EUROPEAN
PLASMA RESEARCH
ACCELERATOR
WITH
EXCELLENCE IN
APPLICATIONS

Status of the EuPRAXIA project

Anna Giribono (INFN-LNF)

On behalf of the EuPRAXIA collaboration

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

LPAW 2025
Laser-Plasma Accelerators Workshop 2025 April 18th, 2025

A New European High-Tech User Facility

Funded by the European Union

European Plasma Research Accelerator With Excellence In Applications

"the first European project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts and laser technology"

Building a facility with very high field plasma accelerators, driven by lasers or beams

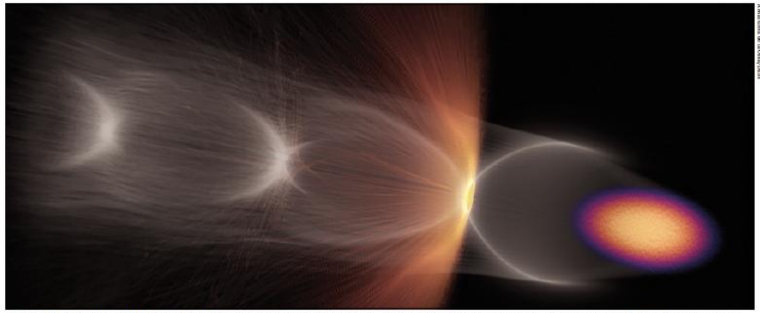
1 – 100 GV/m accelerating field

- Shrink down the facility size
- Improve Sustainability

Producing particles and photons to support several urgent and timely science cases

- *Drive short wavelength FEL*
- *Pave the way for future Linear Colliders*

FEATURE EuPRAXIA



Surf's up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini "beta squeeze" in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

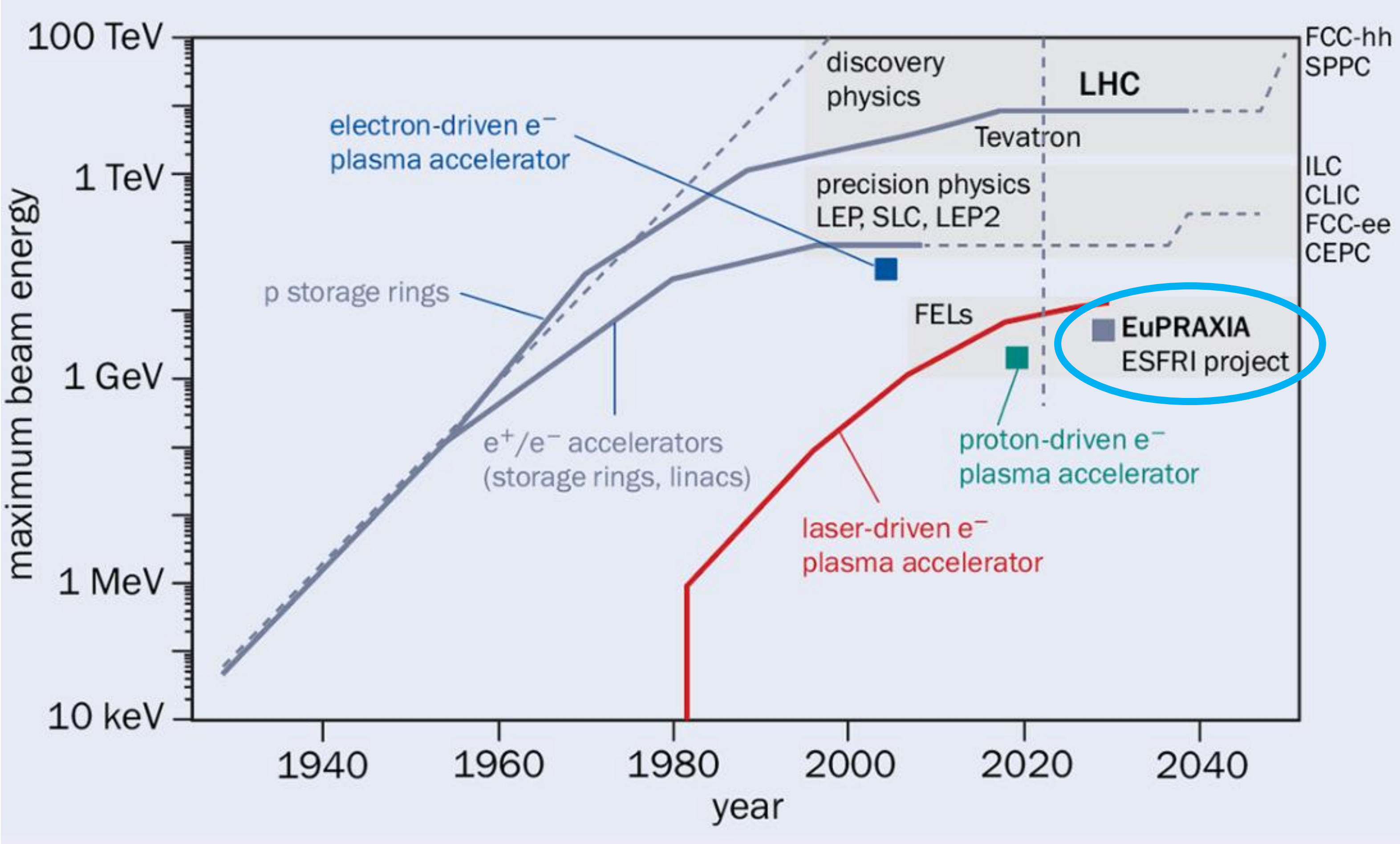
However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

THE AUTHORS
Ralph Assmann *DESY and INFN*, **Massimo Ferrario** *INFN*, **Carsten Welsch** *University of Liverpool/INFN.*

https://cerncourier.com/a/europe-targets-a-user-facility-for-plasma-acceleration/

The Livingstone Diagram

Funded by the European Union



Updated Livingston plot for accelerators, showing the maximum reach in beam energy versus time. Grey bands visualize accelerator applications

Plasma Accelerator Achievements

- Gradients up to **100 GV/m**
- Acceleration > 10 **GeV** of electron beams

EuPRAXIA Scientific Goals

Funded by the European Union

- **Free Electron Laser**
  [EuPRAXIA_MUR]
  [EuPRAXIA_PP]
  [EuPRAXIA_DN]
  [PACRI]

__Flagship Science Goal 1__: EuPRAXIA will deliver free-electron laser (FEL) X rays with 10^9-10^13 photons per pulse to user areas, covering wavelengths of 0.2 nm to 36 nm. The EuPRAXIA FEL pulses are naturally short (down to 0.4 fs) and will therefore provide users with tools for investigating processes and structures in ultra-fast photon science at a reduced facility foot print.

- **Betatron Radiation Source**
  [EuAPS_PNRR]

__Flagship Science Goal 2:__ EuPRAXIA will deliver betatron X rays with about 10^10 photons per pulse, up to 100 Hz repetition rate and an energy of 5-18 keV to users from the medical area. The much reduced longitudinal length of the X ray emission area (point-like emission) leads to an important improvement in image resolution compared to other techniques.

- **Positron Beams**

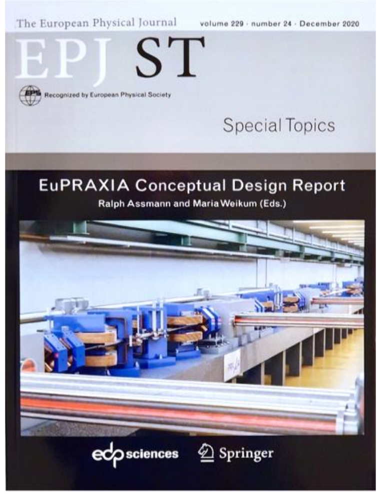
__Flagship Science Goal 3__: EuPRAXIA will deliver positron beams at energies from 0.5 MeV to 10 MeV and a repetition rate of 100 Hz for material science studies. Per pulse about 10^6 positrons will be produced in a time duration of 20-90 picoseconds on the sample, allowing time-resolved studies. EuPRAXIA will here advance the capabilities of existing positron sources in flux and time resolution.

- **e+ / e- beams**

__Flagship Science Goal 4__: EuPRAXIA will deliver electron and positron beams at energies from a few 100 MeV up to 5 GeV for high energy physics related R&D (detectors, linear collider topics). R&D goals include the demonstration of a linear collider stage, a "table top" HEP test beam and studies on positron transport and acceleration towards a linear collider.

- **ICS Photon Beams**

__Flagship Science Goal 5:__ EuPRAXIA will deliver photons from an inverse Compton scattering (ICS) source. The photons of up to 600 MeV and with narrow-band spectrum will enable precision nuclear physics and highly penetrative radiography for users.



600+ page CDR, 240 scientists contributed

- **High Rep. Rate Laser**
  [PACRI]

__Flagship Science Goal 6__: EuPRAXIA will provide access to a multi-stage, high-repetition rate plasma accelerator in the GeV range to users from accelerator science. This R&D platform will allow the testing of novel ideas and concepts, full optimisation of a plasma collider stage, certain fixed target experiments (also in combination with lasers) and performance studies of conventional versus novel accelerator technology.

