Investigation of potential early applications of novel and advanced technologies for colliders

Work package 5

Jens Osterhoff

DESY. Accelerator Division

September 28th, 2023

EAJADE General Meeting

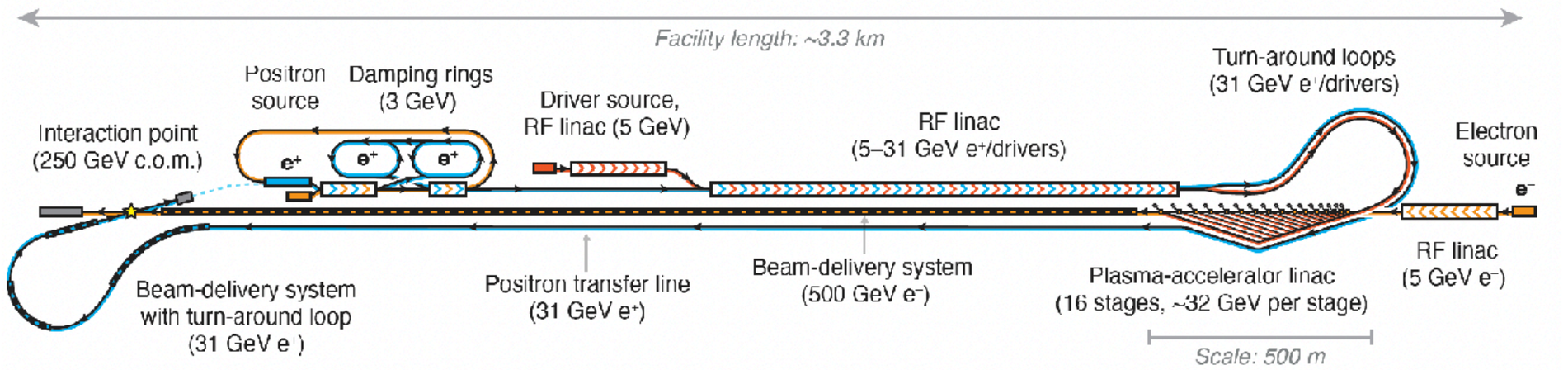
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

EAJADE deepens existing collaborations and creates new ones

Goal is to strengthen the transatlantic and European work on plasma accelerators for particle physics

Work package 5	Plasma wakefield technologies		Start/end month		1/48		
Work package title	Investigation of potential early applications of novel and advanced technologies for colliders						
Lead beneficiary	DESY						
Participating organisation short name**	DESY	CNRS	INFN	UOXF			
Total person-months per participating organisation:	33	1	10	8			

- Investigate the potential of plasma technology for **improved particle collider designs** including **efficiency-maximized plasma accelerator modules** and **positron acceleration.**
- Develop highly-optimized open-source **simulation codes** for **start-to-end study of plasma-based or plasma-augmented particle colliders.**
- **Train Ph.D. students and postdocs** on topics of experimental and theoretical plasma accelerator science.



A Hybrid Asymmetic Linear Higgs Factory (HALHF)

Brian Foster (UOXF/DESY), Richard D'Arcy (DESY/UOXF), Carl Lindstrøm (U Oslo/DESY)
accepted for publication in New Journal of Physics, arXiv: 2303.10150 (2023)

Task 5.1 — Plasma accelerator concepts for future high-energy physics applications

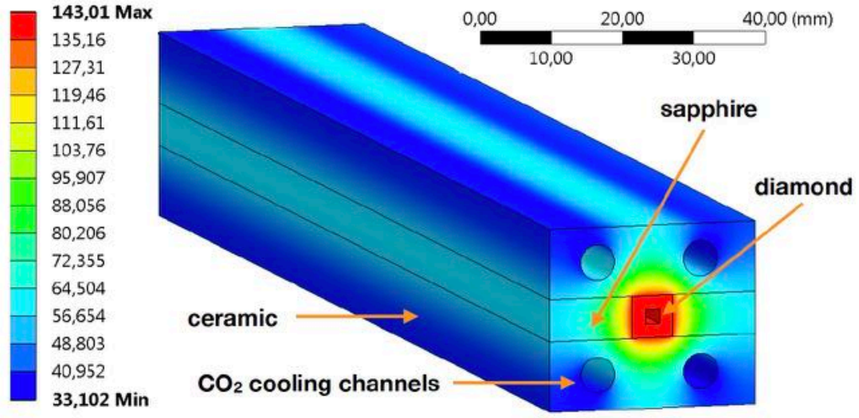
DESY, INFN, CNRS, UOXF — 22 person months

> **Development of novel concepts for solving open challenges in the application of plasma-based accelerators to particle physics**

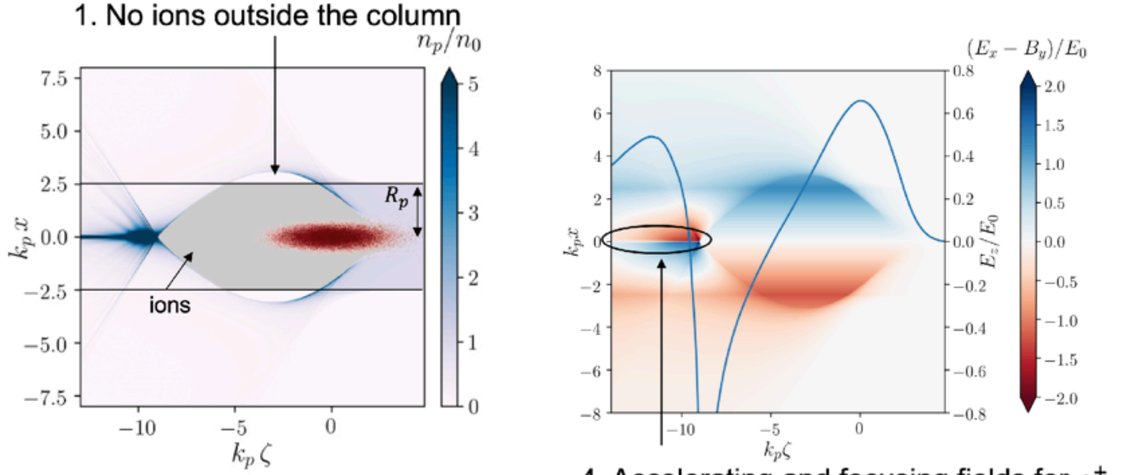
- high-efficiency and collider-beam-quality **positron acceleration scheme,**
- beam polarization maintenance,
- **high repetition rate/high-average power** support,
- beam-quality-conserving plasma staging.

