EARLI: designing a LWFA for AWAKE Run2

High-quality *E*lectron *A*ccelerator driven by a *R*eliable *L*aser for *I*ndustrial uses

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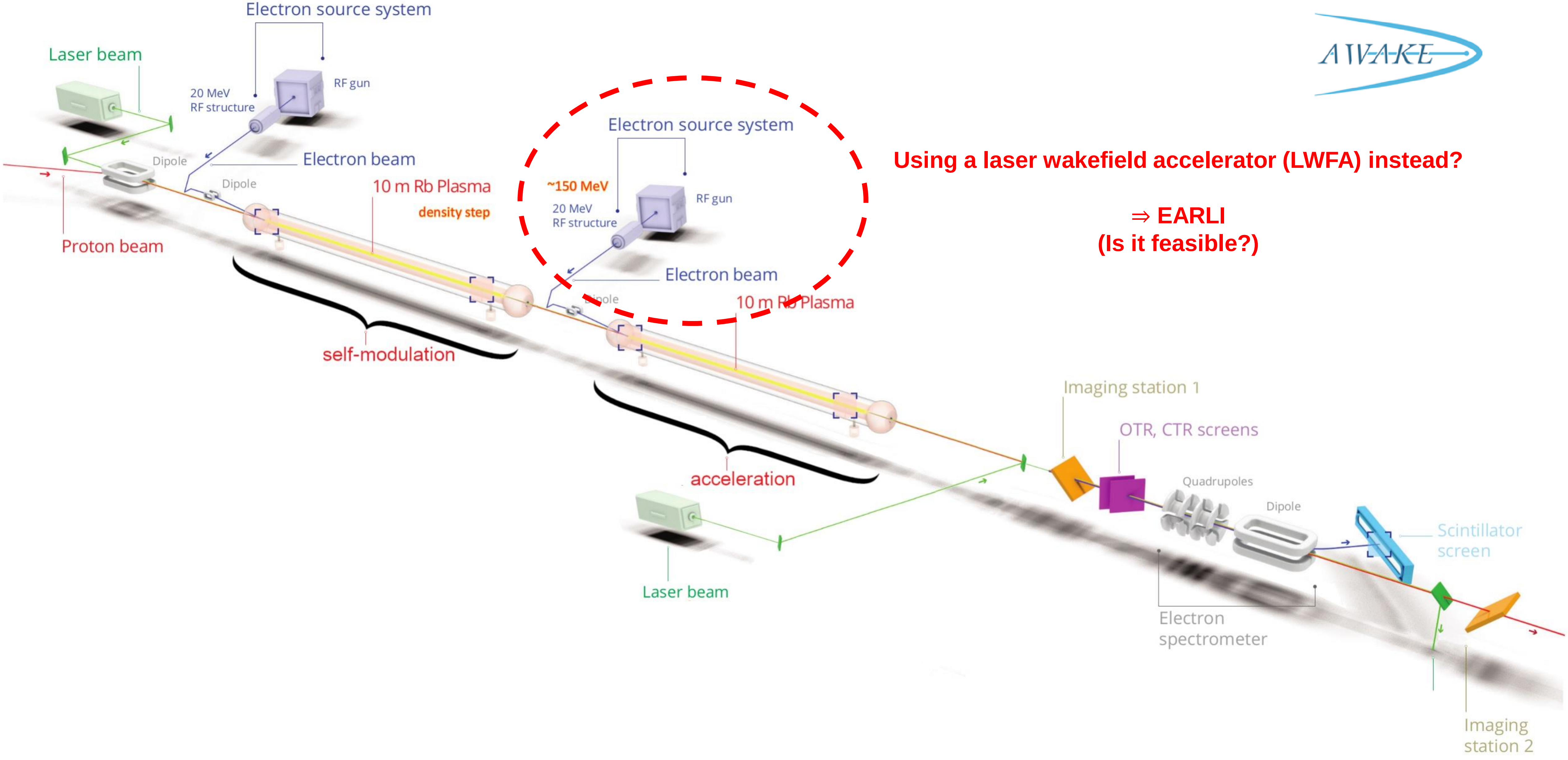
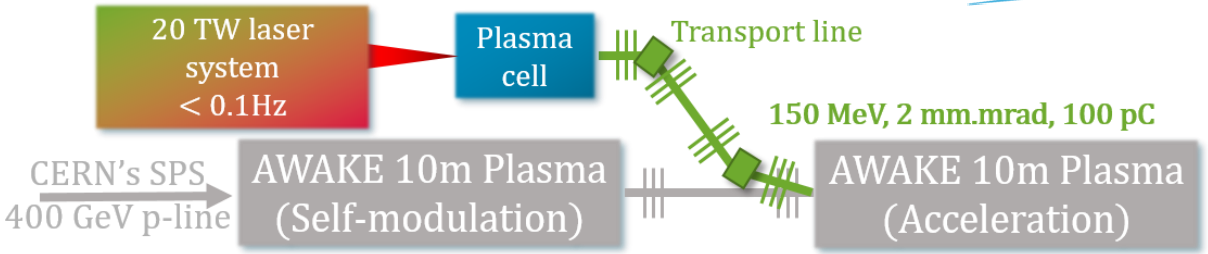
Thales LAS

AWAKE : electron source needed for injection into acceleration stage



Using a laser wakefield accelerator (LWFA) instead?

⇒ EARLI
(Is it feasible?)



EARLI

- **LWFA-based electron injector for AWAKE Run2c**
  - Alternative to RF injector
  - Smaller footprint?
- **Reproducible, high-quality beam for 1- to 2-week runs**
- **Include**
  - A stable laser system 0.01 - 0.1 Hz
  - a plasma cell with adjustable density profiles
  - a transfer line with an S achromat
- **Using methods from conventional accelerators**

AWAKE targeted beam parameters
100-250 MeV
$\Delta E/E$ < 2%
$\varepsilon_{x,y}$ < 2 mm.mrad
α=0
$\sigma_{x,y}$ = 5.75 µm
σ_z = 60 µm
Q = 100 pC
0.01-0.1 Hz

Is EARLI feasible?