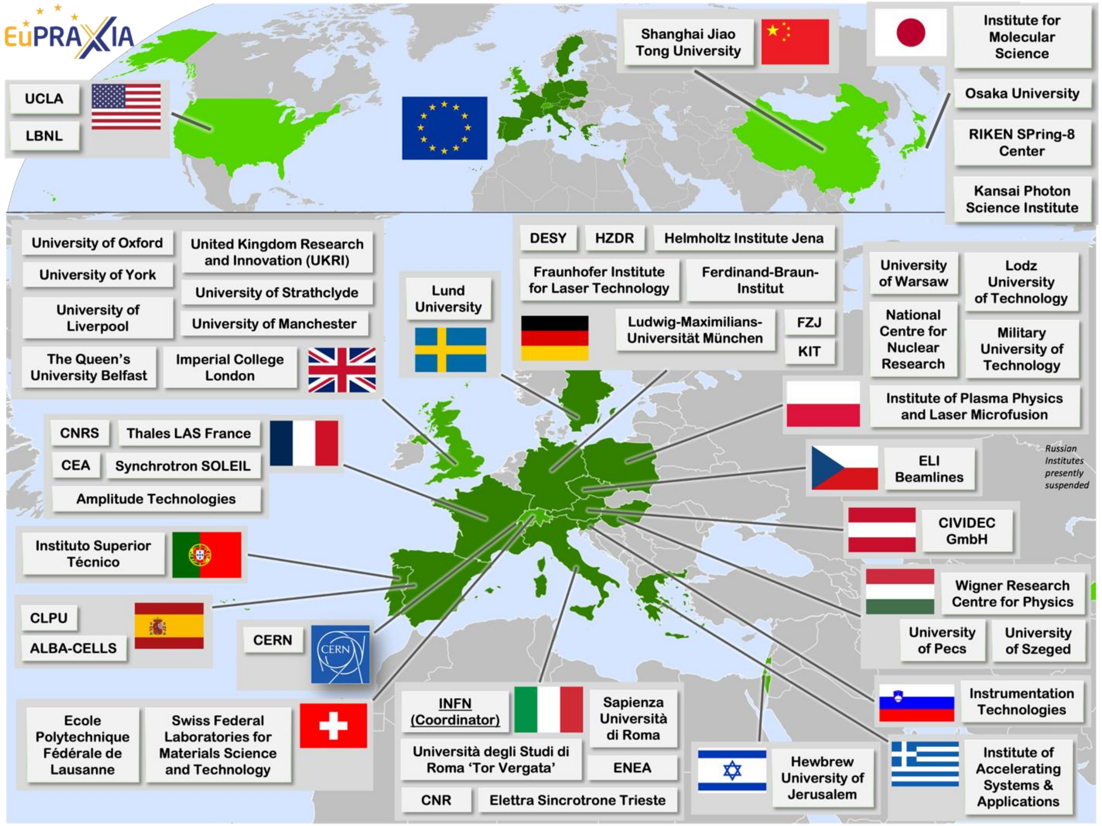
- **Laser Technology**
  [EuAPS_PNRR]

__Flagship Science Goal 7__: EuPRAXIA will provide access to cutting edge laser technology with short pulse length in combination with high energy photon pulses and short electron/positron bunches. Novel schemes of pump probe configurations and ultra-precise timing will be researched, feeding back into laser science.

Wide International Collaboration

Funded by the European Union

- **The EuPRAXIA Consortium today: 54 institutes** from **18 countries** plus CERN
- Included in the **ESFRI** Road Map
- **Efficient fund raising:**
  - –**Preparatory Phase** consortium (funding EU, UK, Switzerland, in-kind)
  - –**Doctoral Network** (funding EU, UK, in-kind)
  - –**EuPRAXIA@SPARC_LAB** (Italy, in-kind)
  - –**EuAPS Project** (Next Generation EU)
  - –**PACRI**



Funded by the European Union

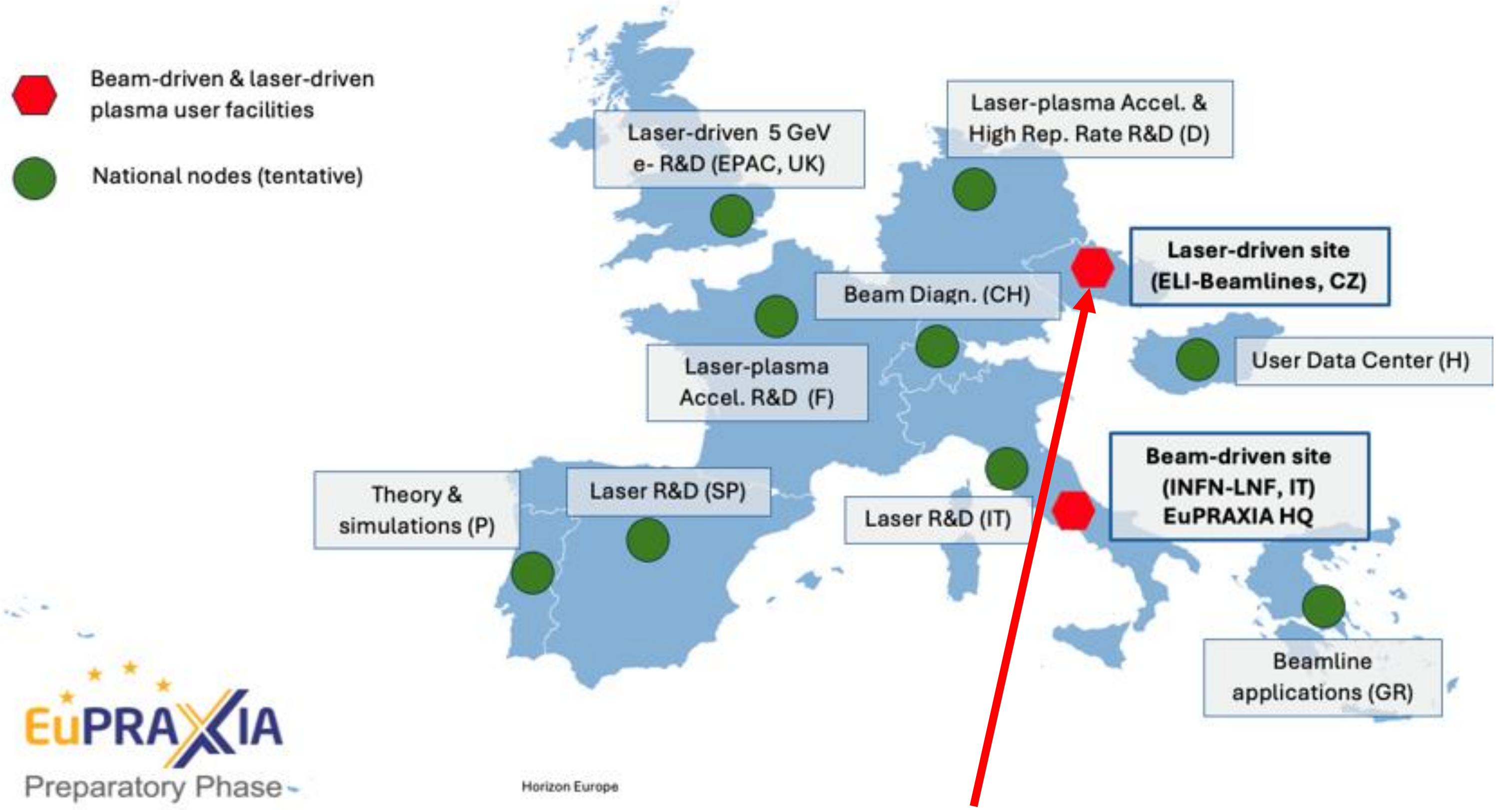
EuPRAXIA selects ELI for the Laser-Driven Accelerator Site

https://www.eupraxia-facility.org/post/eupraxia-selects-eli-for-second-laser-driven-accelerator-site

The EuPRAXIA Consortium selected the ELI Beamlines Facility in Czech Republic as the site for its laser-driven plasma accelerator pillar. *ELI Beamlines was selected for its infrastructure readiness, state-of-the-art laser systems, and comprehensive technical expertise.*

EuPRAXIA also recognises the *important roles of the other candidates for the second site*, EPAC and CNR-INO.

- **EPAC** could contribute to EuPRAXIA as a centre for R&D, focusing on advancing research towards achieving a high-quality 5 GeV electron beam.
- While **CNR-INO** could function as EuPRAXIA's National Node in Italy.



See 'The ELI Beamlines Scientific Programme' D. Margarone's talk for more details