> Secondments to LBNL and DESY.

Actively cooled plasma sources



Positron acceleration in a plasma column



4. Accelerating and focusing fields for e^+

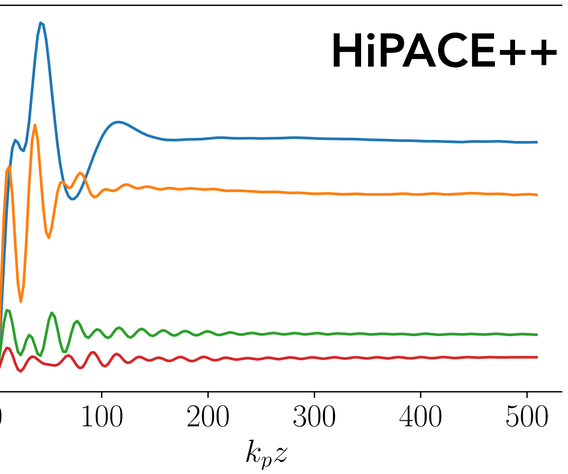
$0.5E_0 \approx 15$ GV/m at $n_0 = 1{\times}10^{17}\ cm^{-3}$

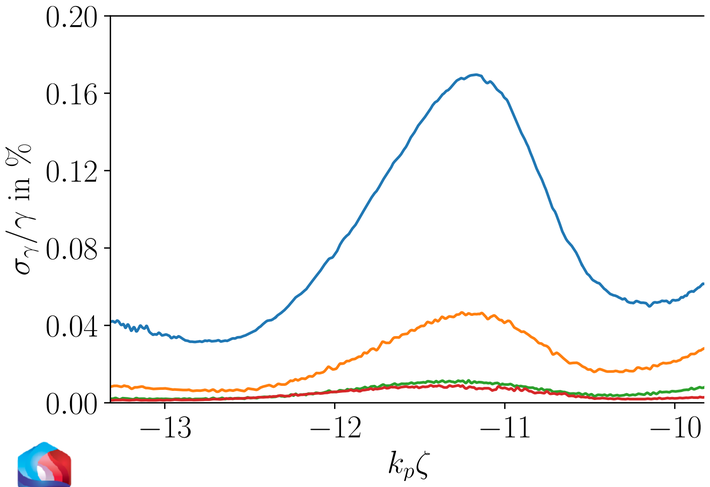
Diederichs *et al.*, PRAB 2020
Diederichs *et al.*, PRAB 2022

10s of nanometer emittance preserved to 1%

Mesh refinement technology causes a “positron miracle”

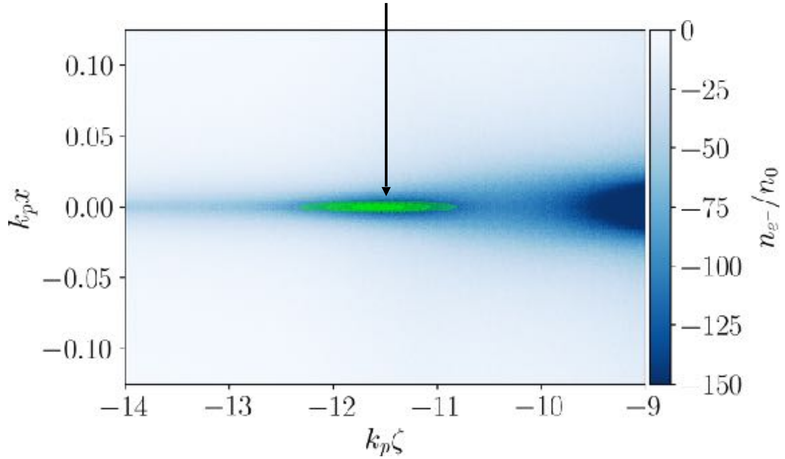
With a temperature, a lower emittance can be better preserved,
while simultaneously achieving a lower slice energy spread and maintaining the same charge



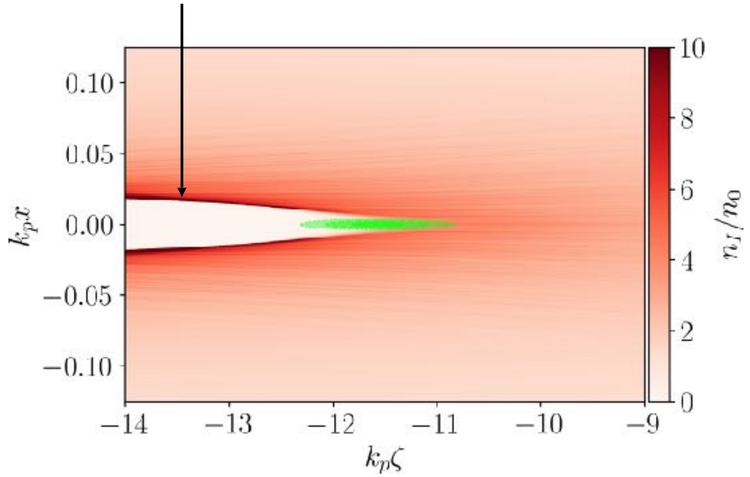


Severin Diederichs

intense positron beam with
$n_b/n_0 \approx 46000$



ion blowout!



