All-optical In-plasma Staging of Laser-Wakefield Accelerators Using Density Tailoring

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

EAAC2025 7th European Advanced Accelerator Conference

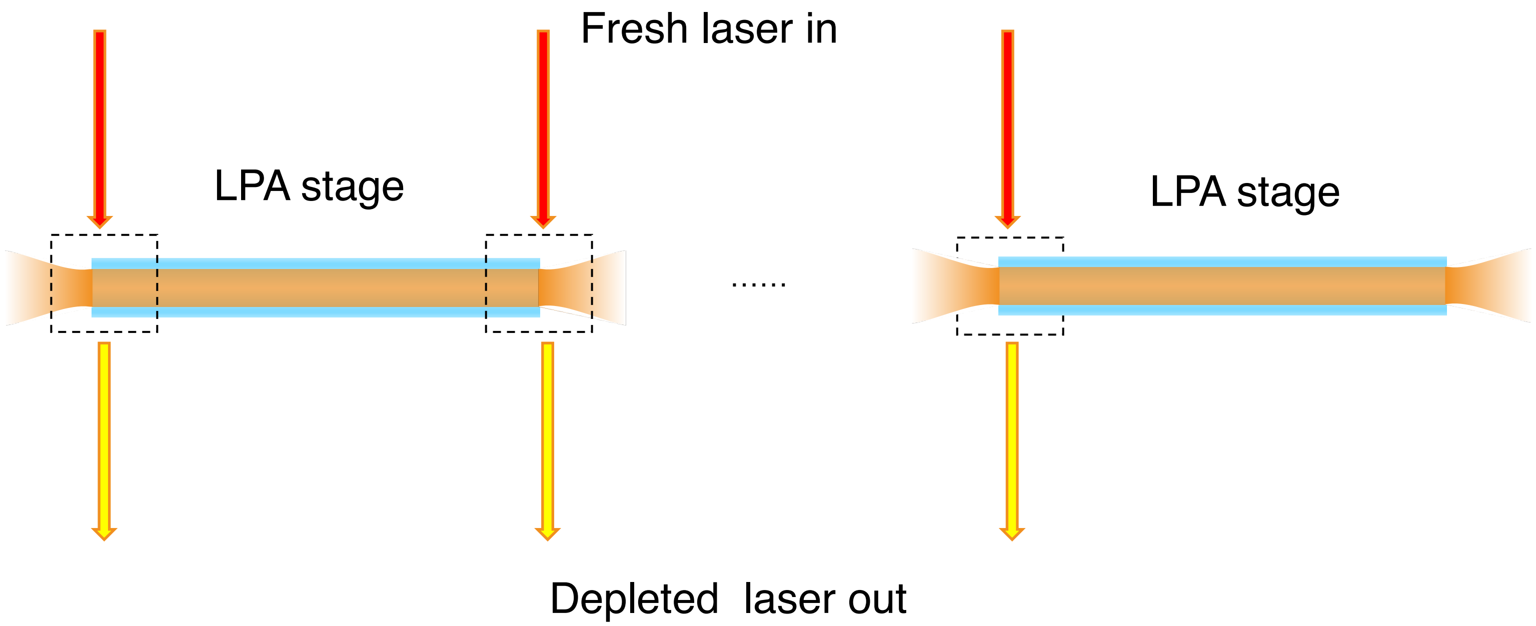
DESY.

Single stage or multistage toward higher energy?

Single stage plasma channel

>1kJ Laser needed to reach ~100 GeV

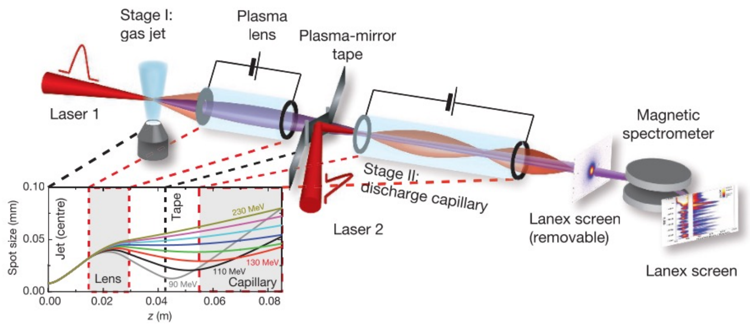
Staging



C. B. Schroeder et al. PRAB **13**, 101301 (2010)

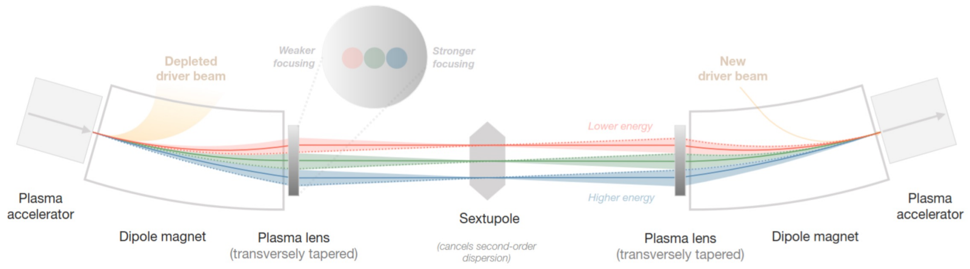
Efforts have been made on multistage coupling for LPA