Headquarter and Site 1: EuPRAXIA@SPARC_LAB

Funded by the European Union

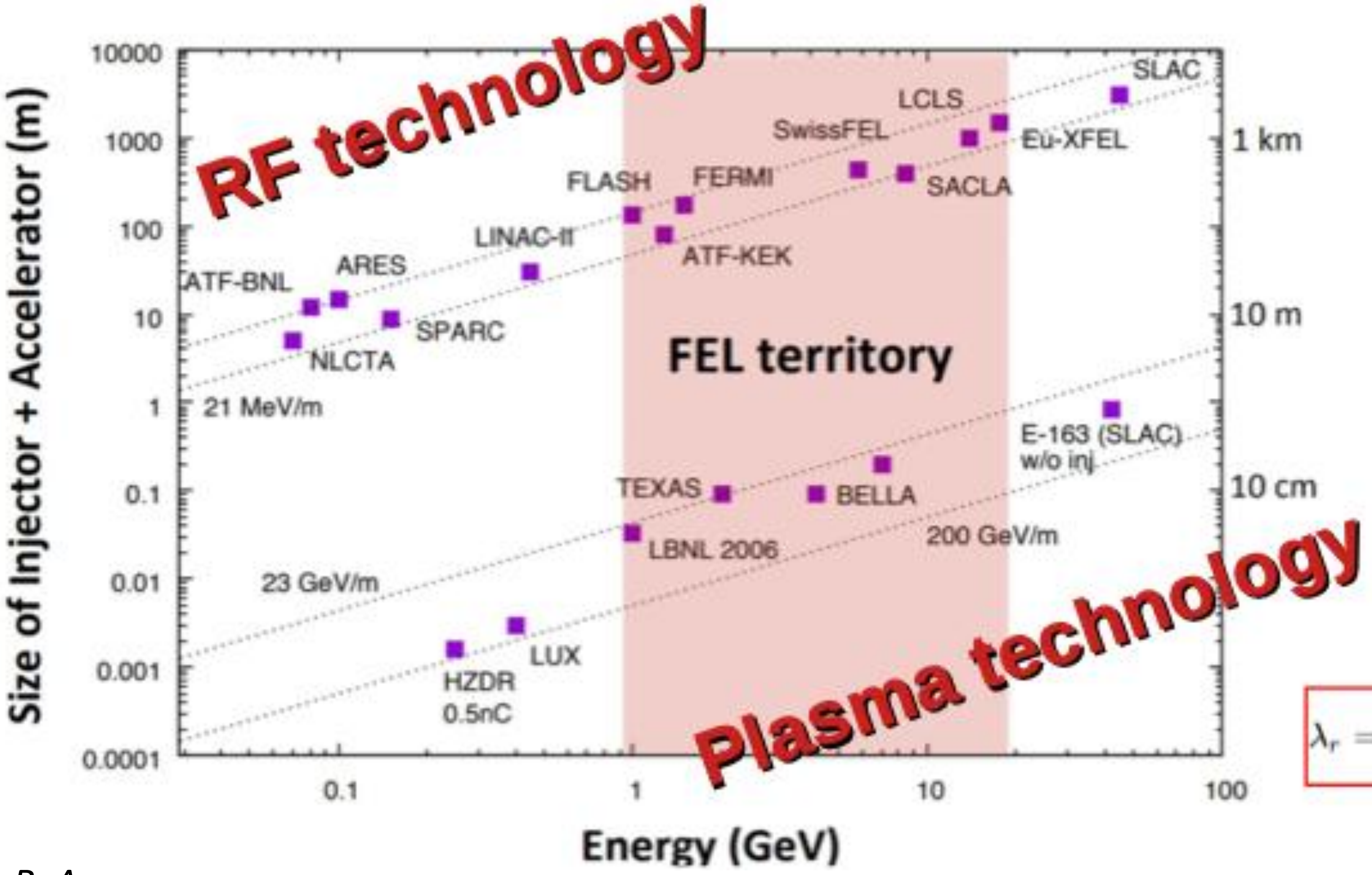
Frascati`s future facility

- > 130 M€ invest funding
- Beam-driven plasma accelerator - *PWFA*
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator **X band with CERN**

- **Technical Design Report completed (due by June 2025)**
- **Construction site opening: September 2026**

Credit: INFN and Mythos – consorzio stabile s.c.a.r.l. www.eupraxia-pp.org

High Quality Beams Required



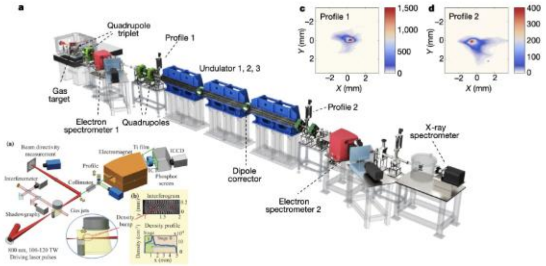
$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

R. Assmann

Basic beam quality achieved in pilot FEL experiments

2021 Plasma FEL Feasibility Proven: Laser-driven

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).



Recent ground-breaking result in China

500 MeV electron beam from a laser wakefield accelerator

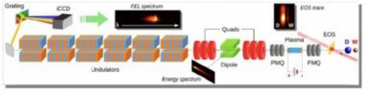
FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)

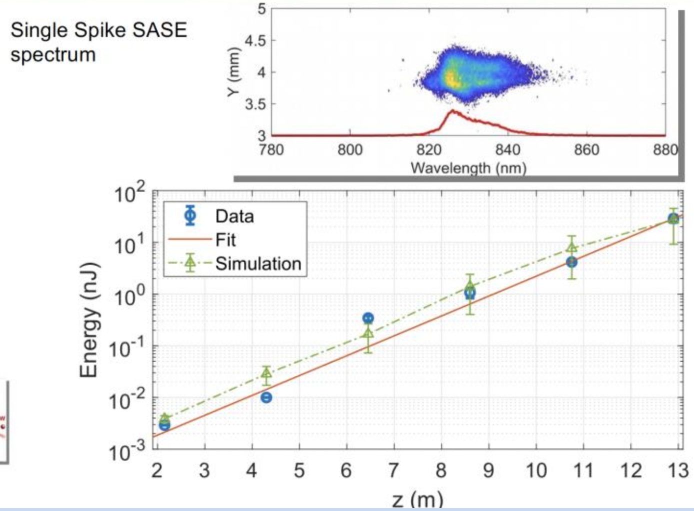
2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

Pompili et al., Nature **605**, 659–662 (2022)





Seeded UV free-electron laser driven by LWFA

Collaboration Soleil/HZ Dresden, published on
Nat. Photon. (2022). https://doi.org/10.1038/s41566-022-01104-w

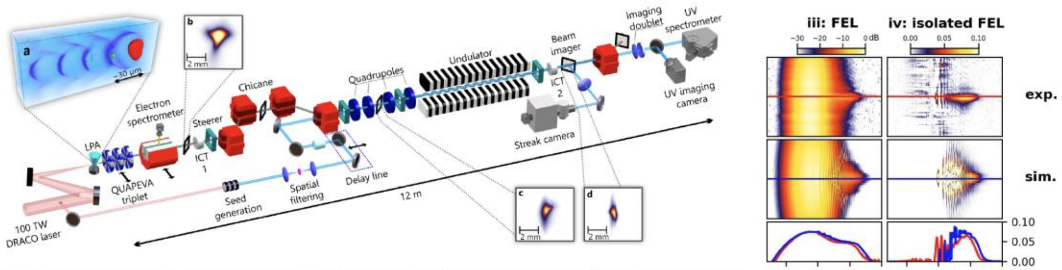
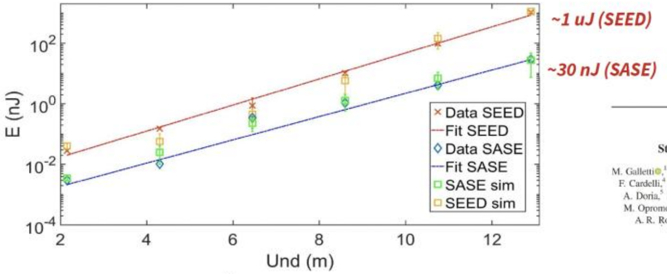


FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled elements: dipoles (*red blocks*), optical lenses (*blue*), mirrors (*grey circled black disks*). Inset **a**: Particle-in-Cell simulation renders of the accelerating structure driven by the laser pulse (*red*), the electron cavity sheet formed from the plasma medium (*light blue*) is visible in *purple* and the accelerated electron bunch visible in *green*. Insets **b,c,d**: Electron beam transverse distribution measured at LPA exit (**b**), at undulator entrance (**c**) and at undulator exit (**d**).

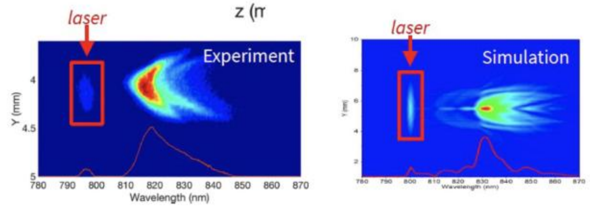
First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)



PHYSICAL REVIEW LETTERS **129**, 234801 (2022)

Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti,[1,2,3,*] D. Alesini,[4] M. P. Anania,[4] S. Arjmand,[4] M. Behtouei,[4] M. Bellaveglia,[4] A. Biagioni,[4] B. Buonomo,[4] F. Cardelli,[4] M. Carpanese,[5] E. Chiadroni,[4,6] A. Cianchi,[1,2,3] G. Costa,[4] A. Del Dotto,[7] M. Del Giorno,[4] F. Dipace,[4] A. Doria,[5] F. Filippi,[5] G. Franzini,[4] L. Giannessi,[4] A. Giribono,[4] P. Iovine,[8] V. Lollo,[4] A. Mostacci,[6] F. Nguyen,[5] M. Opromolla,[9,10] L. Pellegrino,[4] A. Petralia,[5] V. Petrillo,[9,10] L. Piersanti,[4] G. Di Pirro,[4] R. Pompili,[4] S. Romeo,[4] A. R. Rossi,[10] A. Selce,[5,11] V. Shpakov,[4] A. Stella,[4] C. Vaccarezza,[4] F. Villa,[4] A. Zigler,[4,12] and M. Ferrario[4]