***Next:* maximizing efficiency of scheme**

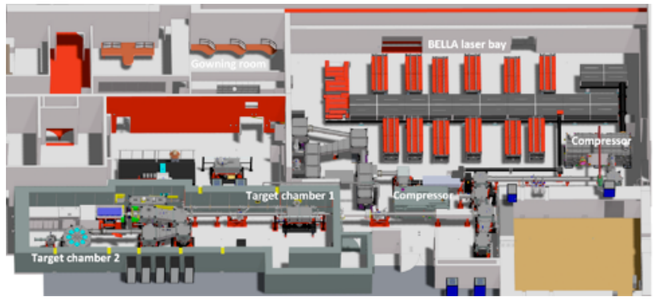
$k_p\epsilon_x$ 0.1 0.025 0.00625 0.002 ≈ 33 nm at $n_0 = 10^{17}$ cm^{-3}

Task 5.2 — Experimental plasma accelerator tests

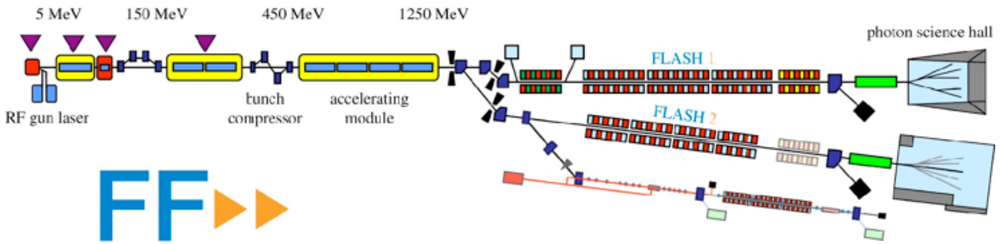
DESY, INFN, UOXF — 19 person-months

> **Experimental tests of novel concepts of plasma accelerator technology for particle physics applications**

- positron acceleration,
- accelerator efficiency maximization,
- beam quality optimization,
- machine learning controls,
- plasma lens technology.



BELLA



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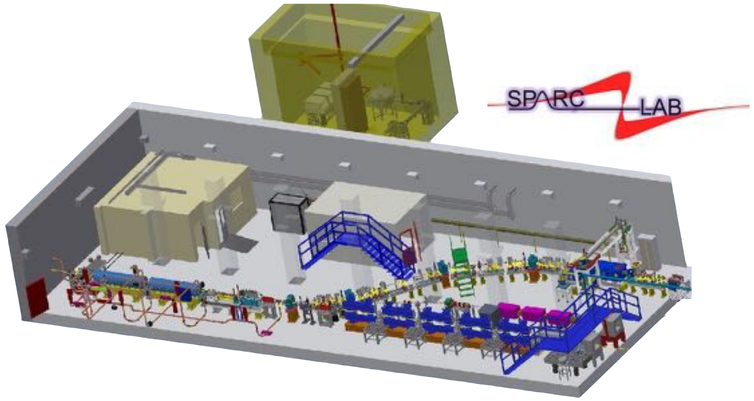
> The to-be-utilized experimental facilities are **FLASHForward** at DESY, **BELLA** at LBNL, **SPARC_Lab** at INFN, and **FACET-II** at SLAC

> This task connects many **leading experimental facilities in the field** and is of highest importance for **cross-fertilization** and the **training of students and postdocs**

> Secondments to LBNL + SLAC, UOXF, INFN and DESY.



Task 5.3 — High-performance computing: development of optimized simulation codes

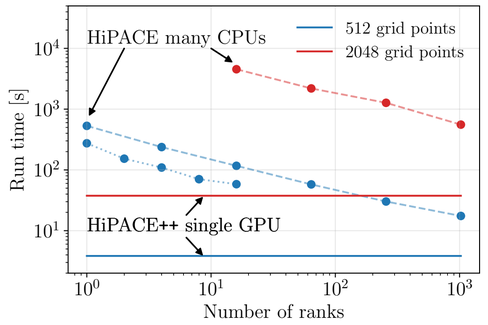
DESY — 11 person-months

> **Development of highly optimized, scalable, and portable open-source simulation codes for full start-to-end calculations of future plasma-based or plasma-augmented particle colliders including tolerance studies.**

> Such tools are currently unavailable and critical for realistic future designs.

> Strengthens the training in modern methods for high-performance computing, machine learning, and code development.

> Secondments to LBNL.

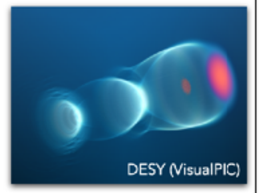


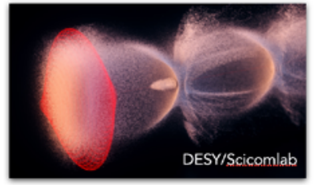
- 10× faster
- 1000× less costly
- scales well to hundreds of GPUs

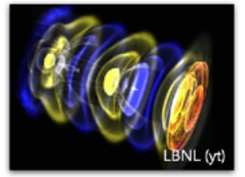
→ OoMs more simulations per $
→ High-res simulations in minutes
→ Production runs on a laptop

DESY/UHH/LBNL develop a portfolio of open-source, high-performance codes for plasma accelerator emulation

