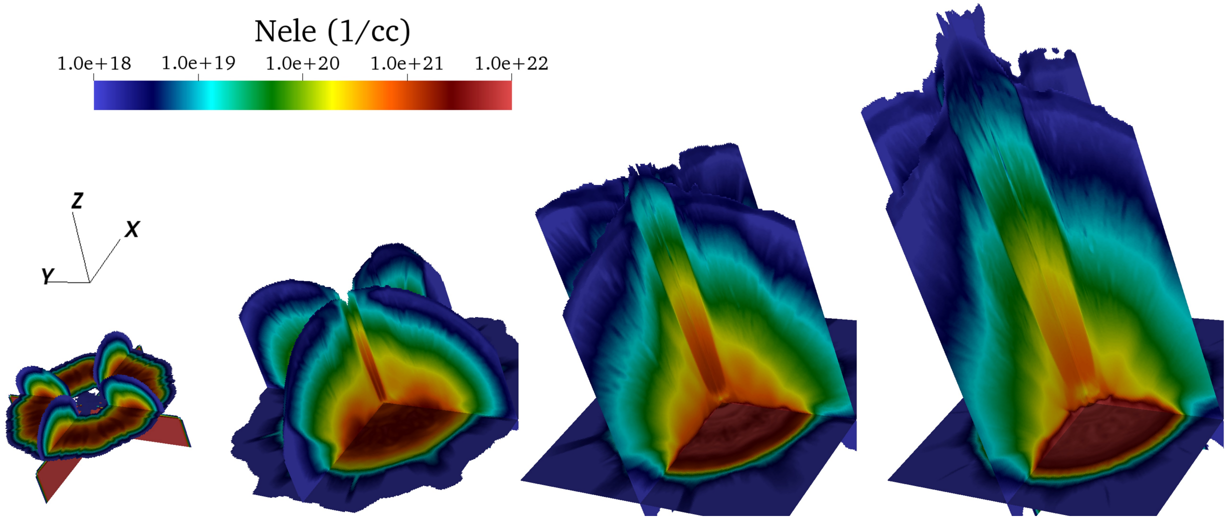
Inverse Bremsstrahlung is a collisional absorption mechanism. When a free electron trapped in a laser field collides with an ion, it will gain the photon energy.

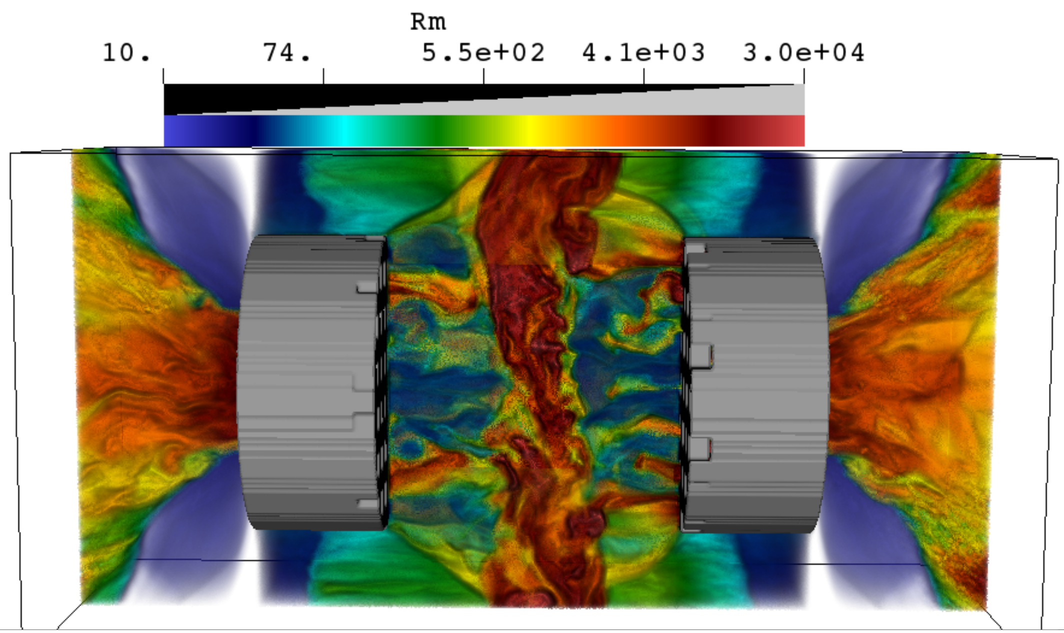


Different uses of FLASH

[FLASH web site]

