EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

WP8 - Overview of activities and contributions to TDR

Jorge Vieira (IST), Henri Vicenti (CEA)

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

Work-package status

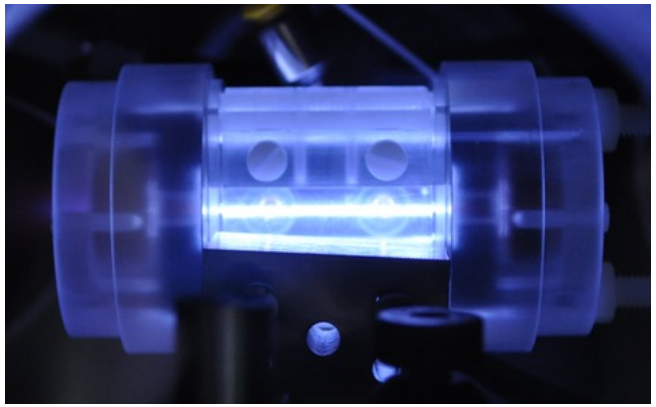
Deliverables

- D8.1 – Report on structures to be funded from national/bilateral/european level for simulation & theory (M12)
- D8.2 – Report on results achieved in the field of theory and simulations (M24)
- D8.3 – Report on status of EuPRAXIA simulated performances (M46)

Milestones

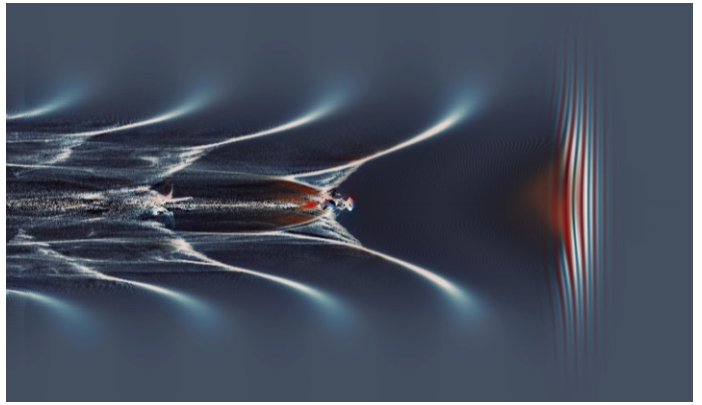
- Update of concepts for EuPRAXIA, systems status report (M24)

Overview



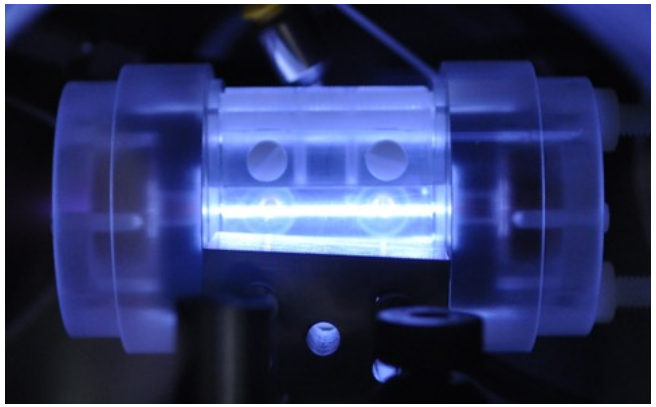
Plasma source modelling
Ionization physics
Heat balance

Laser modelling
Accurate physical fields
Realistic profiles



LWFA modelling
Realistic simulations
Ideal predictions

Overview



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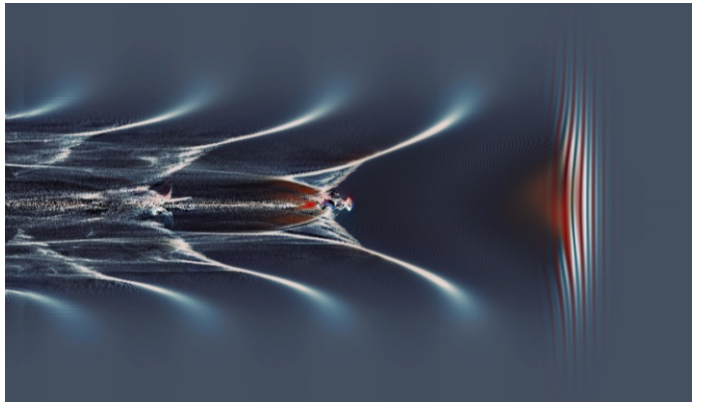


LWFA modelling
Realistic simulations
Ideal predictions

Capillary Heat Balance in High Repetition Rate Regime

Funded by the European Union

Typical parameters for the LUIS – L2 DUHA project (ELI-Beamlines)

- Capillary length, L = 2 cm;
- The capillary cross section, 300×300 μm;
- The capillary external diameter, $2R_0$ = 1 cm;
- Capillary material: sapphire;
- Filling gas: hydrogen
- Energy of the laser pulse, $\mathcal{E}_l = 3$ J;
- Repetition rate, f = 20 Hz;
- Part of this energy deposited in the form of the wake (plasma waves), η = 0.5;
- Electron density, $n_e = 2 \times 10^{18}$ cm^{-3};

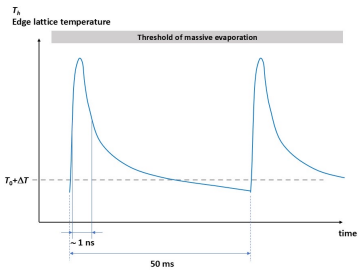
Main assumption: Almost all energy deposited in the form of plasma waves is transferred to the capillary wall in the form of hot electrons (~ 3 keV)

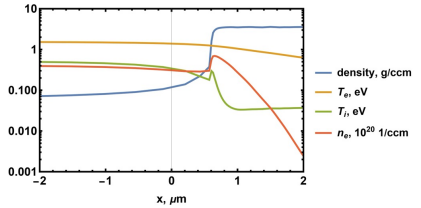
Then, the energy deposited due to the discharge is less by the order of magnitude and can be neglected.

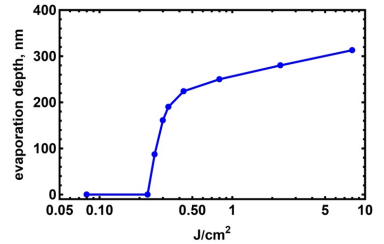
Averaged heat balance $$\Delta T = \frac{\mathcal{E}_l \eta f}{2\pi\kappa(T_0)L} \ln\frac{R_0}{R_{in}} \approx 30°\text{C}$$ acceptable

P. Sasorov et al., JLA (submitted) (2025)

1D HD simulations of the internal capillary wall edge







Under these conditions and assumptions,

- the energy deposited to the internal wall of the capillary per shot in higher than the threshold for massive evaporation, and
- A few 100s nm of the wall evaporates per each shot.