	Quasistatic	Fully electromagnetic
Quasi-cylindrical	**Wake-T (DESY)** → Conceptual designs (sec-min) Open-source https://github.com/AngelFP/Wake-T	**FBPIC (LBNL + UHH)** → LPA with injection Open-source GPU https://github.com/fbpic/fbpic
3D	**HiPACE++ (DESY + LBNL)** → 3D external injection Open-source GPU https://github.com/Hi-PACE/hipace	**WarpX (LBNL + many incl. DESY)** → LPA with injection Open-source GPU https://github.com/ECP-WarpX/WarpX







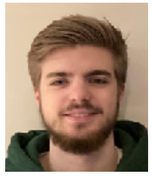
Game changer → Parameter scans instead of single runs in full 3D
Prerequisite for accelerator design

HiPACE++ – The Team

Advanced algorithms and high-performance computing for fast and energy-efficient 3D simulations of plasma acceleration – for everyone


Maxence Thévenet (lead)


Severin Diederichs


Alexander Sinn

DESY – MPA


Axel Huebl


Rémi Lehe


Jean-Luc Vay

LBNL – AMP

ECP project WarpX


Andrew Myers


Weiqun Zhang

LBNL – AMCR

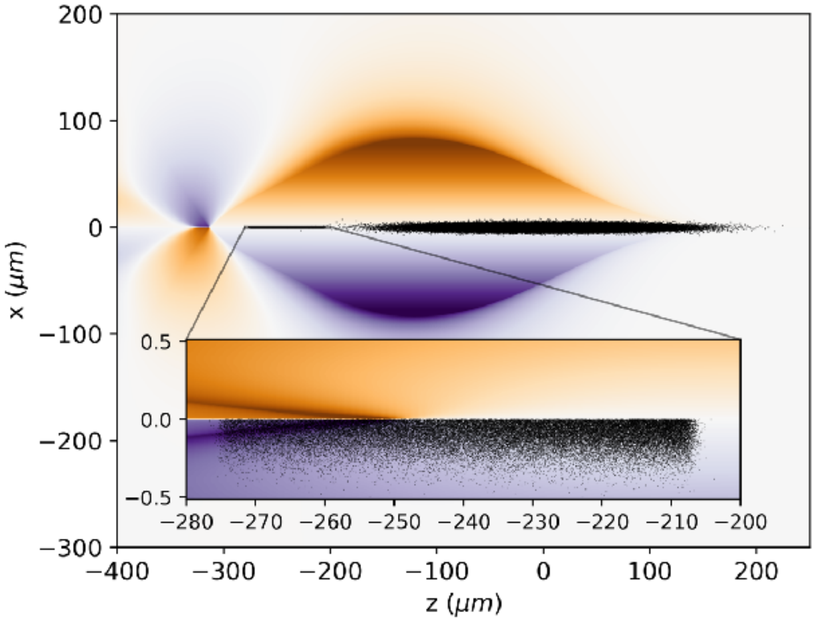
AMReX developers

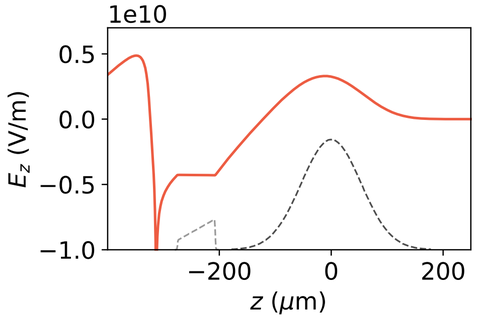

Carlo Benedetti

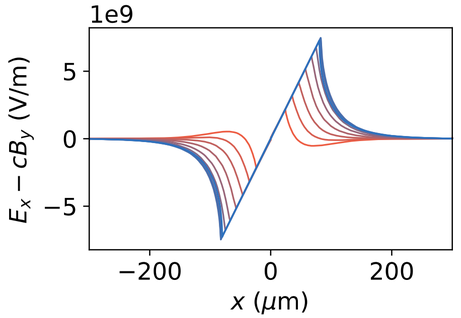
LBNL – BELLA

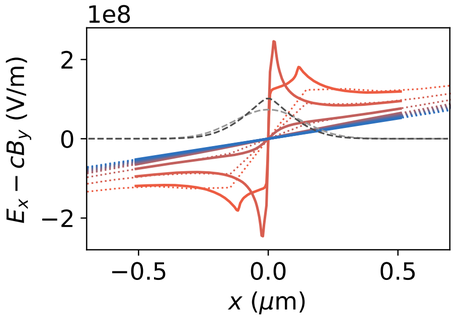
- Started mid-2020
- International project, open-source
- New contributors most welcome!

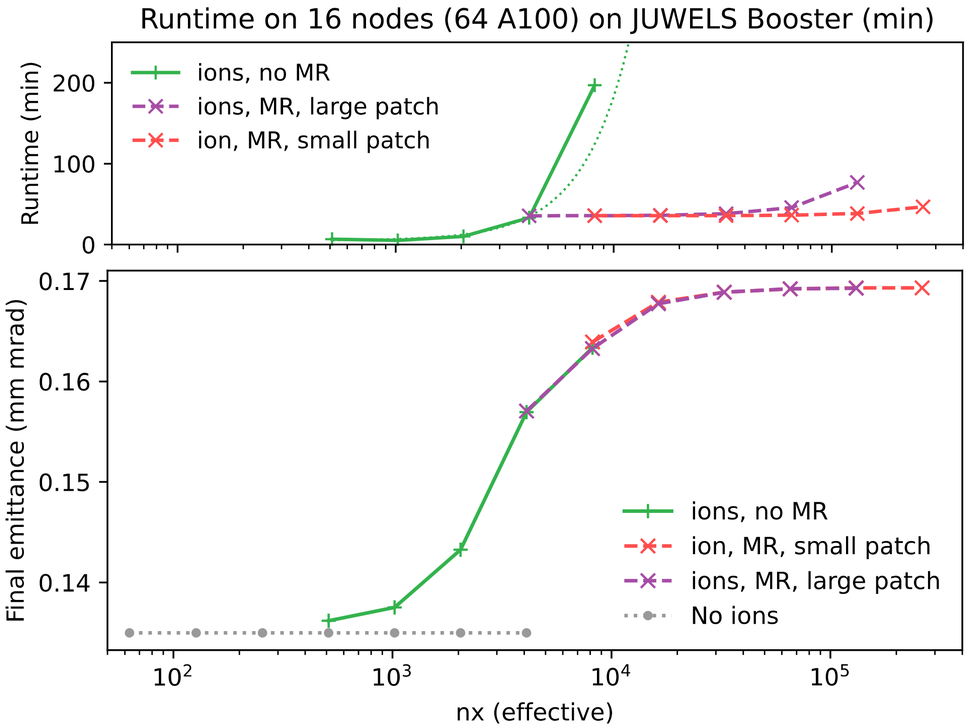
Converged simulations in collider-relevant range are ~~feasible~~ cheap