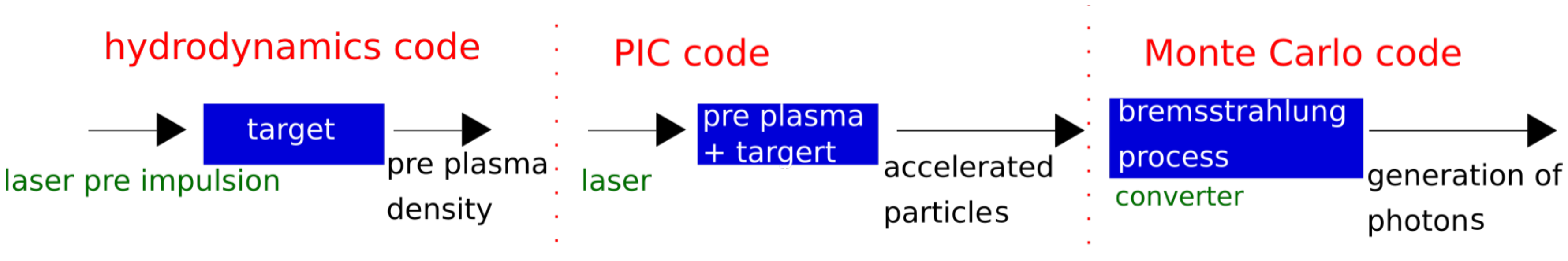






Simulation chain for laser-plasma acceleration

- Hydrodynamic codes are often the first step of a simulation chain
- This type of chain can be used after the experiments to analyse it or before to prepare it



[F.Brun et al. 2023]

Knowing the state of the plasma

One of the main uses of the hydrodynamic code is to know the state of the system. Those examples are the hydro situation due to a pre-pulse before a more intense (UHI) pulse.

- PICO2000 laser was incident on a H2 gas jet
- FLASH was used

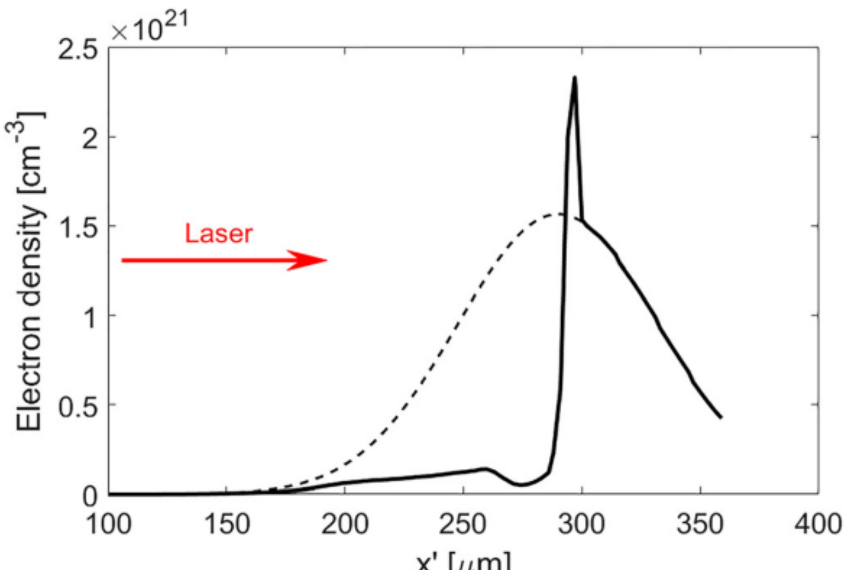


Figure: Dashed line: the initial density profile of the gas jet based on measurements. Solid line: the density profile taking into account the laser ASE[Puyuelo-Valdes et al. 2019]