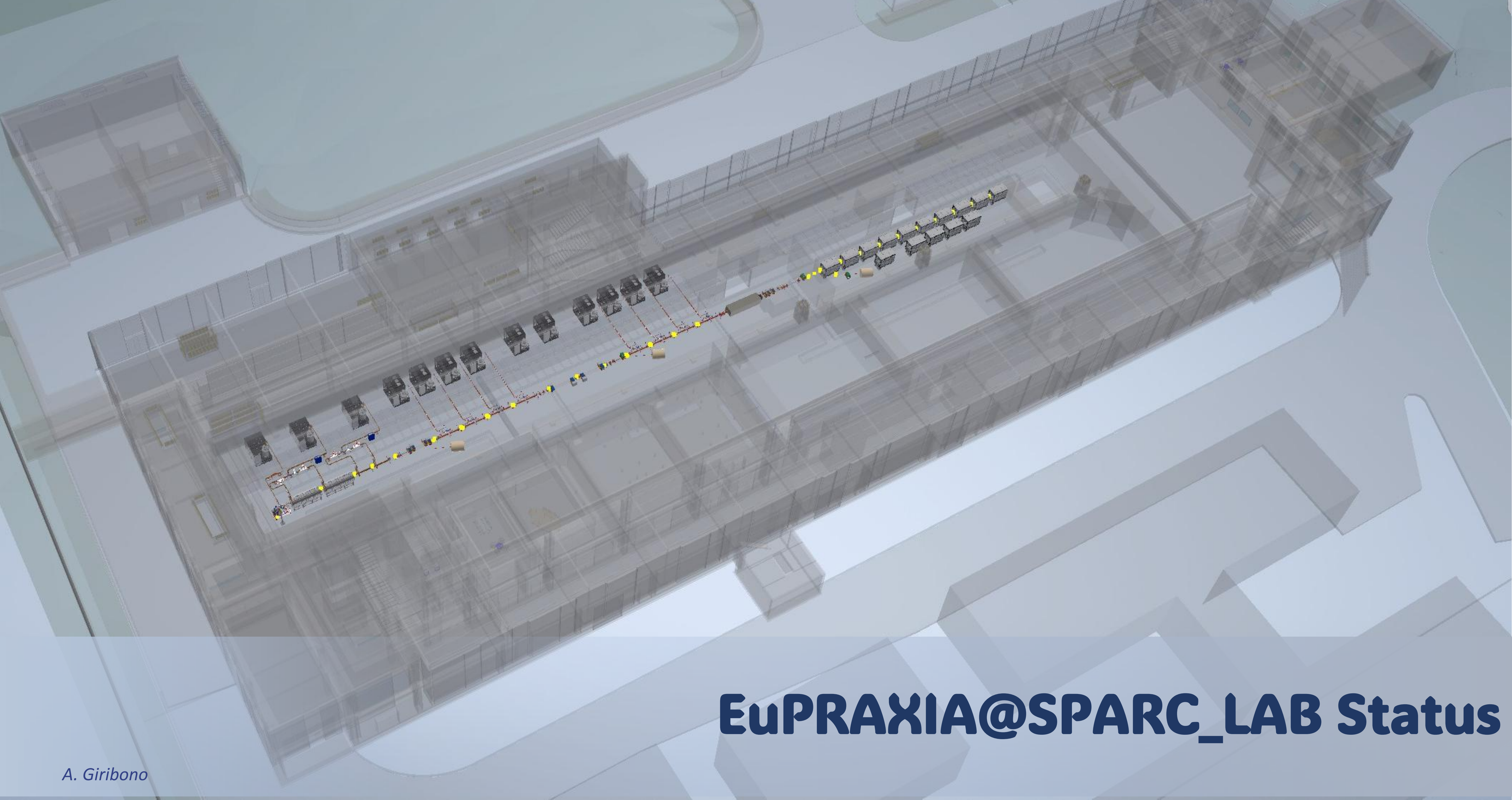


Seeded FEL radiation

- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

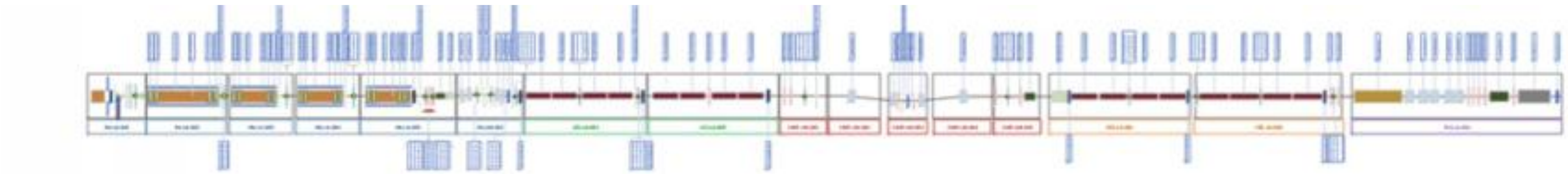
! News: Demonstration of a reliable, high gain laser plasma accelerator driven free electron laser at BELLA center presented at LPAW 2025, April 15 !

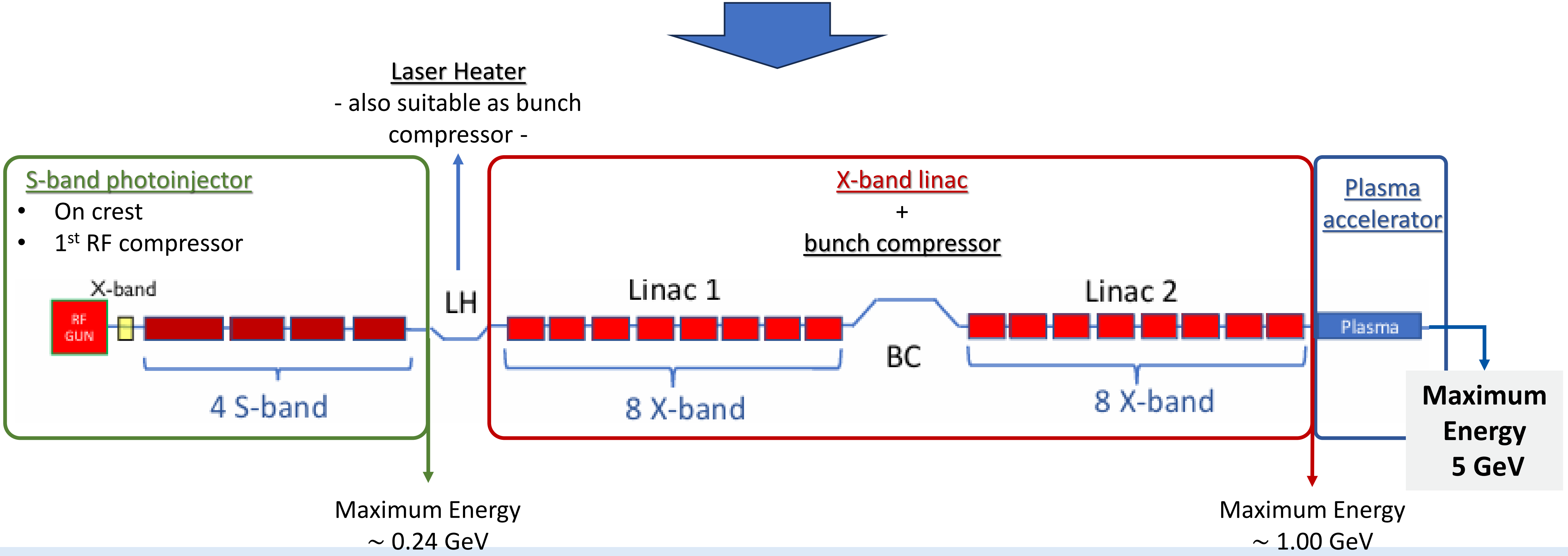
EuPRAXIA@SPARC_LAB machine layout completed



The EuPRAXIA@SPARC_LAB accelerator

Funded by the European Union

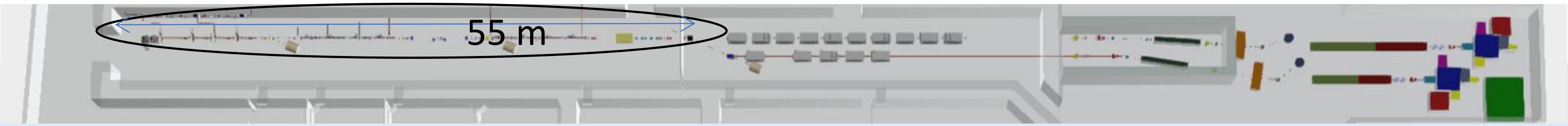




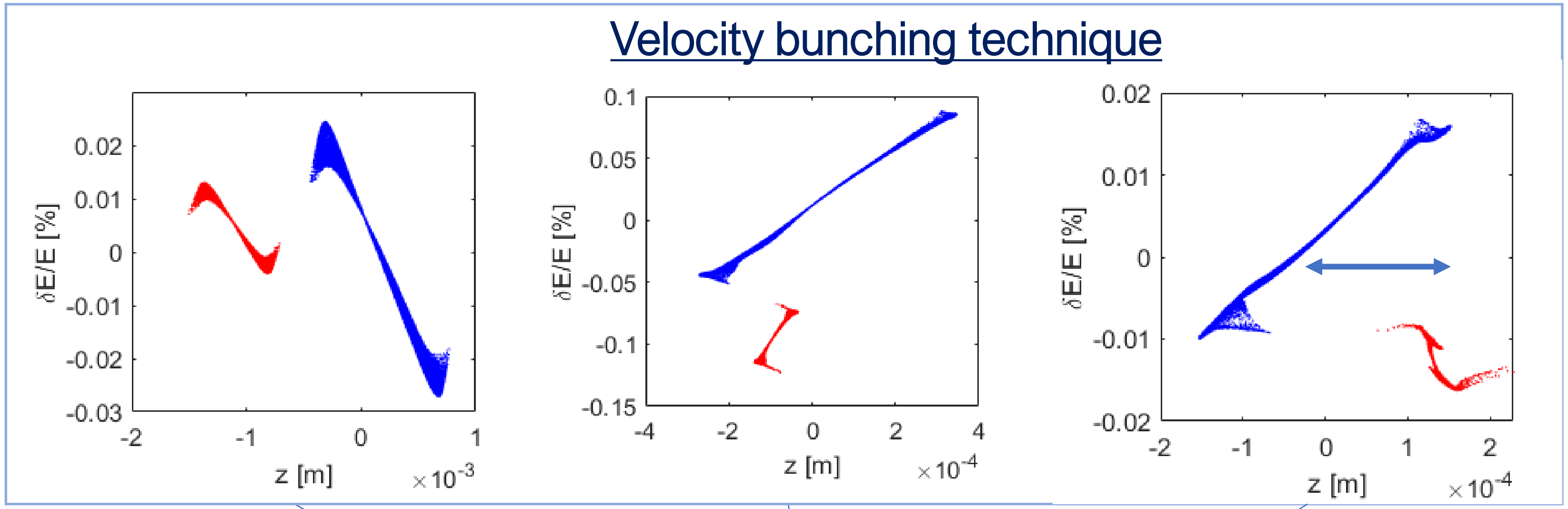
Expected electron parameters from the EuPRAXIA@SPARC_LAB accelerator

Parameter	Unit	PWFA	Full X-band
Electron Energy	GeV	1-1.2	1
Bunch Charge	pC	30-50	200-500
Peak Current	kA	1-2	1-2
RMS Energy Spread	%	0.1	0.1
RMS Bunch Length	μm	6-3	24-20
RMS norm Emittance	μm	1	1
Slice Energy Spread	%	≤0.05	≤0.05
Slice norm Emittance	mm-mrad	0.5	0.5