Jorge Vieira and Henri Vicenti, WP8

HOFI channel modelling
Strong field ionization in PIC simulations

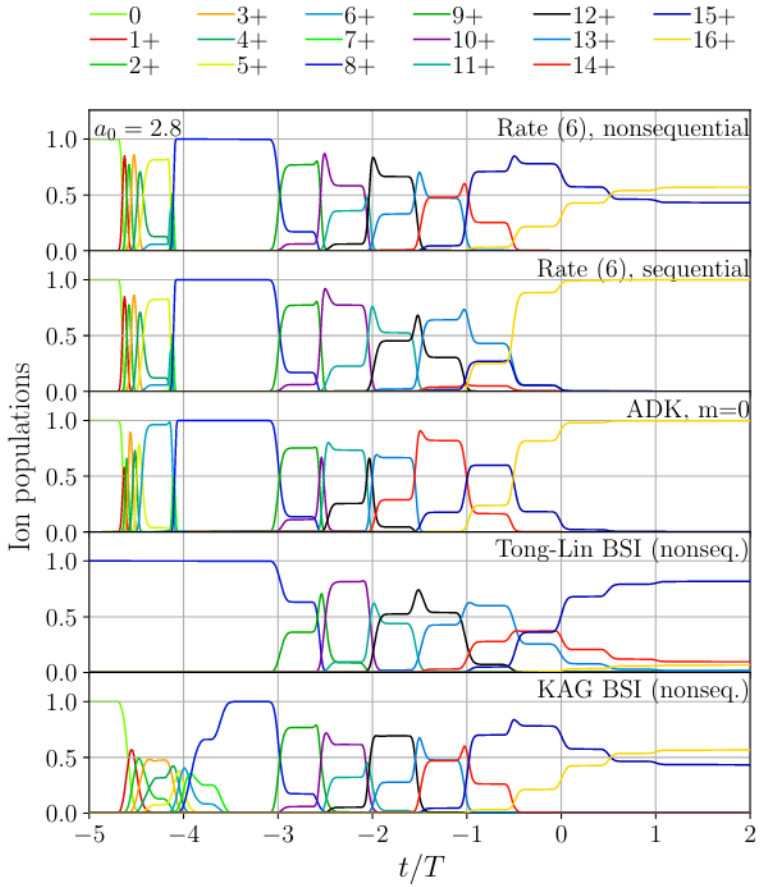
Funded by the European Union

Implementation of strong field ionization in PIC codes

- **Barrier Suppression Ionization**
- **Non sequential ionization pathway**
- **Non zero magnetic quantum number**

Several models have been proposed and Implemented in **Smilei.**

For nitrogen ions, taking into account several Different **ionization pathways** might be necessary (WIP).



A. Mironov et al.,
Strong-field ionization in particle-in-cell simulations
Phys. Rev. E, Sep. 2025.

Sequential PIC-HD-PIC simulations of HOFI channels formation

Funded by the European Union

Investigations on how to best describe HOFI channel formation is underway (PACRI WP3.1).
Preliminary work with a sequential workflow :

1 – PIC simulation to describe the initial ionization state (~ ps).
2 – Hydrodynamic simulation to compute the hot plasma expansion into a channel. (~ns)
3 – PIC simulation to evaluate laser guiding inside the channel (~ps)

Proof of concept has been achieved. The process needs to be benchmarked and optimized.

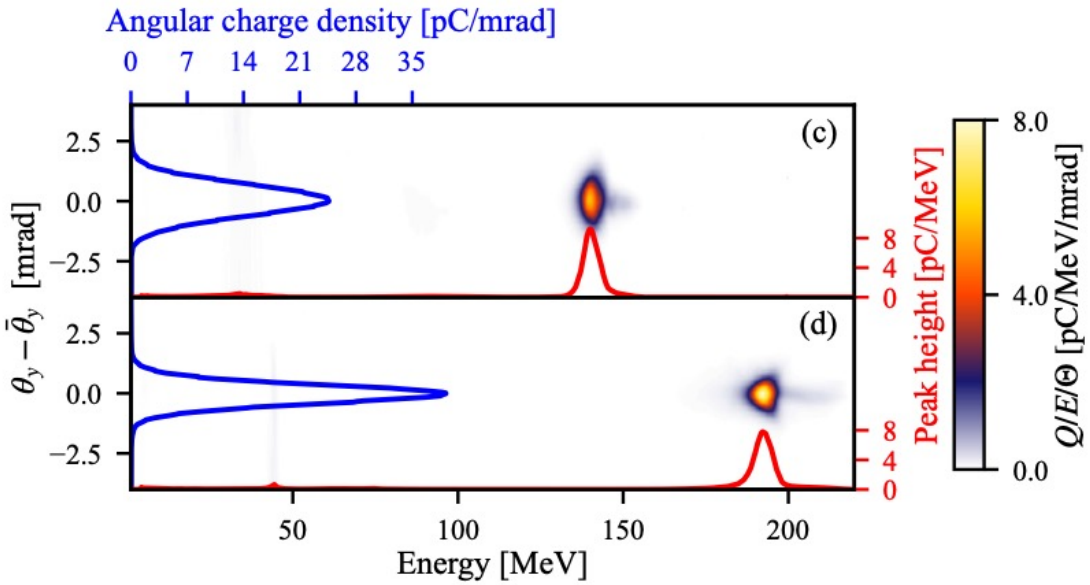
High quality electron beams obtained through plasma-based beam shaping at gas cell exit

Funded by the European Union

https://arxiv.org/pdf/2506.18047

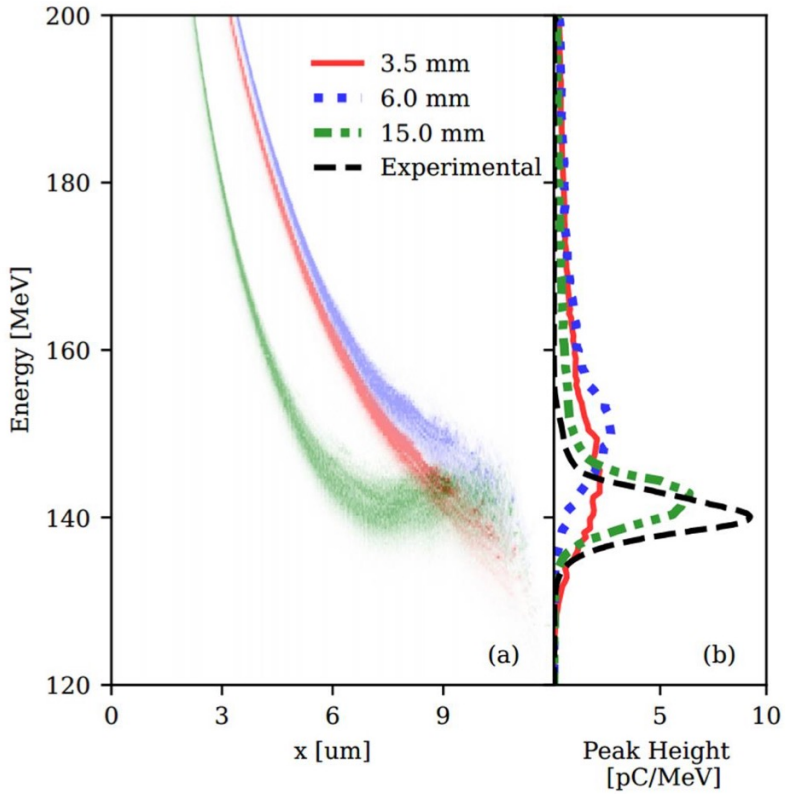
Best beam parameters

- Q = 40 pC
- E = 193 MeV, ΔE/E < 3%
- Divergence = 0.5 mrad



T. L. Steyn et al.,
Invited presentation at EAAC2025

Comparison between simulation and experiment



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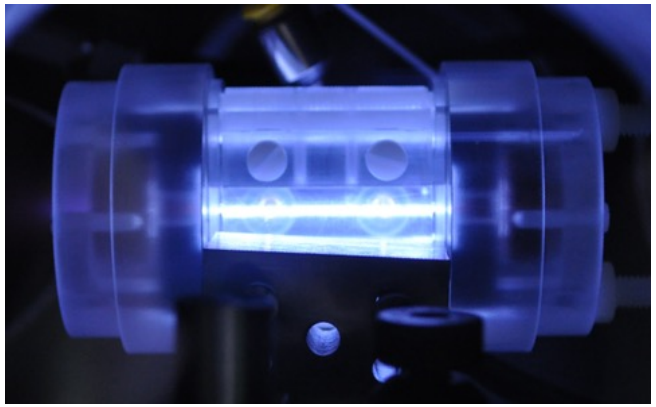