- TITAN laser was on a hydrogen
- TROLL was used

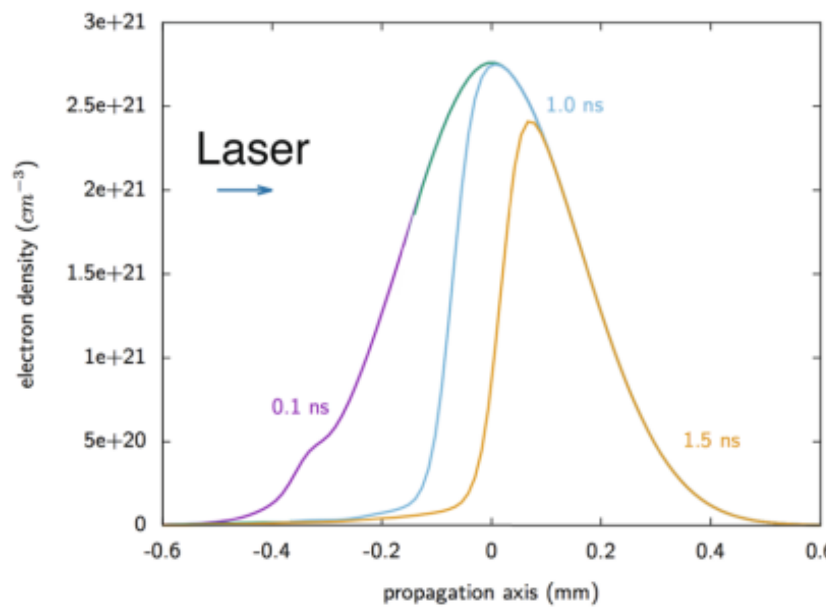


Figure: Hydrodynamic simulation of the spatial profle of the ion density of the Hydrogen gas jet at various times (as indicated) afer the start of its irradiation by the prepulse[Chen et al. 2017]

Knowing the state of the plasma

- Hydrodynamic codes can also be used for preliminary study before an experiment
- TROLL was used to know the state of two colliding blast wave