- **Beam quality (laser-plasma interaction)**
- **Transfer line**
- **Laser system**

Design of a laser-plasma accelerator centered on beam physics

Current phase

1. **Assess the targeted beam parameters at the final user**
   - AWAKE needs
2. **Explore the most promising configurations to reach these beam parameters, which can fit the available space**
   - LWFA scheme and plasma density profile suitable for e⁻ injection by ionisation (published data and team expertise)
   - Transfer line configuration with two dipoles and 8 quadrupoles
   - Laser configuration
3. **Launch massive optimizations**
   - From injection up to the final user, including plasma acceleration stage and transfer line
   - Exploration of parameter ranges of the 6D beam
   - Numerical + physics-based optimisations
4. **Estimate the reproducibility and stability, with error/tolerance analysis**
5. **Determine the needed beam measurements, their positions and their resolutions**
6. **Assess the feasibility**
   - Cost, size, beam quality,…
7. **Launch the fabrication of laser, plasma, magnetic and diagnostic components**
8. **Conduct the beam commissioning until targeted beam parameters are reached**

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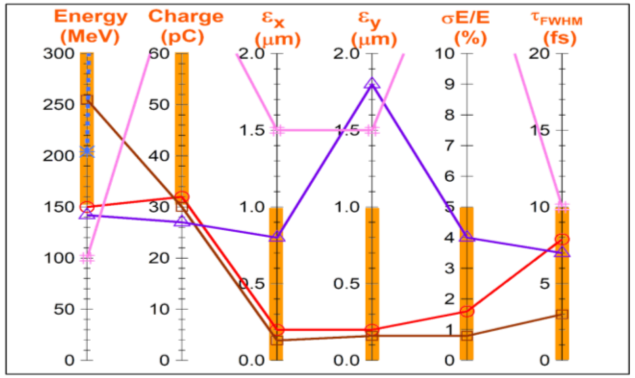
Close to EuPRAXIA's first LWFA stage



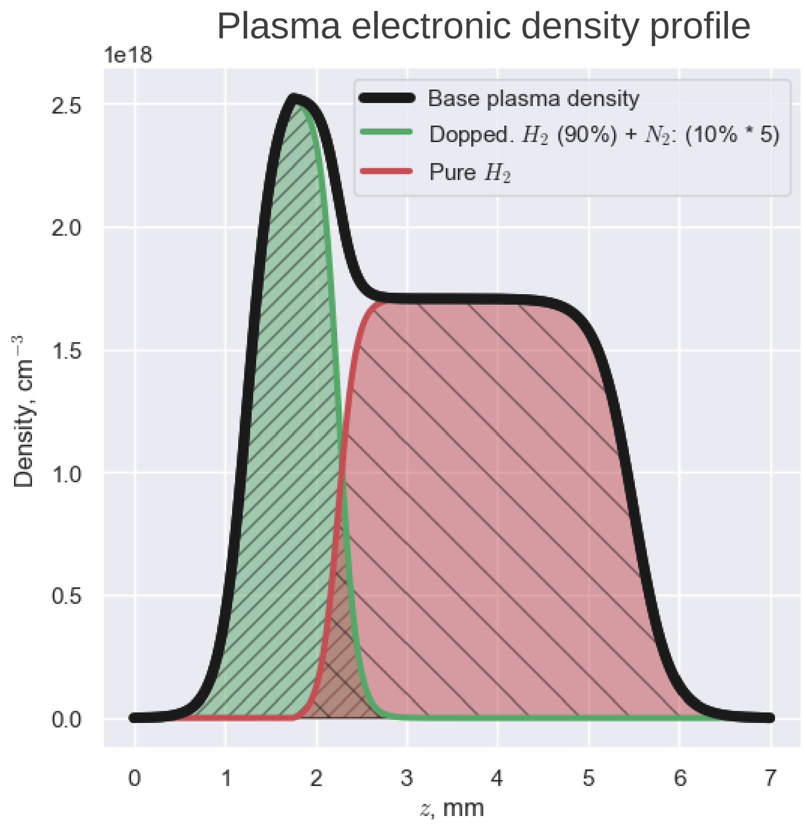
Example: EuPRAXIA's first optimization results

[EuPRAXIA Conceptual Design Report]

[Nghiem et al., *PRAB* (2020)]

Configuration for preliminary laser-plasma PIC simulations

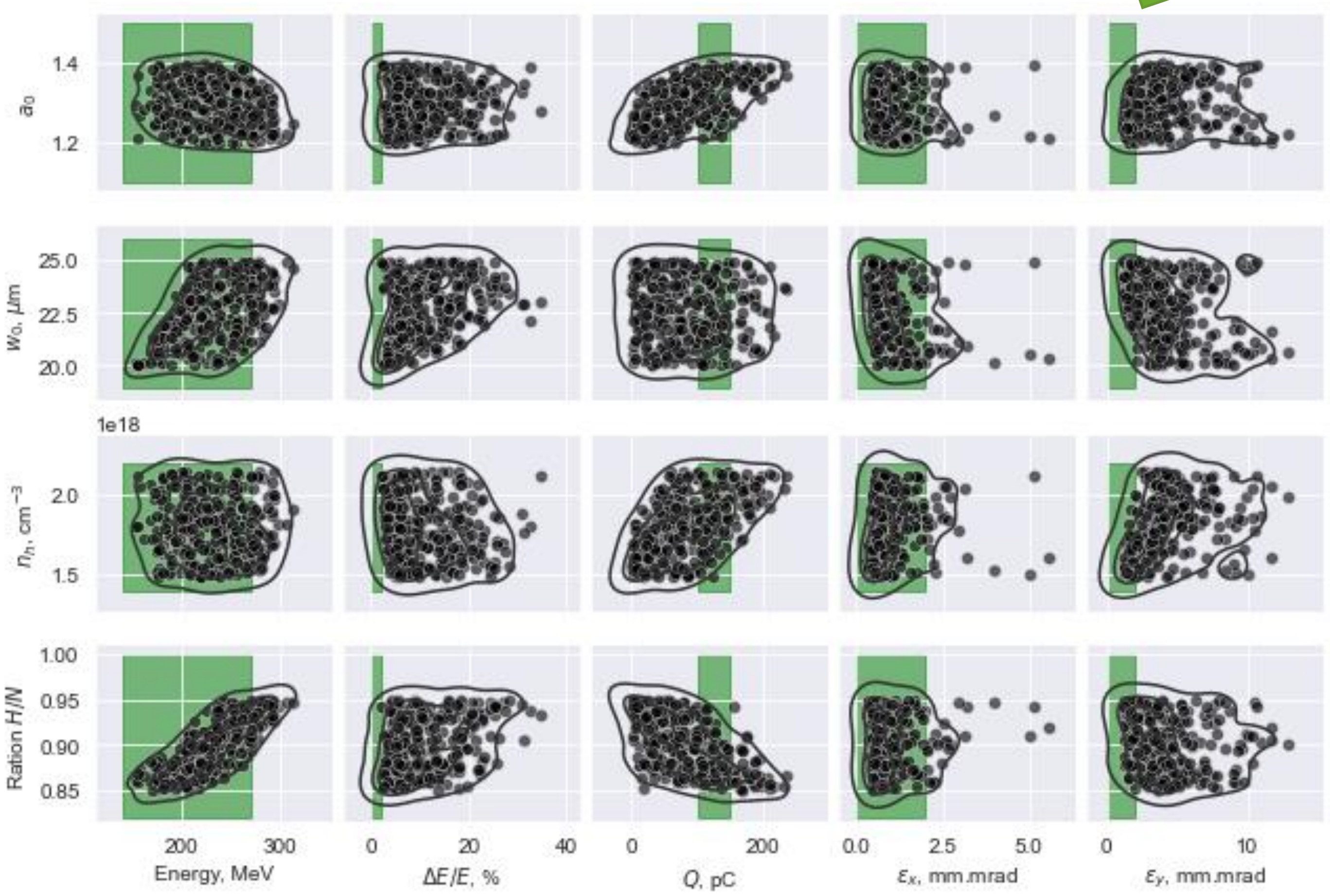
- **Plasma source**
  - Ionisation injection scheme (90% H2 + 10% N2)
    - Background plasma electrons from H and up to 5th ionisation state of N
    - Trapped electrons from 6th and 7th ionisation of N.
  - Profile with density gradient to stop injection [Kirchen et al., *PRL* (2021)] and [Couperus et al., *Nature Comm.* (2017)]
- **Laser pulse**
  - Flattened Gaussian beam
- **Laser-plasma simulations**
  - Objective: find configuration points that provide the desired beam characteristic
    - Focus on the charge (100 pC), emittance (2 mm.mrad) and energy spread (2%)
  - Simulation parameters:
    - Plasma
      - Longitudinal profile with two gas components
      - Density n_H
      - Proportion H2/N2
    - Laser
      - Normalized intensity a_0
      - Waist w_0
      - Focus position
      - Pulse length τ