Tape-based plasma mirror



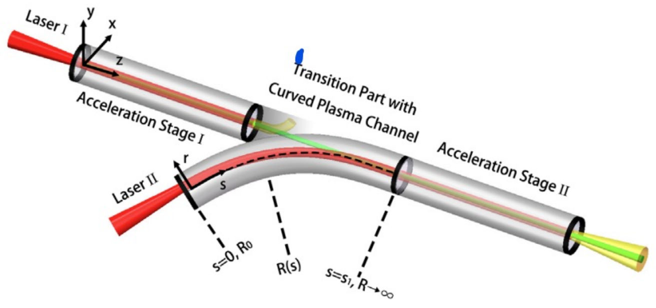
S. Steinke, *et al*. *Nature* **530**, 190–193 (2016]

Non-linear achromatic plasma lens



P. Drobniak et al. arXiv:2411.00925 **[physics.acc-ph]**

Curved Plasma Laser Guiding



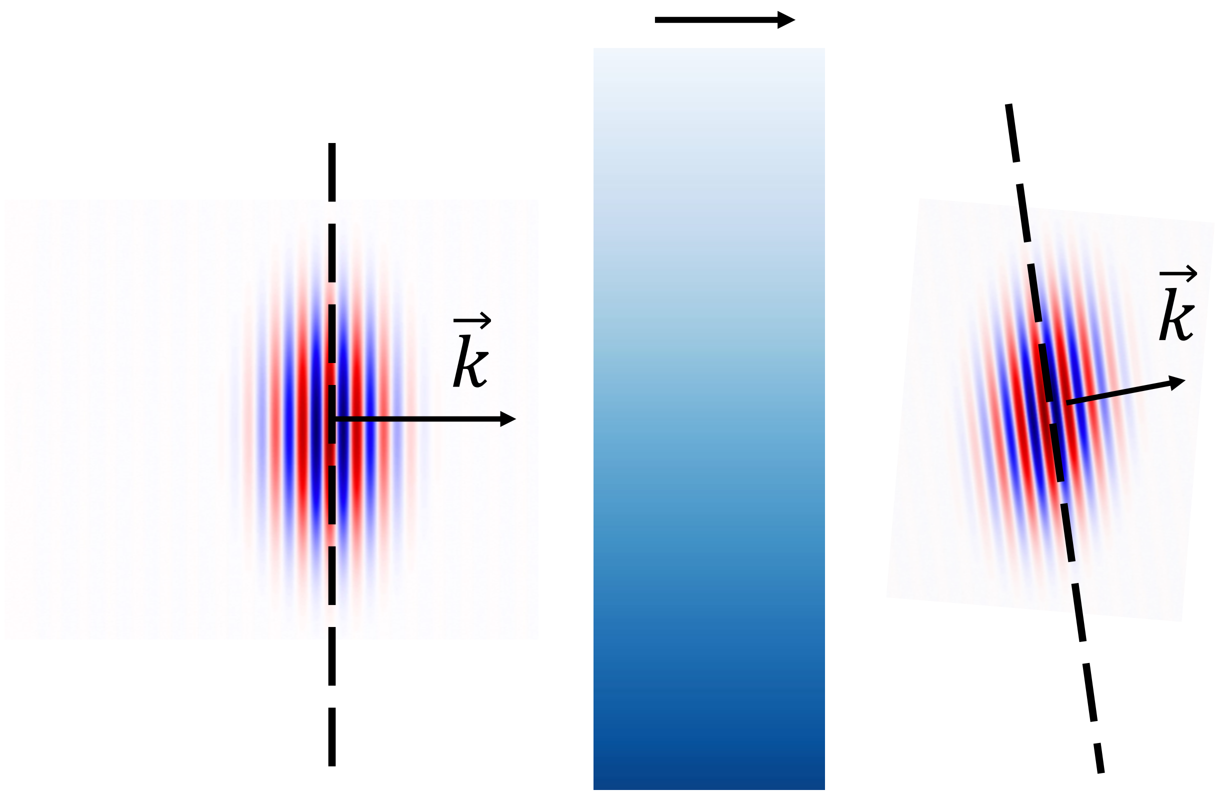
X. Zhu et al. PRL **130**,215001(2023)

Staging comes with the challenges like:

