EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

WP8 – Theory and simulations
Final report

Jorge Vieira (IST), Henri Vincenti (CEA)

EuPRAXIA-PP final meeting

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

Work-package status

Funded by the European Union

Deliverables

D8.1	Report on structures to be funded from national, bilateral and european level for simulation & theory	*M12*	✓ **done**
D8.2	Report on results achieved in the field of theory and simulations	*M24*	✓ **done**
D8.3	Report on status of EuPRAXIA simulated performances	*M46*	✓ **done**

The work reported in D8.1 – D8.3 has produced journal articles, conference proceedings and presentations, with further publications in preparation.

Milestones

MS16 *M24* ✓ **done**

Update of concepts for EuPRAXIA, systems status report

All WP8 deliverables and milestones have been completed and submitted.

This talk summarises **past activities**, focuses on the **content of D8.3**, and closes with the **new developments** that followed it.

Contents

Funded by the European Union

- Overview of previous modeling activities
- Contents of deliverable 8.3
- Advance since last deliverable
- Conclusions

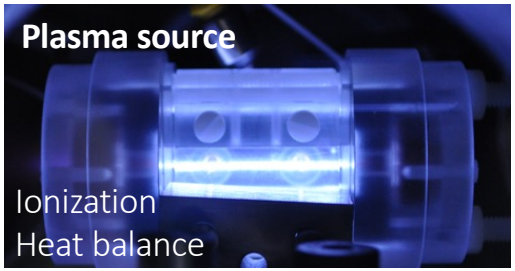
Contents

Funded by the European Union

- **Overview of previous modeling activities**
- **Contents of deliverable 8.3**
- **Advance since last deliverable**
- **Conclusions**

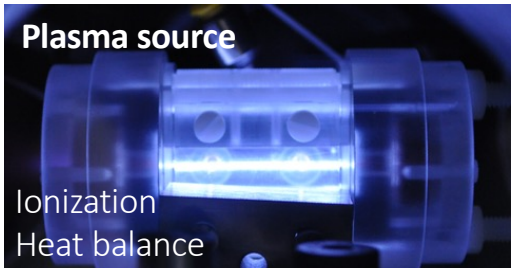
Status at the 2025 EuPRAXIA-PP annual meeting

Funded by the European Union



Status at the 2025 EuPRAXIA-PP annual meeting

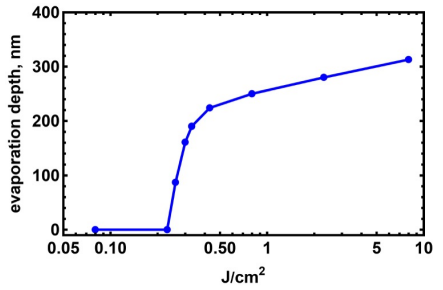
Funded by the European Union



Plasma source modelling

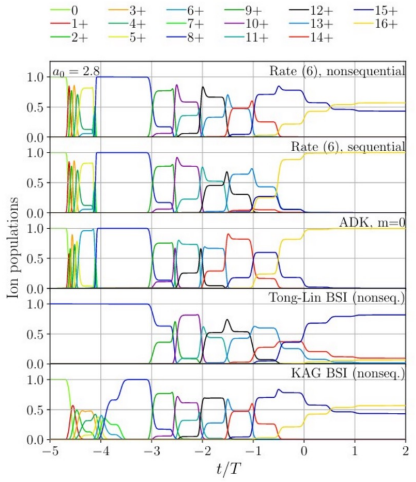
- **Capillary heat balance** at high repetition rate (LUIS – L2 DUHA, ELI-Beamlines): 3 J, 20 Hz, sapphire capillary
  - Average heating ΔT ≈ 30 °C — acceptable
  - A few 100 nm of the wall evaporate per shot

P. Sasorov et al., JLA (2025)



- **Strong-field ionization** models implemented and benchmarked in PIC codes
- **HOFI channel formation**: sequential PIC → hydrodynamic → PIC workflow, proof of concept achieved

· *A. Mironov et al., Phys. Rev. E (2025)*



Status at the 2025 EuPRAXIA-PP annual meeting

Funded by the European Union

Plasma source

Ionization
Heat balance

Laser

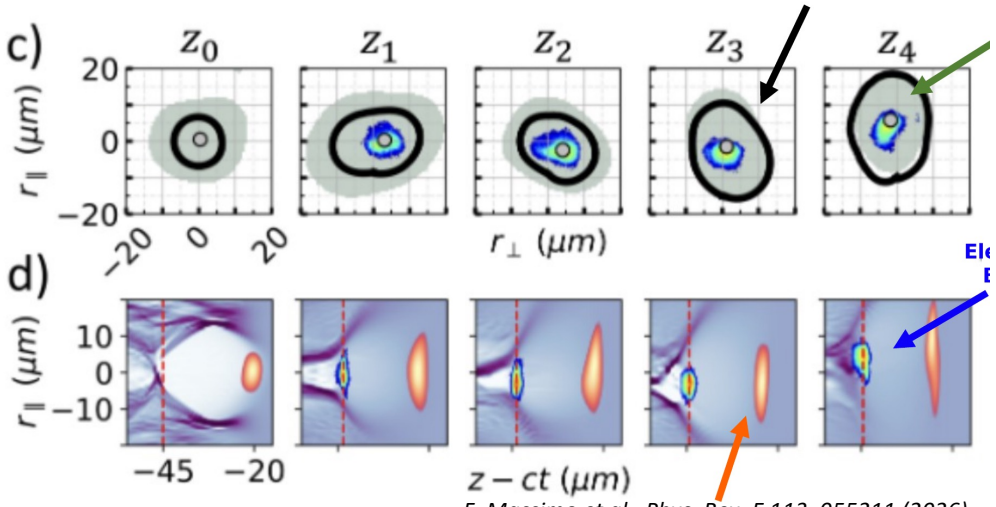
Accurate physical fields
Realistic profiles

LWFA

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

Laser modelling

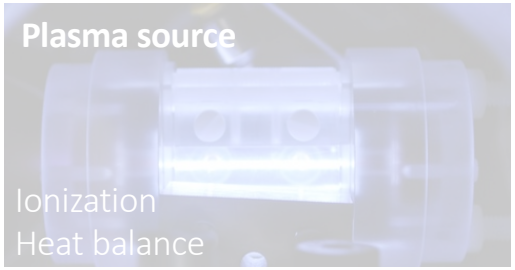
- **Laser-field reconstruction** (GSA-MD phase retrieval) for cylindrical geometry, released as open-source code
- **Realistic laser profiles** from LASY + WarpX and from a new 3D laser module in OSIRIS (near field + measured Zernike aberrations)
- **Arbitrary**, exact laser injection methods in PIC



F. Massimo et al., Phys. Rev. E 113, 055211 (2026)
I. Moulanier et al., Phys. Plasmas 33, 073105 (2026)

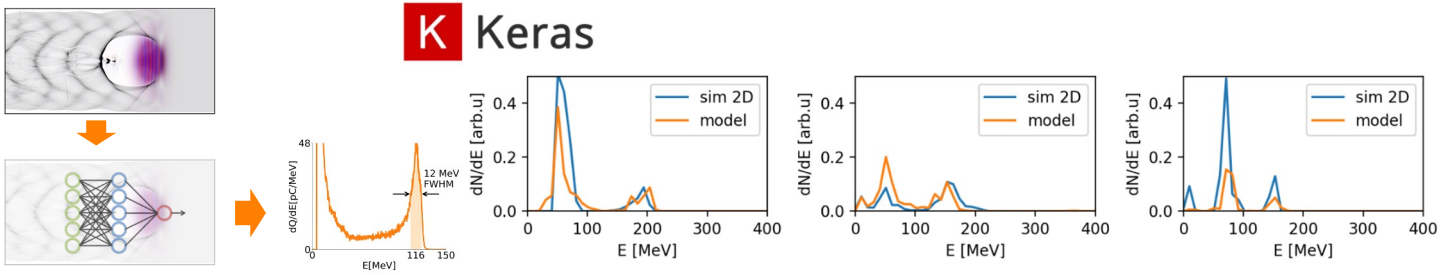
Status at the 2025 EuPRAXIA-PP annual meeting

Funded by the European Union



LWFA modelling

- Aberrations make the focus non-uniform and asymmetric, reshape the wake and **degrade the emittance**; energy and projected energy spread are less affected
- Surrogate models trained on numerical and experimental data
- Bayesian / ML optimisation of the plasma profile and of the laser parameters
- Plasma-based beam shaping at the gas-cell exit: Q = 40 pC, E = 193 MeV, ΔE/E < 3%, 0.5 mrad
- Ionisation-injection design for a 20 J driver, benchmarked reduced model vs full PIC



T. L. Steyn et al., EAAC2025 · O. Finlay, B. Thakur et al. (in preparation) · D. Lemos et al. (in preparation)

Contents

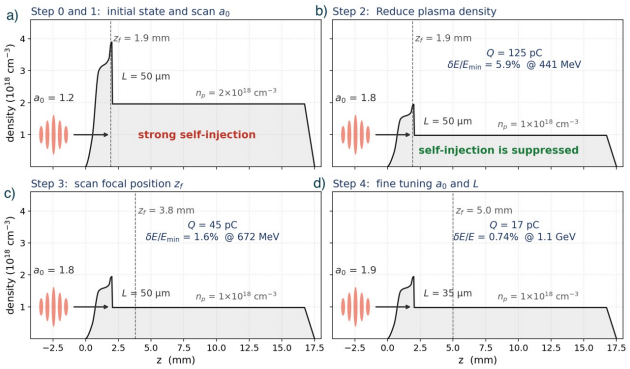
Funded by the European Union

- Overview of previous modeling activities
- **Contents of deliverable 8.3**
- Advance since last deliverable
- Conclusions

