Simulation/theory considerations for a plasma-based collider

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MPA1 team: theory and simulation for plasma acceleration

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Accurate simulations are a mandatory first step to HEP applications

But bringing the simulation ecosystem to the required level takes time and effort

- **Proposed plasma-based collider designs rely on multi-stage, quality-preserving electron (positron?) acceleration**

- **Demonstrated/available today**
  Several RZ/3D realistic stages with ideal coupling → expensive!

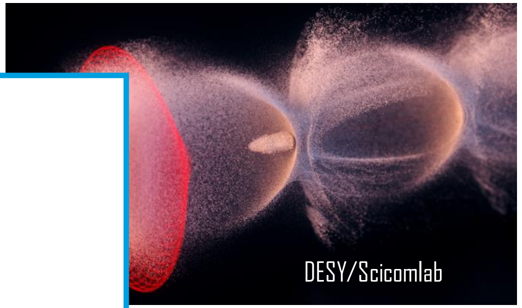
- **Needed for design and theory**
  Conceptual design: reduced simulations
  Reduced simulations, Global/local optimization
  Technical design: accurate simulations including all physics
  Realistic concepts (focusing, laser removal, etc.)
  → Need to improve simulations
  1. High-Performance Computing HPC (portability GPU, efficient I/O, etc.)
  2. Efficient algorithms
  3. Share the efforts when possible Open-source

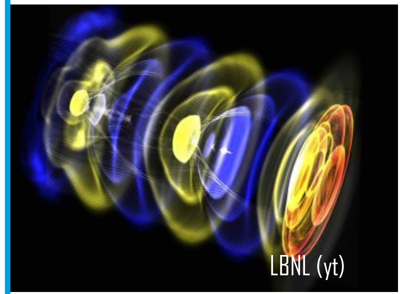
- **Plasma target dynamics**
  - Hydrodynamics for plasma target tailoring, plasma lenses
  - High average power: fs – ms dynamics

DESY uses/develops different codes for various applications

From few-second laptop runs to many-GPU HPC simulation to cover all needs

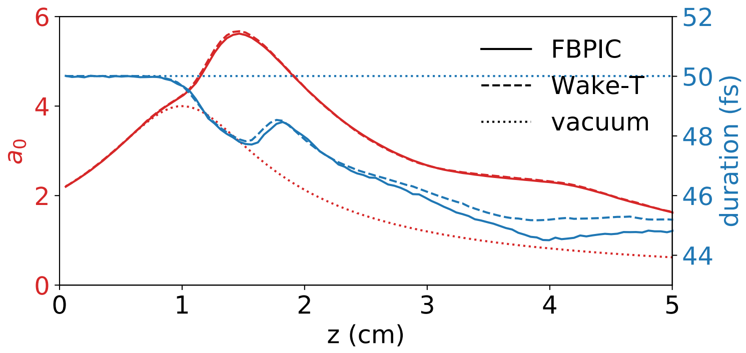
	Quasistatic	Electromagnetic
Quasi-cylindrical	**Wake-T** (DESY) → *Conceptua* Open-source https://github.co	**FBPIC** (LBNL + UHH + ...)
3D	**HiPACE++** (DE → *3D Quasist* Open-source https://github.com/Hi-PACE/hipace	https://github.com/ECP-WarpX/WarpX