- Laser in&out coupling -- **All-optical**
- Beam capturing -- **In-plasma**
- …

In-plasma laser coupling is possible by refraction

$$\Delta\phi = \frac{v_{\emptyset} D}{c} = (1 + \frac{{\omega_p}^2}{2{\omega_l}^2})$$



Assume a Gradient profile of:

$$n_e = n_0\left(1 - \frac{y}{L}\right)$$

Gradient length: *L*

The deflection angle:

$$\theta = \frac{\lambda_l^2 e^2 D}{8\pi^2 m_e \varepsilon_0 c^2} \frac{\partial n}{\partial \vec{x}} \sim 10\ mrad$$

Spatio-temporal coupling derived as:

Group Delayed Dispersion (s^2)= $\frac{dt_0}{d\omega} = \frac{{\omega_p}^2}{{\omega_l}^3} t$

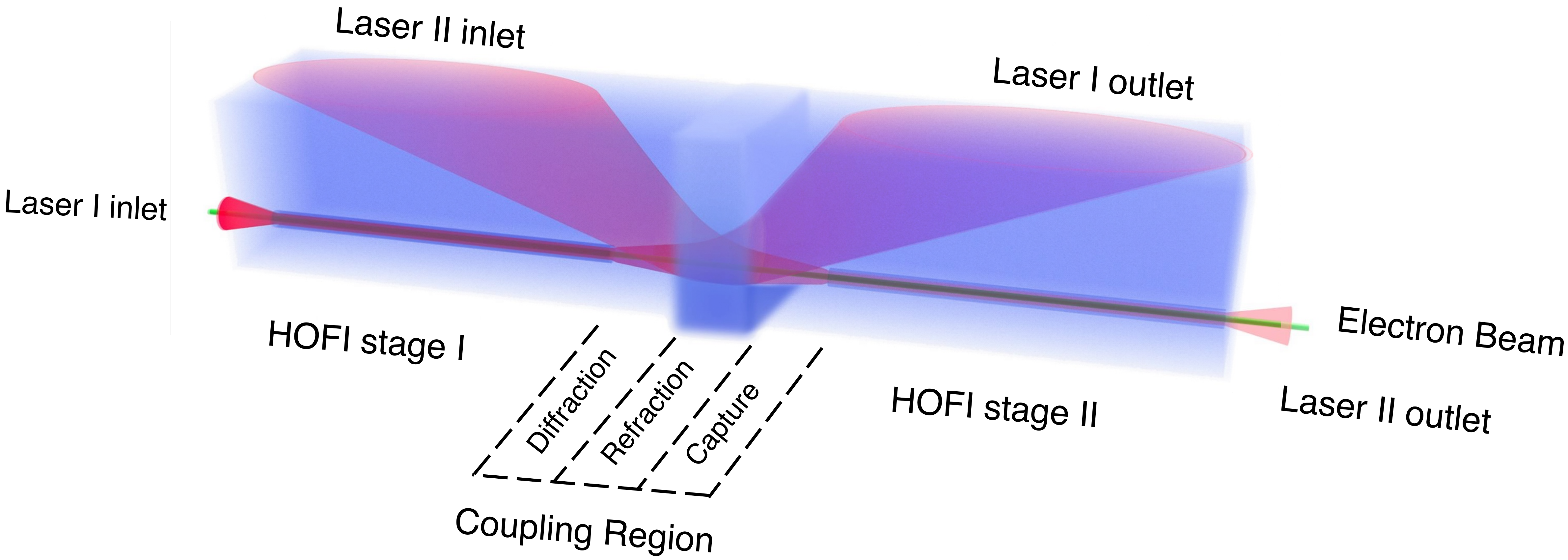
Angular Dispersion (s)= $\frac{d\theta_0}{d\omega} = \frac{e^2 n_0 D}{m_e \epsilon_0 \omega^3 L}$

Spatial Dispersion (m·s)= $\frac{dx_0}{d\omega} = \frac{e^2 n_0 D^2}{m_e \epsilon_0 \omega^3 L}$