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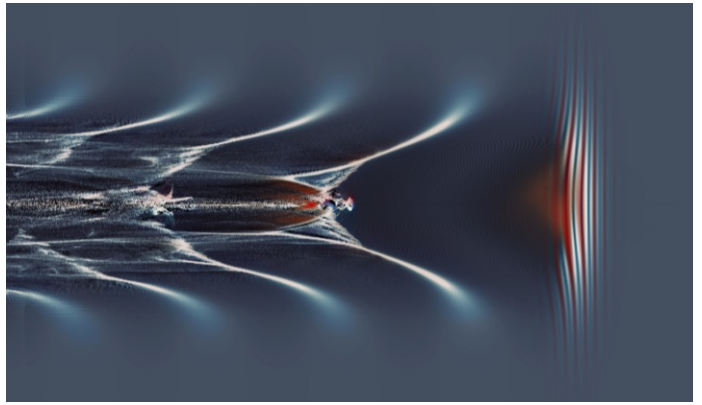
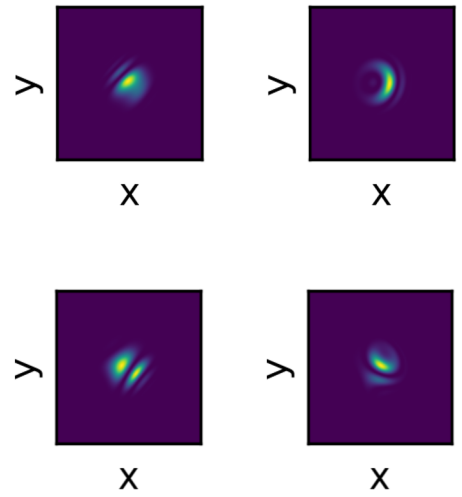


LWFA modelling
High quality e- acceleration
Surrogate, reduced, and full models

Realistic laser models

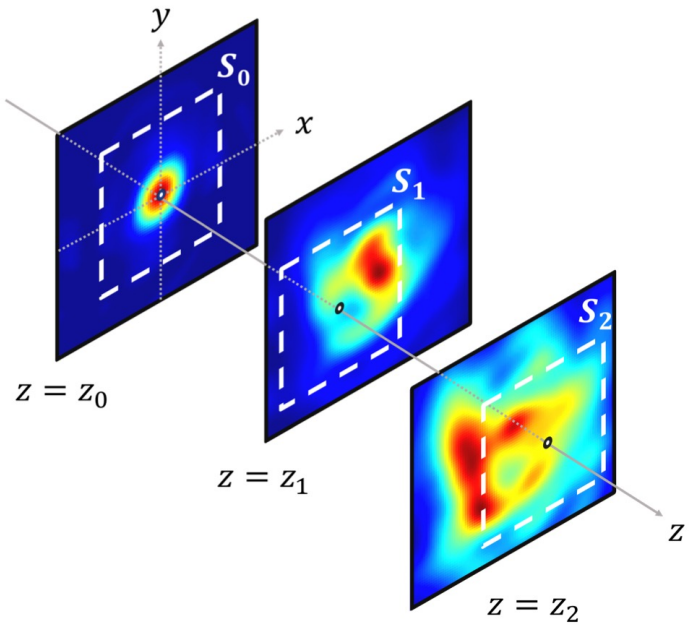
Funded by the European Union

Simulate the effect of non-ideal laser profiles



Using the LASY library and the Particle-In-Cell code WarpX to simulate non-ideal laser profiles shaped by a deformable mirror. We plan to study how the **pulse shape affects Laser Wakefield acceleration**.

Laser field reconstruction algorithm

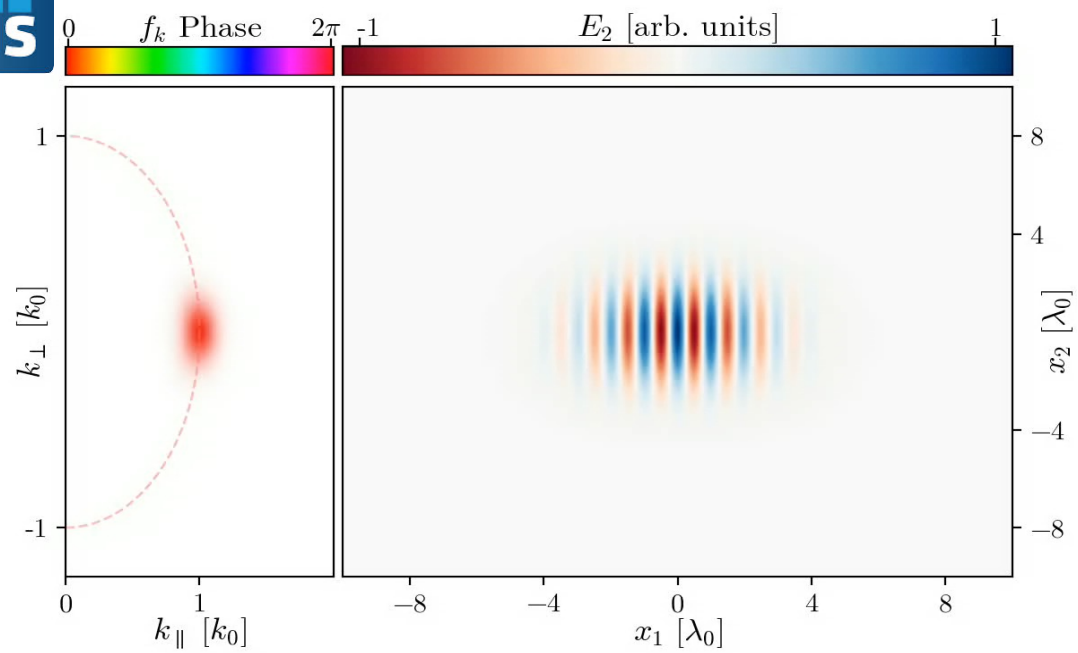


I. Moulanier et al.,
J. Opt. Soc. Am. B 40(9), 2450-2461 (2023)

Realistic laser models

Funded by the European Union

Plane wave expansions

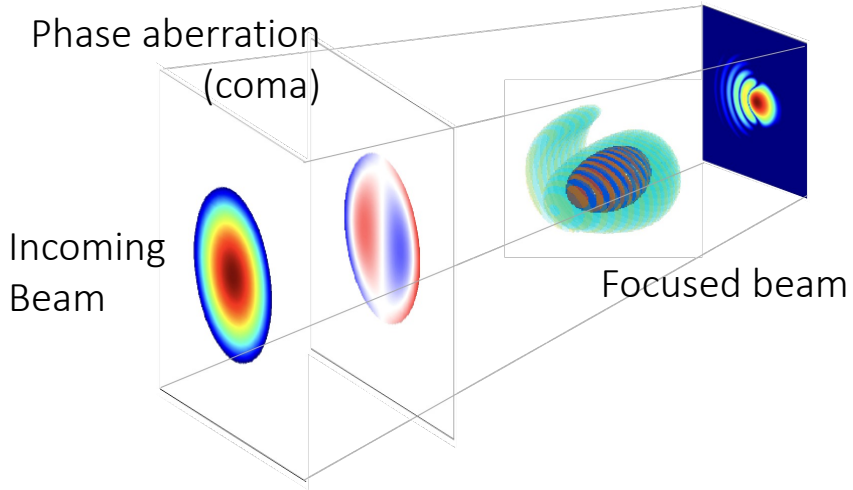


Arbitrary control over pulse shape :