Contents of deliverable D8.3

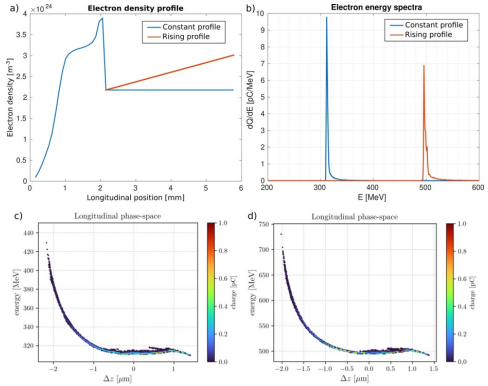
Funded by the European Union

Shock-injection



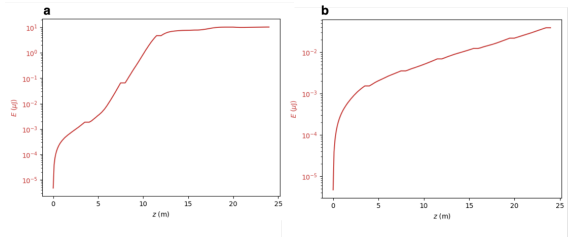
A physics informed recipe for high quality e- acceleration

High quality e- acceleration at ELI



Ionization-truncated and shock injection

Free-electron-laser simulations



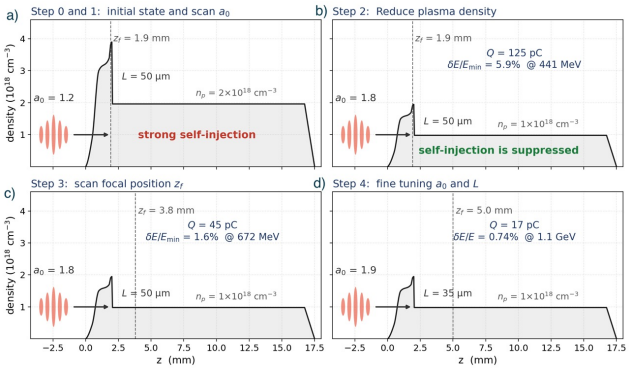
Assessing possible lasing with a 1 GeV LWFA beam

Contents of deliverable D8.3

Funded by the European Union

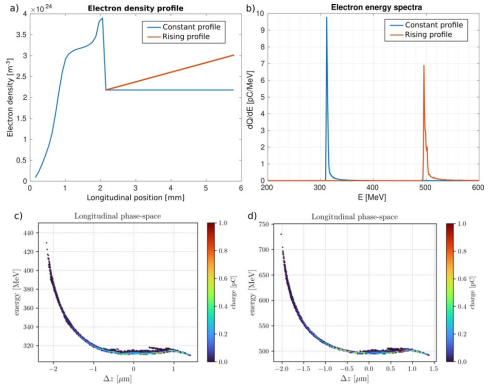
Work is relevant for Phase 0 (Goal: >300 MeV) **and Phase 1** (Goal: 1 GeV) **of EuPRAXIA@ELI implementation**

Shock-injection



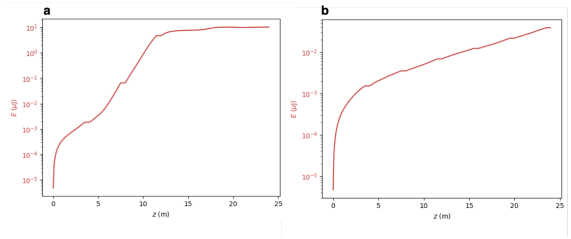
A physics informed recipe for high quality e- acceleration

High quality e- acceleration at ELI



Ionization-truncated and shock injection

Free-electron-laser simulations



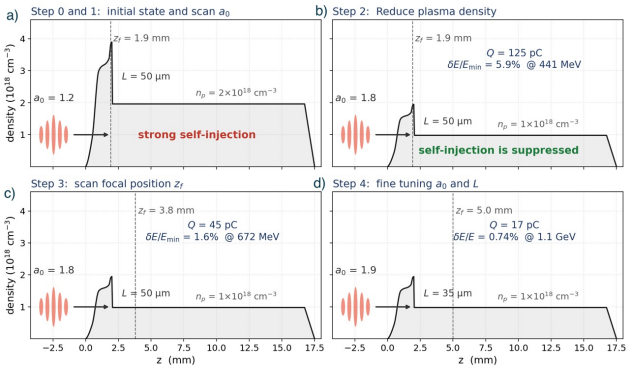
Assessing possible lasing with a 1 GeV LWFA beam

Contents of deliverable D8.3

Funded by the European Union

Work is relevant for Phase 0 (Goal: >300 MeV) **and Phase 1** (Goal: 1 GeV) **of EuPRAXIA@ELI implementation**

Shock-injection



A physics informed recipe for high quality e- acceleration

High quality e- acceleration at ELI

Ionization-truncated and shock injection

Free-electron-laser simulations

Assessing possible lasing with a 1 GeV LWFA beam

High-quality 1 GeV LWFA electrons

Funded by the European Union

Simulation parameters (Quasi-3D)

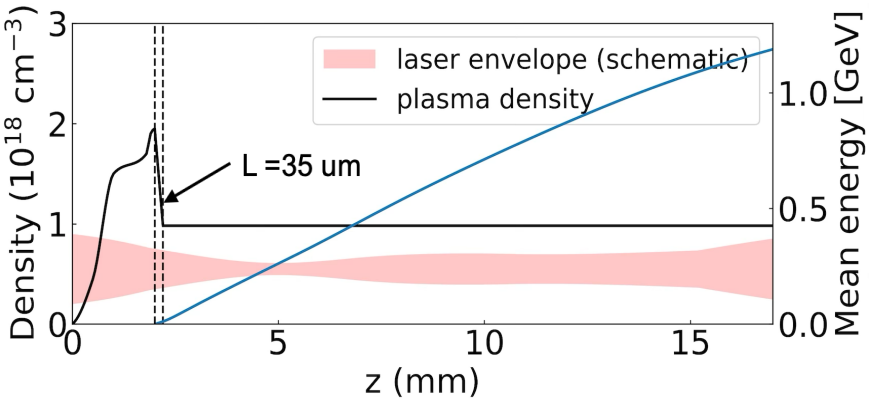
Laser: a_0 =1.9 (5J)

Wavelength: 800 nm, guassian profile

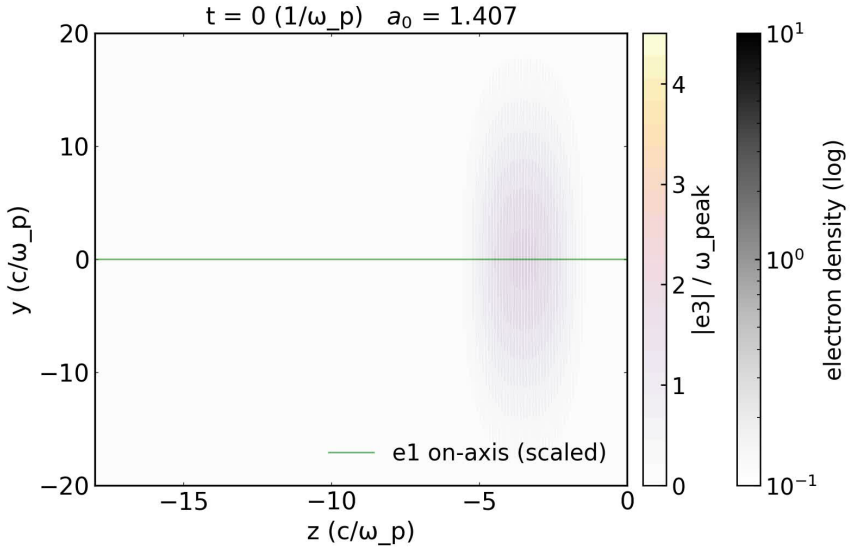
Waist size (FWHM in intensity): 42.47 μm

