EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

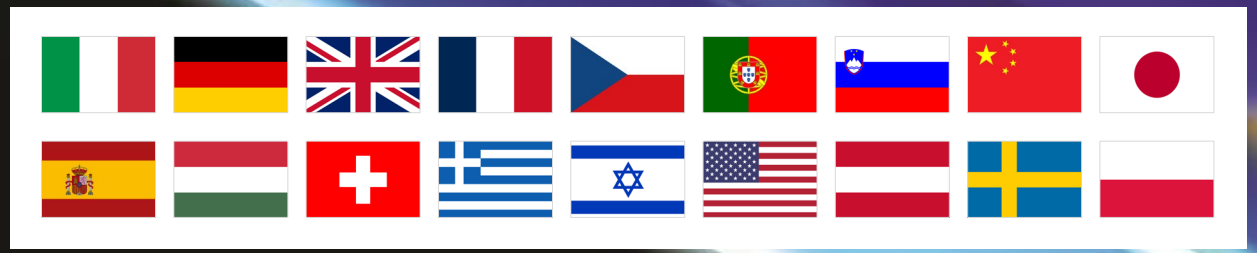
EuPRAXIA
Preparatory Phase

Start-to-end simulations

Maxence Thévenet, DESY

EuPRAXIA-PP Meeting, Elba, September 23-27, 2024

WP8 – Theory & simulations



This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

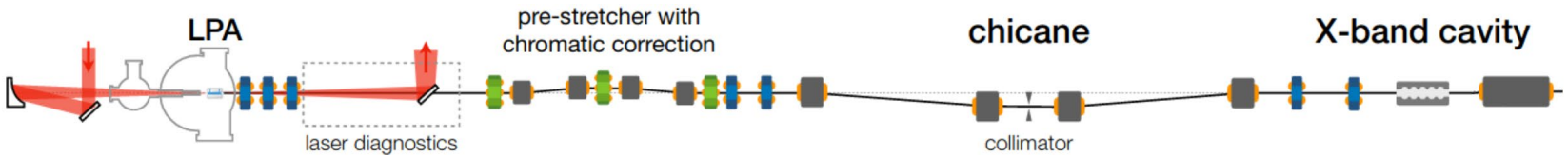
DESY.

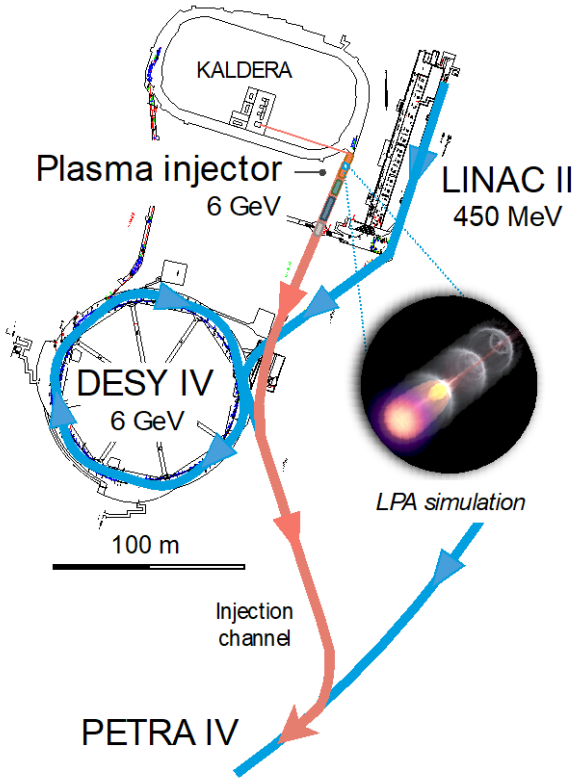
Plasma acceleration requires multi-physics

Funded by the European Union

Example 1. A Plasma Injector for PETRA IV (PIP4)

The team: I. Agapov, S. Antipov, R. Brinkmann, A. Ferran Pousa, S. Jalas, L. Jeppe, M. Kirchen, W. P. Leemans, A. R. Maier, A. Martinez de la Ossa, J. Osterhoff, R. Shalloo, M. Thévenet, P. Winkler





