

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

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

Hydrodynamic equations

$$
\bullet \ \tfrac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0
$$

$$
\bullet \ \rho(\tfrac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}) + \nabla p = 0
$$

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

Where $\mathbf{u}, \, \rho$ 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

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

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

Eulerian Code

Fixed mesh and the quantities inside change \Rightarrow naturally more diffusive

Problem with gradients \rightarrow Adaptative Mesh Rafinement

Lagrangian Code

Mesh deforms with the quantities

really expensive and hard to parallelize

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

 \mathcal{M} , the formula microdynamic codes for particle acceleration and presentation of the FLASH codes for \mathcal{M}

- **o** 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

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

THE FLASH CODE

The Flash Center Code Group is pleased to announce the release of an updated version of the FLASH code: FLASH 4.7!

The FLASH code is a publicly available, high performance computing, multiphysics application code. FLASH consists of inter-operable modules that can be combined to generate different applications. The FLASH architecture allows arbitrarily many alternative implementations of its components to co-

DOWNLOADS

Code Request: If you are an external user and you are interested in using the FLASH code in your project, you can request access to the code. Download: If you have been through the request process, you can download current and prior versions of the FLASH code here. QuickFlash-1.0.0.tar.bz2; Data analysis library for **FLASH HDF5 files; see**

http://quickflash.sourceforge.net/home/index.html for more information

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

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
- **o** Laser deposition
- \bullet ...

Physics not included

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

 $M.$ François Use of hydrodynamic codes for particle acceleration and presentation of the FLASH codes for \sim

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 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 Dierent use of hydrodynamic codes

- 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 \bullet before to prepare it

[F.Brun et al. 2023]

Knowing the state of the plasma Know the state of the plat

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

- TITAN laser was on a hydrogen
- $3e+21$ $2.5e + 21$ 1.0_{ns} _aser $electron$ density $(cm⁻³)$ $2e + 21$ $1.5e + 21$ $1e + 21$ 0.1 ns $5e+20$ 1.5_{ns} n -0.4 -0.2 0 0.2 -0.6 0.4 0.6 propagation axis (mm)

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

• TROLL was used

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 \bullet 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]

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Knowing the state of the plasma

irradiated by multi-petawatt laser **Towards bright gamma‑ray fash generation from tailored target** where \mathcal{L} 899–902. https://doi.org/10.1103/PhysRevLett.84.899 (2000). 40. Nedorezov, V. G., Turinge, A. A., & Shatunov, Y. M. Photonuclear experiments with Compton-backscattered gamma beams. *Phys.- Uspekhi***47**, 341–358, https://doi.org/10.1070/pu2004v047n04abeh001743(2004).

 t thin enough the ASE pedestal drills the target resulting in no interaction when the main pulse ℓ $\overline{}$

https://doi.org/10.1088/0741-3335/57/11/113001 (2015).

Prokopis Hadjisolomou $^{1\boxtimes}$, Tae Moon Jeong 1 & Sergei V. Bulanov 1,2 $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$

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require additional eforts on positioning and alignment of the target. However, it was noticed that the use of

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tailored targets is favorable for the laser-target interaction and their use is widely employed.

15 fs 2.6 × 10²⁸ Wm⁻² **Figure 1.** (A) Electron number density as given by MHD simulations (data taken from reference⁶⁰), following 2.6×10^{-10} 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 reference⁶⁰ (blue line) compared with the 10 PW main laser pulse profile presently employed (red line). γ (**B**) The ASE pedestal profile used in referer 56. Zhang, L. Q. *et al.* Brilliant attosecond γ-ray emission and high-yield positron production from intense laser-irradiated nano-micro lithium solid electron density. The orange saturated contour is overcritical for las *Eng.* **8**, e34. https://doi.org/10.1017/hpl.2020.30 (2020). **is reached.** (**A**) Electron number der

available, revealing a preplasma regime which to the best of our knowledge has never been considered in PIC

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. 61. Arber, T. D. *et al.* Contemporary particle-in-cell approach to laser-plasma modelling. *Plasma Phys. Control. Fusion* **57**, 113001.

Check for up

 \mathcal{A} . Structure-preserving second-order integration of relativistic charged particle trajectories in electro-order in

 -4

2
Lange

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 \sim $\frac{0}{\sqrt{2}}$

 15 fs , $2.6 \times 10^{28} \text{ Wm}^{-2}$

 \sim -2 \sim $-$

intensities exceeding 1027 Wm−²

16

Knowing the state of the plasma

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

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acceleration (RITA) \mathcal{A} netic vortex acceleration (MVA) \sim

FIG. 7. (a) Electron density snapshot from FLASH simulation of anosecond pedestal-target interaction for the case of laser contrast ... anosecond pedestal-target interaction for the case of laser contrast
of 10^{-7} . Dashed-black lines sketch the initial location of the channel of TO The Dasned-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} . electron temperature and density, respectively, and multiple energy scaling with $\frac{1}{2}$ $\frac{1}{2}$. Multiple other mechanisms are 10^{-7} .

front side of the target. Oblique incidence ensures the absence of the backreflection of the laser pulse, which is safer for

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 a predictions[Cook et al. 2020]

➔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