Duration (FWHM in intensity): 27.68 fs

Focal position zf: 5 mm



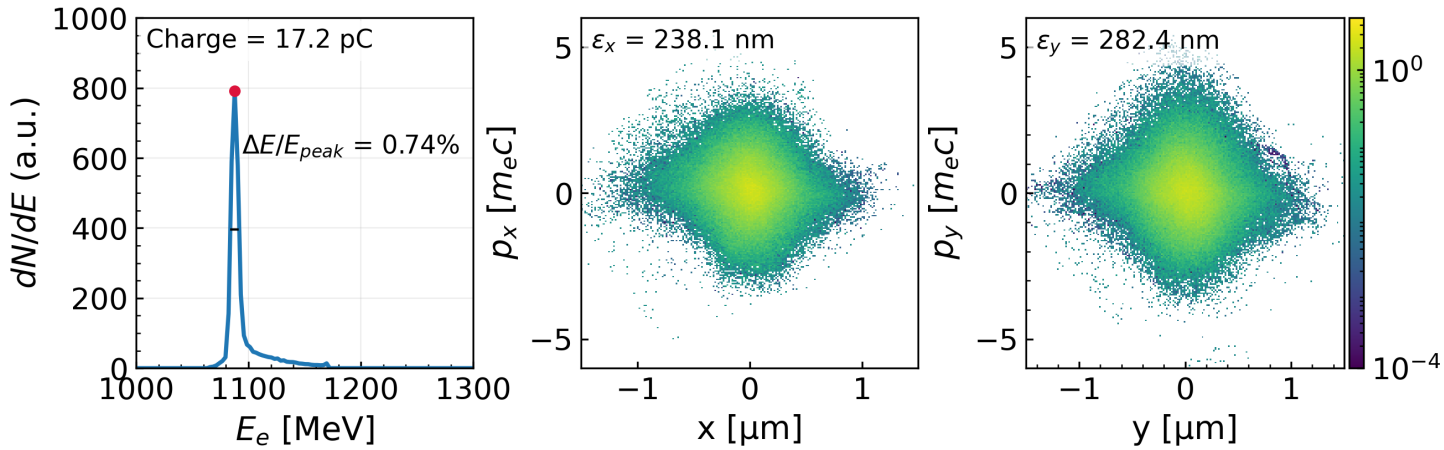
High-quality 1 GeV generation



An FEL-grade 1 GeV beam

Funded by the European Union

Quasi-3D OSIRIS simulation, 5 J driver



Beam parameters

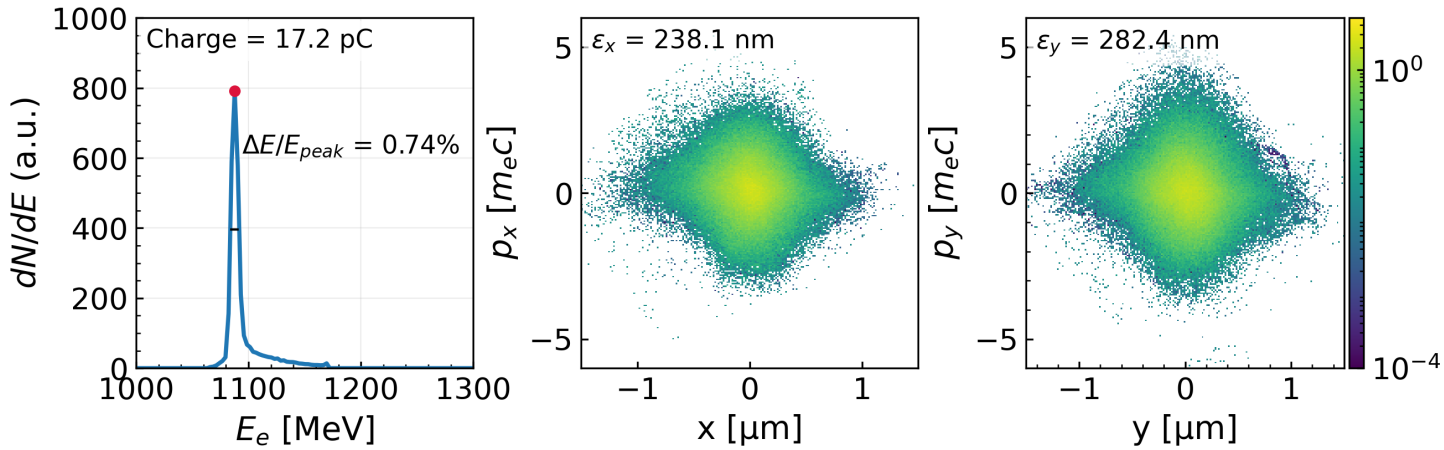
Mean energy	ΔE/E (FWHM)	Charge	Emittance	Slice ΔE/E
1.1 GeV	**0.74 %**	**17.2 pC**	**238 / 282 nm**	**0.1 – 0.4 %**

Jorge Vieira and Henri Vincenti, WP8

An FEL-grade 1 GeV beam

Funded by the European Union

Quasi-3D OSIRIS simulation, 5 J driver



The workflow scales from 500 MeV to 1 GeV and beyond — these parameters meet the requirements for driving a compact FEL.

Beam parameters

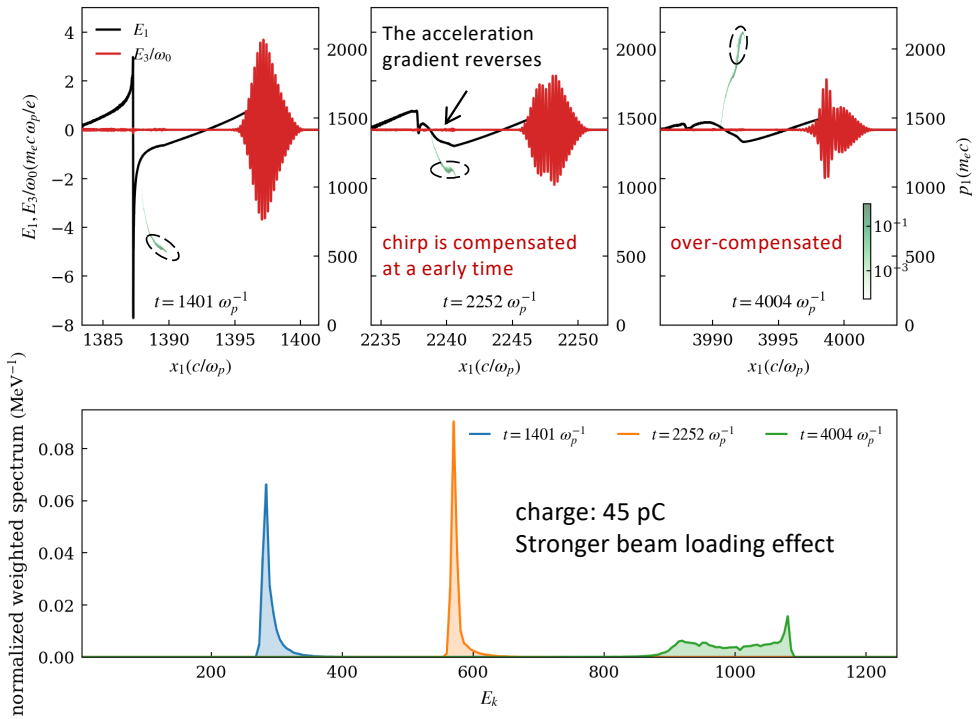
Mean energy	ΔE/E (FWHM)	Charge	Emittance	Slice ΔE/E
1.1 GeV	**0.74 %**	**17.2 pC**	**238 / 282 nm**	**0.1 – 0.4 %**