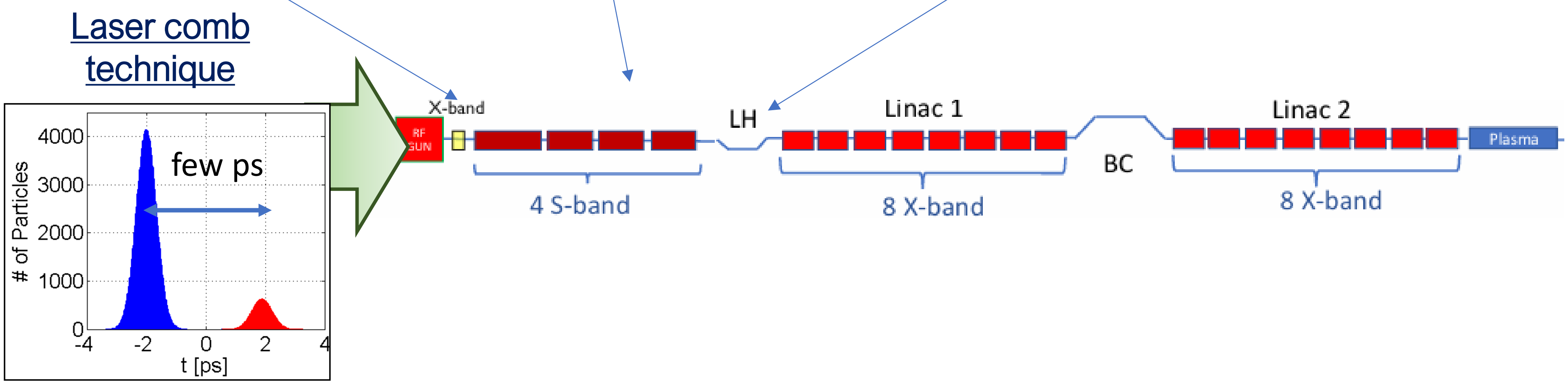
- Two different configurations:
  - **Main**: ∼500 MeV beam from the X-band linac + 60 cm capillary **PWFA** acceleration up to **1.2 GeV**
    - Smaller accelerated charge
    - Shorter pulses
    - Final energy easily upgradable in future with similar building occupancy (∼ m)
  - **Secondary**: ∼**1 GeV** beam from the **X-band** linac alone (with additional RF power)
    - Larger charge per bunch
    - Longer pulses
    - At the upper limit of RF technology (not easily upgradable without extending the occupancy)



High brightness beam generation: the SPARC like S-band photoinjector



Routinely operation at SPARC_LAB!



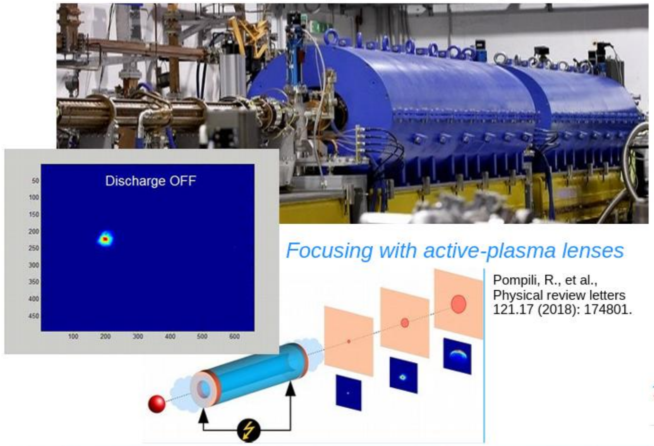
[*] M. Ferrario et al, NIMA Vol. 637, Issue 1, pp 43-46 (2011) doi: https://doi.org/10.1016/j.nima.2010.02.018

The SPARC_LAB experience

Funded by the European Union

Milestones

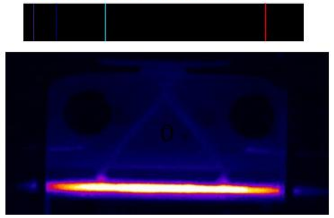
Activities with the high-brightness SPARC photo-injector



Focusing with active-plasma lenses

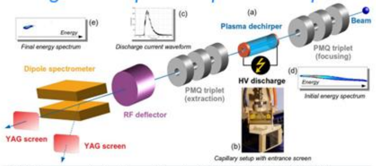
Pompili, R., et al., Physical review letters 121.17 (2018): 174801.

Plasma characterization



Biagioni, A., et al., Journal of Instrumentation 11.08 (2016)

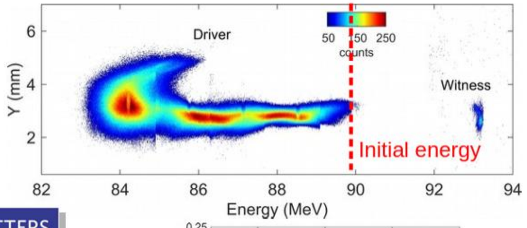
Longitudinal phase-space manipulation



V. Shpakov et al. Phys. Rev. Lett. 122, 114801 (2019)

Control of the energy spread

4 MeV acceleration in 3 cm plasma with 200 pC driver
~133 MV/m accelerating gradient
2x10^{15} cm^{-3} plasma density
<u>Demonstration of projected energy spread compensation</u>
Spread from 0.2% to 0.12%

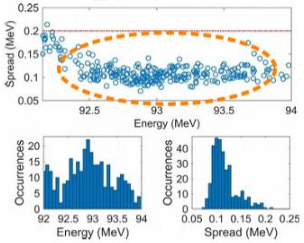


nature physics — LETTERS

https://doi.org/10.1038/s41567-020-01116-9

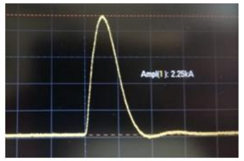
Energy spread minimization in a beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, M. P. Anania, M. Behtouei, M. Bellaveglia, A. Biagioni, F. G. Bisesto, M. Cesarini, E. Chiadroni, A. Cianchi, G. Costa, M. Croia, A. Del Dotto, D. Di Giovenale, M. Diomede, F. Dipace, M. Ferrario, A. Giribono, V. Lollo, L. Magnisi, M. Marongiu, A. Mostacci, L. Piersanti, G. Di Pirro, S. Romeo, A. R. Rossi, J. Scifo, V. Shpakov, C. Vaccarezza, F. Villa and A. Zigler

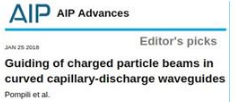


Particle bending with plasma

- Yet another use of plasma
- The large magnetic fields produced in the plasma can be used to bend particles
  - *Compactness. Large deflection angles*
  - *Tunability. The bending is tuned by adjusting the discharge-current*
  - *Cheap solution*
  - *Tunable dispersion (dispersion-free also possible) by changing the discharge current*



D. Pellegrini, T. De Nardis, G. Grilli



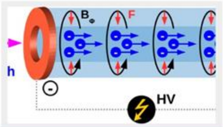
AIP Advances

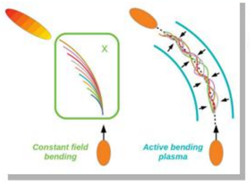
Editor's picks

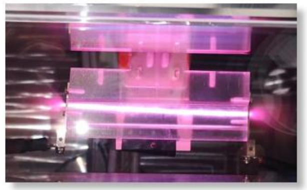
JAN 25 2018

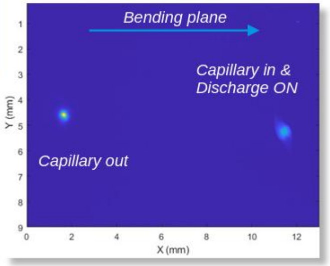
Guiding of charged particle beams in curved capillary-discharge waveguides

Pompili et al.

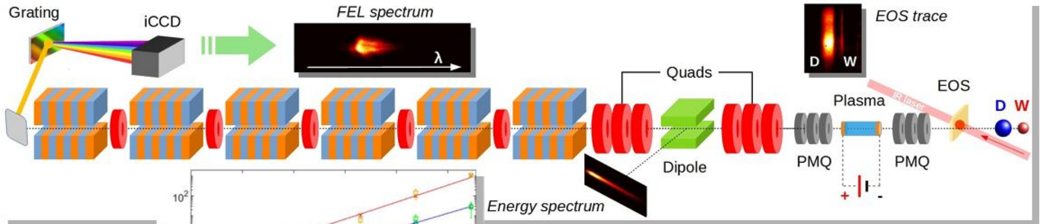


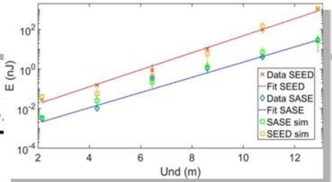






First demonstration of FEL lasing





nature

Article | Published: 25 May 2022

Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, ... M. Ferrario

Nature 605, 659–662 (2022)

PHYSICAL REVIEW LETTERS

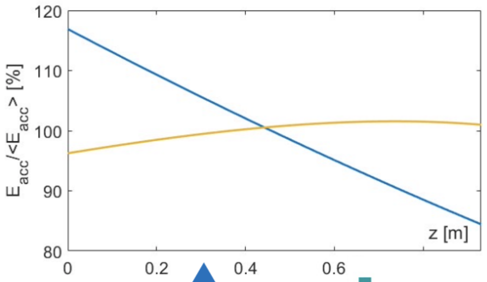
Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

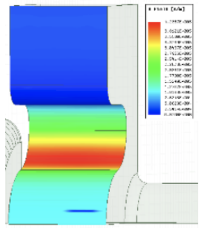
M. Galletti et al.