Pulse Front Tilt (s)= $\frac{dt_0}{dx}$

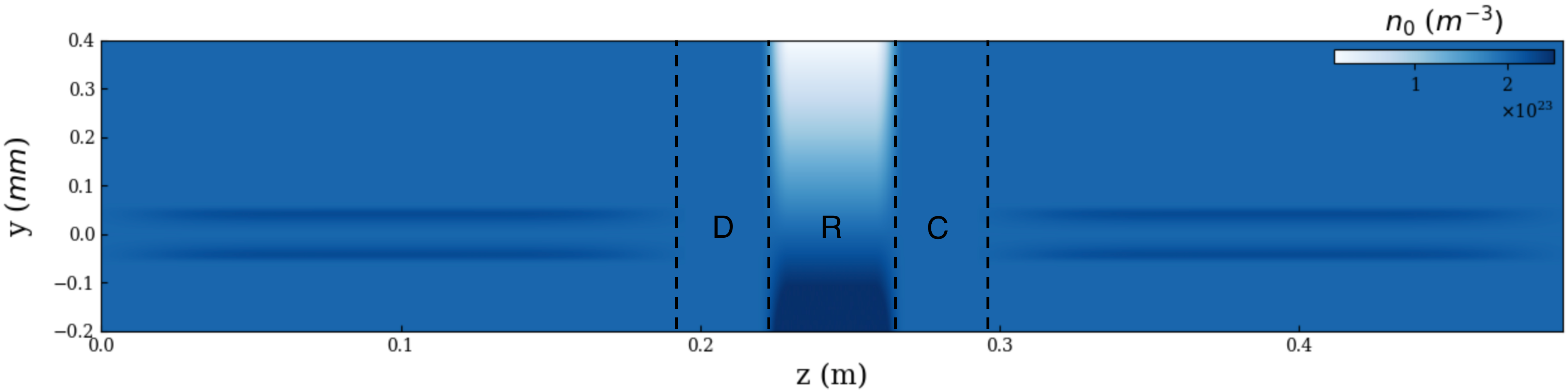
Selcuk Akturk et al. OPTICS EXPRESS 12(19), 4401(2004)/D. E. Mittelberger et al. PRE **100**, 063208 (2019)

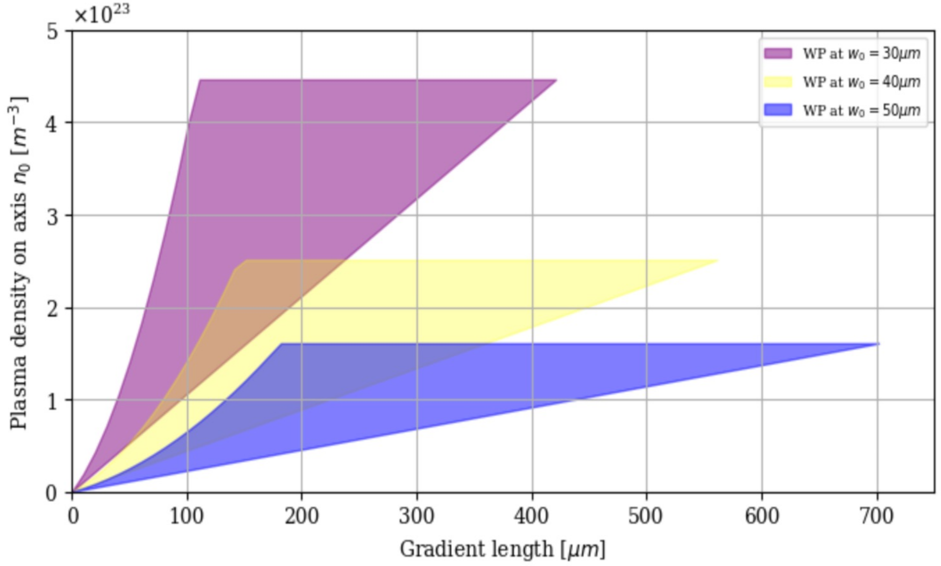
A design of plasma density profile is proposed to realize staging



- Laser in-&out-coupling **using transverse density gradient** without solid structures
- Witness **stays in plasma** in coupling region, confined by self-driven wakefield

The density profile is refined to couple the driver and witness

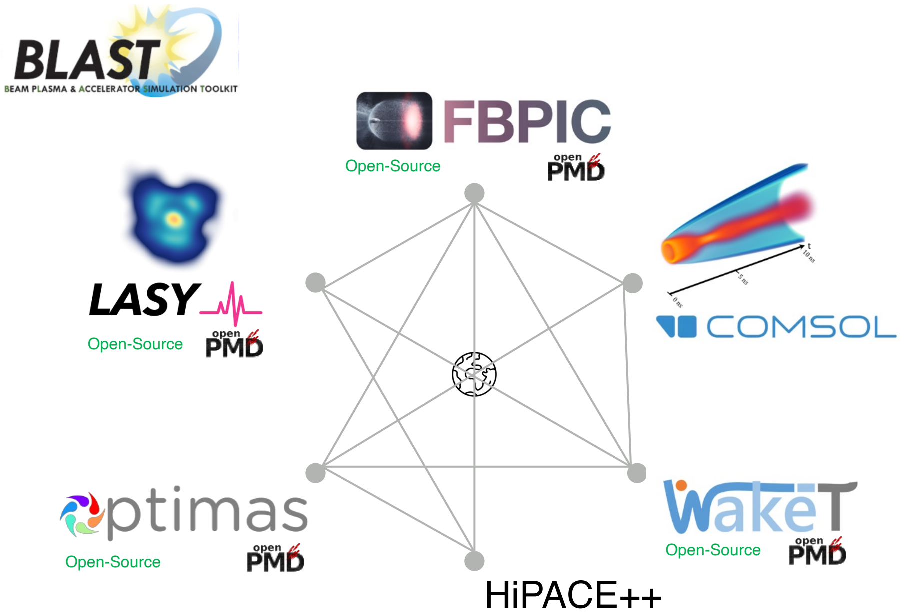




- Operating density is around $\sim 10^{17}\ cm^{-3}$
- Density gradient length is $\sim 10^2\ \mu m$
- Diffraction/Capturing region long enough to release and capture the beam