Jorge Vieira and Henri Vincenti, WP8

Goal: lower energy spread by chirp compensation

Funded by the European Union

Non-optimal parameters



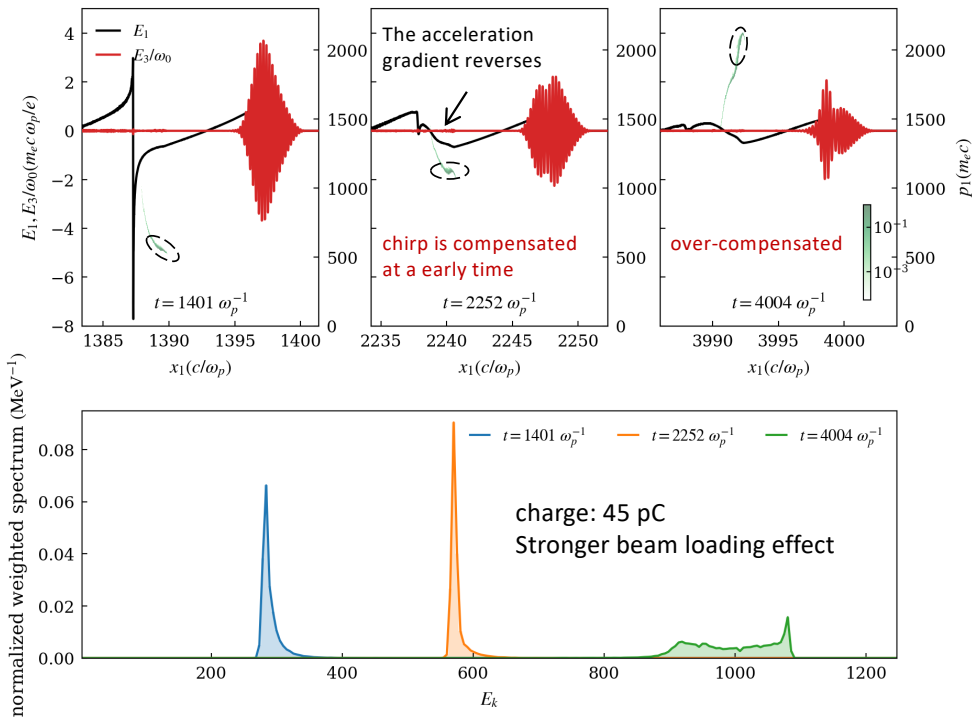
a_0 = 1.8, L=50 μm, z_f = 3.8 mm

X. Wu et al.

Goal: lower energy spread by chirp compensation

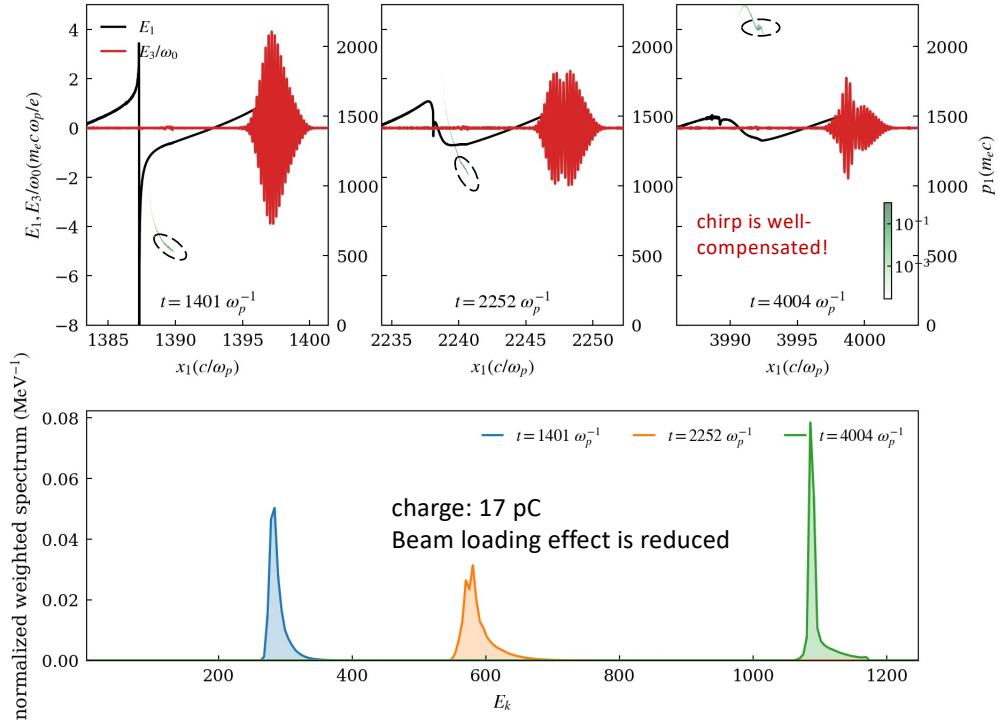
Funded by the European Union

Non-optimal parameters



a_0 = 1.8, L=50 μm, z_f = 3.8 mm

Optimal parameters



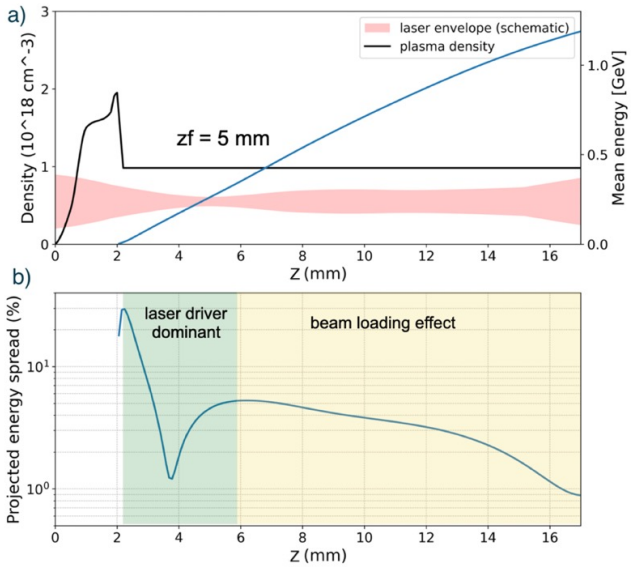
a_0 = 1.9, L=35 μm, z_f = 5.0 mm

X. Wu et al.

Shock injection: what sets the energy spread

Funded by the European Union

Laser evolution vs. beam loading



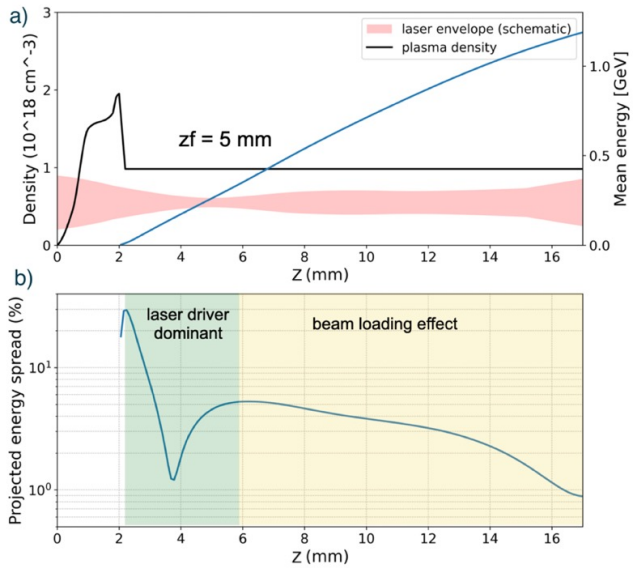
- Injection and early acceleration ⇒ **negative chirp**, energy spread grows
- As laser weakens, **beam loading flattens** field and compensates chirp
- Target: compensation must vanish exactly **at the final energy**

X. Wu et al.

Shock injection: what sets the energy spread

Funded by the European Union

Laser evolution vs. beam loading



- Injection and early acceleration ⇒ **negative chirp**, energy spread grows
- As laser weakens, **beam loading flattens** field and compensates chirp
- Target: compensation must vanish exactly **at the final energy**

X. Wu et al.

Four experimentally controllable ingredients

Reducing downramp length L:

Increases charge. If too short, injection is too high, excessive beam loading

Increase laser intensity a_0

Increases injected charge. Triggers self-injection if pushed too far.

Reduce plasma density n_p

Reduce self-focusing effects, suppresses self-injection

Effects of increasing focal position z_f

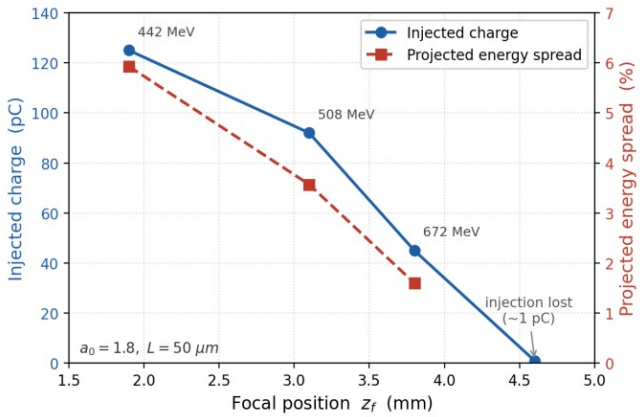
reduces injected charge and enhances driver intensity at later stages.
Chirp compensation at high energy but injection stops if pushed too far

Goal: suppress self-injection and compensate chirp

A recipe for high-quality electron beams

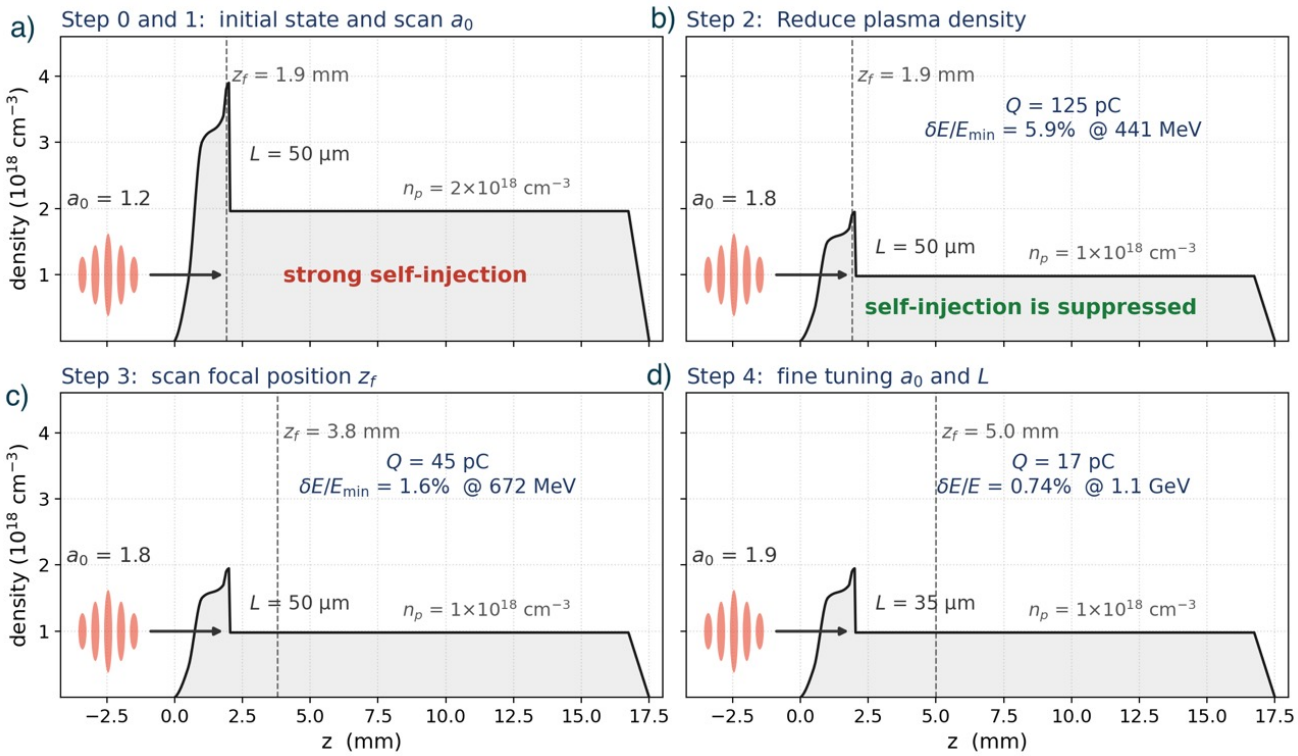
Funded by the European Union

Focal position scan



- **0–1.** Scan a_0 to find the self-injection threshold
- **2.** reduce n_p is self-injection persists
- **3.** Scan z_f — chirp compensated at higher energy
- **4.** Fine-tune a_0 and L to keep the charge low