Conceptual Design Report 2020-2024 *to be published*

beam
laser
no plasma

LPA injection + acceleration

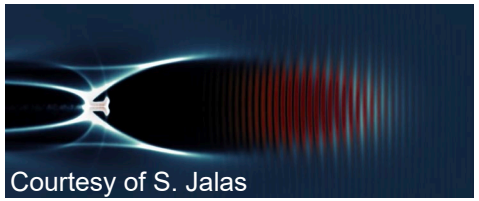
beam

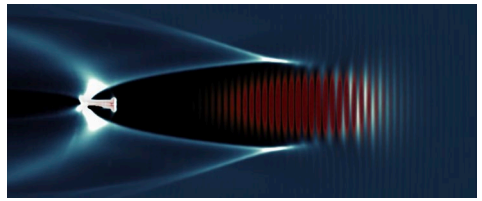
Beamline

Electromagnetic particle-in-cell (PIC)

Quasi-static PIC

Electrostatic / transfer matrices

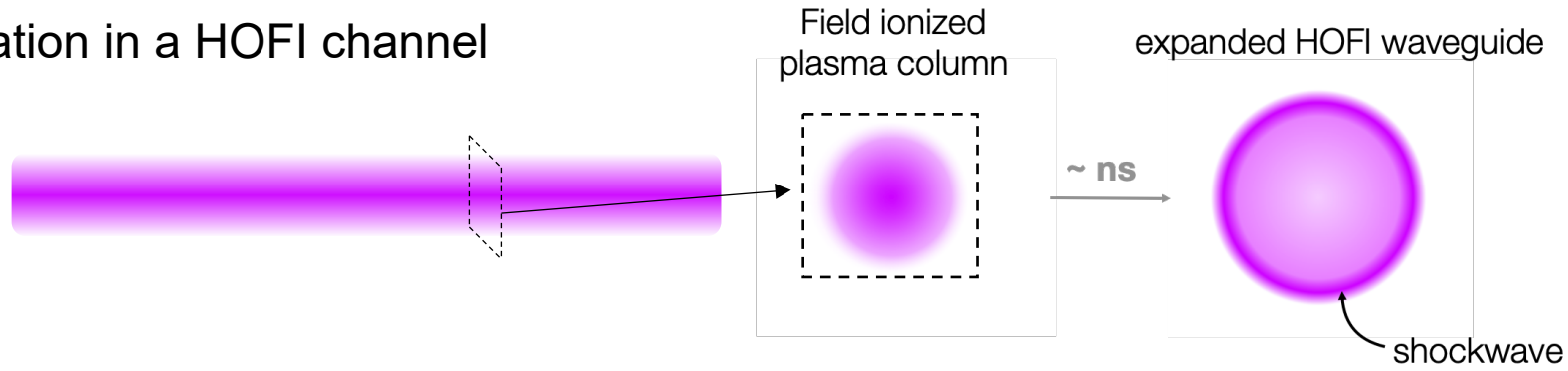




Plasma acceleration requires multi-physics

Funded by the European Union

Example 2. Laser Plasma Acceleration in a HOFI channel



Realistic laser Gas profile

Laser ionization

Ionization, laser propagation

Density and temperature

HOFI expansion

Plasma fluid dynamics

Density

Realistic laser

Plasma injection

electromagnetic PIC

Laser Beam

Acceleration

quasi-static PIC

Requirements

- Simulation codes
- Transfer electron beam
- Transfer plasma profile
- Transfer laser pulse (exp./sim.)
- Transfer ad-hoc quantities

Application
FEL, ICS, QED, biology, …

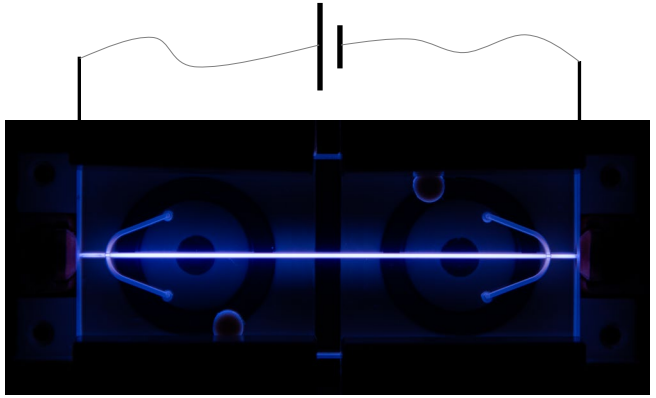
C. G. Durfee et al., Physical Review E 51, 2368 (1995)
R. Shalloo et al. *PRE* 97.5 (2018)