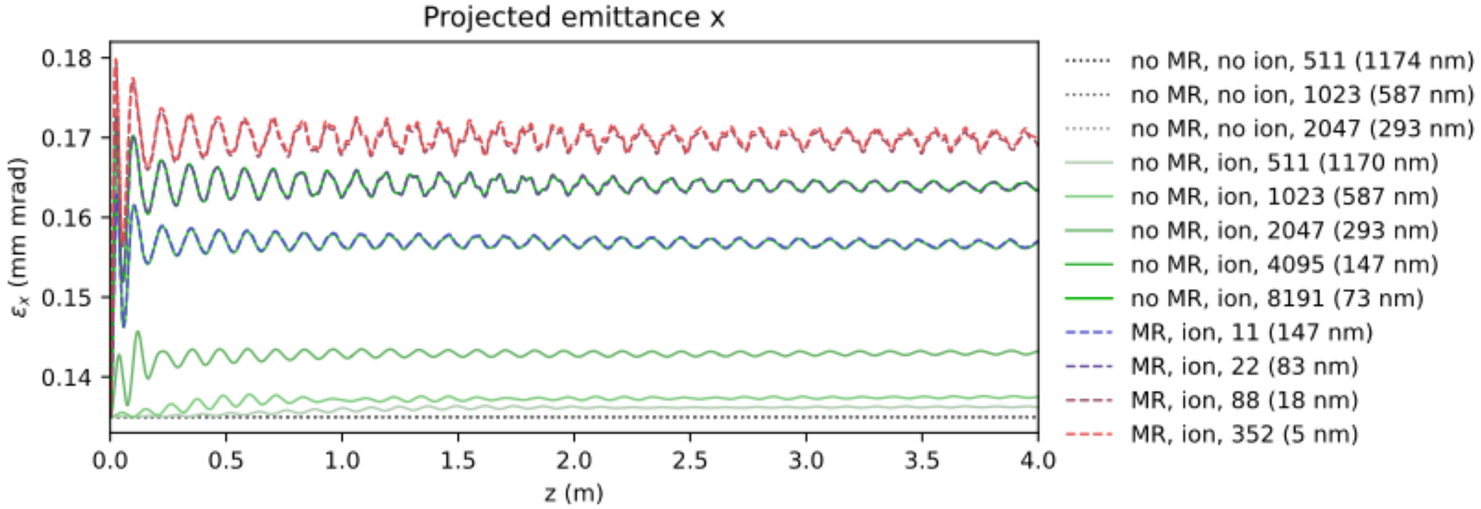






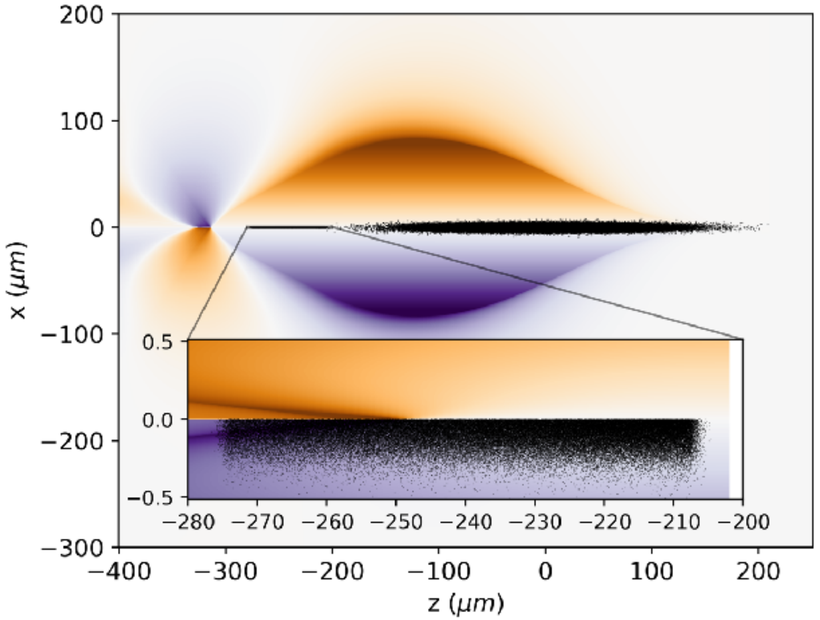




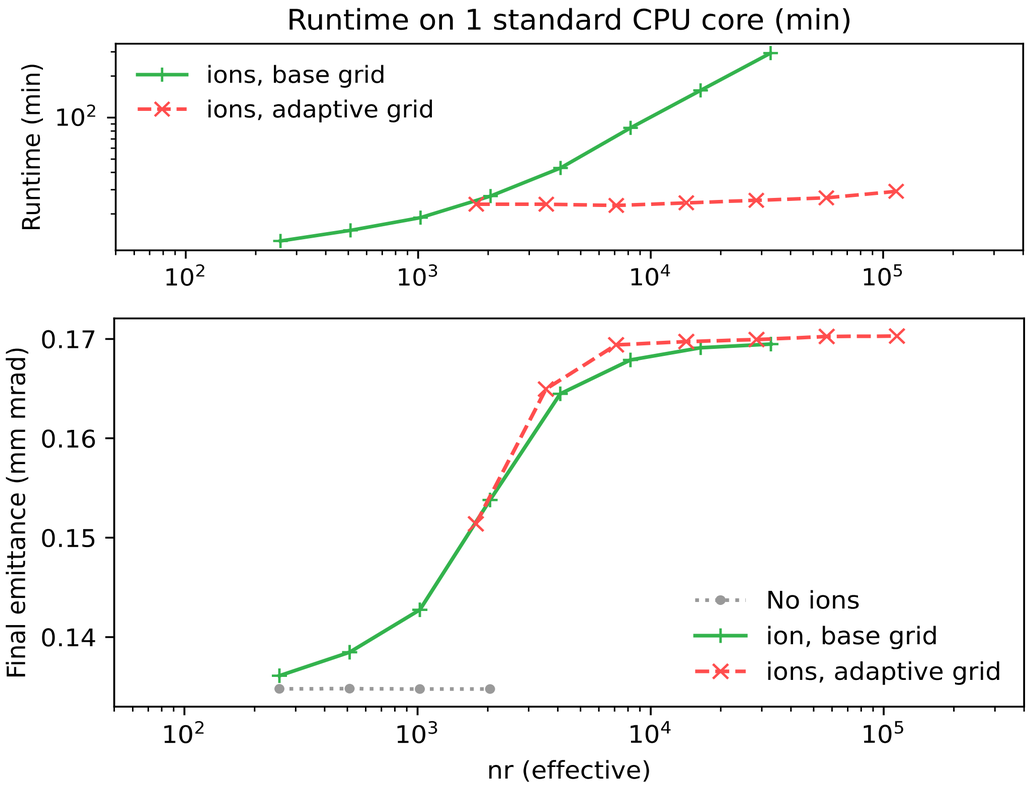