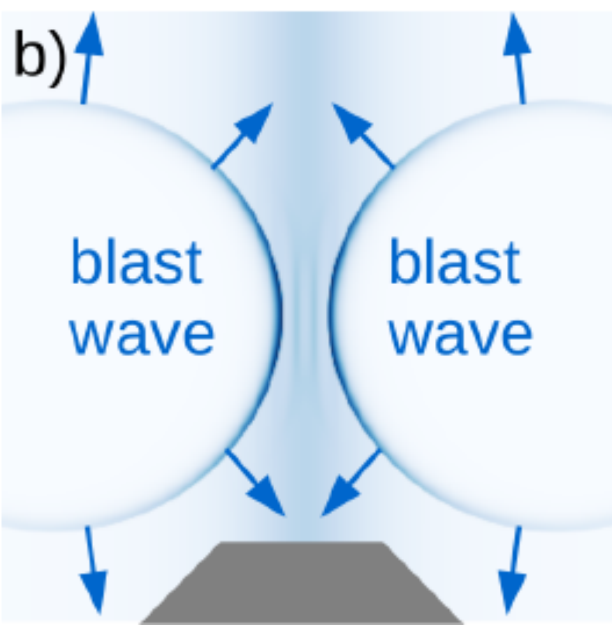


Figure: Principle of the plasma tailoring, side view

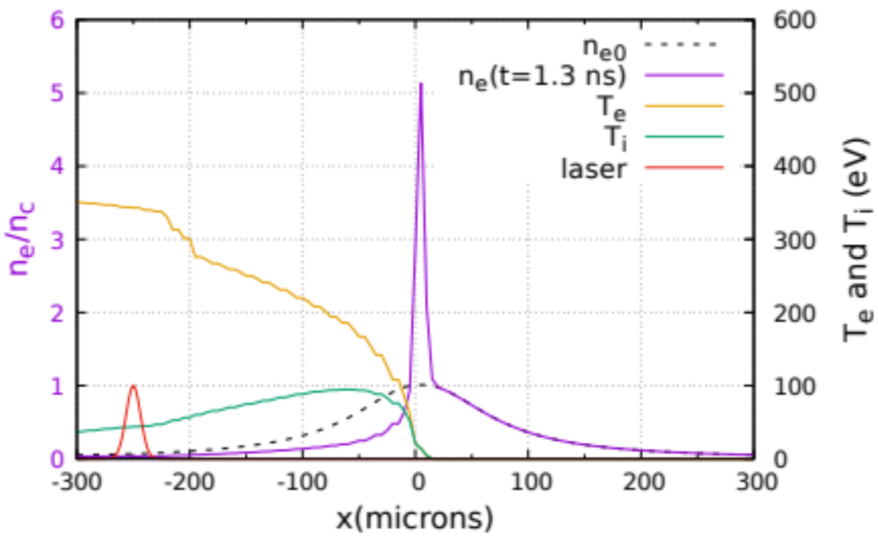


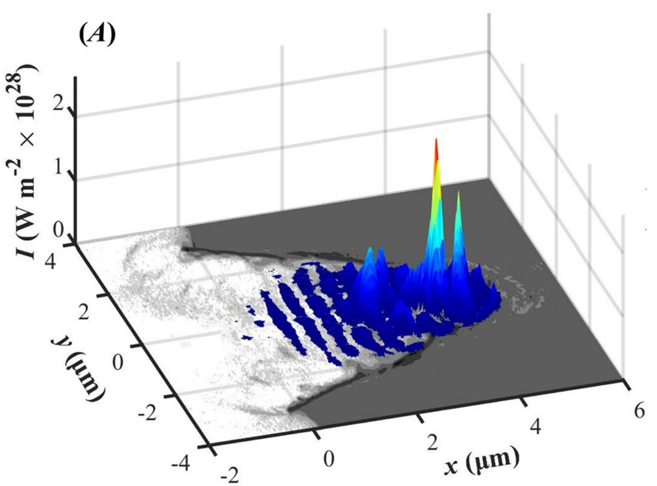
Figure: Profiles of density (ne/nc, violet curve) and temperature (Te: orange curve; Ti: green curve)[Marquès et al. 2020]

Knowing the state of the plasma

Towards bright gamma-ray flash generation from tailored target irradiated by multi-petawatt laser

Scientific Reports | (2022) 12:17143

Prokopis Hadjisolomou[1]✉, Tae Moon Jeong[1] & Sergei V. Bulanov[1,2]