Numerical optimization of LPA simulations

- **Currently, up to 700 runs using FBPIC and Smilei**
  - Numerical optimisation of the beam parameters
  - Random input parameters between selected ranges
  - Assisted by machine learning (ongoing)

AWAKE target
100-250 MeV
$\Delta E/E$ < 2%
$\varepsilon_{x,y}$ < 2 mm.mrad
Q = 100 pC

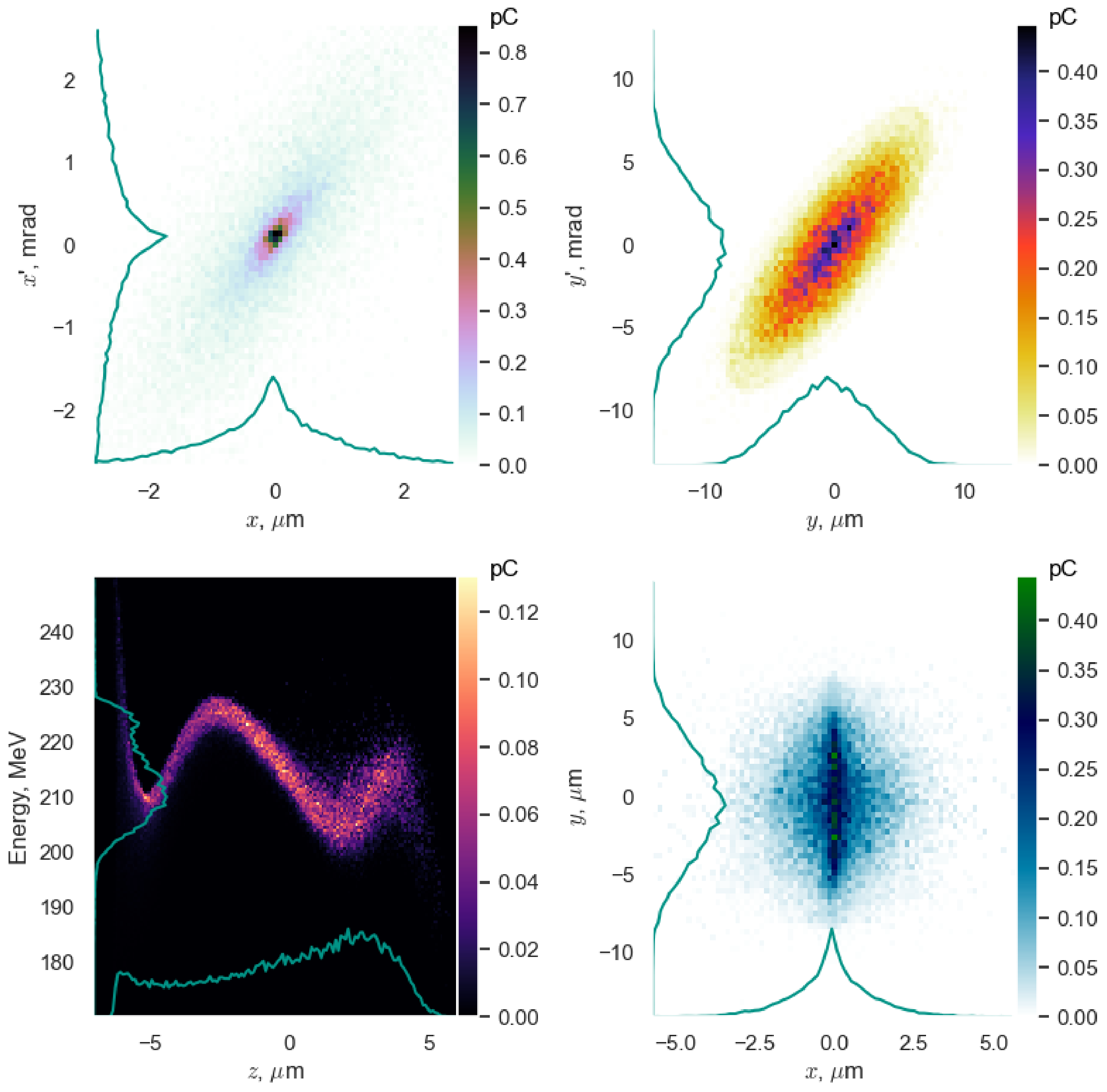


Laser polarised in y in the simulation
⇒ Larger ε_y

Low $\Delta E/E$ challenging!