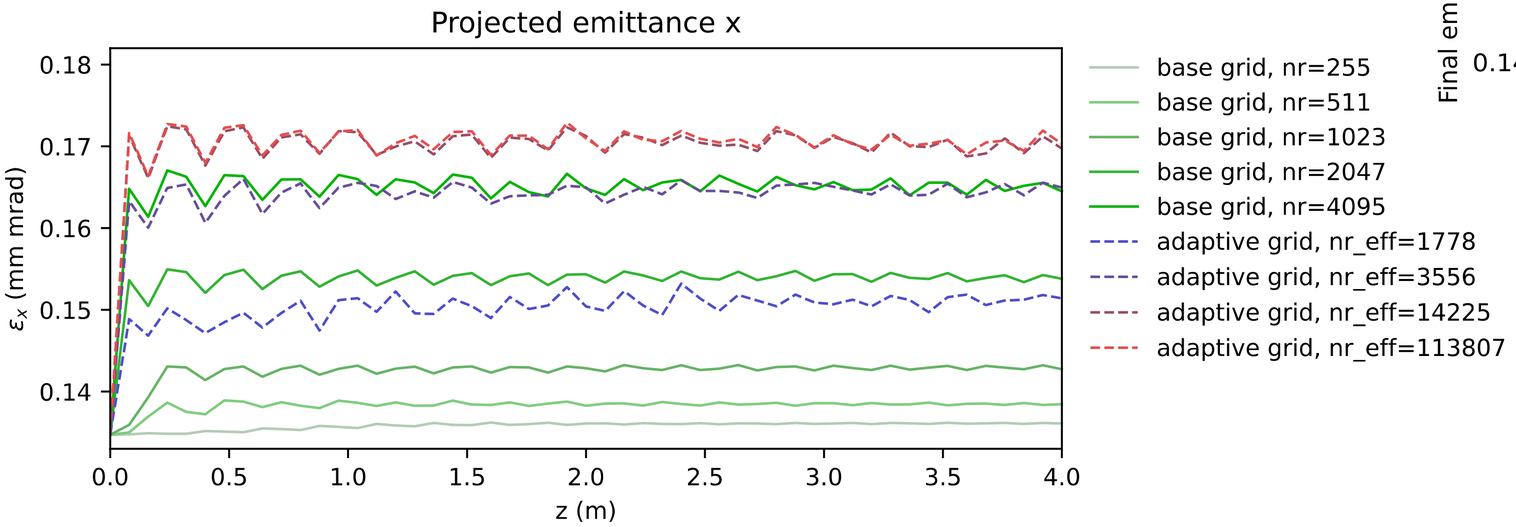
- Fine everywhere = Coarse + MR
- MR allows for convergence at modest cost