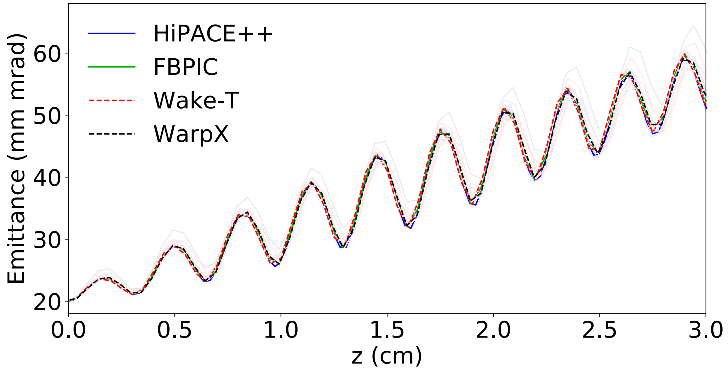
Laser wakefield acceleration

3×10^{17} cm^{-3}, 40 μm, 1 cm ramps



Beam-driven wakefield acceleration

1 GeV, 5 μm width, 20 μm emittance, 1 nC, 20 μm long, 10^{17} cm^{-3} plasma, $n_b/n_0 = 8$

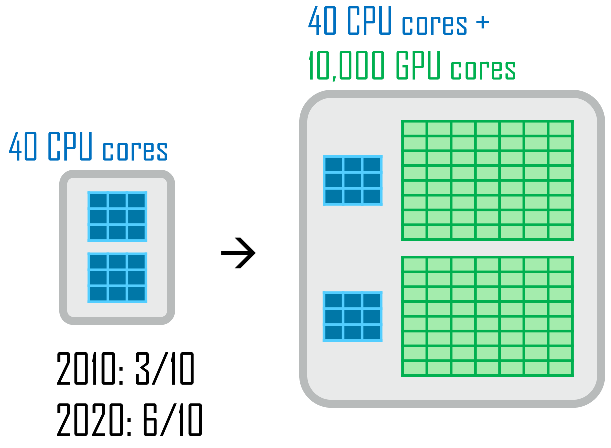


In collaboration with the WarpX team, LBNL

Multiple options: **PIConGPU**, **OSIRIS** (presentation by R. Fonseca)

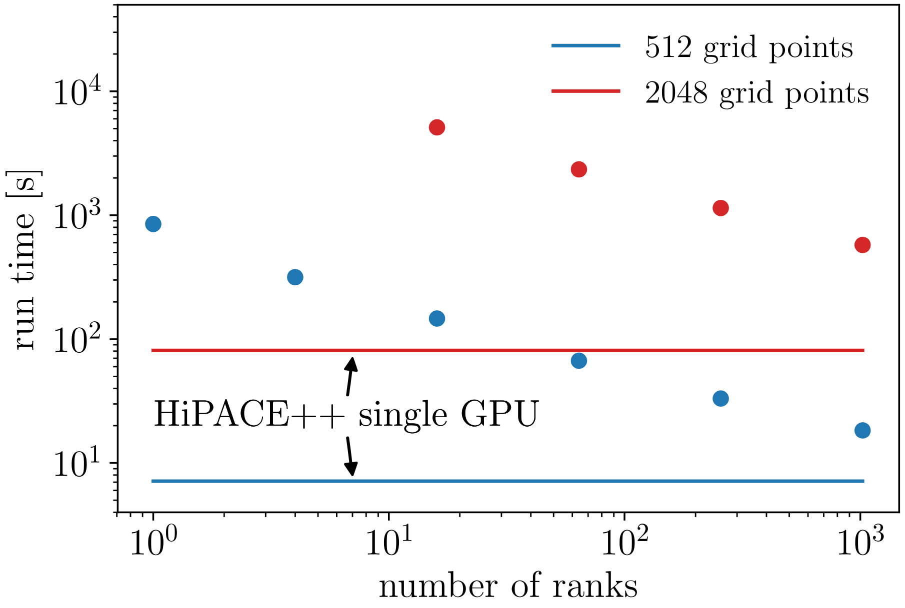
HiPACE++: open-source portable quasistatic PIC

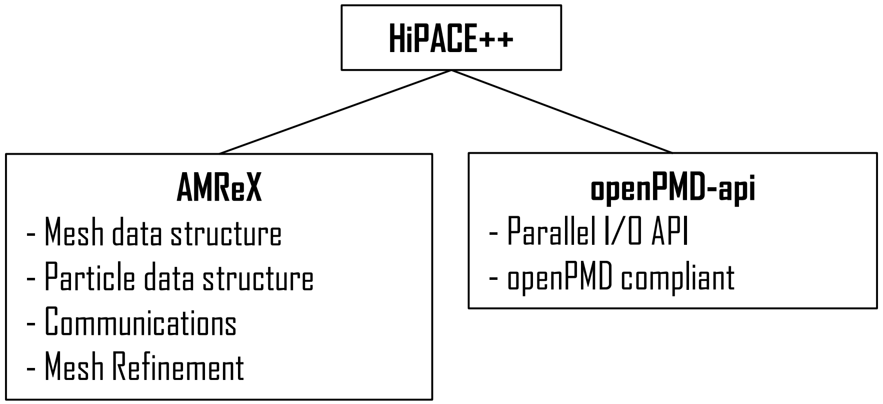
10-100x speedup over (fast!) legacy code HiPACE



- Developed at DESY and LBNL, Open-source, GPU-capable (portable)
- Relies on well-established libraries

→ Support theory activities (positron acceleration, hosing instability, staging, etc.), and assist experiments