Phys. Rev. Lett. 129, 234801 – Published 29 November 2022

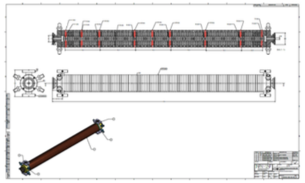
World`s Most Compact RF Linac: X Band

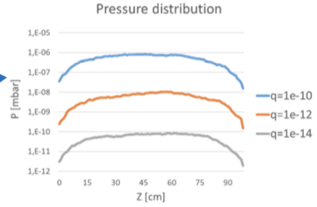
Funded by the European Union

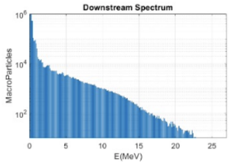




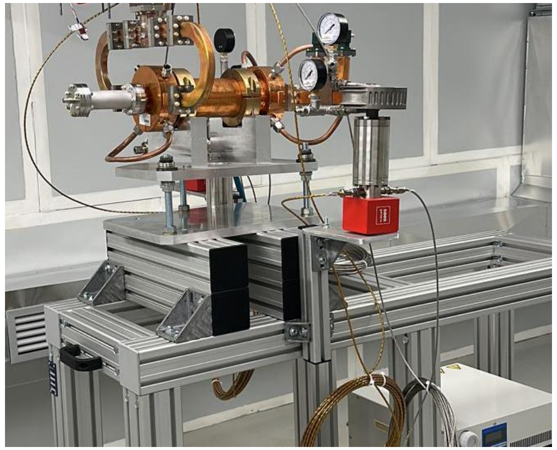
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*



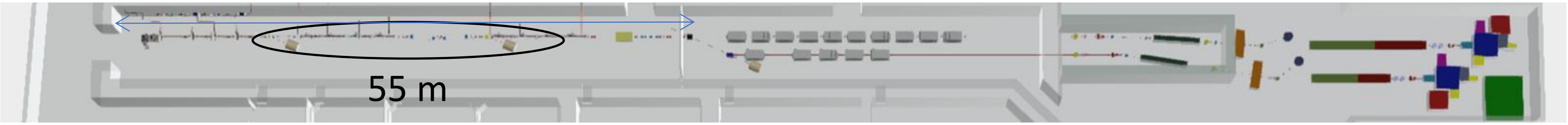




PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt impedance R [MΩ/m]	93-107	100
Effective shunt Imp. $R_{sh\ eff}$ [MΩ/m]	350	347
Peak input power per structure [MW]	70	
Input power averaged over the pulse [MW]	51	
Average dissipated power [kW]	1	
P_{out}/P_{in} [%]	25	
Filling time [ns]	130	
Peak Modified Poynting Vector [W/μm²]	3.6	4.3
Peak surface electric field [MV/m]	160	190
Unloaded SLED/BOC Q-factor Q_0	150000	
External SLED/BOC Q-factor Q_E	21300	20700
Required Kly power per module [MW]	**20**	
RF pulse [μs]	**1.5**	
Rep. Rate [Hz]	**100**	



X-band cavity prototype under test at TEX facility (INFN-LNF)

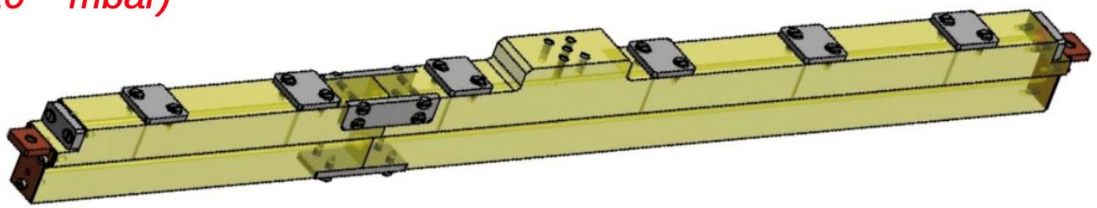


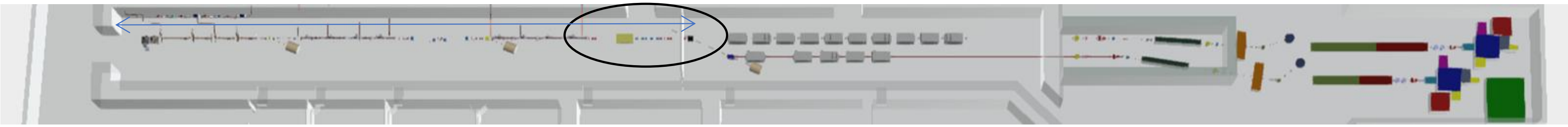
Courtesy D. Alesini

Plasma Module

- 40 cm long capillary → 1st prototype for the EuPRAXIA facility
  - *Made with special junction to allow negligible gas leaks (<10^{-10} mbar)*
- Operating conditions
  - *1 Hz repetition rate (to be increased up to 100 Hz)*
  - *10 kV – 380 A minimum values for ionization*
  - *6 inlets for gas injection. Electro-valve aperture time 8-12 ms*

A. Biagioni, V. Lollo



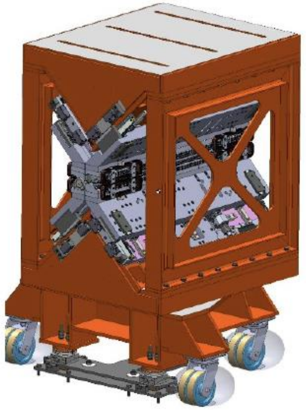


Courtesy A. Biagioni, R. Pompili

Radiation Generation: FEL

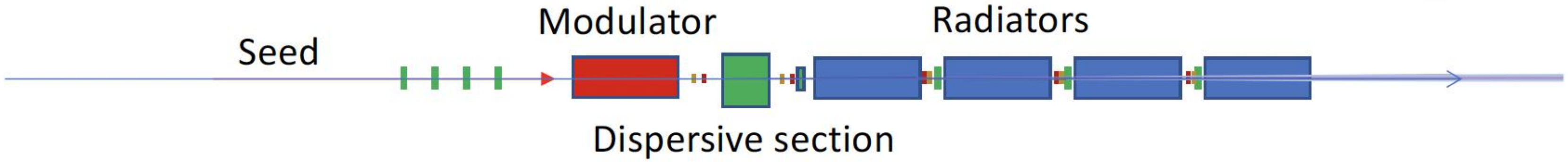
Two FEL lines:

1) *AQUA*: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)

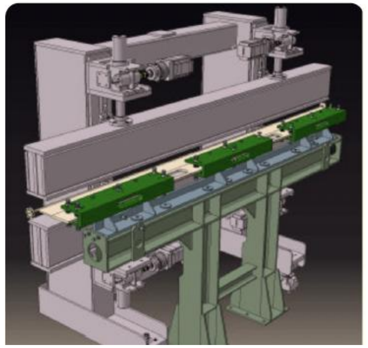


SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress

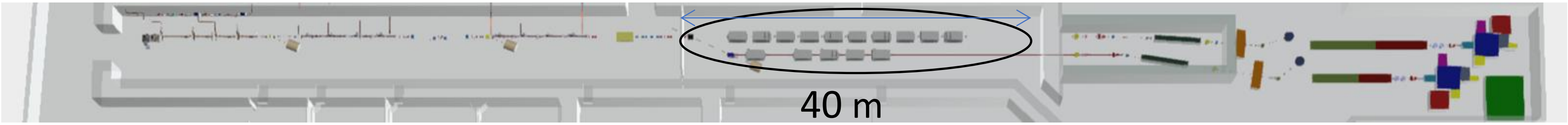
2) *ARIA*: VUV seeded HGHG FEL beamline for gas phase



FERMI FEL-1 Radiator



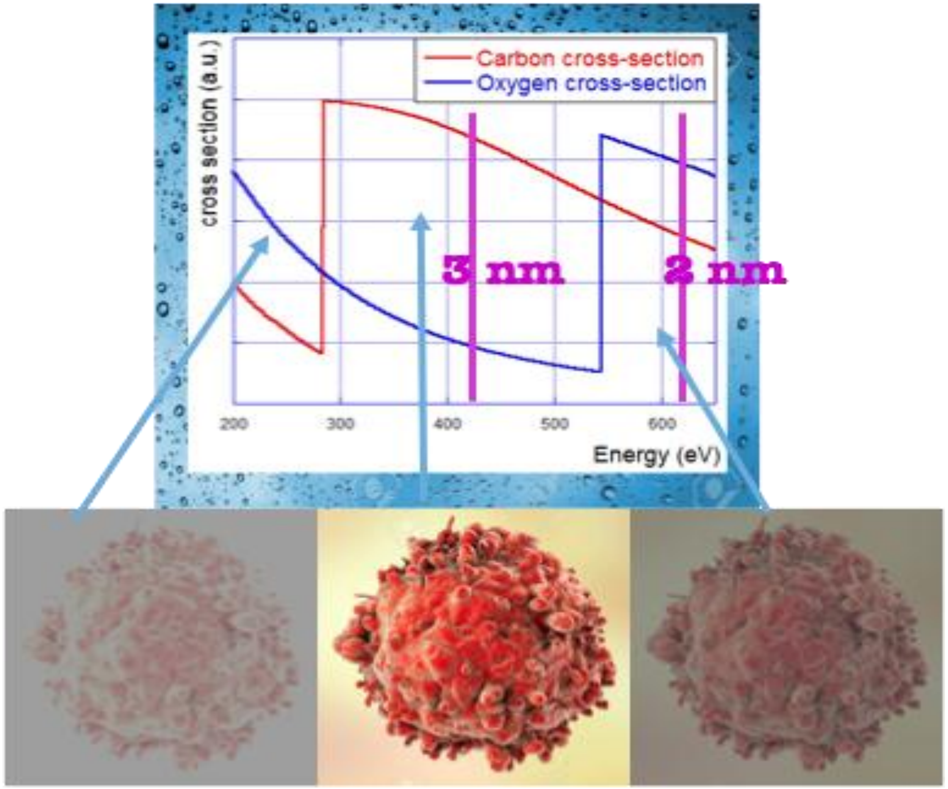
SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 50 - 100 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.