Main processes simulated with different codes

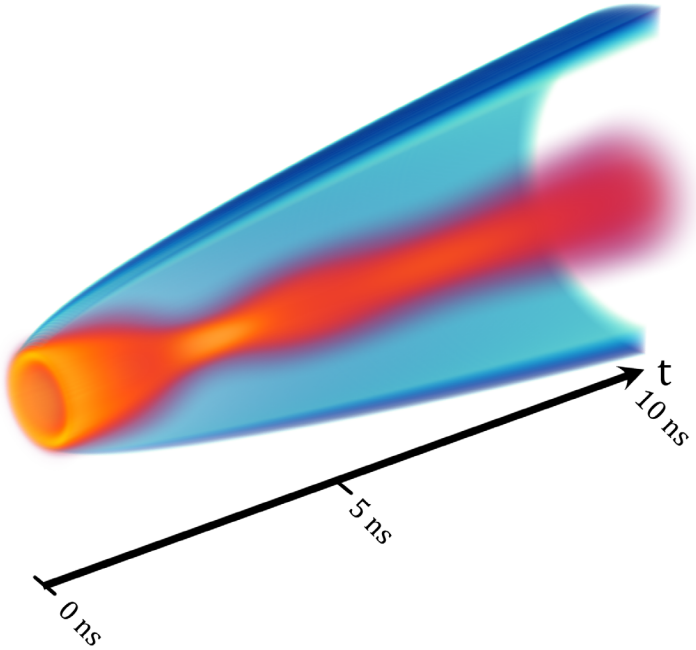
Funded by the European Union

- **COMSOL - HYQUP.** plasma fluid dynamics
  - Simulate HOFI (Hydrodynamic Optical-Field-Ionized) channels

  - Simulate plasma discharge capillary



Time evolution of the HOFI channel (blue) and guided laser (red)

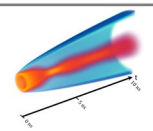


M. Mewes et al. PRR 5, 033112 (2023)
M. Mewes et al. *in preparation*

Main processes simulated with different codes

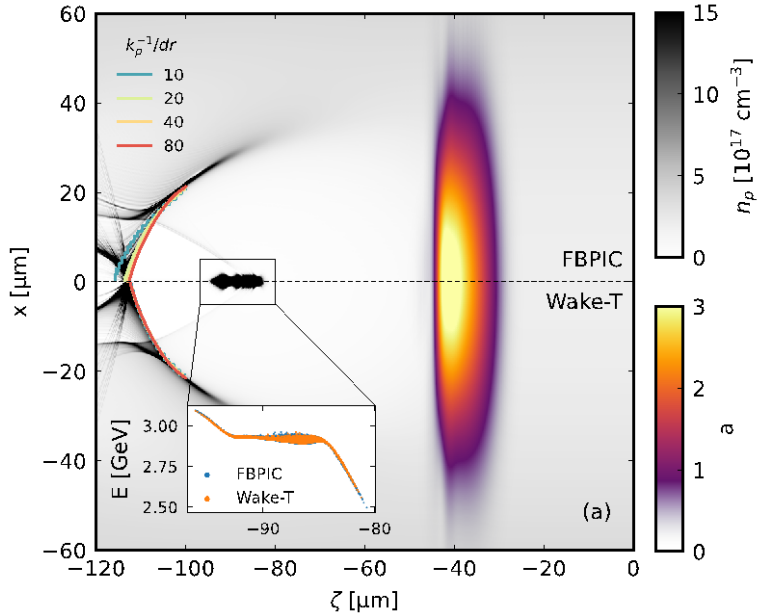
Funded by the European Union

➢ **COMSOL - HYQUP.** plasma fluid dynamics



➢ **Wake-T.** quasi-static & cylindrical wakefield on a laptop

- 2D (axisymmetric) quasistatic
- Laser-driven or beam-driven
- Python, second/minutes on a laptop
- Recent: Adaptive grid & ion motion