The recipe, illustrated on a 1 GeV beam



X. Wu et al.

Jorge Vieira and Henri Vincenti, WP8

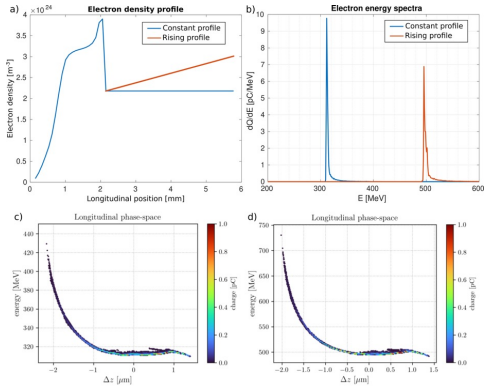
Contents of deliverable D8.3

Funded by the European Union

Shock-injection

A physics informed recipe for high quality e- acceleration

High quality e- acceleration at ELI



Shock injection and ionization truncated injection

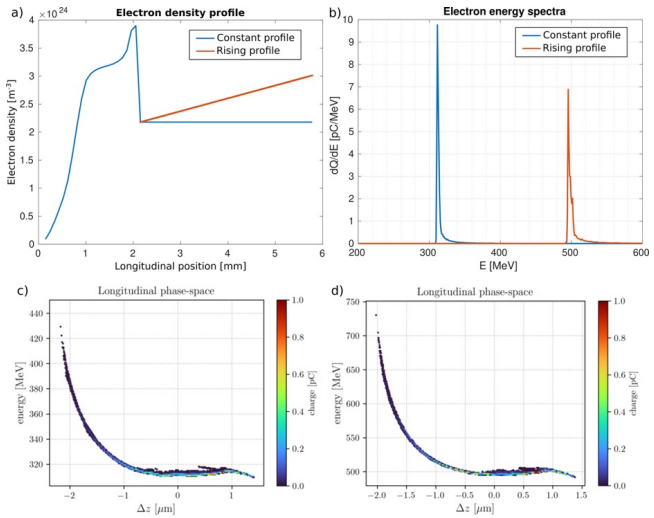
Free-electron-laser simulations

Assessing possible lasing with a 1 GeV LWFA beam

Choosing the injector for EuPRAXIA@ELI

Funded by the European Union

Density down-ramp (shock) injection (OSIRIS, 1.6 J)



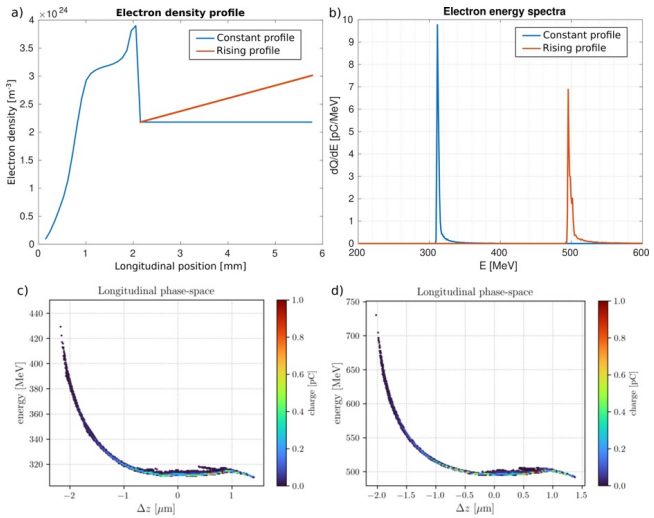
- a_0 = 1.4, w_0 = 35 µm, 25 fs
- Constant profile: **310 MeV**, 34 pC, ΔE/E = 1.0 %, slice 0.30 %
- +40 % density rise: **500 MeV**, 33 pC, ΔE/E = 0.6 %, slice 0.43 %
- Localised injection ⇒ **energy spread at or below 1 %**

M. Matys et al.

Choosing the injector for EuPRAXIA@ELI

Funded by the European Union

Density down-ramp (shock) injection (OSIRIS, 1.6 J)



- a_0 = 1.4, w_0 = 35 µm, 25 fs
- Constant profile: **310 MeV**, 34 pC, ΔE/E = 1.0 %, slice 0.30 %
- +40 % density rise: **500**
- Localised injection ⇒ **e**

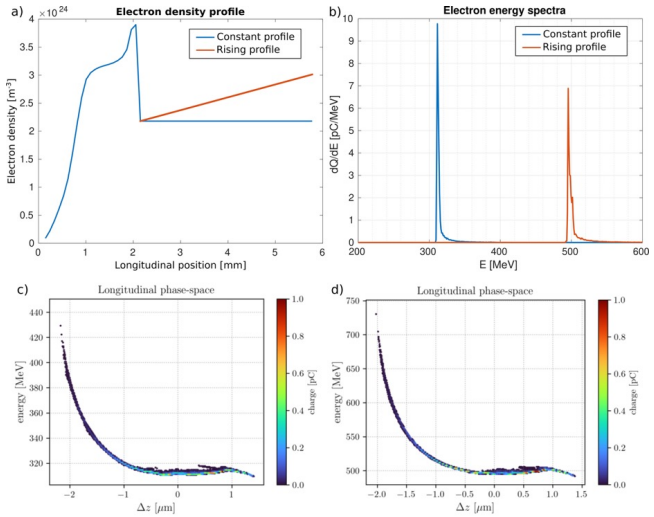
FEL saturation at λ = **55.48** nm in **4 m** undulator.

M. Matys et al.

Choosing the injector for EuPRAXIA@ELI

Funded by the European Union

Density down-ramp (shock) injection (OSIRIS, 1.6 J)

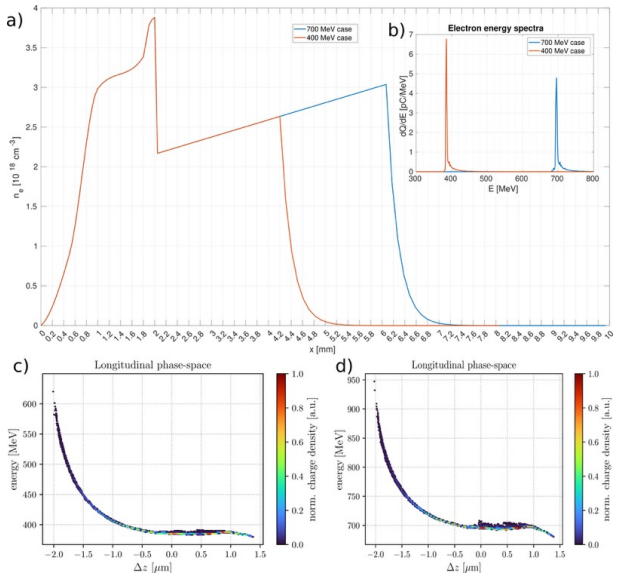


- a_0 = 1.4, w_0 = 35 µm, 25 fs
- Constant profile: **310 MeV**, 34 pC, ΔE/E = 1.0 %, slice 0.30 %
- +40 % density rise: **500**
- Localised injection ⇒ **e**

FEL saturation at λ = **55.48** nm in **4 m** undulator.

M. Matys et al.

Shock injection: energy tuning and exit down-ramp

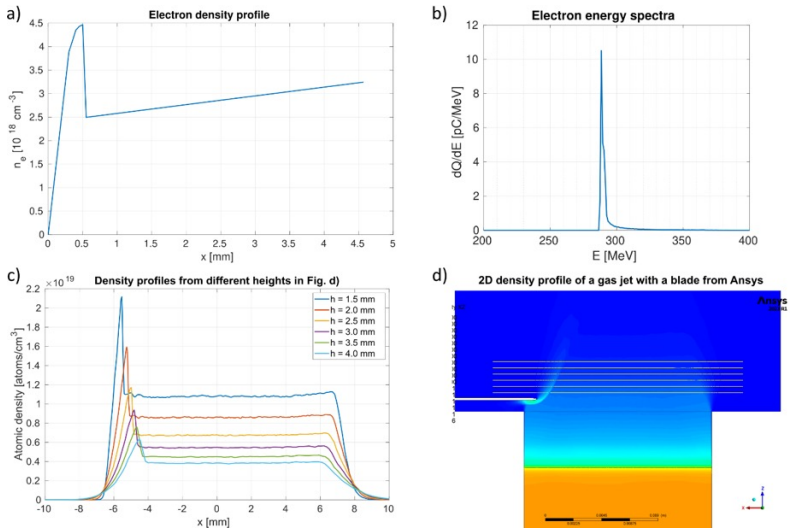


- Lengthening rising section tunes the energy up to **730 MeV** at ΔE/E ≈ 1 %
- Exponential exit ramp (L = 0.2 mm) **halves divergence**: 1.14/1.28 → 0.52/0.62 mrad at 700 MeV

Towards the first experiments at ELI

Funded by the European Union

Early-stage L2 laser and a feasible gas target



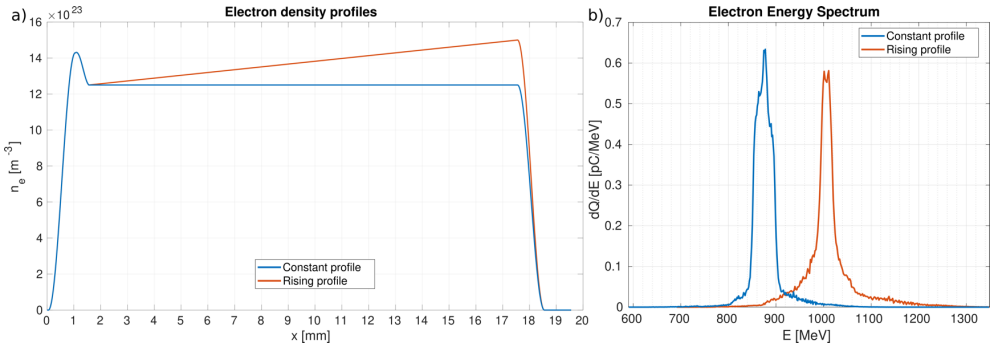
- w_0 = 35→**20 µm**, a_0 = 1.4 → **2** (≈ 1.6 J), simplified density profile
- **300 MeV, 32 pC, ΔE/E = 0.7 %**, slice 0.4 % — relevant for EUV FEL studies
- Next: PIC coupled to **CFD gas-jet-with-blade** profiles

M. Matys et al.

Choosing the injector for EuPRAXIA@ELI

Funded by the European Union

Truncated ionization injection (Smilei, 3.3 J)