Self developed code ecology forms up a complete workflow

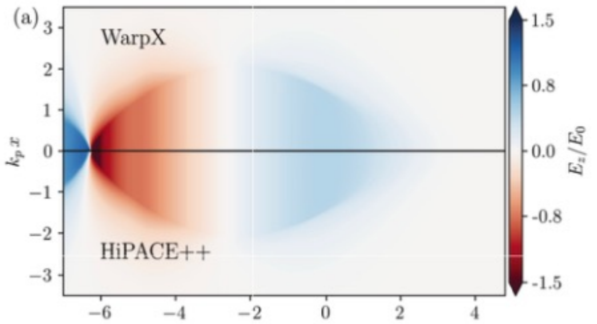
Simulate wakefield acceleration and more…



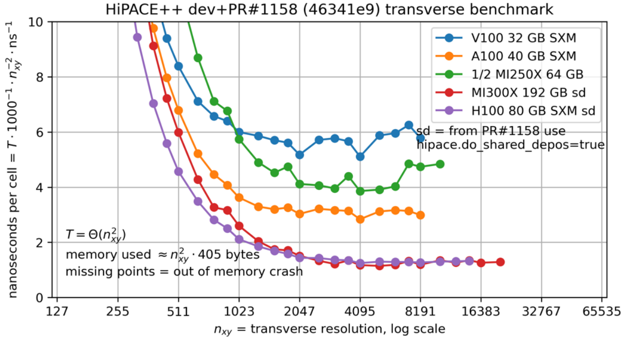
Real combination of simulation tools in past or present studies

More contributors are welcome!