Numerical convergence:
9 hours** on a NVIDIA A100 **GPU

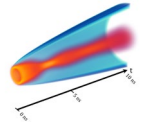
Numerical convergence:
***7 min** on a **CPU** core*

Open-source https://github.com/AngelFP/Wake-T
moving soon to https://github.com/Wake-T/Wake-T
Ferran Pousa et al., *in preparation*

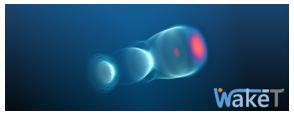
Main processes simulated with different codes

Funded by the European Union

- **COMSOL - HYQUP.** plasma fluid dynamics

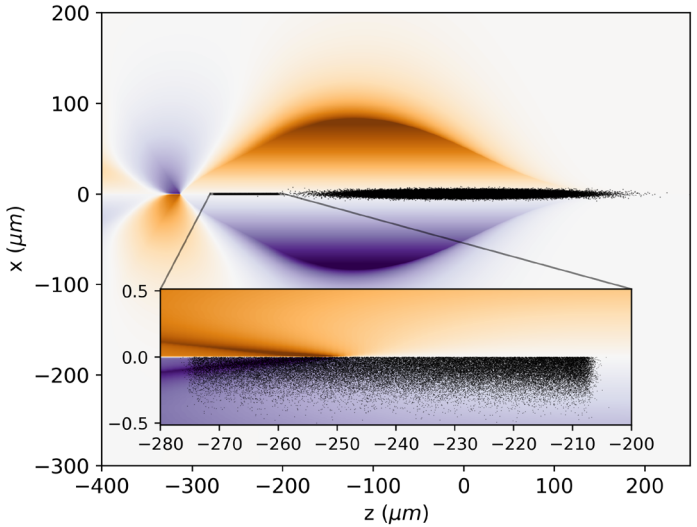


- **Wake-T.** quasi-static & cylindrical wakefield on a laptop



- **HiPACE++.** quasi-static PIC in 3D on GPU

  - Multi-physics
  - C++, on top supercomputers
  - Recent: Mesh refinement
  - Soon: new physics, Python, optimization

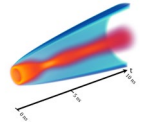


S. Diederichs et al. *Comput. Phys. Comm.* 278, 108421 (2022)
Open-source https://github.com/Hi-PACE/hipace

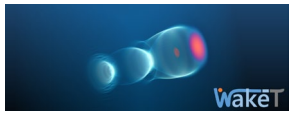
Main processes simulated with different codes

Funded by the European Union

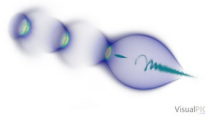
- **COMSOL - HYQUP.** plasma fluid dynamics



- **Wake-T.** quasi-static & cylindrical wakefield on a laptop



- **HiPACE++.** 3D quasi-static PIC on GPU



- **<u>Quasi-static codes make challenging simulations very affordable</u>**
  - **<u>5 nanometer</u>** resolution for convergence (ion motion)
  - HiPACE++ run < 0.1% supercomputer allocation

General approach to simplify S2E pipelines

Funded by the European Union

Requirements

- Simulation codes
- Transfer electron beam
- Transfer plasma profile
- Transfer laser pulse (exp./sim.)
- Transfer ad-hoc quantities

- Independent codes + helpers
- Build upon community work
- Avoid standards proliferation

openPMD

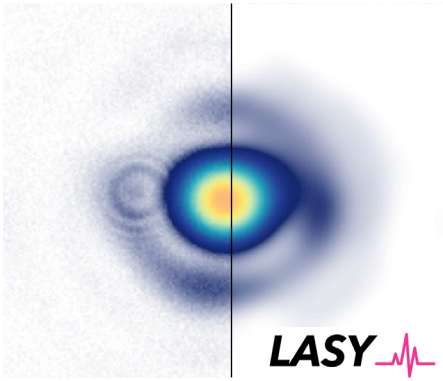
Open standard for Particle Mesh Data (HZDR, LBNL, …)