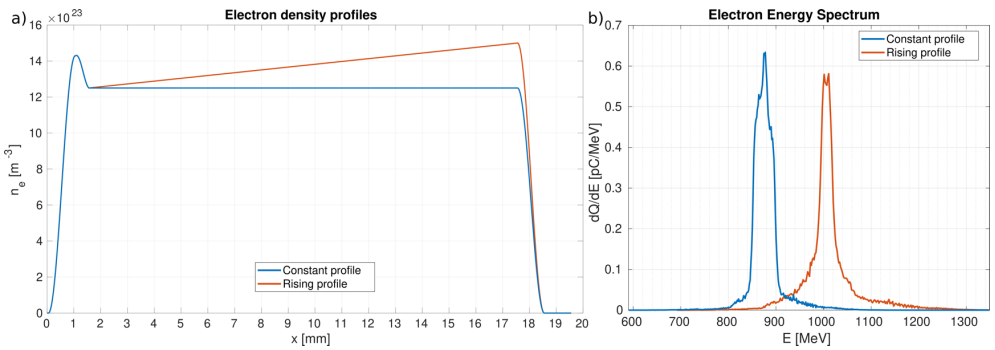
- 95% He + 5% N_2 injection stage, pure He accelerator; a_0 = 2.72, w_0 = 20 µm, 35 fs
- Constant profile: **880 MeV**, 28 pC, ΔE/E = 5.2 %
- Rising profile: **1.01 GeV**, 28 pC, ΔE/E = 2.8 %
- Robust and experimentally consolidated, but the **injection volume is too large** — energy spread stays above the FEL requirement

M. Matys et al.

Choosing the injector for EuPRAXIA@ELI

Funded by the European Union

Truncated ionization injection (Smilei, 3.3 J)

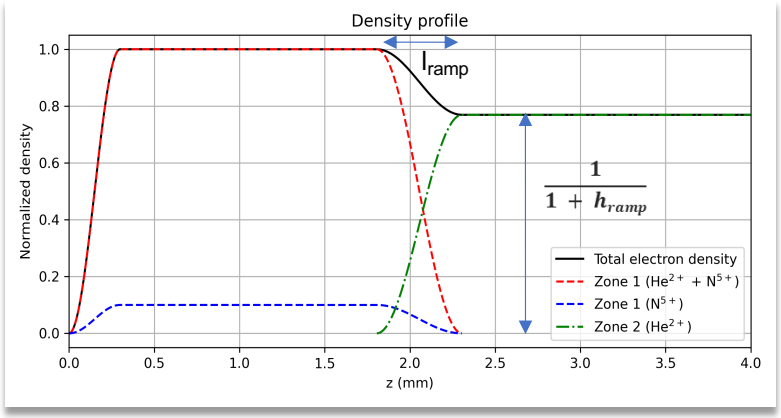


- 95% He + 5% N_2 injection stage, pure He accelerator; a_0 = 2.72, w_0 = 20 µm, 35 fs
- Constant profile: **880 MeV**, 28 pC, ΔE/E = 5.2 %
- Rising profile: **1.01 GeV**, 28 pC, ΔE/E = 2.8 %
- Robust and experimentally consolidated, but the **injection volume is too large** — energy spread stays above the FEL requirement

M. Matys et al.

Bayesian optimization: hybrid down-ramp+ionization injection

FBPIC + Optimas - Jean Zay supercomputer (IDRIS, FR).



Laser Parameters : a_0 = 1.7, T = 25 fs, w_0 = 30 µm, λ = 800 nm

Gas Parameters : n_e = 1.6e24 m^{-3}, He^{2+} , N^{5+} (ionizable)

Varying parameters: ramp length&height, focus position, % of N_2

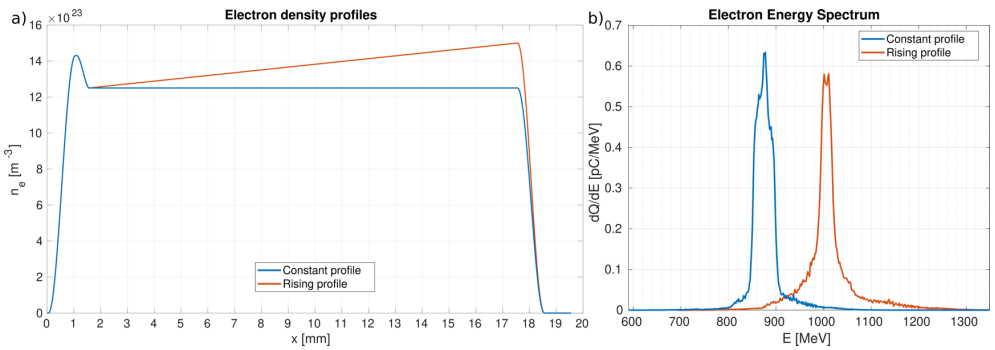
Proxy Kad, Luca Fedeli

Jorge Vieira and Henri Vincenti, WP8

Choosing the injector for EuPRAXIA@ELI

Funded by the European Union

Truncated ionization injection (Smilei, 3.3 J)

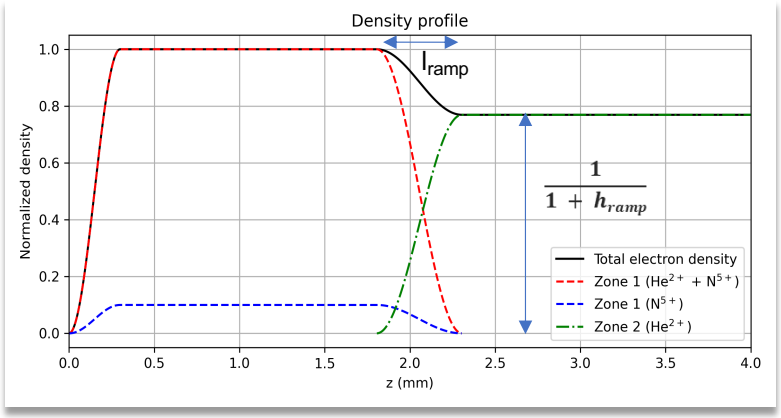


- 95% He + 5% N_2 injection stage, pure He accelerator; a_0 = 2.72, w_0 = 20 µm, 35 fs
- Constant profile: **880 MeV**, 28 pC, ΔE/E = 5.2 %
- Rising profile: **1.01 GeV**, 28 pC, ΔE/E = 2.8 %
- Robust and experimentally consolidated, but the **injection volume is too large** — energy spread stays above the FEL requirement

M. Matys et al.

Bayesian optimization: hybrid down-ramp+ionization injection

FBPIC + Optimas - Jean Zay supercomputer (IDRIS, FR).



Laser Parameters : a_0 = 1.7, T = 25 fs, w_0 = 20 µm, λ = 800 nm

Gas Parameters : n_e =

Varying parameters: r

E_med = 328.08 MeV
E_mad = 11. 48 MeV (3.5%)
Charge = 48 pC

Proxy Kad, Luca Fedeli

Jorge Vieira and Henri Vincenti, WP8

Contents of deliverable D8.3

Funded by the European Union

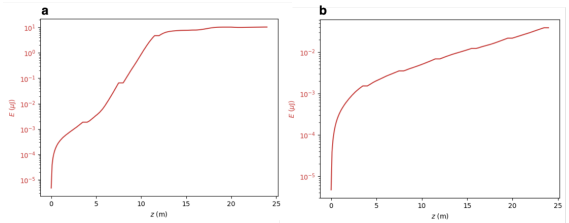
Shock-injection

A physics informed recipe for high quality e- acceleration

High quality e- acceleration at ELI

Ionization-truncated and shock injection

Free-electron-laser simulations

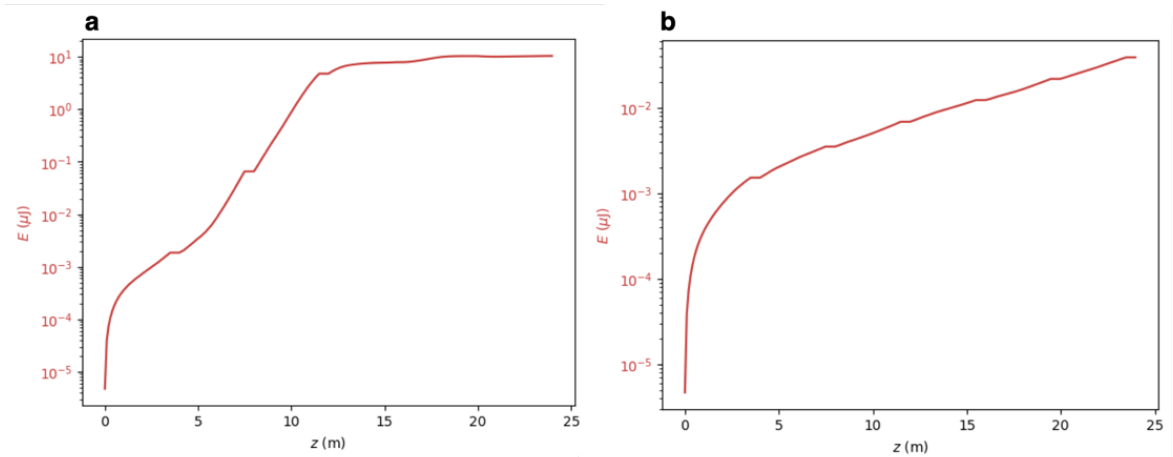


Assessing possible lasing with a 1 GeV LWFA beam

Free-electron-laser simulations at 1 GeV

Funded by the European Union

Radiated energy along the undulator



a) ideal bunch, chirp neglected **b) including the energy chirp**

- Undulator period 15 mm, targeting **3 nm** x-ray emission
- Time-dependent and time-independent simulations of the FEL instability