HIPACE++: a 3D Quasi-static GPU-portable, open-sourced PIC code



Source: S. Diederich et al. Computer Physics Communications 278 (2022) 108421



Source: Alexacnder Sinn

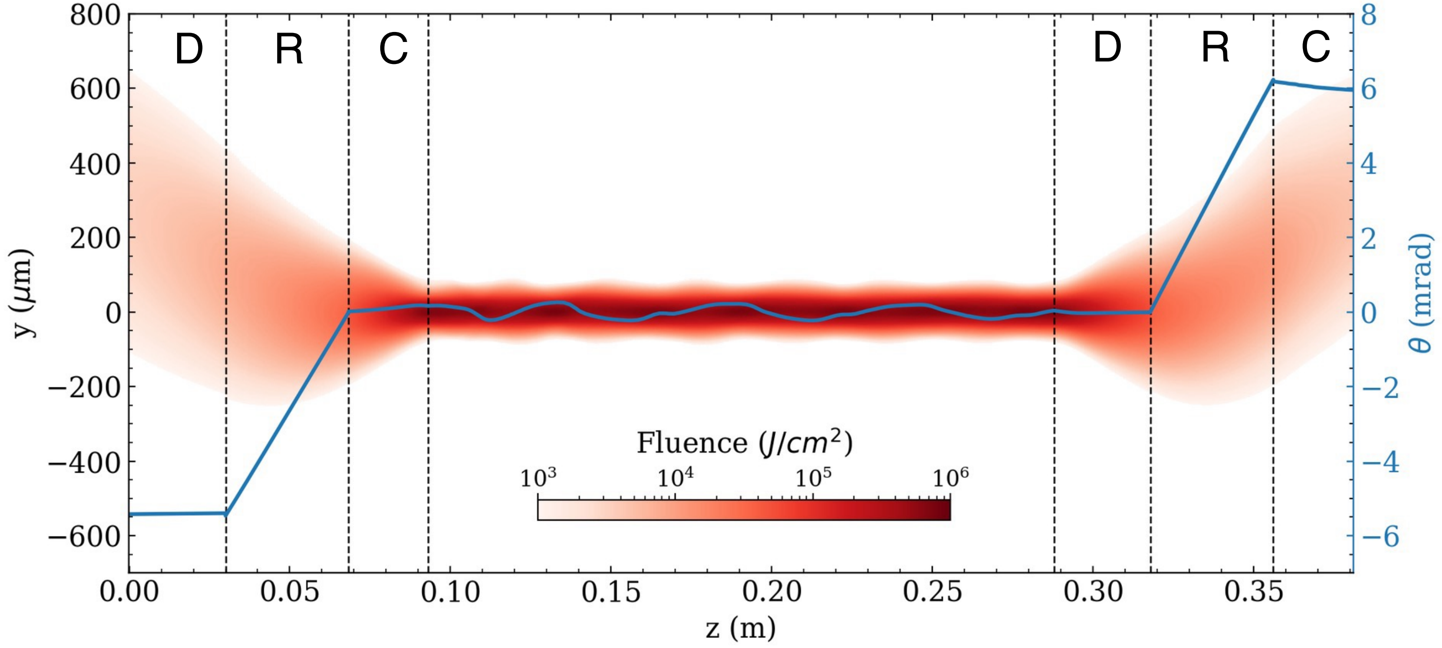
Numerics highlights

- Super fast: Less than 2 min for one 30 cm 3D LPA stage simulation
- Advanced algorithms, parallel and mesh refinement
- Multiphysics
- Portable *laptops, gaming GPUs, JUWELS Booster, LUMI, Perlmutter, etc.*
- Builds on Linux, Windows, MacOS

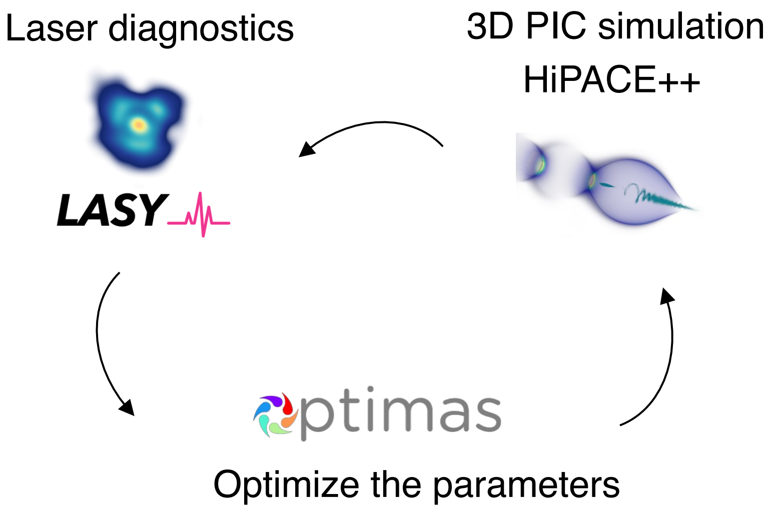
All simulations are 3D, start-to-end and realistic

Bayesian optimization with PIC provides a good laser guiding

Evolution of the drive laser in a staging unit with
$n_0 = 2 \times 10^{17}$ cm^{-3} , $L = 400\ \mu m$ and $w_m \approx 39$ µm



What laser should we initialize?