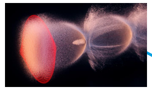


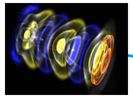


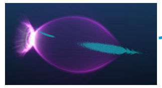
Paper S. Diederichs *et al.* coming soon
Diederichs, S., *et al. PRAB* 23.12 (2020): 121301
https://github.com/AMReX-Codes/amrex
https://github.com/openPMD/openPMD-api
https://github.com/Hi-PACE/hipace
https://hipace.readthedocs.io

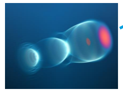
Start-to-end simulations are critical to develop new designs

A very common workflow is PIC + X, we address it with the openPMD standard

FBPIC 

WarpX 

HiPACE++ 

Wake-T 

...

openPMD

- ✓ Archive (FAIR) & share
- ✓ Analyze & plot (openPMD-viewer, VisualPIC)
- ✓ Interface with other codes

  Beam optics, ICS, FEL, ML → openPMD → ... + Y etc.

Standard for particle and mesh data

Pioneered at HZDR, contributors worldwide

https://github.com/openPMD
https://github.com/openPMD/openPMD-api
https://github.com/openPMD/openPMD-viewer

openPMD: high-quality standard for particle and mesh data,

- reliable tool for start-to-end simulations
- adopt FAIR principles for longevity
- encourage benchmarks and collaboration for a global effort in a (reasonably) user-friendly way.

https://www.go-fair.org
https://github.com/AngelFP/VisualPIC

Conceptual design study: a plasma injector for PETRA IV (PIP4)

PIP4 can be a milestone for design studies in view of a plasma-based collider

The team

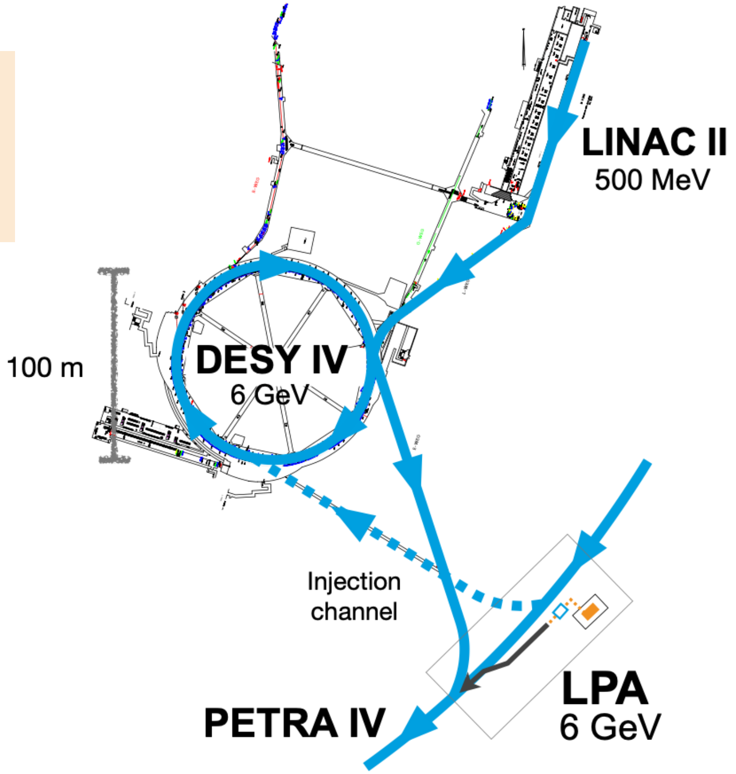
I. Agapov, S. Antipov, R. Brinkmann, A. Ferran Pousa, S. Jalas, L. Jeppe, M. Kirchen, W. P. Leemans, A. R. Maier, A. Martinez de la Ossa, J. Osterhoff, M. Thévenet

Petra IV [1] is the upgrade of the Petra III storage ring for synchrotron radiation (2.3 km, 6 GeV), proposing orders-of-magnitude increase in X-ray brightness.