F. Nguyen et al.

What this tells us

- The **slice energy spread is small enough** for the FEL instability to develop
- But the bunch is produced with an **energy chirp**, which strongly reduces the growth rate
- Ideal case: **10 mJ** radiated over 25 m of undulator
- With chirp: **0.039 mJ** — the instability starts, but saturation would need more than 25 m, beyond the experimental hall
- ⇒ **Chirp removal / compensation** is the key next step

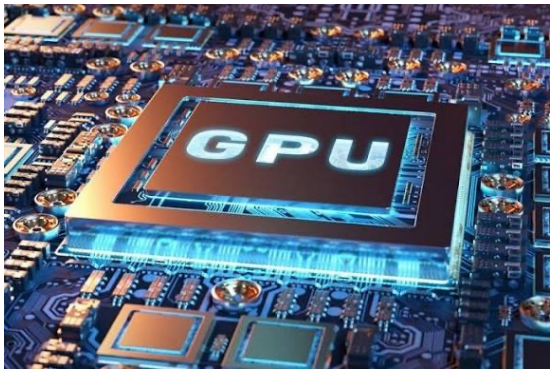
Contents

- Overview of previous modeling activities
- Contents of deliverable 8.3
- **Advance since last deliverable**
- Conclusions

Recent developments after D8.3

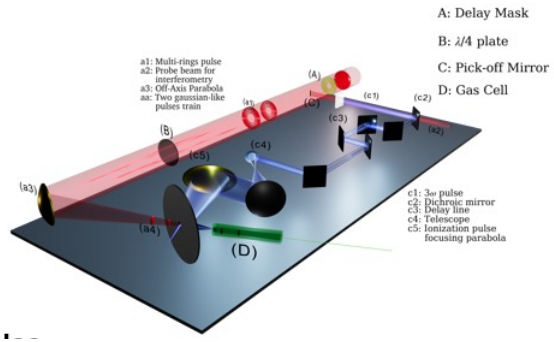
Funded by the European Union

Generalized PIC parallelization



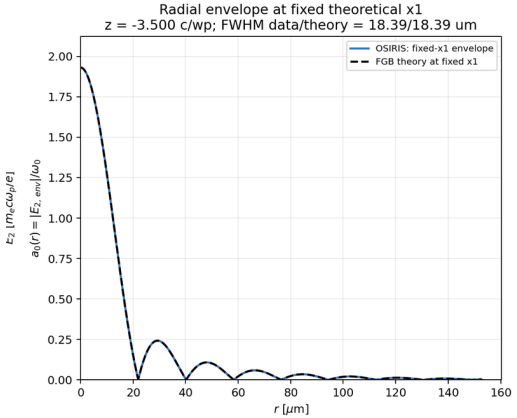
CPUs and GPUs, one algorithm

ReMPI



FEL quality results

Flattened beam profiles



Realistic focal spots for experiments EuPRAXIA@ELI

Generalized PIC parallelization for CPUs and GPUs

R. A. Fonseca, *Plasma Phys. Control. Fusion* 68 (2026) 085054 · open access · doi:10.1088/1361-6587/ae9c96

Funded by the European Union

11.6 GPart s^{-1}
single NVIDIA A100 (2048^2 grid, 64 part/cell)

~14×
GPU vs. CPU socket — ~0.8 GPart s^{-1} per socket with explicit SIMD

96%
weak-scaling efficiency to 16 GPUs on Deucalion

How it works

- **Micro-domain decomposition** — the grid is split into ~32^2-cell tiles; each tile maps to one CPU thread or one GPU thread block, with fields and current staged in L1 / shared memory for coalesced access.
- **Parallel particle tile sort** — a four-step migration keeps one contiguous particle buffer with minimal data movement: only ~12% of GPU and ~4% of CPU runtime, and load-balanced under order-of-magnitude density contrast.
- **Native backends, shared algorithm** — OpenMP with SIMD intrinsics on CPUs, CUDA/HIP on GPUs, MPI overlapped with tile updates across devices. Explicit vectorization alone is worth up to 4.3×, and the same scheme carries over to spectral solvers and quasi-3D (z, r) geometry (3.7 GPart s^{-1} on one A100).

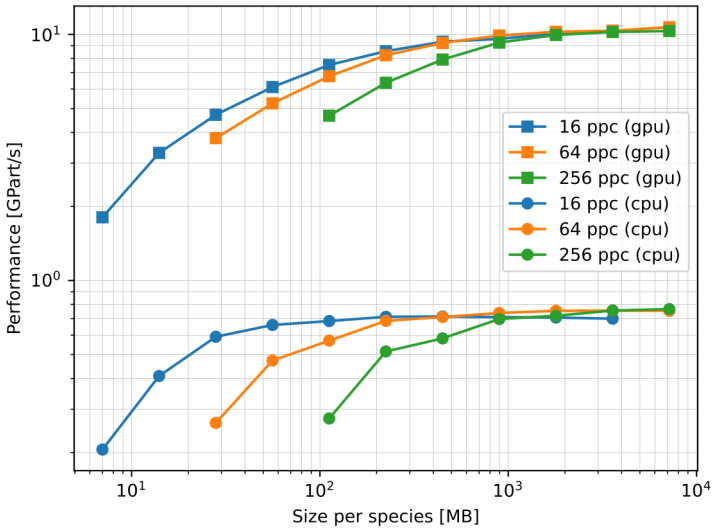
Same algorithm, validated on:

x86 · AVX-512 | Arm · SVE | NVIDIA · CUDA | AMD · HIP | Intel · SYCL

Open source (AGPL 3.0): github.com/ricardo-fonseca/zpic-parallel

Performance vs. problem size

Peak throughput for problems above ~1 GB per species, at any particles/cell.
Squares: A100 80 GB PCIe. Circles: Xeon Gold 6336Y 24c.



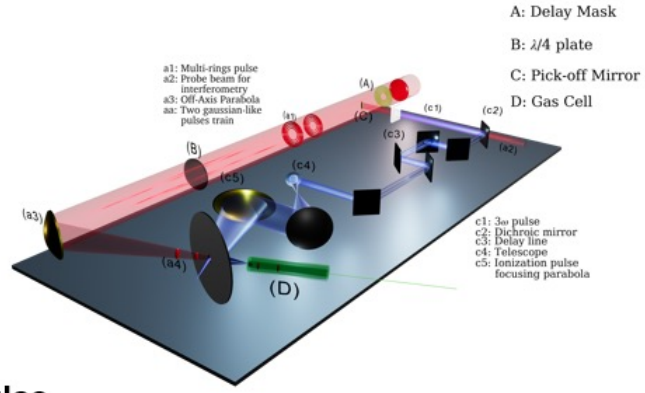
EuPRAXIA ReMPI preliminary FEL quality results with L2-DUHA

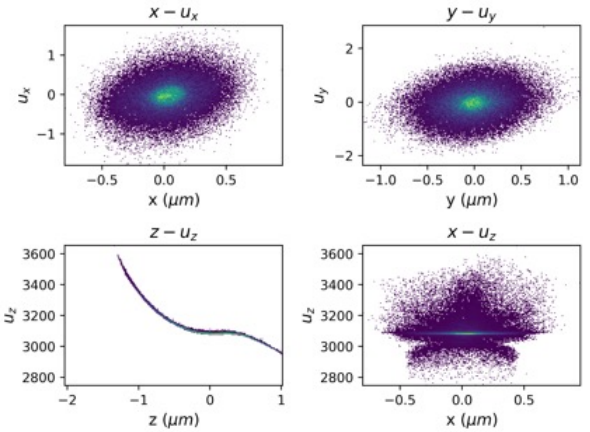
Funded by the European Union

eli

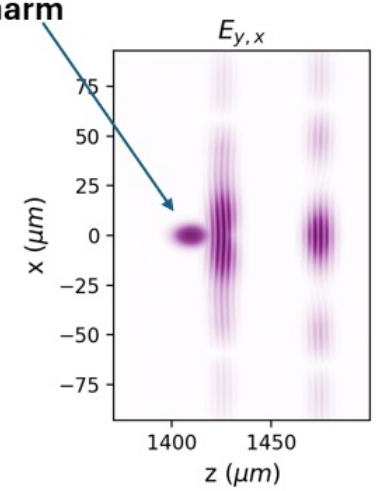
CNRINO
CONSIGLIO NAZIONALE DELLE RICERCHE
ISTITUTO NAZIONALE DI OTTICA

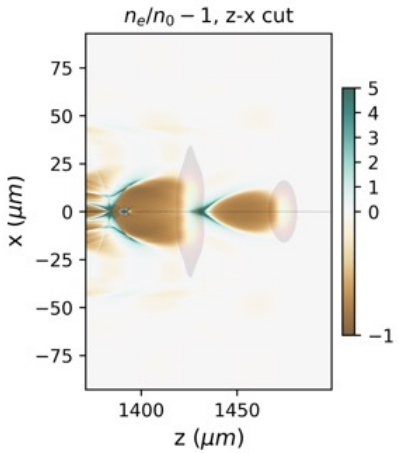
***Setup from P. Tomassini et al., Sci Reports* 15, 40794 (2025).**