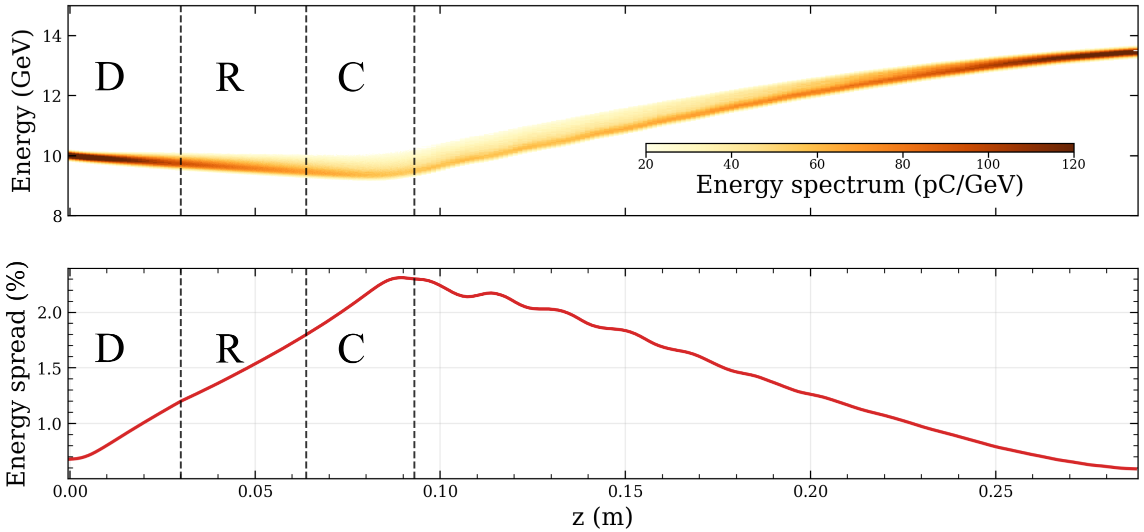


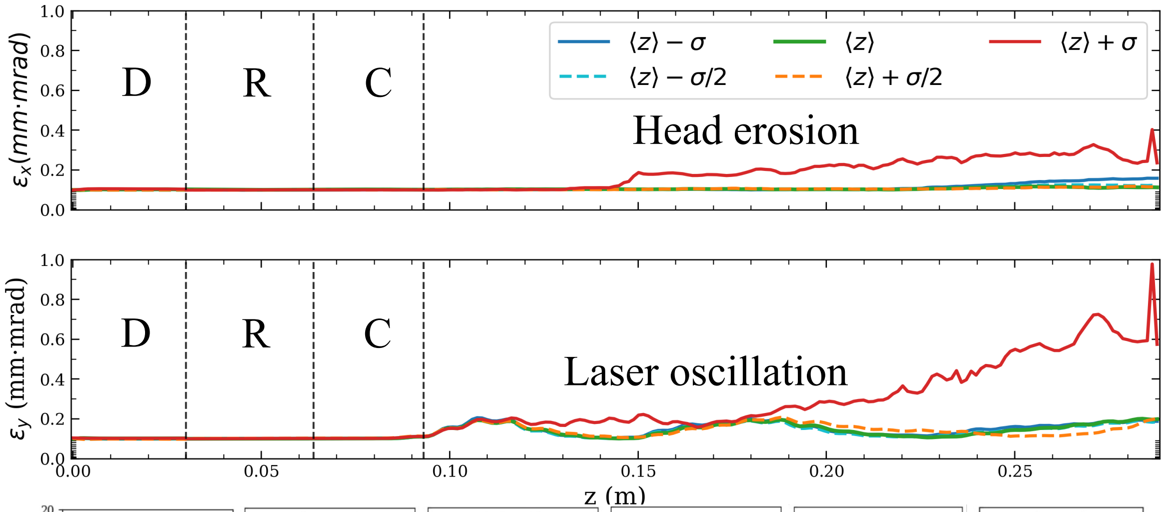
- *Bayesian optimisation helps align and guide the laser*
- *Small oscillation comes from slight pulse front tilt*

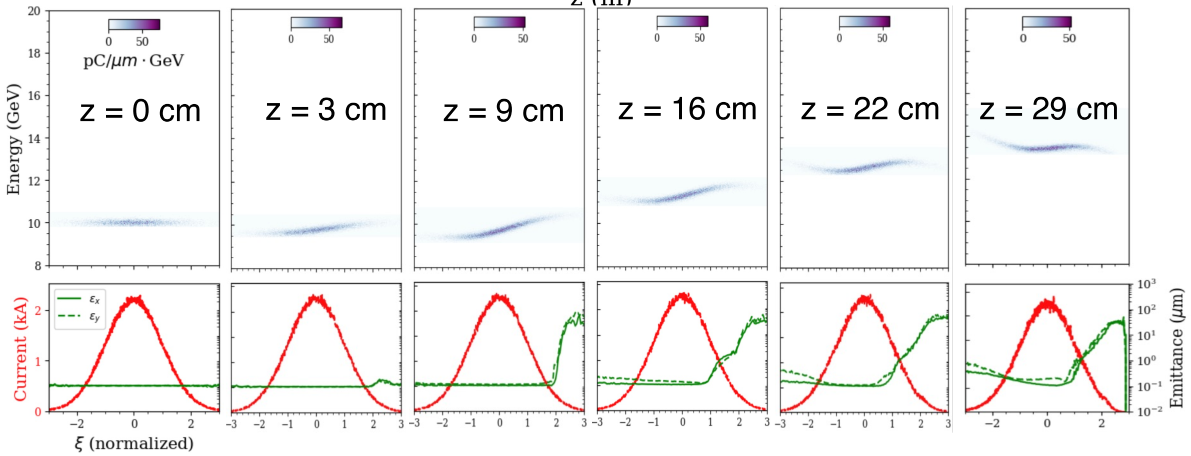
Laser parameters at this WP

E_0 (J)	13.92 J
w_0 (μm)	50
z_{foc} (mm)	93.05
y_0 (mm)	0.267
θ (mrad)	-5.46
β (s)	$-0.45 \times 10^{-17}\ s$
ζ (m·s)	$0.4{\times}10^{-18}\ m \cdot s$

Working point for the second stage from 10 GeV







- **100% beam are captured** and accelerated!
- **4(-0.5) GeV energy gain**
- **Beam loading** is handled by adjusting the chirp