AQUA beamline scientific case

Funded by the European Union

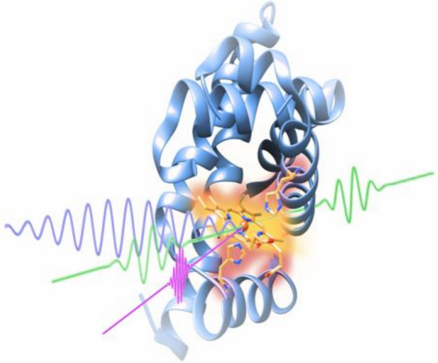
In the energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state.
Possibility to study dynamics ~10^{11} photons/pulse needed

And other experimental techniques and typology of samples

- Coherent imaging
- X-ray spectroscopy
- Raman spectroscopy
- Photo-fragmentation of molecules



Courtesy F. Stellato

EuPRAXIA@SPARC_LAB
Start to End Simulation Results

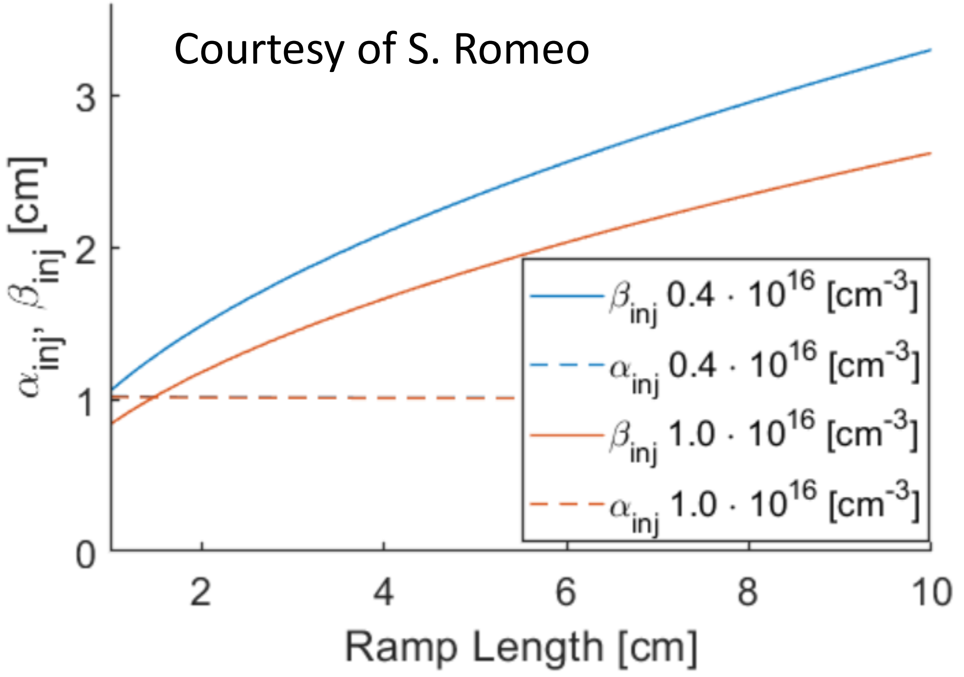
Radiation Parameter	Unit	PWFA	Full X-band
Wavelength	nm	**3-4**	4
Pulse length (fwhm)	fs	**15.0**	-
Photons per Pulse	$\times 10^{12}$	**0.1- 0.25**	1
Photon Bandwidth	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$\left(\frac{s\ mm^2 mrad^2}{bw(0.1\%)}\right)$	$\mathbf{1\text{–}2\ \times 10^{28}}$	$1\ \times 10^{27}$

Electron Beam Parameter	Unit	PWFA	Full X-band
Electron Energy	GeV	**1-1.2**	1.2
Bunch Charge	pC	**30 - 50**	200-500
Peak Current	kA	**~ 3.0**	1-2
RMS Energy Spread	%	**< 1**	0.1
RMS Bunch Length	μm	**3-6**	24-20
RMS norm. Emittance	μm	**0.7 – 1.2**	1
Slice Energy Spread	%	**≤0.05**	≤0.05
Slice norm Emittance	mm-mrad	**0.5 – 0.8**	0.5
Energy jitter	%	**< 1**	0.1

- **Bold values indicate the main working point**

Working point optimisation of the comb beam for plasma acceleration

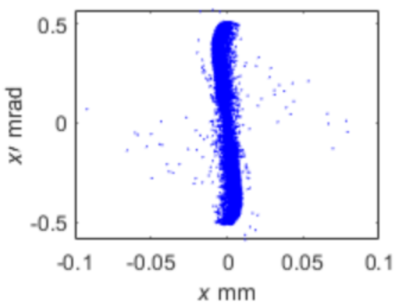
- The working point optimisation starts from desired plasma accelerating gradient and beam brightness at FEL entrance.
- It relies on **following considerations**
  - **Longitudinal phase space** →
    - Double RF compression in the photoinjector for fine-tuning of bunch current profile and spacing
    - Avoiding beam overlapping that leads to anomalous dynamics in the plasma and the downstream transport line to the FEL (driver removal through chicane)
  - **Transverse phase space** → matching to the plasma in terms of Twiss parameters
    - emittance preservation through the insertion of plasma ramps
  - **Matching in the X-band linac** with *'fodo'-like* behaviour and low beta function (<30 m) → better control of wakefields in case of misalignments

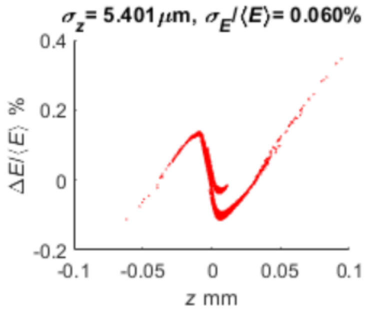


[*] S Romeo *et al* 2023 *Plasma Phys. Control. Fusion* **65** 115005**DOI** 10.1088/1361-6587/acfbf6

1 GeV electron beams with PWFA

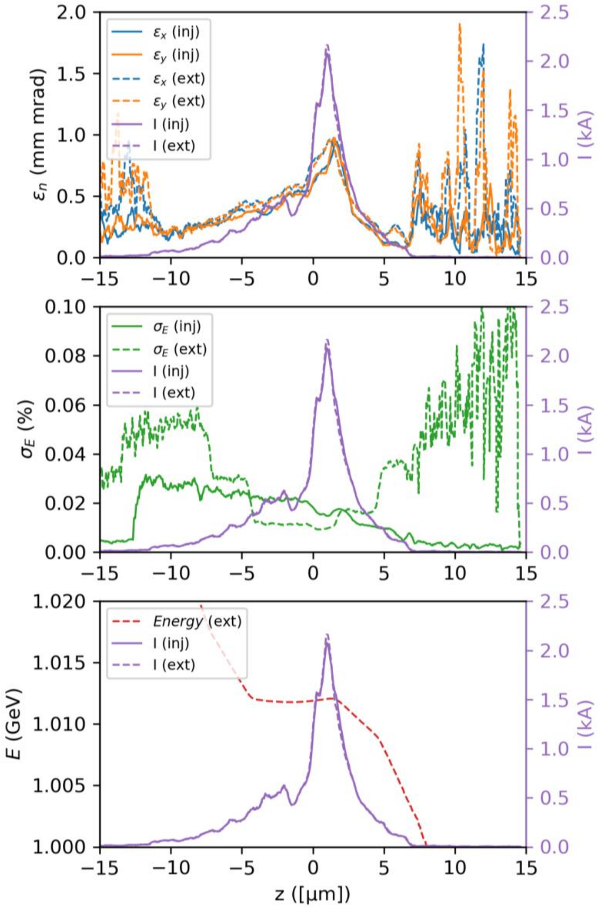
Funded by the European Union



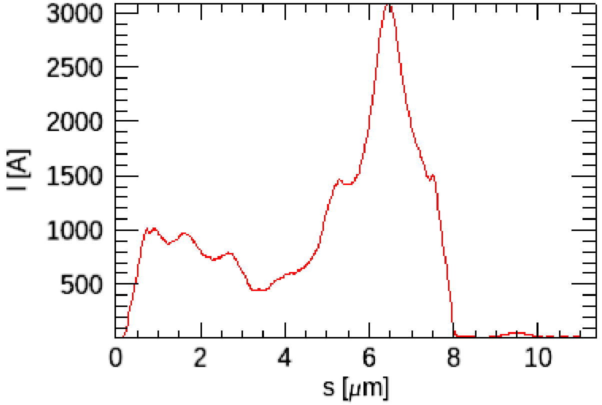


@linac exit	witness	driver
Charges	30-50	200 - 500
Energy (GeV)	0.5 – 1.0	0.5 – 1.0
I_{peak} (kA)	2 - 3	0.5 – 2.5
dE/E (‰)	0.06 – 0.08	0.13 – 0.20
Proj. Emitt xy (mm-mrad)	0.65	1.5 – 4.0
Delay (ps)	0.5 – 1.0	1.5 – 4.0

Beam parameters @linac exit



Witness slice analysis @plasma exit



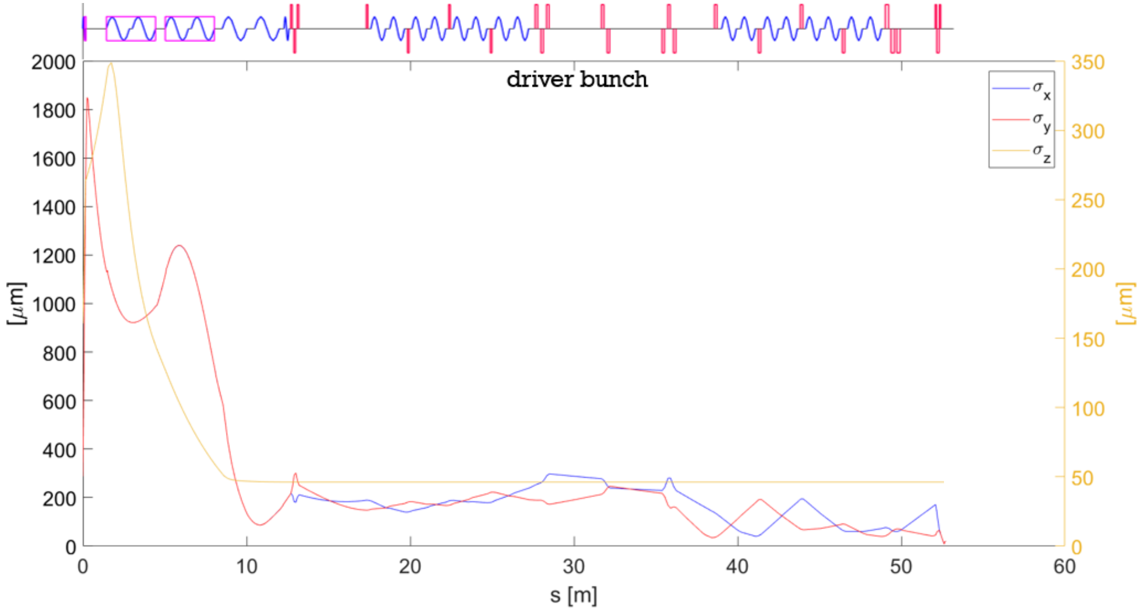
Energy (GeV)	1
Energy jitter (%)	1
I_{peak} (kA)	3.07
dE/E (‰)	0.46
Proj. Emitt x	0.69
Proj. Emitt y	0.65