LASY

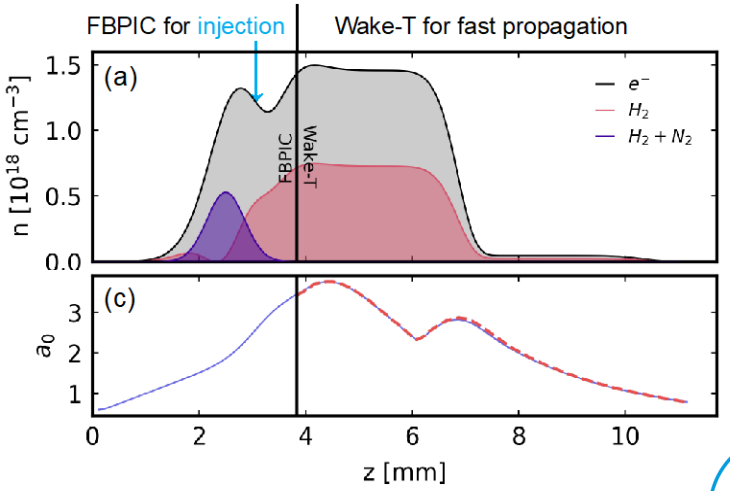
LAser manipulations made eaSY (DESY, LBNL, LOA, …)

https://github.com/openPMD
https://github.com/openPMD/openPMD-api
https://github.com/openPMD/openPMD-viewer
https://github.com/LASY-org/lasy

Experiment to simulation



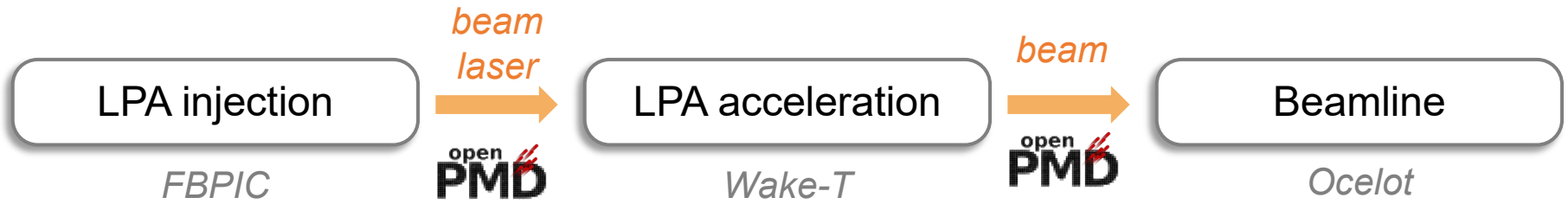
Simulation to simulation



This approach is implemented in recent studies

Funded by the European Union

Example 1. A Plasma Injector for PETRA IV (PIP4)