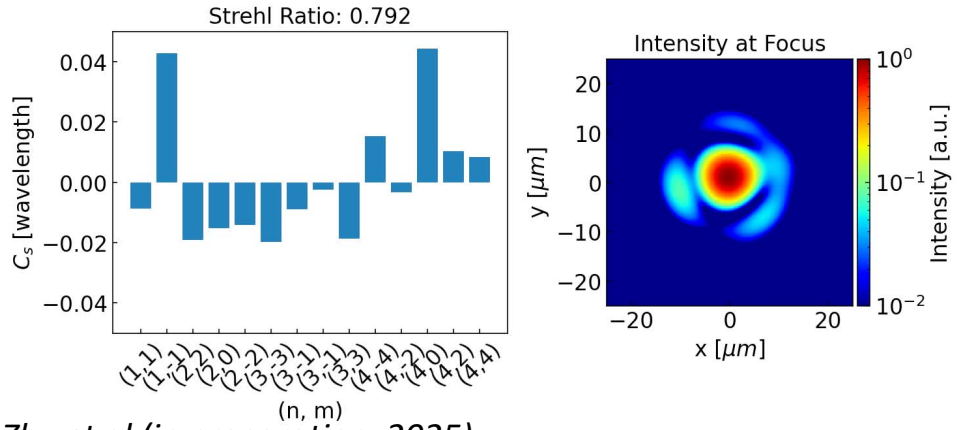
- Frequency
- Transverse size
- Longitudinal size
- Injection position
- Transverse profile

R. Almeida et al (in preparation, 2025)

Zernike polynomial decomposition

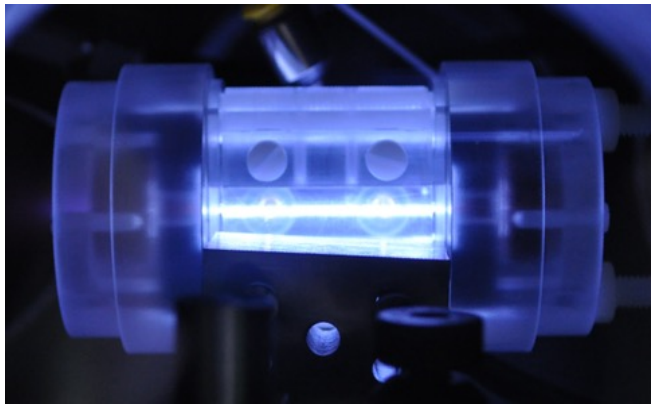


Halo and asymmetry



X. Zhu et al (in preparation, 2025)

Overview



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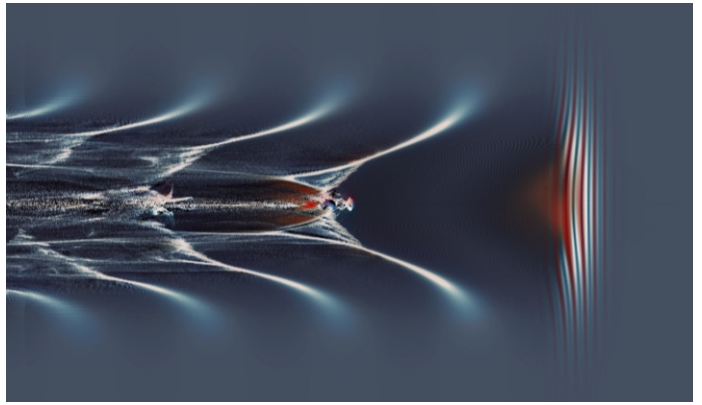
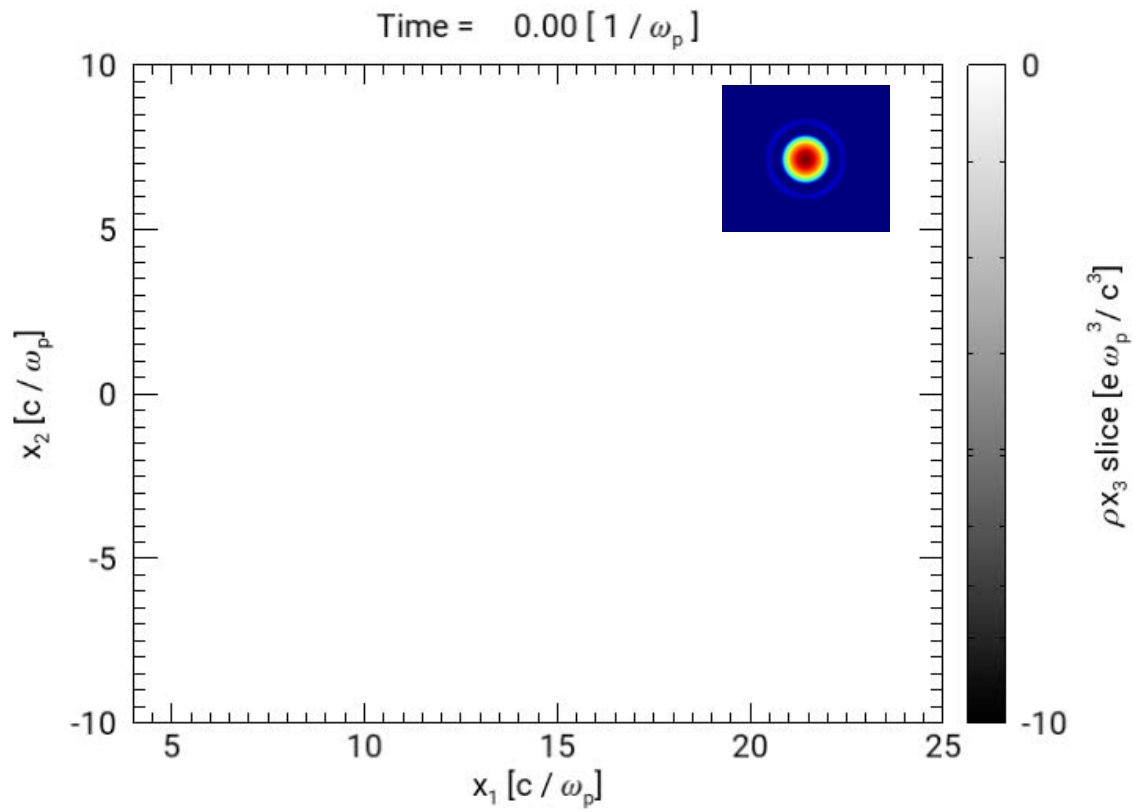


LWFA modelling
Influence of realistic models
Surrogate, reduced and full models of high quality e- acceleration