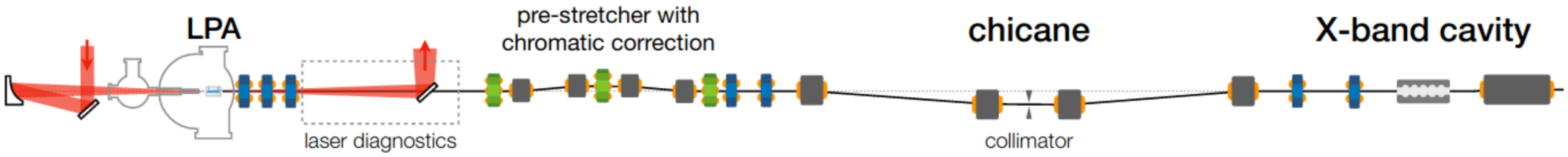
Specs: 6 GeV, > 1 nC/s, 1% momentum acceptance, 10 mm.mrad

- LPA based on the LUX design [2]
- 500 MeV prototype [3] & 6 GeV injector
- Novel energy compression concepts required [4]

→ CDR in 2022 (S2E simulations), commissioning in the decade



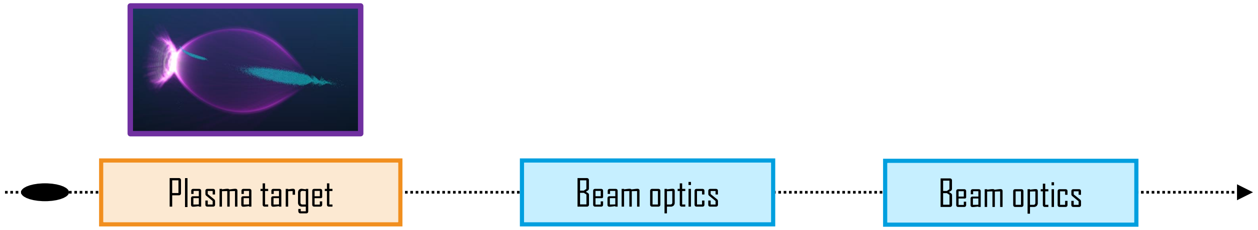
Can the whole injector be replaced by LPA?



[1] https://www.desy.de/research/facilities__projects/petra_iv
[2] Kirchen, Manuel, *et al.* *PRL* 126.17 (2021); LUX PI: A. R. Maier
[3] Antipov *et al.*, IPAC 2021 poster TUPAB025 , article coming soon
[4] Ferran Pousa *et al.*, IPAC 2021 poster TUPAB151, article coming soon

Multi-physics studies for conceptual designs have several aspects

Plasma acceleration requires multiple aspects of multi-physics simulations



Multi-physics plasma simulations

- Kinetic (PIC)
- Collisions, ionization
- Synchrotron radiation (SR)

Plasma target

- High average power

  Kaldera, FLASHFORWARD▸▸
- MHD simulations
- Capillary discharge [1]
- Guiding

Beamline

- Beam optics
- SR/CSR
- Photon generation
- Beam consumers

Complex non-linear systems

→ Ensembles of simulations for design studies (not a single "lucky" shot)

→ Optimization (e.g. Ref. [2] at LUX)

[1] G. Boyle *et al.*, submitted
[2] S. Jalas *et al.*, PRL 126, 104801 (2021)

Questions for the community

Part 1

What intermediate physics applications/steps do you see until a HEP linear collider?

- Injection into a storage ring (PIP4)
- Light sources (LPA-driven FEL)

What is the role of your work here?

- Multi-physics, portable & efficient simulation codes for plasma acceleration
- Adoption/development of standards and code practices for benchmarks and S2E simulations
- Approaches for long-term plasma dynamics (hydrodynamic plasma for guiding, high-power, etc.)
- Develop theory and propose concepts

Questions for the community

Part 2

What are the important milestones for the next 10 years to get there from today?

- Develop and share high-quality low-level libraries: I/O, portability (GPU), multi-physics
- Propose methods and tools for multi-scale (fs-ms) problems, further theoretical understanding

What additional support is needed to achieve these?

- Software engineers & numerical analysis
- Involve the hydrodynamics plasma simulation community

What should be proposed as deliverables until 2026? Please list in order of priority.

- Demonstrate plasma-based injectors
- Innovative concepts for beam quality
- Open-source tools for long-term plasma dynamics with relevance for plasma acceleration

Is the R&D work for each of those deliverables already funded and, if not, what additional resources / support would be needed?

- Software engineers

Questions for the community

Part 3

What can be done with the existing and planned funding base?

- Theoretical/simulation studies for the main challenges (staging, repetition rate, beam quality, etc.)
- Intermediate applications
  - Conceptual designs & implementation for practical application (e.g. storage ring)
  - Light sources like FEL

Thank you for your attention

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