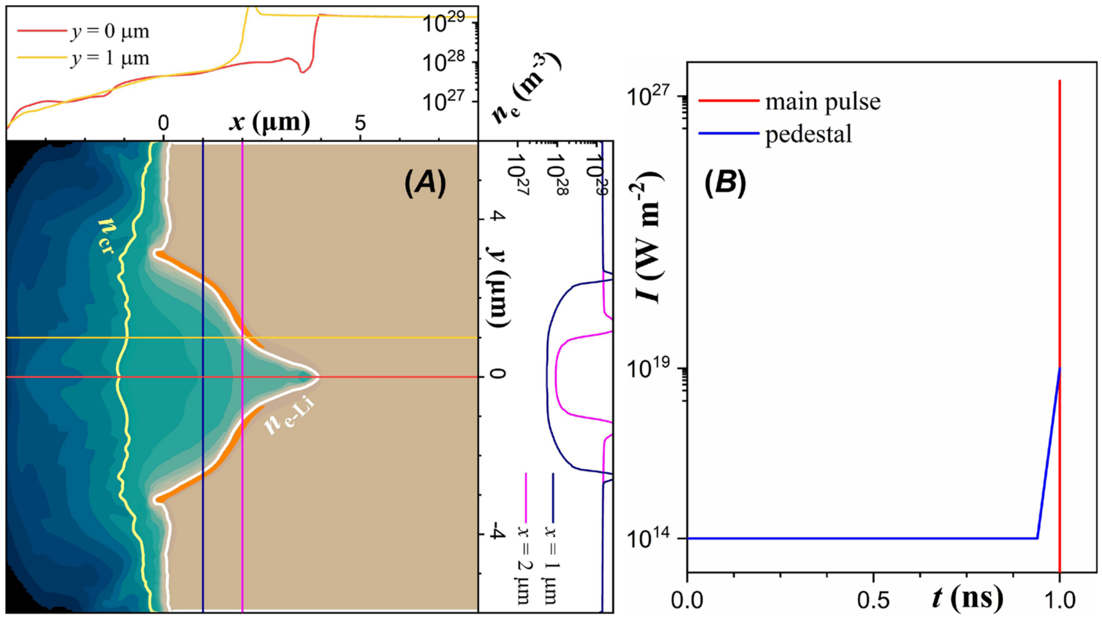


Figure 1. (**A**) Electron number density as given by MHD simulations (data taken from reference[60]), following irradiation of a lithium foil. The yellow contour line is at the critical density and the white contour line is at the lithium solid electron density. The orange saturated contour is overcritical for laser intensities above 10^{27} Wm^{-2}. (**B**) The ASE pedestal profile used in reference[60] (blue line) compared with the 10 PW main laser pulse profile presently employed (red line).

60. Tsygvintsev, I. P. Results of RHD simulation of ns-prepulse with 3DLINE code for different target materials, https://doi.org/10.5281/ZENODO.6412637(2022). Data come under CC BY 4.0 license.

Knowing the state of the plasma

PHYSICAL REVIEW RESEARCH **4**, 033248 (2022)

Laser ion acceleration from tailored solid targets with micron-scale channels

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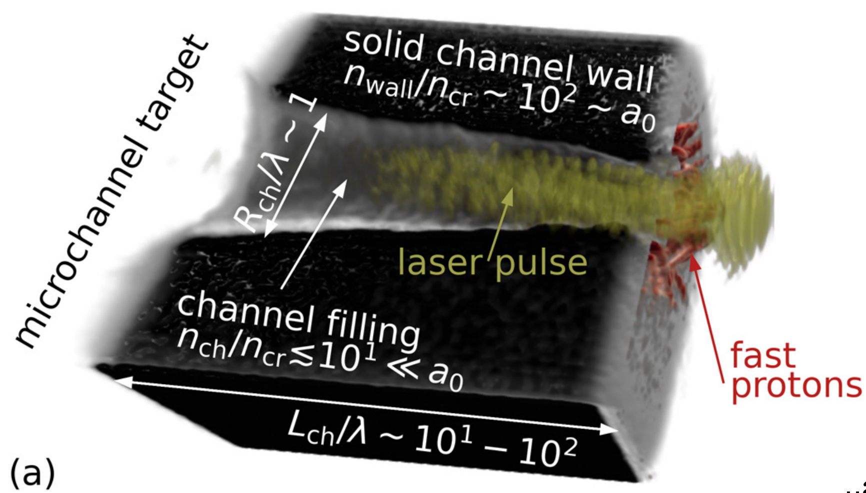