Aberrations influence laser-plasma interactions

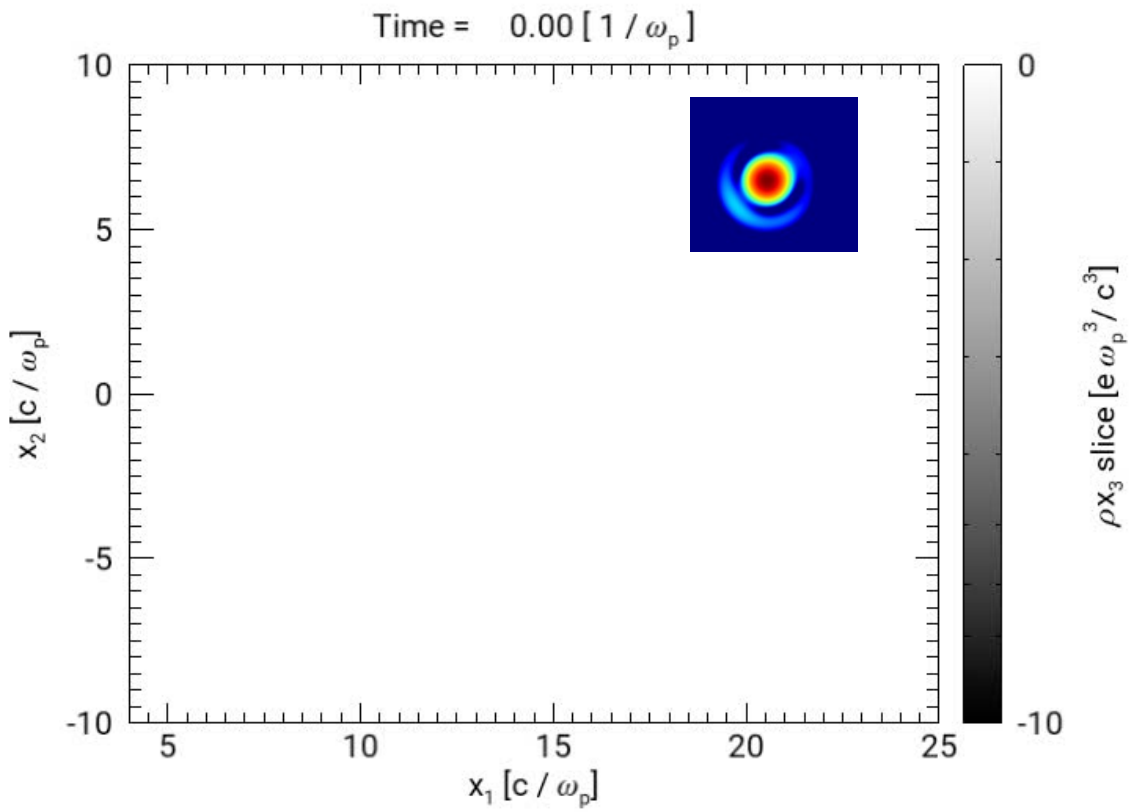
Funded by the European Union

No phase aberrations (Strehl ratio=1.0)



X. Zhu et al (in preparation, 2025)

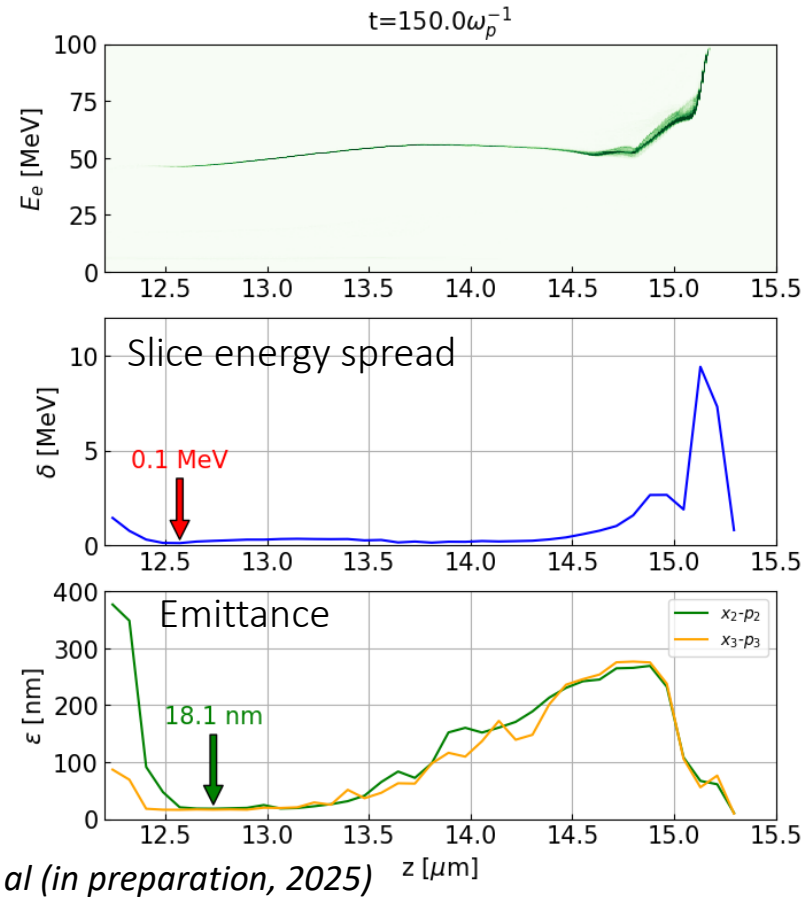
With phase aberrations (Strehl ratio = 0.86)



Aberrations can degrade beam emittance

Funded by the European Union

No phase aberrations (Strehl ratio=1.0)