Here, 300 runs with FBPIC

Example of a preliminary result: electron beam properties

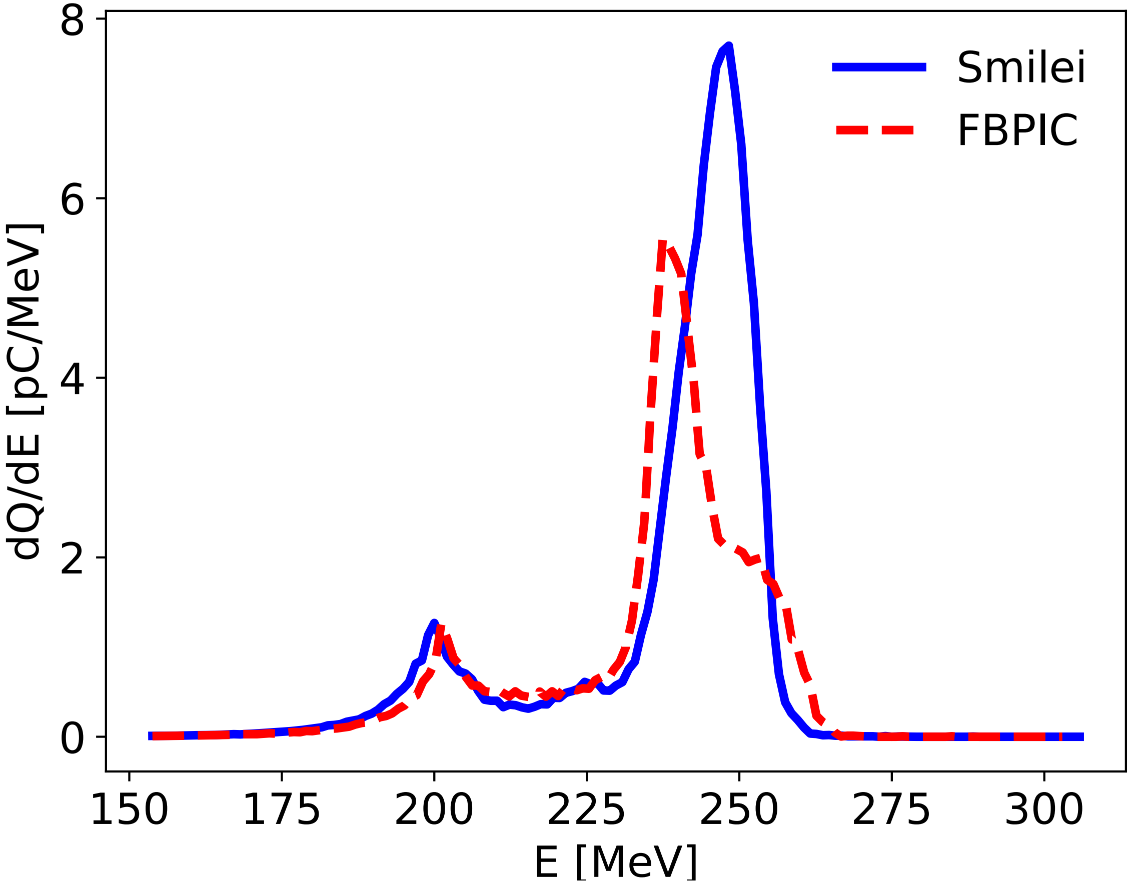


Inputs
Flattened Gaussian laser beam
a_0 = 1.34
w_0 = 23.0 µm
τ = 25 fs
n_H = 1.7e18 cm-3
Ratio H/N = 0.88

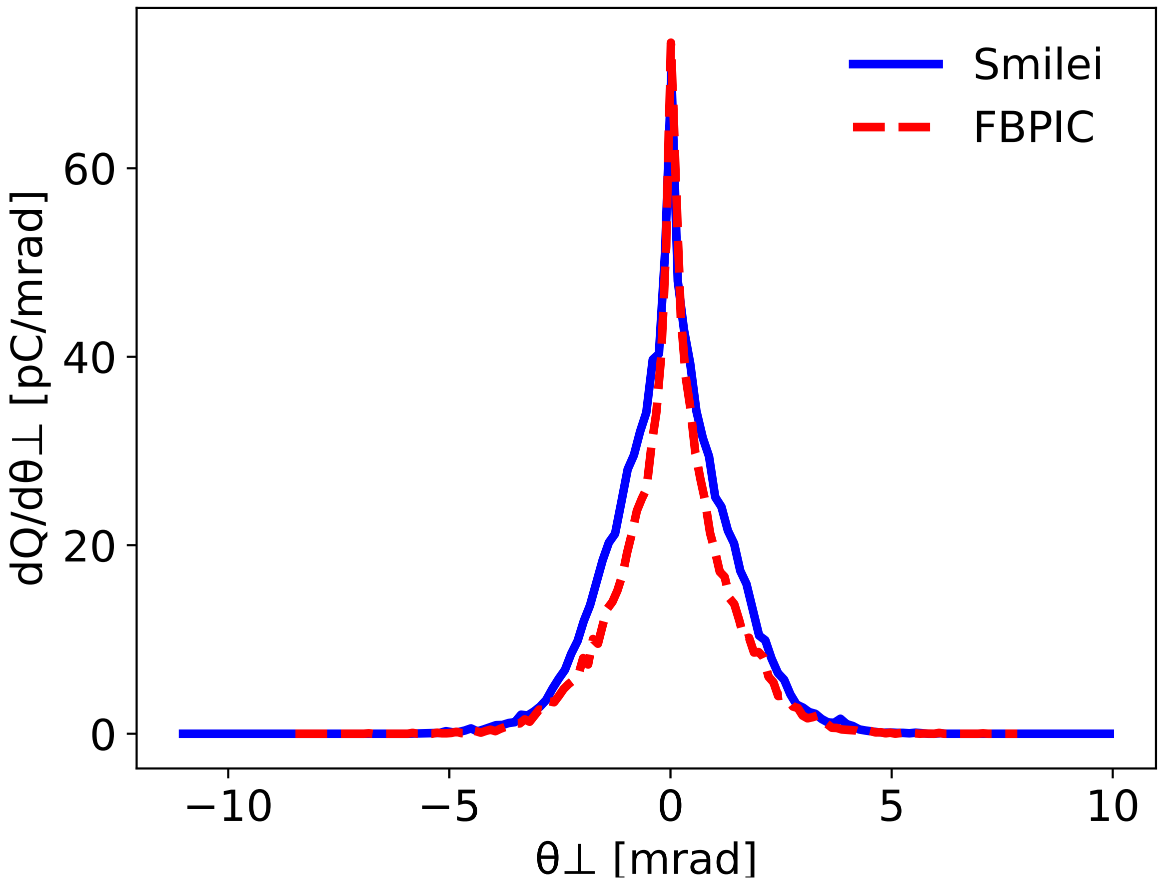
Optimisations based on beam physics (ongoing)

EARLI simu 1	AWAKE target	EARLI simu 2
213 MeV	100-250 MeV	236 MeV
3.9 %	$\Delta E/E$ < 2%	4,1 %
0,5; 2.9 mm.mrad	$\varepsilon_{x,y}$ < 2 mm.mrad	0.5; 1.9 mm.mrad
4.5 µm	$\sigma_{x,y}$ = 5.75 µm	3.6 µm
3 µm	σ_z = 60 µm	2.6 µm
108 pC	Q = 100 pC	62 pC