Realistic simulations of collider parameters on a laptop with Wake-T



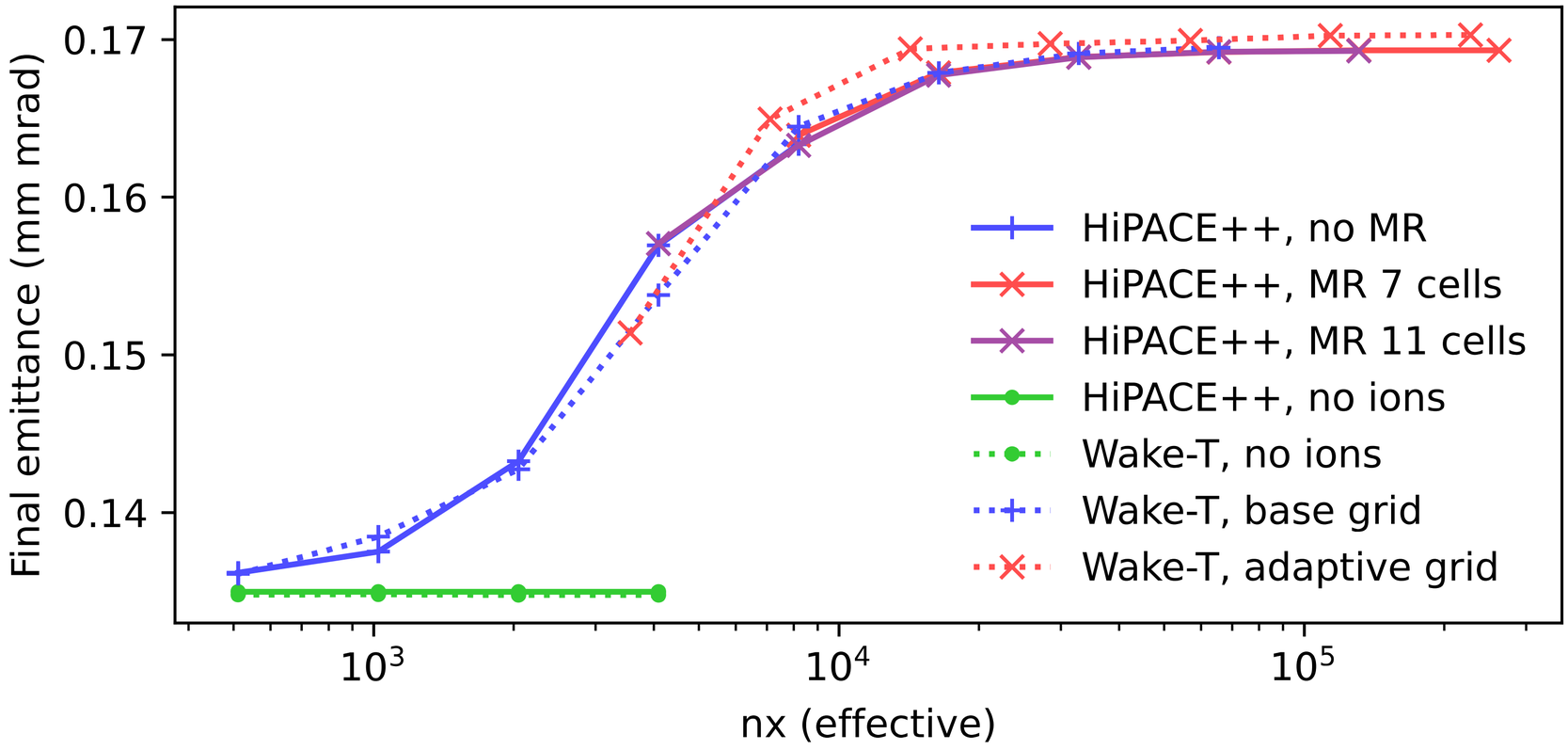
Ángel Ferran Pousa





- Adaptive grid = fine resolution everywhere
- MR allows for convergence at modest cost

HiPACE++ and Wake-T converge to very similar results



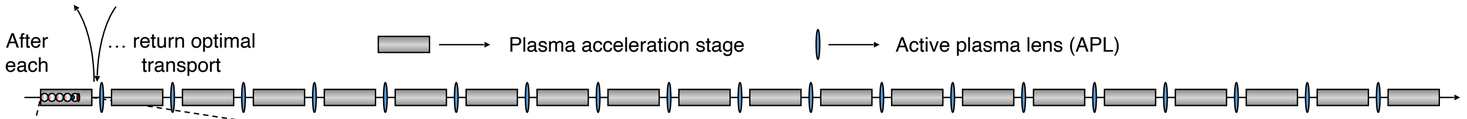
Cost-efficient modeling of > 100 GeV plasma electron linacs

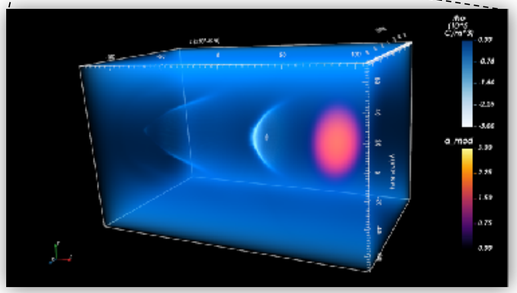
Enabling the simulation of future plasma-based colliders

- Cost of 3D particle-in-cell simulations strongly limits the study of plasma-based colliders.
- LBNL develops exascale Warp-X code to enable 3D start-to-end collider modeling.
- DESY develops cost-efficient Wake-T code based on reduced models.
- **Goal:** can we use Wake-T for efficient modeling of plasma colliders?