X. Zhu et al (in preparation, 2025)

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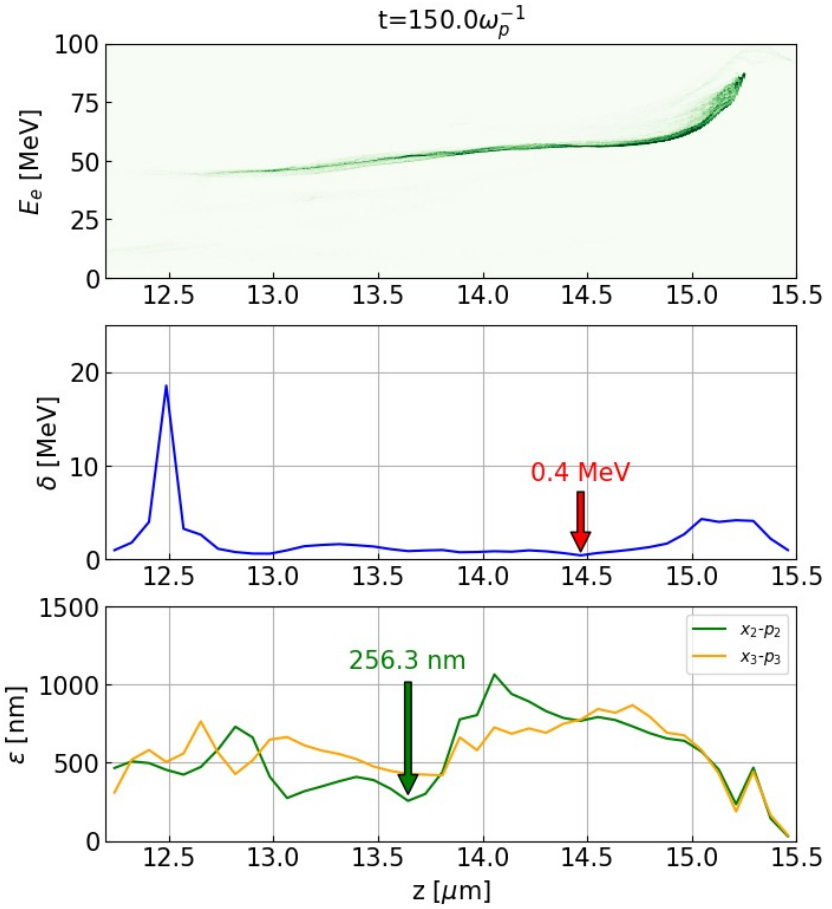
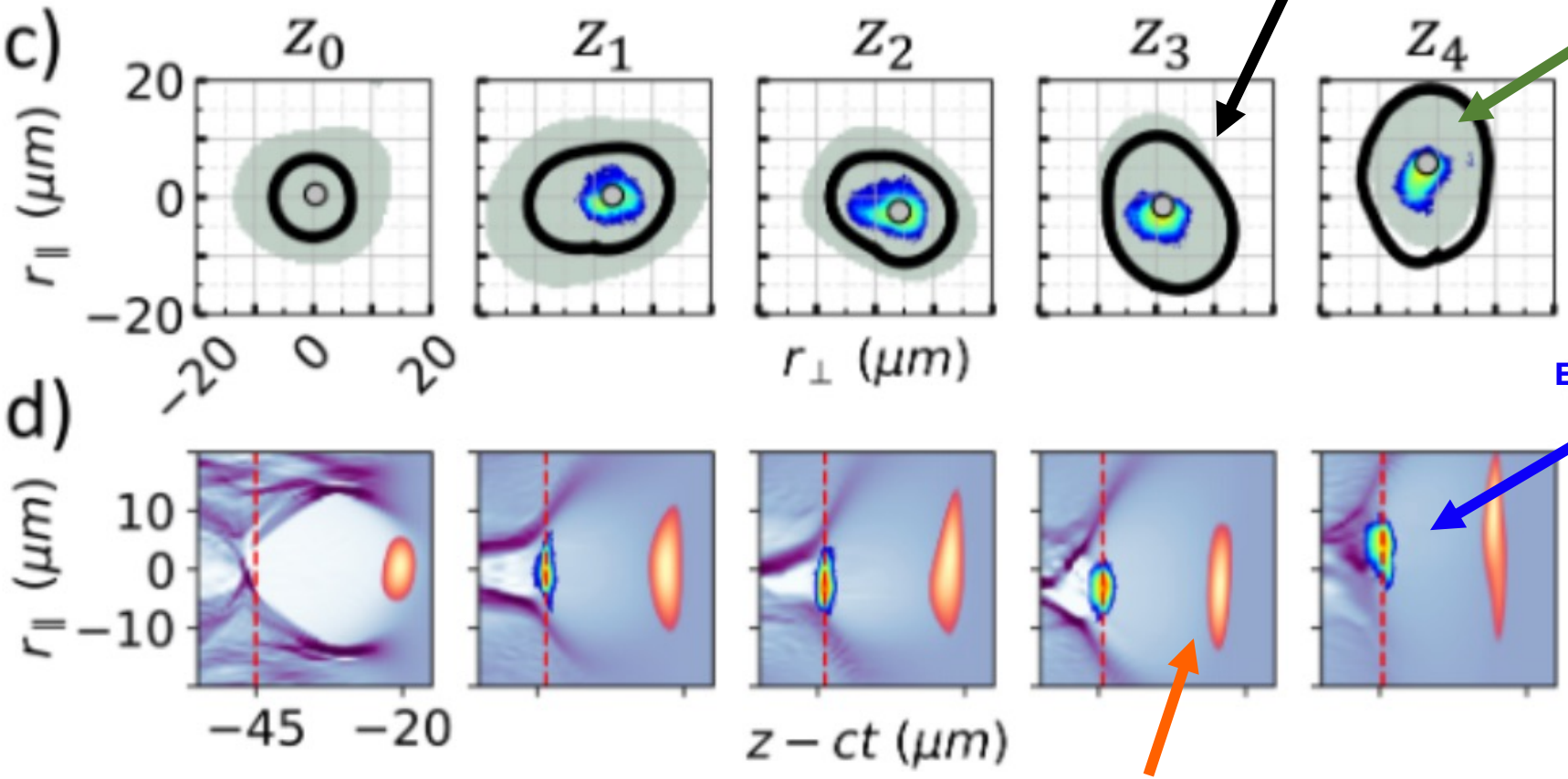


Reconstructed laser fields allow to study the effects of realistic laser energy distributions in LWFA

Funded by the European Union

Transverse planes



I. Moulanier et al., EAAC2023 Proceedings
https://hal.science/hal-04727699

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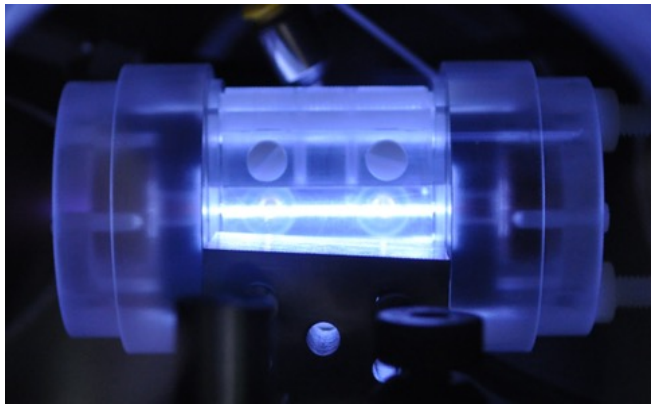

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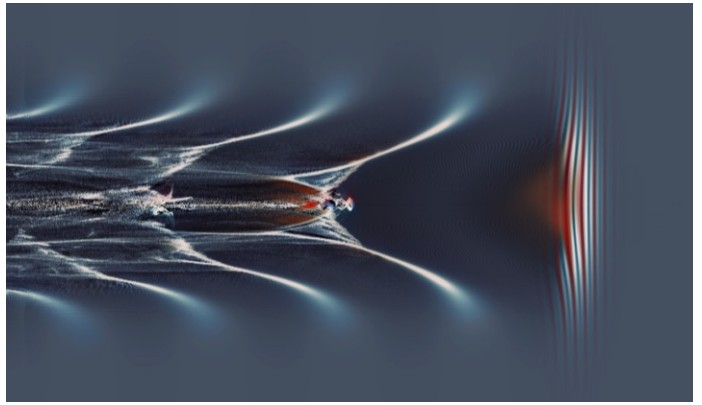
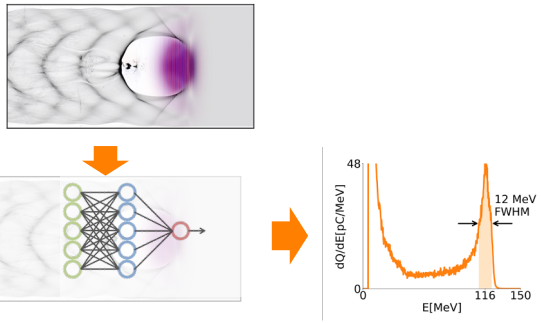