Electron beam energy spectrum



Electron beam angular spectrum



Smilei: (Laser envelope model) [F. Massimo et al., *Phys. Rev. E* (2020)]

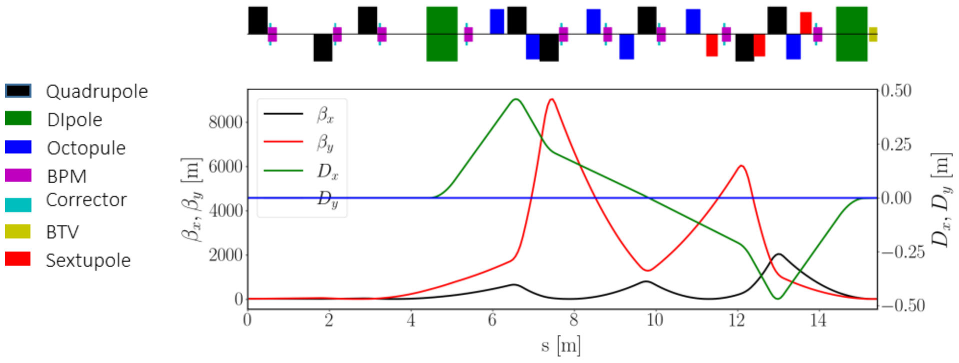
FBPIC: (Boosted-frame) [R. Lehe et al., *Comp. Phys. Comm.* (2016)]

Feasibility study of a transfer line

- **Several configurations for the transfer line were investigated**
- **Need to**
  - keep the same transverse beam size of 5 μm
  - lengthen the longitudinal beam size from 2 μm to 60 μm

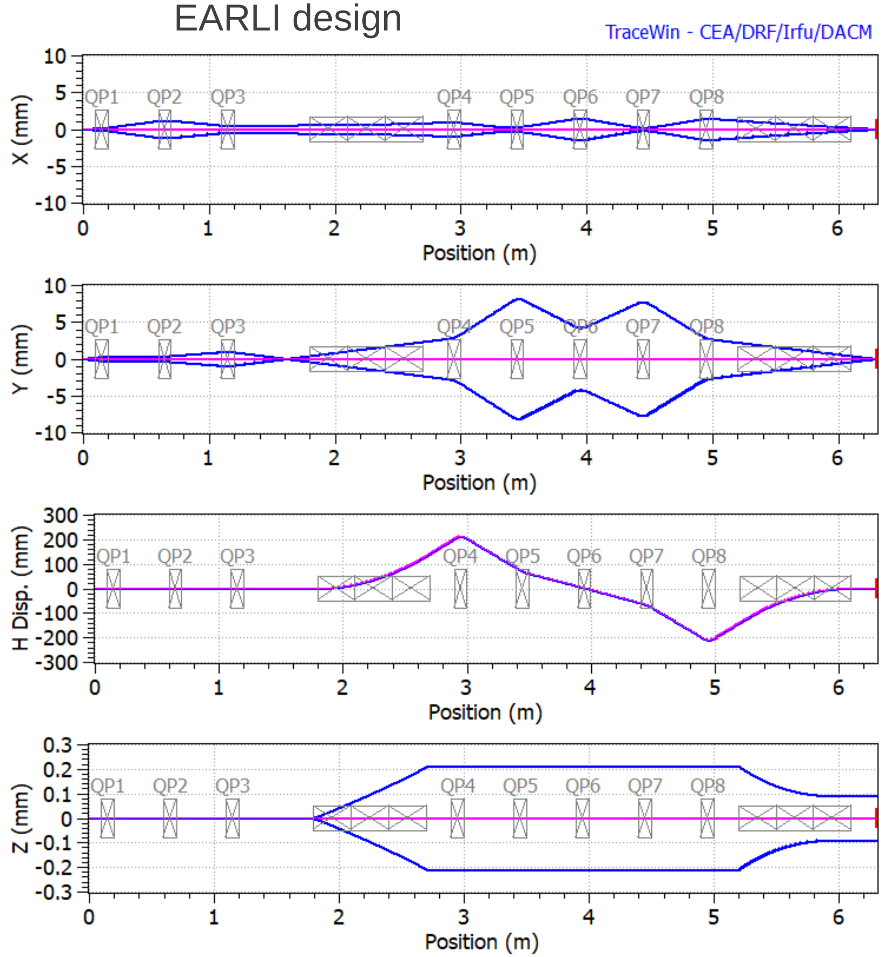
- **A transfer line was already designed by CERN for the RF electron gun, where the beam transverse size should be reduced from 270 μm to 5 μm, and the beam length must be kept unchanged.**

CERN source	AWAKE target	EARLI plasma source
$\varepsilon_{x,y}$ = 2 mm.mrad	$\varepsilon_{x,y}$ = 2 mm.mrad	$\varepsilon_{x,y}$ = 2 mm.mrad
$\boldsymbol{\sigma_{x,y} = 270}$ **μm**	$\sigma_{x,y} = 5.75$ μm	$\sigma_{x,y} = 5$ μm
$\sigma_z = 60$ μm	$\sigma_z = 60$ μm	$\boldsymbol{\sigma_z = 2}$ **μm**



CERN design by V. Bencini, R. Ramjiawan, F. Velotti

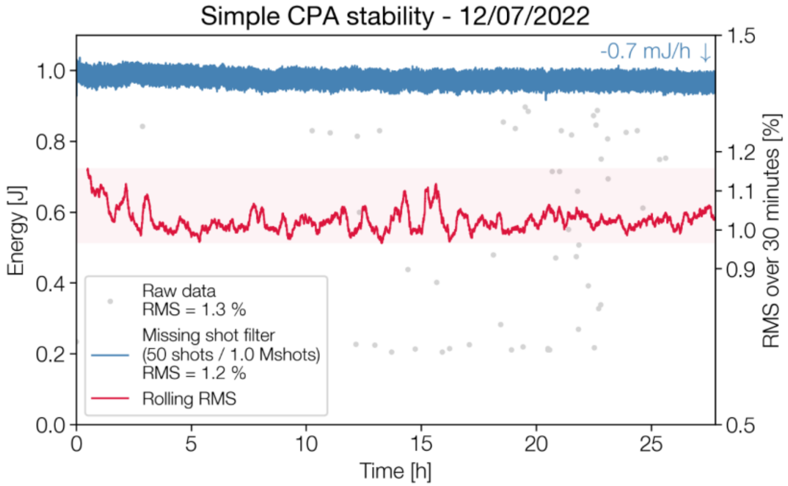
EARLI design



- A 5-quad achromatic section → almost symmetric for beam size, antisymmetric for dispersion D_x
- A 3-quad capture section
- Total length ~ 6 m
- Similar to the CERN design