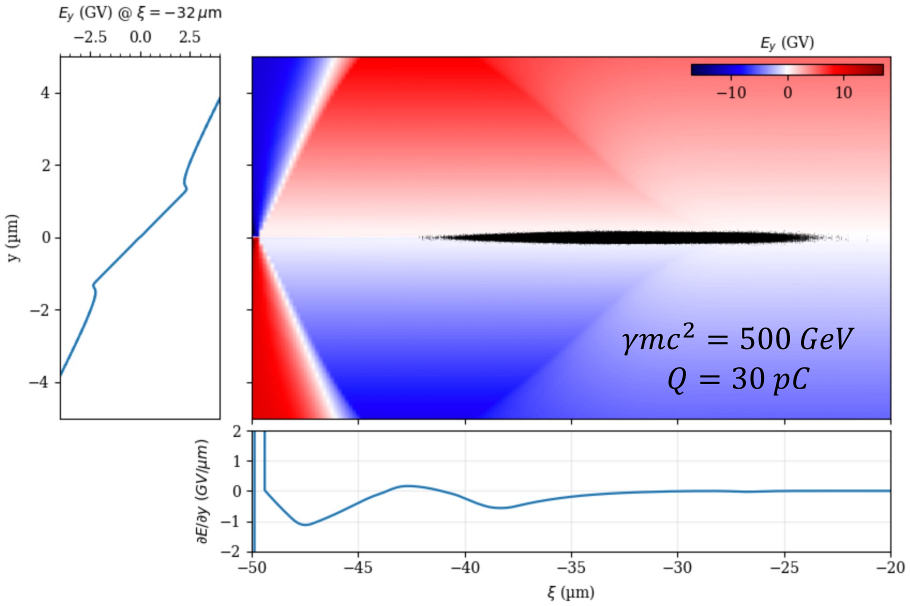
- **Emittance is mostly preserved**

The concept is inherently compatible with ion motion

Mached rms bunch size:

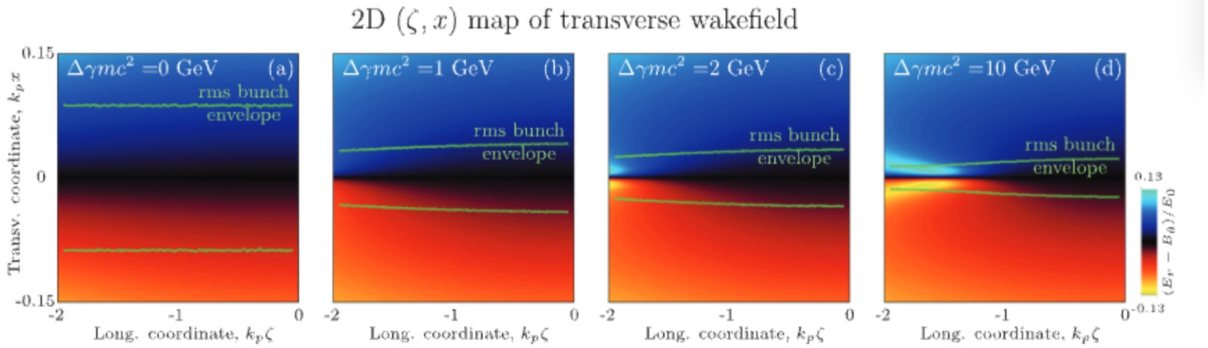
$$\sigma_y = k_p^{-\frac{1}{2}} \left(\frac{2\epsilon_{n,y}^2}{\gamma_b} \right)^{1/4}$$

- Assuming ion are stationary and full blow-out



- Electron motion due to partial blow-out
- Ion motion due to increase of charge density

Longitudinal tailored matched beam can be produced as witness stays in plasma



[C. Benedetti et al. Physics of Plasmas **28**, 053102 (2021)]

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LPA Applications

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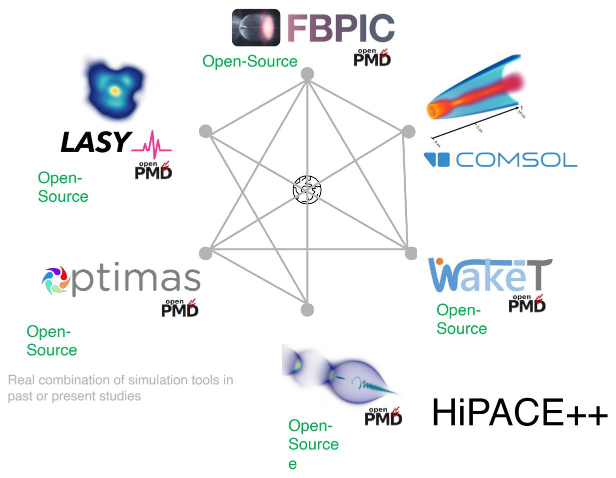
Conclusion

- With **realistic s2e 3D simulations** we demonstrate in-plasma staging
- **3.5 GeV gain** from second HOFI LPA stage with **capturing ratio of 100%**
- **Beam loaded, emittance preserved** in most of the beam
- **Compatible with strong ion motion** and adiabatic matching



Perspectives

- Main challenges are **head erosion and laser coupling**
- **Later stages are easier**, even with strong ion motion
- Still working on laser coupling, emittance preservation, etc.
- Being wrapped up for publication, to be submitted next weeks.