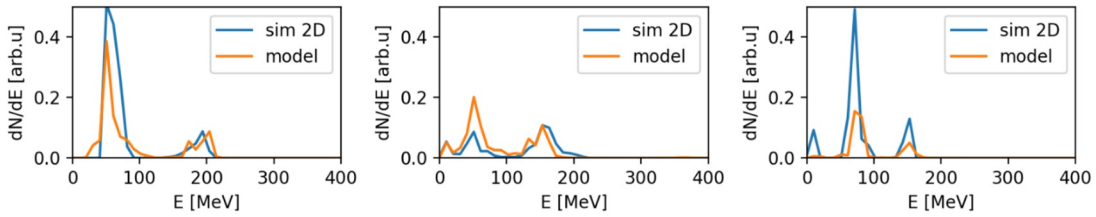
LWFA modelling
Influence of realistic models
Surrogate, reduced and full models of high quality e- acceleration

Machine learning for LWFAs

Funded by the European Union

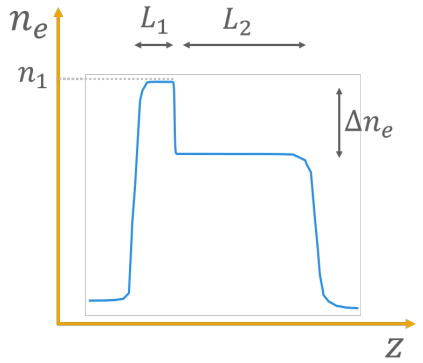
Train a surrogate model on LWFA data

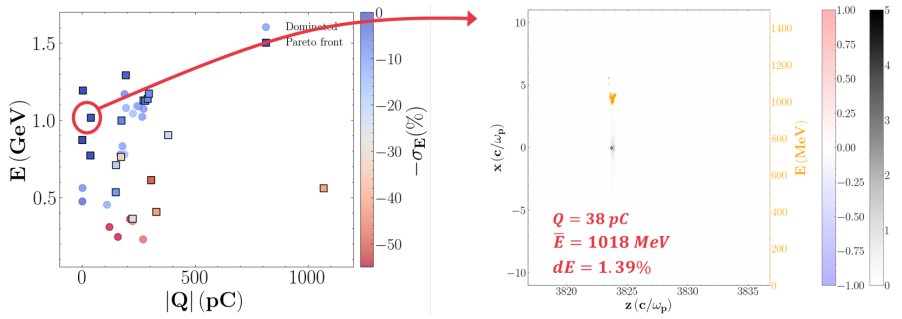




Developing solutions to train **surrogate models** of laser-driven electron accelerators using numerical and experimental data. A campaign to collect data on our 100TW laser UHI100 is foreseen in late 2025.

Machine learning optimisation for high quality electron acceleration





Optimised:

- plasma profile
- selection of laser parameters.

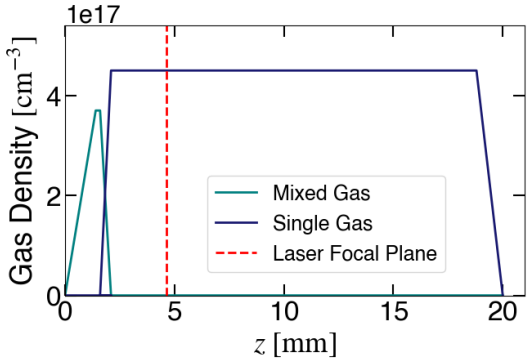
Jorge Vieira and Henri Vicenti, WP8

Ionisation injection LWFA driven by a 20 J laser
Reduced and full PIC benchmarks

Funded by the European Union

Optimisation + benchmark towards LWFA driven FEL at EPAC

- Setup: Ionization-injection injector + accelerator driven by **20 J Laser (EPAC)**
- Reduced model machine-learning optimization (FBPIC)
- Full PIC benchmark in 3D (Osiris)



	FBPIC	OSIRIS (a_0 = 2.234)	OSIRIS (a_0 = 2.3)
Cell size (longitudinal x transverse)	30 nm x 0.8um	25.4 nm x 0.8 um	25.4 nm x 0.8 um
Mean energy	0.99 GeV	0.97 GeV	0.96 GeV
Energy spread (rms)	0.6%	0.9%	1.0%
Emittance	4.2 / 1.4 [π mm mrad]	4.38 / 1.46 [π mm mrad]	4.72 / 1.92 [π mm mrad]
Charge	25 pC	28.8 pC	50.4 pC

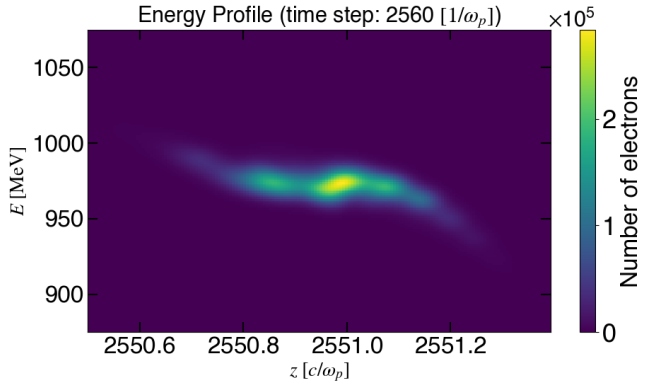
O. Finlay, B. Thakur et al (in preparation, 2025)

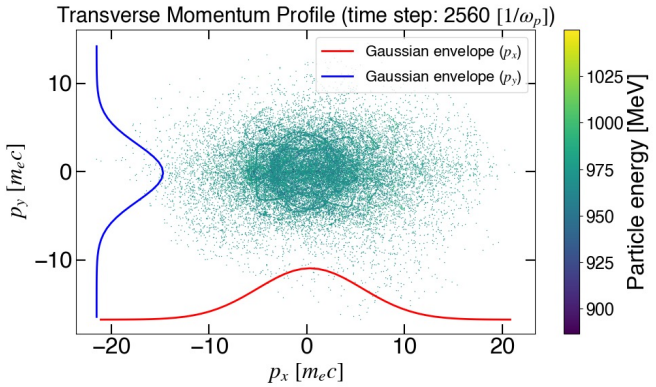
Ionisation injection LWFA driven by a 20 J Laser
High-quality e- generation and radiation

Funded by the European Union

Optimized ionization injection

Beam Parameters	Values
Mean energy	0.97 [GeV]
Energy spread	0.9%
Divergence (x/y)	2.83 / 1.70 [mrad]
Emittance (x/y)	4.38 / 1.46 [mm mrad]
Charge	28.8 [pC]
Longitudinal size	2.23 [μm]
Transverse size (x/y)	7.93 / 4.55 [μm]
Betatron critical energy	11.2 keV