EARLI laser system will be designed according to requirements defined by LWFA simulations

- **Collaboration with Thales for the industrial laser**



More than 24 hours operating results of a THALES 1J 10Hz 25fs CPA TiSa laser

Focal spots

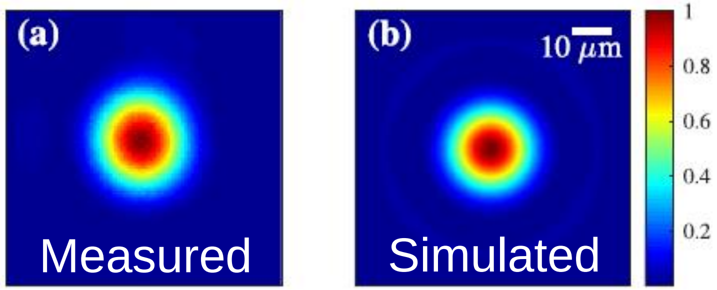
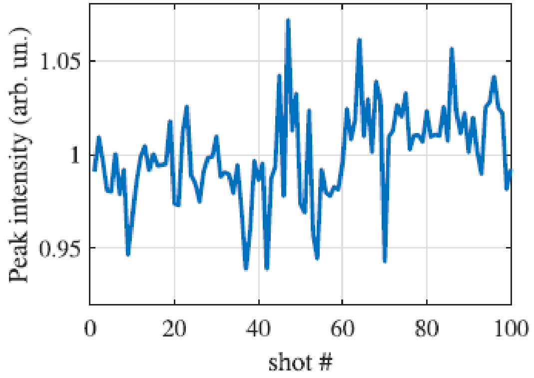


FIG. 6. Focal spots of red alignment and main IR laser beams: (a) measured and (b) simulated red (660 nm) focal spots with $f/25$; (c) measured and (d) simulated main IR laser focal spots with $f/17$.



Focal-spot stability over 100 consecutive shots: (a) peak intensity fluctuations vs shot number;

[Commissioning and first results from the new 2 × 100 TW laser at the WIS, Kroupp et al., *Matter Radiat. Extremes* (2022) (System from THALES LAS)]

Conclusion

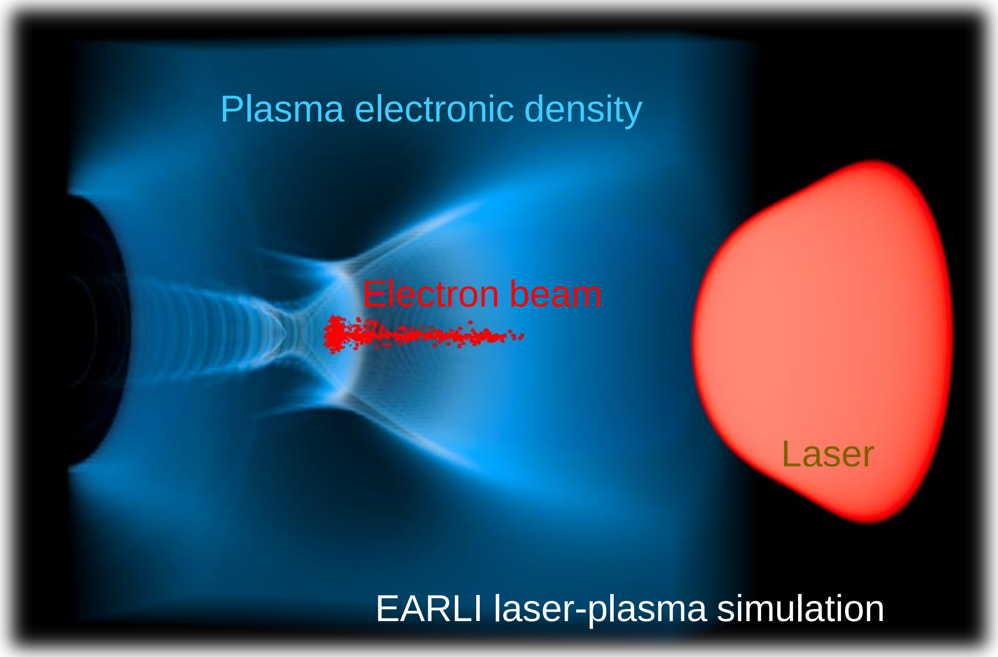
- **Laser wakefield acceleration (LWFA) has demonstrated its ability to generate high-quality electrons in a compact way**
- **Transition from laboratory experiments to full industrial accelerators (for users)**

- **EARLI**
  - A reliable and reproducible LWFA injector
  - Toward a full plasma accelerator for AWAKE
  - Stepping stone for LWFA with users
  - Crucial to beam quality control after exiting the plasma cell
  - Key for other existing projects (EuPRAXIA, PALLAS, APOLLON,…)
- **Phase 1: Design and feasibility study (Ongoing)**
  - ⇒ Conceptual design report considered
- **Phase 2: Experiments, beam commissioning and operations**

Is EARLI feasible?

- **Beam quality (laser-plasma interaction)** **⇒ Yes! (Numerically)**
- **Transfer line** **⇒ Yes! (similar to CERN design?)**
- **Laser system** **⇒ Ongoing**

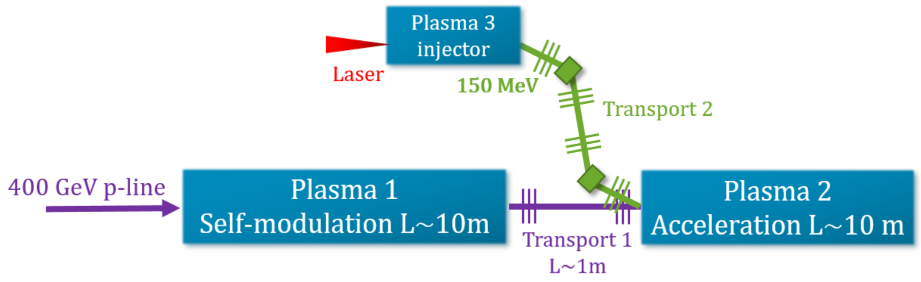
Thank you for your attention!