1 month
in April 23

optimas
Bayesian optimization

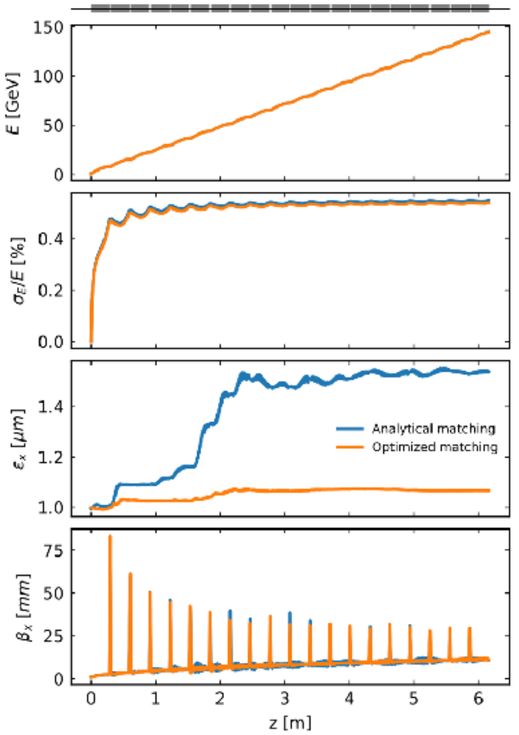




Successful start-to-end modeling of 20-stage linac

- Included live optimization of beam transport.
- Developed optimas and Wake-T to enable this workflow.
- Improved original design to preserve beam quality.
- Published results: A. Ferran Pousa et al, Proc. IPAC 23, TUPA093 (2023)

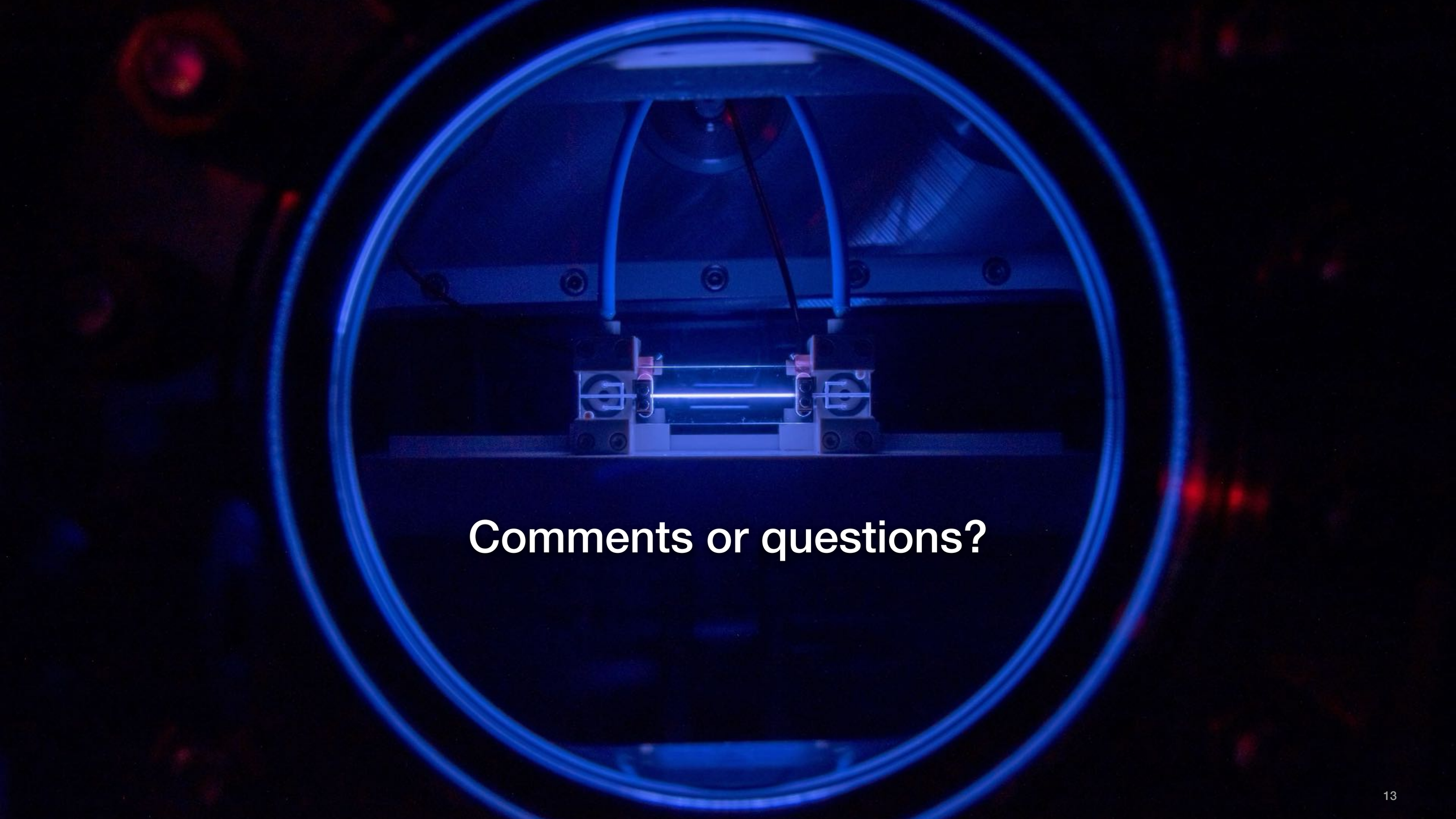
Beam evolution in optimized 20-stage plasma linac



Our deliverables and summary

- **5.1 PosAccPWARep** (month 24, tasks 5.1, 5.2):
  Report on concepts for positron acceleration in a plasma accelerator-based collider
  and on active plasma lenses for efficient positron capturing.
- **5.2 PWAFinRep** (month 46, tasks 5.1, 5.2):
  Report on plasma accelerator module design in the context of concepts for high-repetition rate
  and high-average power acceleration, staging, and beam-quality and natural efficiency limits.
- **5.3 SimCodeFinRep** (month 48, task 5.3):
  Report on simulation code development and the role of machine learning-based optimization techniques
  for full-start-to-end simulations of a plasma-based collider; the report includes details on training progress
  for Ph.D. students in the therefore required software architectures and concepts.

- First secondment has concluded, many more to come in the near future
- Excellent progress for D5.1 and D5.3; joint work on D5.2 is in preparation



Comments or questions?