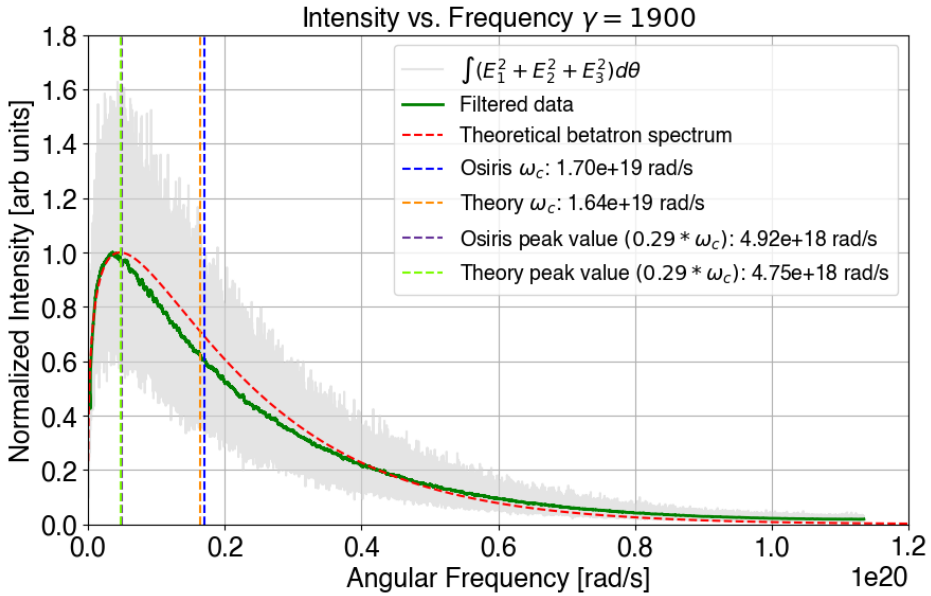




O. Finlay, B. Thakur et al (in preparation, 2025)

Betatron radiation

RaDiO Radiation Diagnostic for QSIRIS

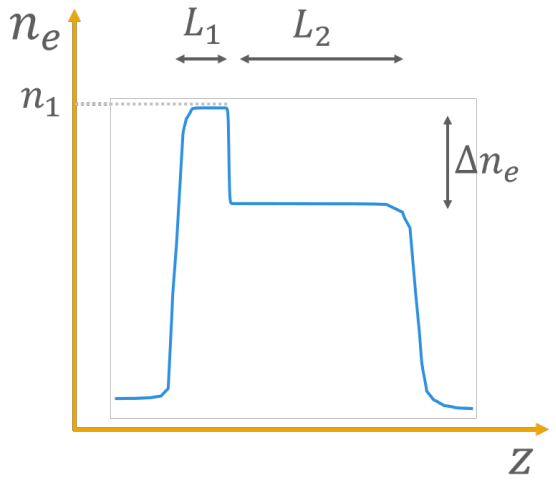


LWFA down-ramp injection with 5 J laser 1% energy spread and >10 mm mrad emittance

Funded by the European Union

Input laser and plasma parameters

Parameters relevant for ELI-EuPRAXIA Site 2



Variable Parameters
- L_1 - 1st plateau length
- L_2 - 2nd plateau length
- n_1 - 1st plateau electron plasma density
- Δn - density step

} Density Profile

D. Lemos, et al (in preparation, 2025)

Optimization results

Parameter	Value (→ FWHM mask)
Charge	38.58 pC → 35.38 pC
Energy	1017.28 MeV → 1017.04 MeV
Energy Spread (RMS/mean)	1.39% → 1.10%
Size RMS in x direction	4.93 μm → 4.98 μm
Size RMS in y direction	5.47 μm → 5.56 μm
Size RMS in z direction	1.28 fs → 1.22 fs
Divergence in x direction	2.43 mrad → 2.48 mrad
Divergence in y direction	2.77 mrad → 2.83 mrad
Emittance in x direction	0.0060 μm → 0.0061 μm
Emittance in y direction	0.0074 μm → 0.0076 μm
Normalized Emittance in x direction	11.99 μm → 12.18 μm
Normalized Emittance in y direction	14.67 μm → 15.12 μm
Gamma Twiss in x direction	982.21 m^{-1} → 1005.72 m^{-1}
Gamma Twiss in y direction	1036.19 m^{-1} → 1050.16 m^{-1}

Plasma

$L_1 \sim 113\ \mu m$ $\quad n_1 = 1.8 \times 10^{18} cm^{-3}$

$L_2 \sim 3.78\ mm$ $\quad \Delta n = 0.2 \times 10^{18} cm^{-3}$

Laser

$a_0 = 1.58$ $\quad z_f = 1.89\ mm$ $\quad E_0 = 5J$

$w_0 = 38\ \mu m$ $\quad \tau_{FWHM} = 42\ fs$ $\quad \lambda_0 = 800\ nm$

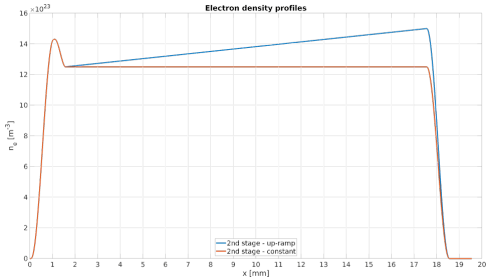
High quality electron acceleration in LWFA

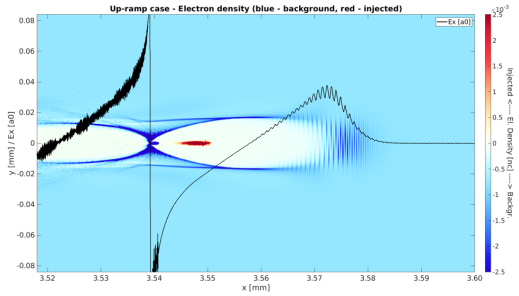
Funded by the European Union

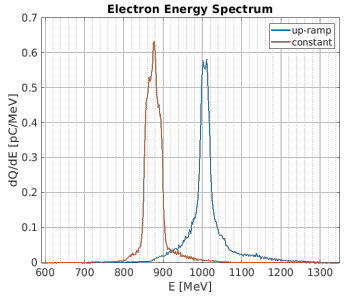
1 GeV electron beam with low energy spread and emittance.
Constant profile and up-ramp in the 2nd stage.

Input laser and plasma parameters

Gas mix 1st stage	$n_{e,1}$,max (cm^{-3})	$n_{e,2}$,start (cm^{-3})	$n_{e,2}$,end (cm^{-3})	λ (μm)	a_o	w_o (μm)	τ (fs)	E (J)
95% He + 5% N_2	1.43×10^{18}	1.25×10^{18}	1.50×10^{18}	0.82	2.72	20	35	3.3







Slide made by M. Matys et. al, ELI Beamlines (CZE)
Collaboration with IST (PT), CNRS (FR) EPAC (UK)

PIC simulation results

El. Beam Parameter	2nd stage – up-ramp	2nd stage – constant
E_{mean} (MeV)	1012.3	878.48
Q_{Total} (pC)	28.412	28.395
$\varepsilon_{n,y}$ (mm·mrad)	1.978	2.265
$\varepsilon_{n,z}$ (mm·mrad)	1.202	1.293
ΔE/E (%)	2.848	5.187
Q_{FWHM} (pC)	13.912	22.389

Summary and conclusions

Overview of activities

- Development of machine-learning-based surrogate models for fast LWFA predictions
- A suite of laser injection algorithms is now available for realistic laser modelling
- Ionization physics and heat exchange physics is being investigated to assist plasma source design

Main contributions to TDR:

- Design of high quality LWFA-based electron injector
- Tolerance studies support
- High accuracy simulations including measured laser pulses
- Collaborative proposals to obtain the required supercomputing resources

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Discussion

- % level energy spread and low emittance are possible (ideal simulations) with 20 J lasers (EPAC)
- Requirements for lasing with 1 GeV electrons have not yet been demonstrated for 5J lasers (ELI)
- Experiments demonstrated lasing in the UV using 0.5 GeV electrons