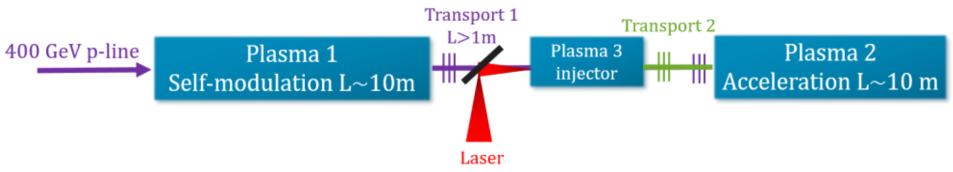
EARLI configurations

Three configurations investigated

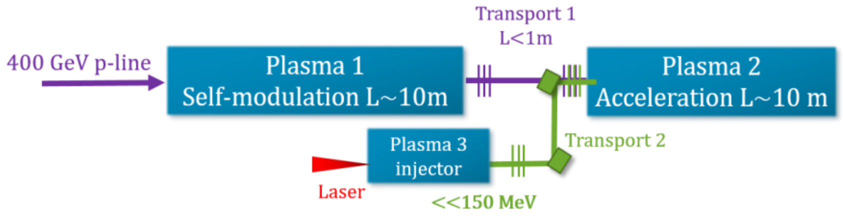
- **Configuration 1: using the transfer line from the LINAC under study**
  - The transfer line is managed by CERN.
  - EARLI must respect the beam quality requirements of this transfer line. Those requirements, especially the bunch length may be difficult to meet.



- **Configuration 2: placing the plasma cell of EARLI along the axis of the proton bunch**
  - A major difficulty comes from the focal length (>1m) of the laser.
  - After the Plasma3, the laser coming out must also be reflected in a similar way as focusing with a plasma mirror.
  - Compact focusing of the laser upstream Plasma3 and collection downstream Plasma3 can be achieved with plasma mirrors. However, their reliability from shot to shot and over the extended period envisaged for the experiments has not been established and probably requires a significant amount of R&D.
  - Beam stretching



- **Configuration 3: Building a specific transfer line for the LPA**
  - This transfer line can be based on the LINAC transfer line.
  - Can reduce restrictions on the beam quality.
  - Can help to increase the beam length.
  - Could be more compact

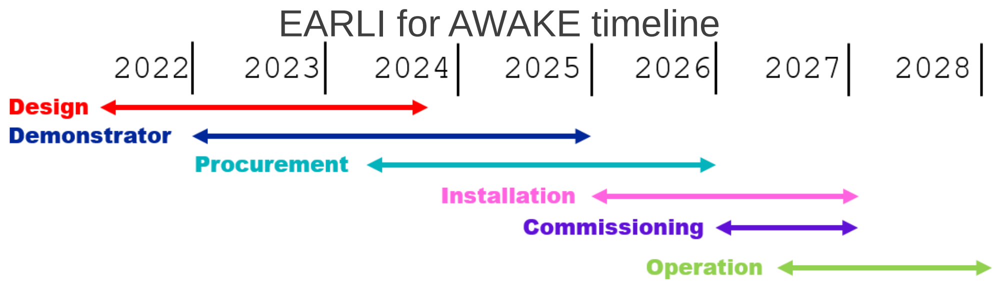


EARLI: a LWFA for AWAKE

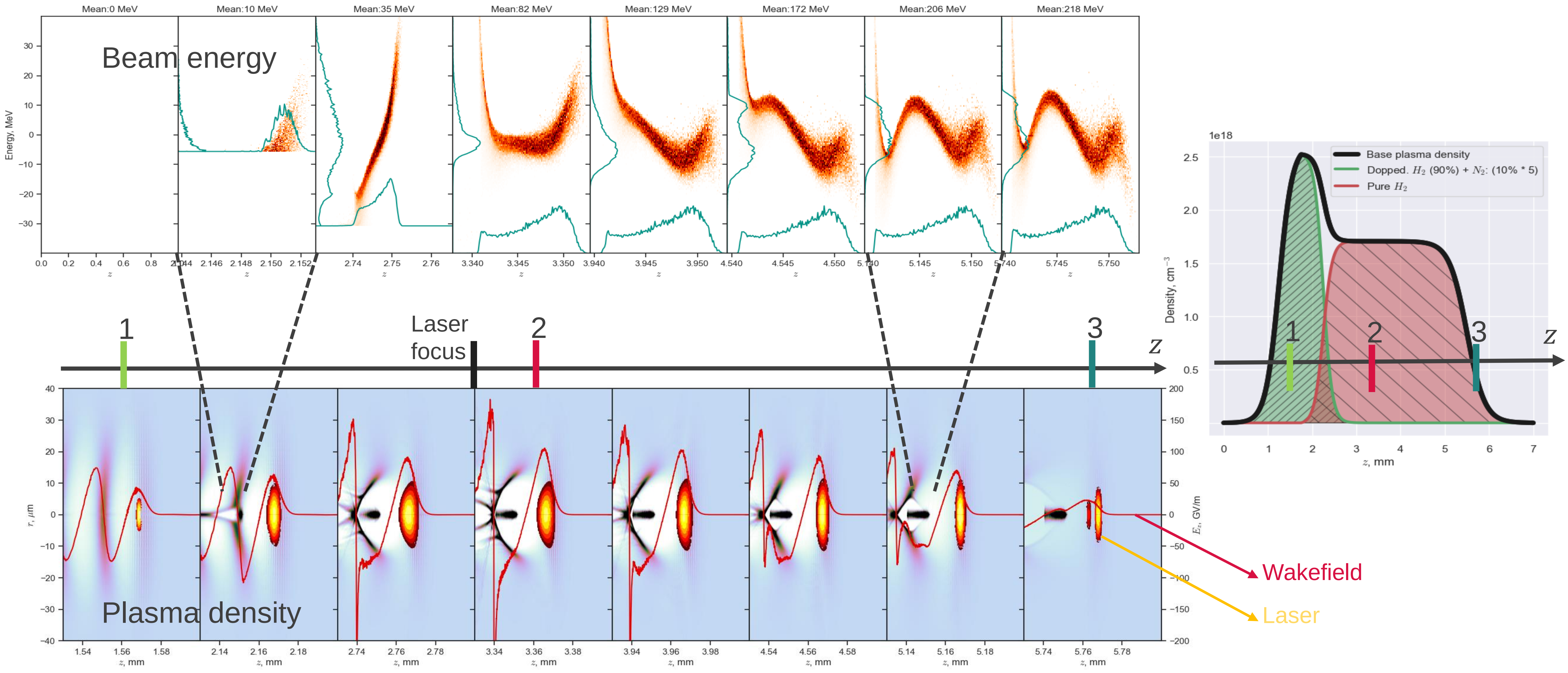
- **Phase 1: Design by numerical simulation and feasibility study**
  - Investigating the beam
    - Optimizations to obtain the targeted beam parameters
    - From injection up to the final user
    - Including all acceleration stages and transfer lines
    - Exploration of parameter ranges of the 6D beam
  - Definition of the physical parameters of components (lasers, plasmas, magnetic elements, …)
    - Main parameters
      - Beamline simulations
      - Laser-plasma simulations
      - Design of the laser
    - Including performance and tolerance study
  - Definition of beam measurements
    - Determine the needed beam measurements, their resolutions and their positions in the line
  - Assess feasibility (costs, size, …)