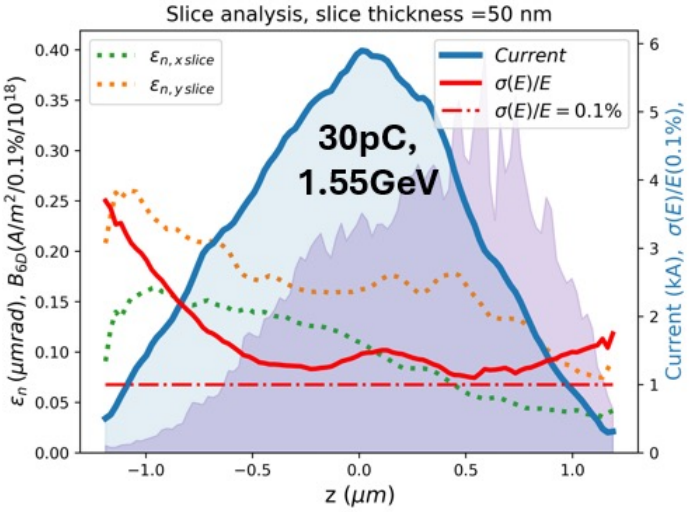




Ionization pulse
III harm







Jorge Vieira and Henri Vincenti, WP8

Flattened laser profiles in OSIRIS

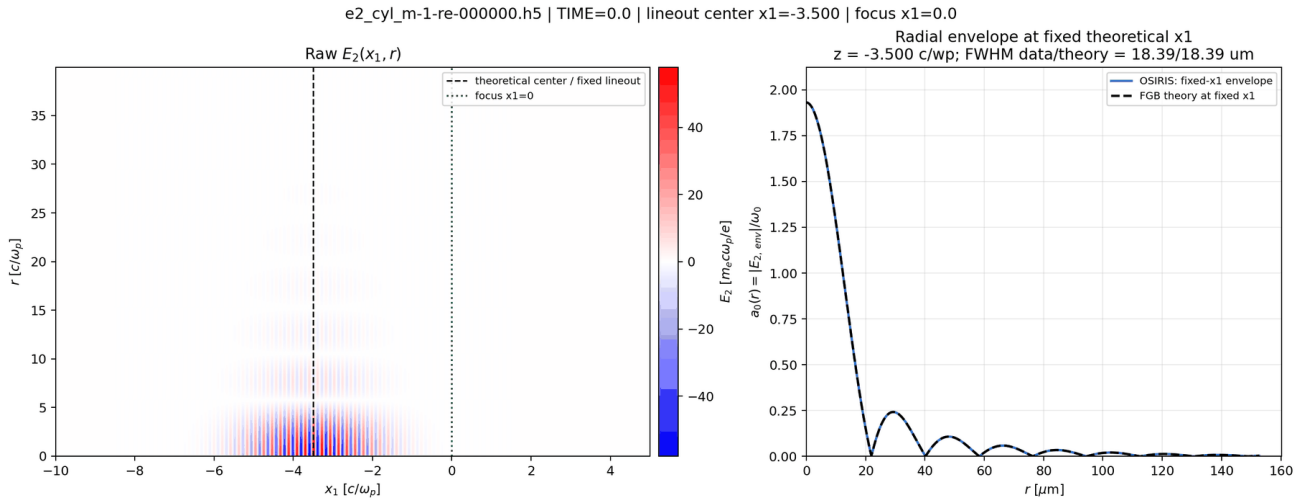
Funded by the European Union

Why flattened beams?

- Real high-power beam lines do **not** deliver a Gaussian focus
- Large-aperture, apodised and beam-shaped systems — as anticipated at EuPRAXIA@ELI — produce **flat-top (flattened Gaussian) profiles**
- To predict what an experiment will actually give, the driver in the simulation must be the driver in the laboratory
- **Flattened Gaussian beams (FGB)** are now available as an exact laser initialisation in OSIRIS

X. Wu et al.

Benchmark: OSIRIS field vs. FGB theory



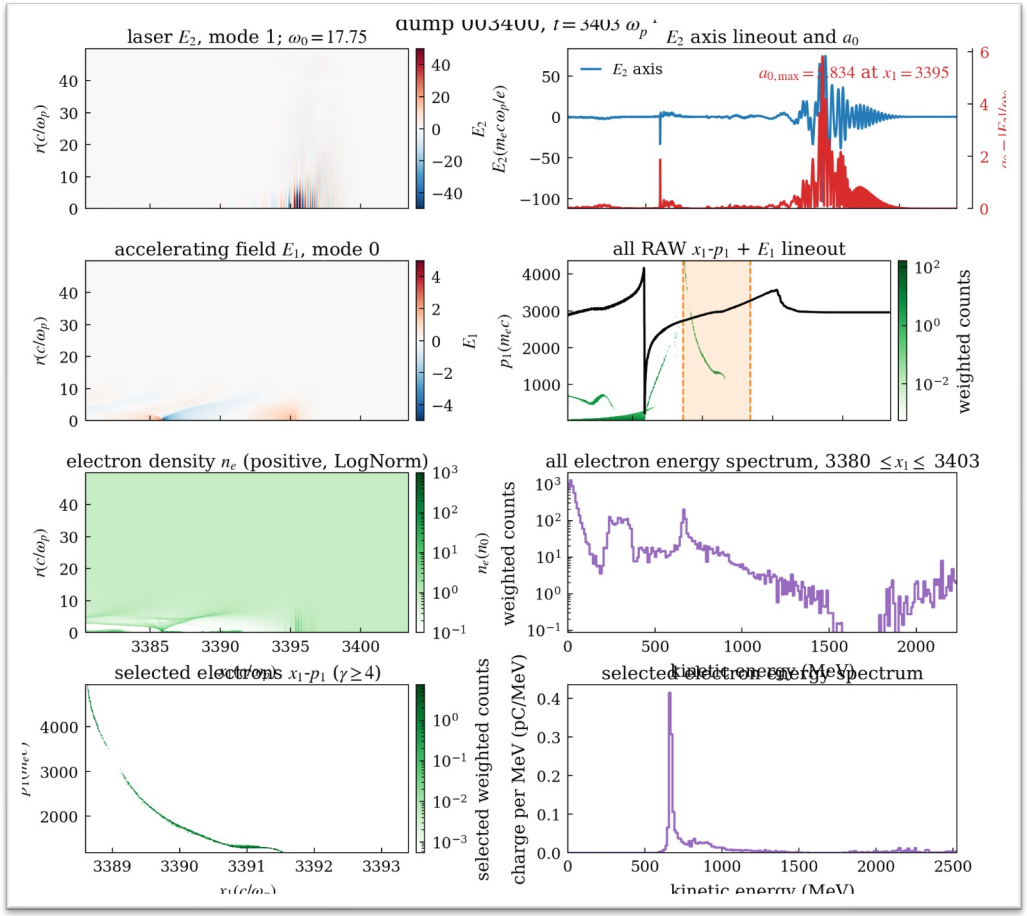
- Exact vacuum propagation of the FGB from the injection plane to focus, in cylindrical geometry with azimuthal mode decomposition
- The radial envelope extracted from the simulated field follows the analytical FGB solution **to within the diagnostic resolution** (FWHM 18.39 µm, data = theory)

Flattened laser profiles in OSIRIS

Funded by the European Union

Why flattened beams?

- Real high-power beam lines do **not** deliver a Gaussian focus
- Large-aperture, apodised and beam-shaped systems — as anticipated at EuPRAXIA@ELI — produce **flat-top (flattened Gaussian) profiles**
- The transverse profile sets the wake structure, the injected charge and the emittance
- To predict what an experiment will actually give, the driver in the simulation must be the driver in the laboratory
- **Flattened Gaussian beams (FGB)** are now available as an exact laser initialisation in OSIRIS



X. Wu et al.

Contents

Funded by the European Union

- Overview of previous modeling activities
- Contents of deliverable 8.3
- Recent advance since last deliverable
- **Conclusions**

Summary and conclusions

Funded by the European Union

Deliverable D8.3

- A **physics-informed recipe** for shock injection — suppress self-injection, strengthen the driver, keep the charge low — yields **1.1 GeV, 0.74 % energy spread, 17 pC, ~250 nm emittance**, and scales from 500 MeV upwards
- At **EuPRAXIA@ELI**, shock injection outperforms truncated ionization injection (≤ 1 % vs. > 2 % energy spread); an exit down-ramp halves the divergence, and a scenario matched to the early L2 laser gives 300 MeV at 0.7 %
- **FEL simulations** confirm that the slice energy spread allows lasing at 3 nm, but the residual energy chirp limits the radiated energy to 0.039 mJ instead of 10 mJ

Since the report

- **Generalized PIC parallelization** for CPUs and GPUs: one algorithm, native backends, open source
- **ReMPI** produces FEL-grade e-beams
- **Flattened Gaussian beams** in OSIRIS, benchmarked against theory — realistic drivers for the EuPRAXIA@ELI experiments

Outlook

- Remove or compensate the bunch energy chirp to reach FEL saturation within the hall
- Couple PIC to CFD gas-target profiles for experimentally feasible designs
- Push the ELI scenarios to higher energy with realistic, measured laser profiles

Jorge Vieira and Henri Vincenti, WP8

“Recipe” for obtaining high-quality electrons

Funded by the European Union

Part I: suppress self-injection

1. Scan laser intensity a_0 (with the waist adjusted accordingly) to locate the threshold below which no self-injection occurs.

a_0=1.8, n_0 =2e18 cm^{-3}, L = 50 μm, z_f = 1.9 mm

2. If self-injection persists across the scan, it is suppressed by reducing the plasma density.

a_0=1.8, n_0 =1x10^{18} cm^{-3}, L = 50 um, z_f = 1.9 mm

Part II: Compensate chirp

To prevent over-compensation of the beam energy chirp, a balance between laser driver and electron beam should be achieved

3. Scan the focal position: strengthens driver and weakens beam loading.

a_0=1.8, n_0 =1x10^{18} cm^{-3}, L = 50 μm, z_f = 3.8 mm

4. Fine-tunning downramp length and laser intensity: control down-ramp injection.

a_0=1.9, n_0 =1x10^{18} cm^{-3}, L = 35 μm, z_f = 5.0 mm

X. Wu et al.