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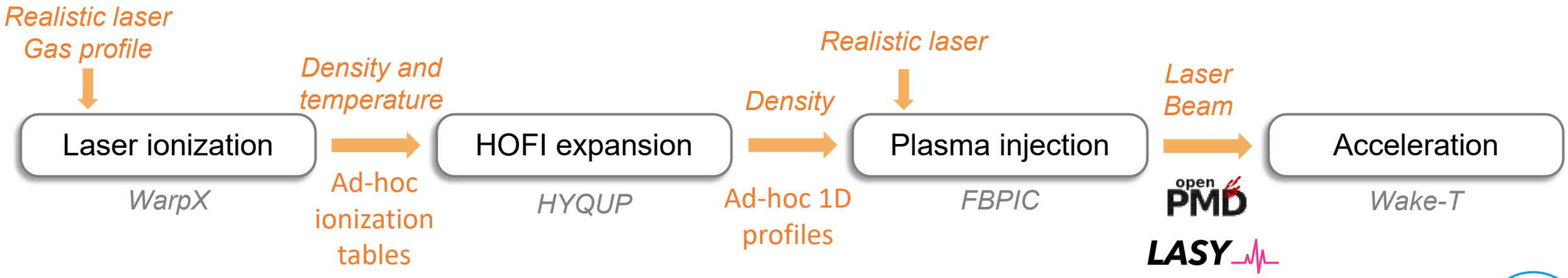
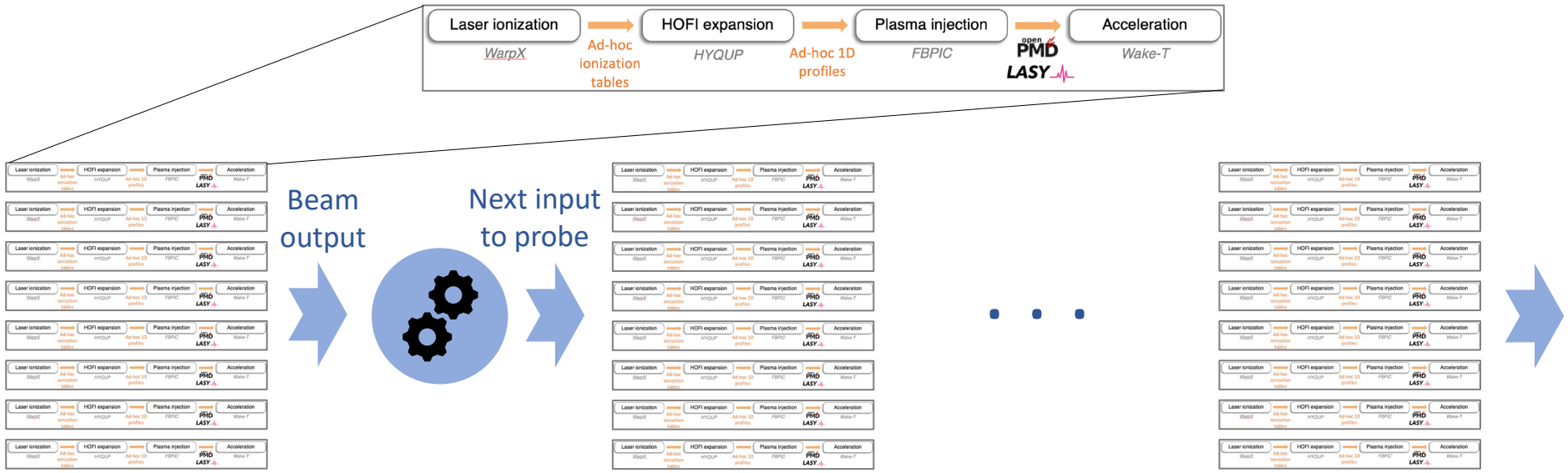


FBPIC: R. Lehe (LBNL), M. Kirchen (DESY) et al., https://github.com/fbpic/fbpic
R. Lehe et al., Comput. Phys. Commun. 203, 66 (2016).
M. Kirchen et al., Phys. Rev. E 102, 013202 (2020).

WarpX: J.-L. Vay and ECP team (LBNL) et al., https://github.com/ECP-WarpX/WarpX
Ocelot: S. Tomin (DESY) et al., https://github.com/ocelot-collab/ocelot

That was alright. Now I want the best beam.

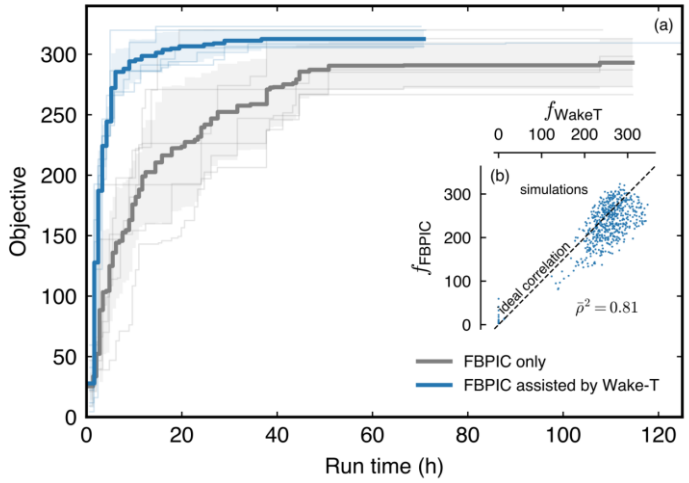


optimas

Optimization **at** **s**cale

Bayesian Optimization – experiments and simulations

LBNL, DESY, ANL



https://github.com/optimas-org/optimas

Conclusion

- Start-to-end studies are becoming the norm. Often start from experiment.
- Approach with common standard openPMD + targeted libraries LASY & Optimas.
- Modularity important as use cases differ a lot.
- Compatible with a "*backbone*" approach e.g. HALHF.
- Next steps: use plasma standard, beam manipulation, share methods.