Feedback loop required

- **Phase 2: Experiments, simulations, beam commissioning and operations**
  - Mastering the beam
  - Participating to beam commissioning
    - Building scenario
    - Participating to implementation
  - Participating to beam operation
    - Defining the routine points
    - Setting tuning and correction procedures
    - Building the theoretical model for the real machine



Preliminary results: snapshots at different positions along the density profile

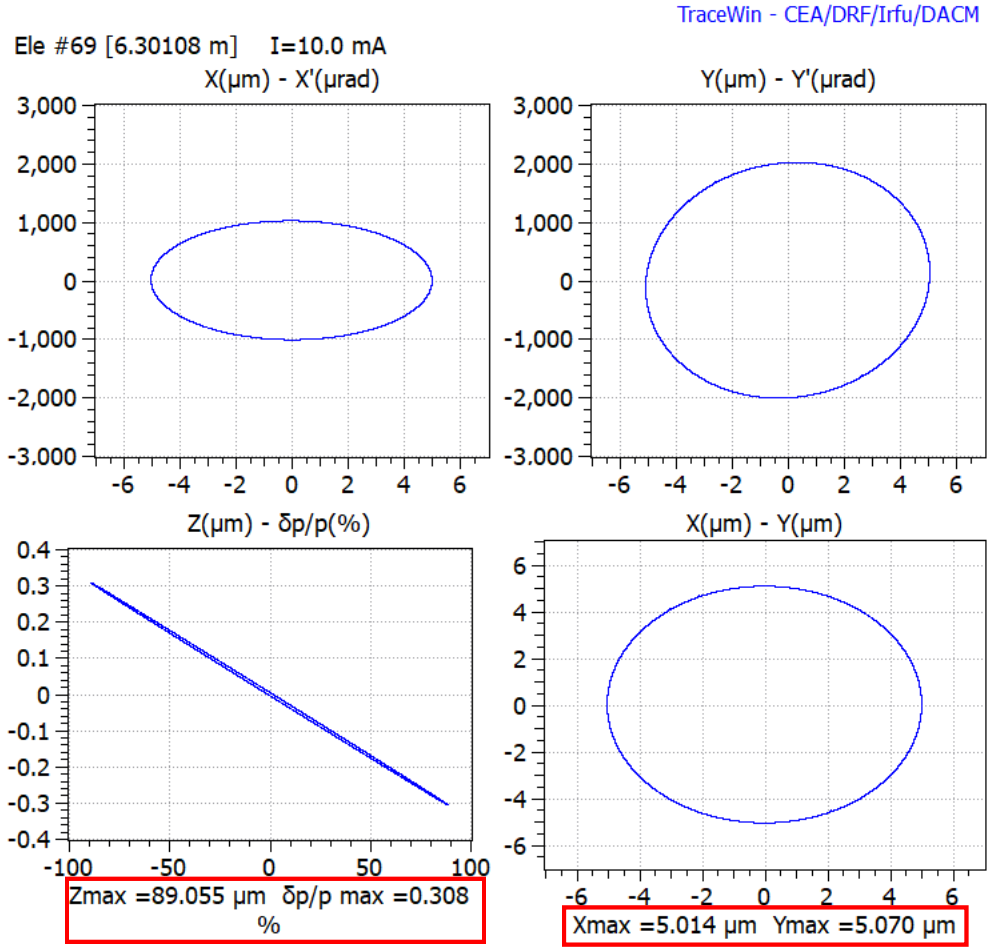


- Optimisations based on beam physics
  - Each of these steps will be investigated in detail in order to reach the targeted beam parameters

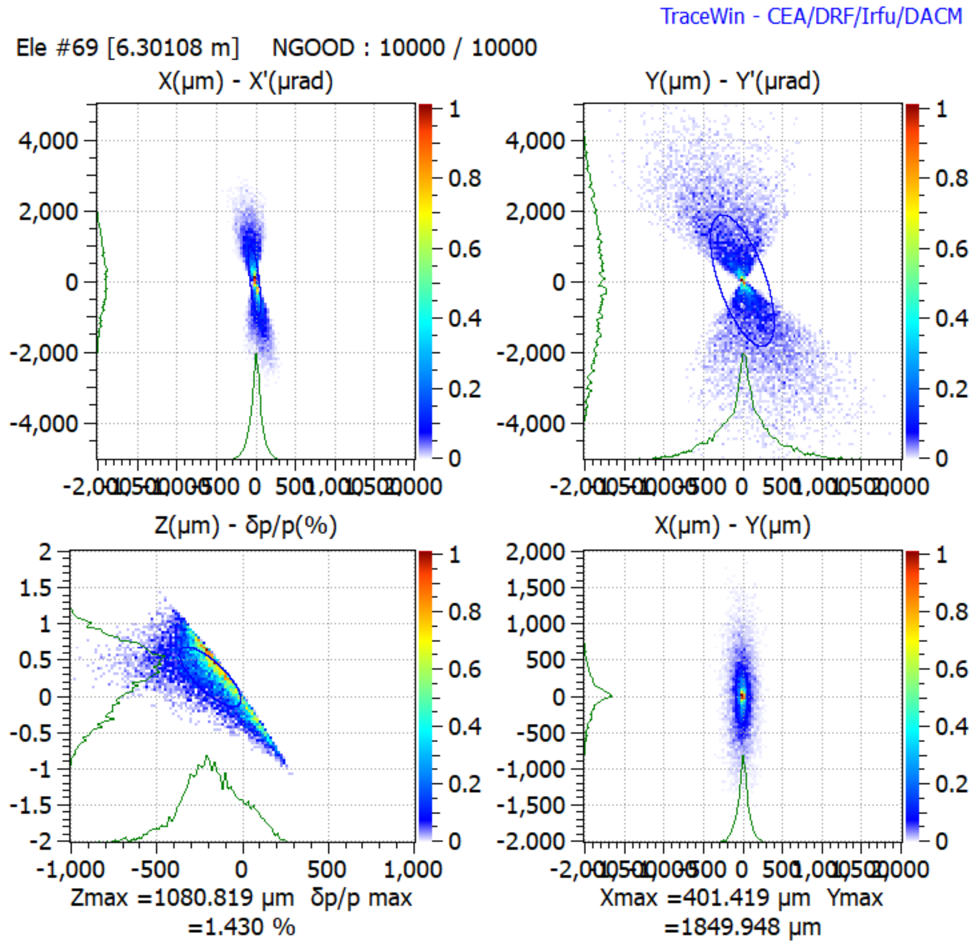
Beam parameters at the output of the transfer line

Input similar to the beam from LPA simulations

OUTPUT in envelope mode



OUTPUT in multiparticle mode



Too much aberration that should be damped by sext., oct. like in CERN design