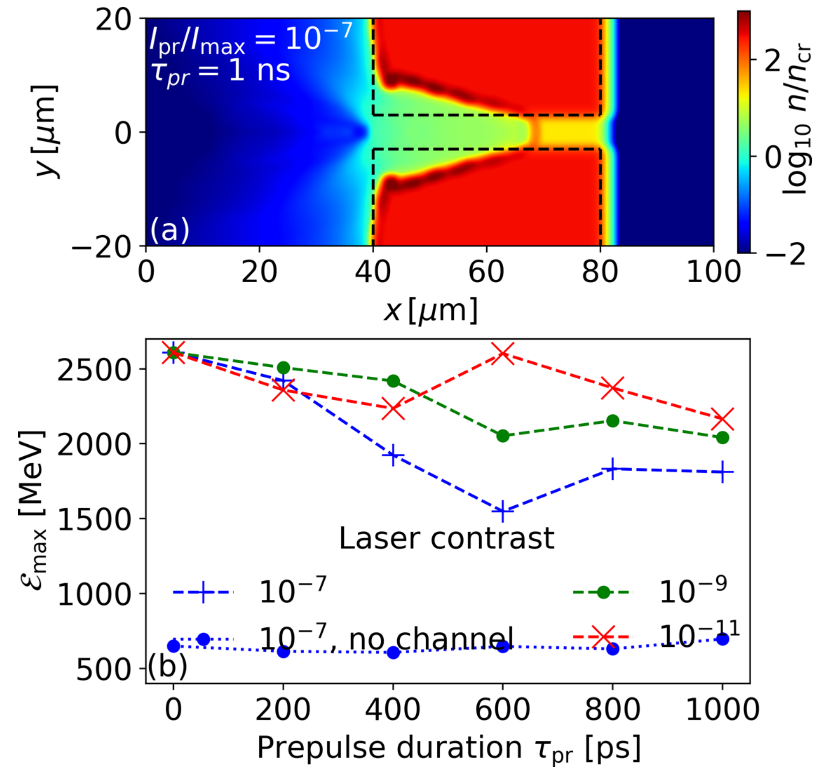

FIG. 7. (a) Electron density snapshot from FLASH simulation of ..anosecond pedestal-target interaction for the case of laser contrast of 10^{-7}. Dashed-black lines sketch the initial location of the channel structure. (b) Maximum ion energy dependence on pedestal duration for different laser contrasts (10^{-11}, 10^{-9}, 10^{-7}) and no channel case for laser contrast 10^{-7}.

Knowing the state of the plasma

- A modified version of FLASH was used to simulate capillary discharges
- Custom boundary conditions were used to capture realistic conductivities and magnetic field evolution
- Simulations in accordance with theory

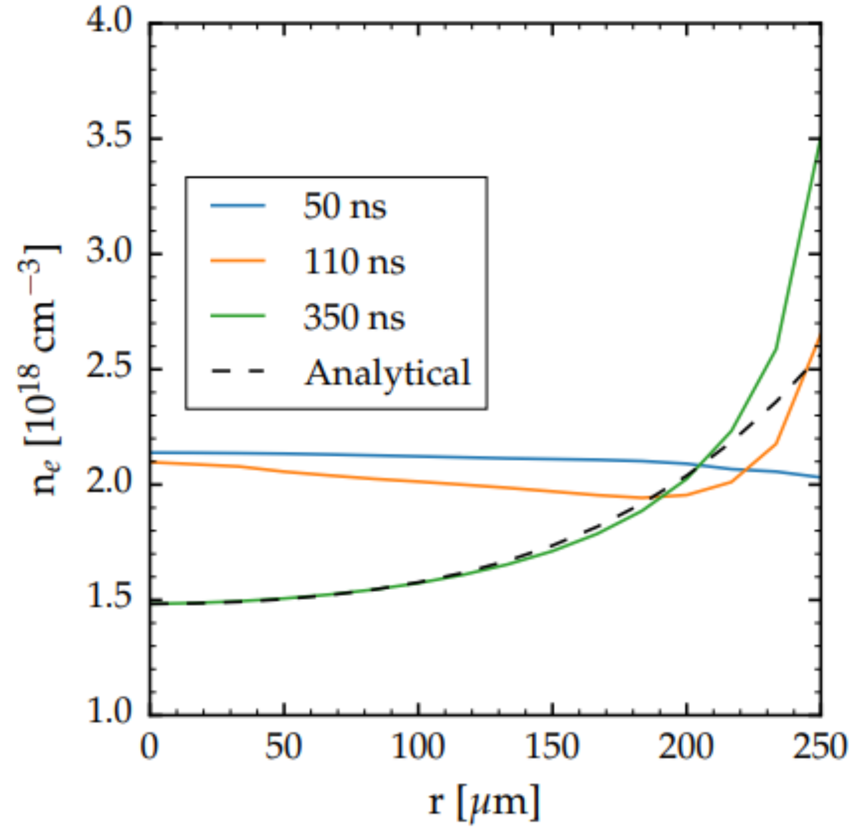

Figure: Temporal evolution of radial density and distributions are plotted above for each of the three phases of capillary evolution, alongside comparisons to the steady-state analytic predictions[Cook et al. 2020]

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Conclusions

➔Hydro codes are used for large scale simulations and can be put at the beginning of a simulation chain

➔There are two families of hydro codes: eulerian and lagrangian

➔FLASH is a multi-physics eulerian open-access hydrodynamic code

➔Hydro codes can be used in a variety of situations for laser-plasma acceleration: to know the state of the system or in prelimirary studies