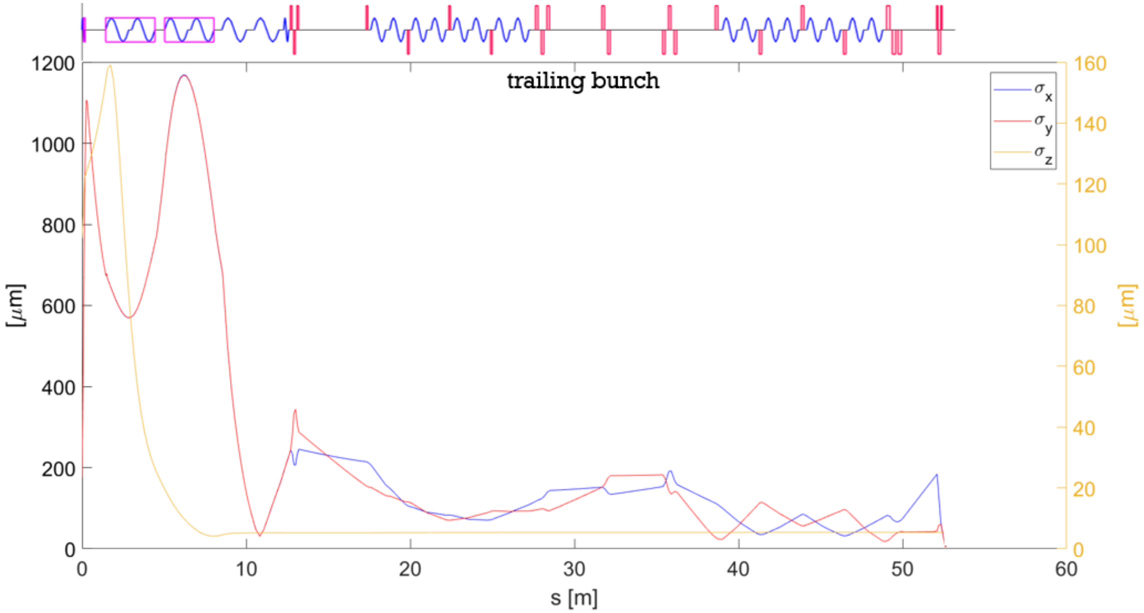
Witness slice analysis (upper) and rms parameters (lower) @FEL entrance

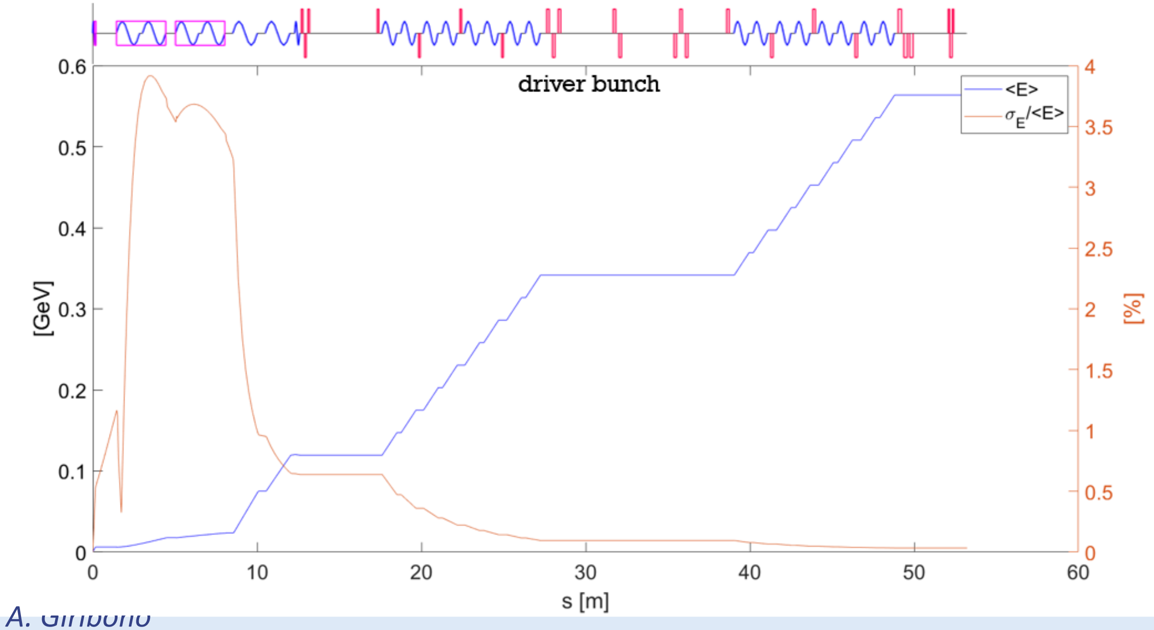
From the cathode to the FEL entrance

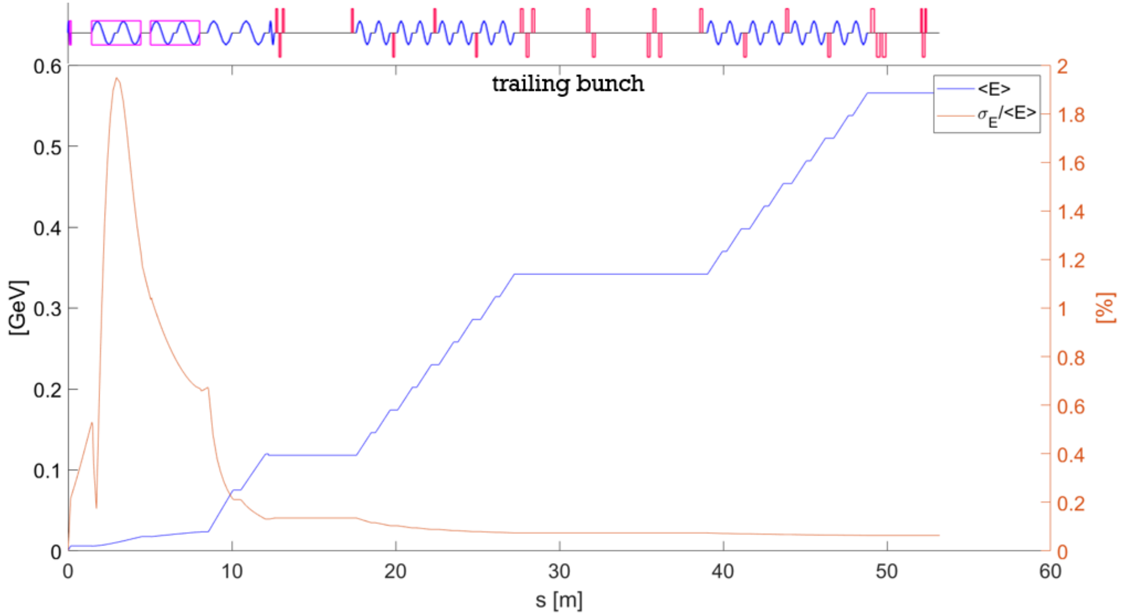
** each regime corresponds to a different sim code → TStep, ASTRA, Elegant, , Architect, Genesis …*

Beam Parameters through the linac
200 + 30 pC case



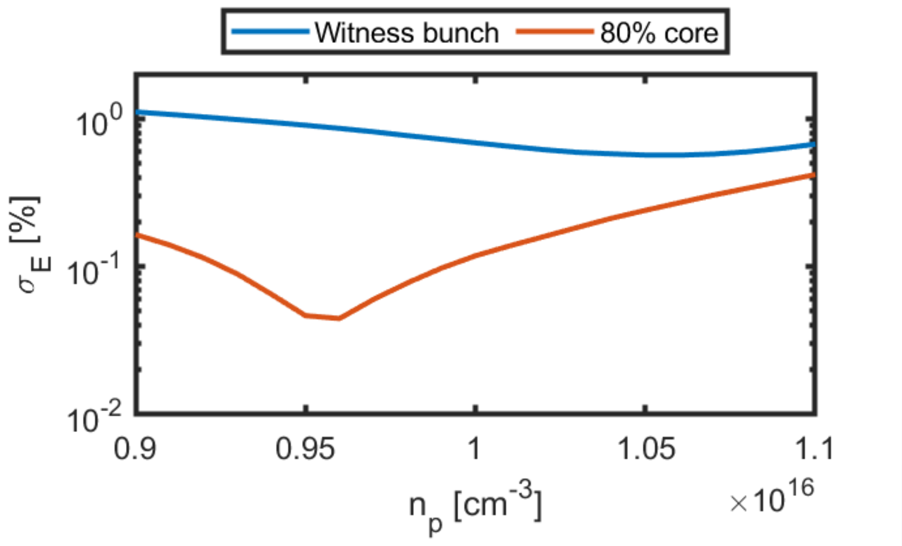






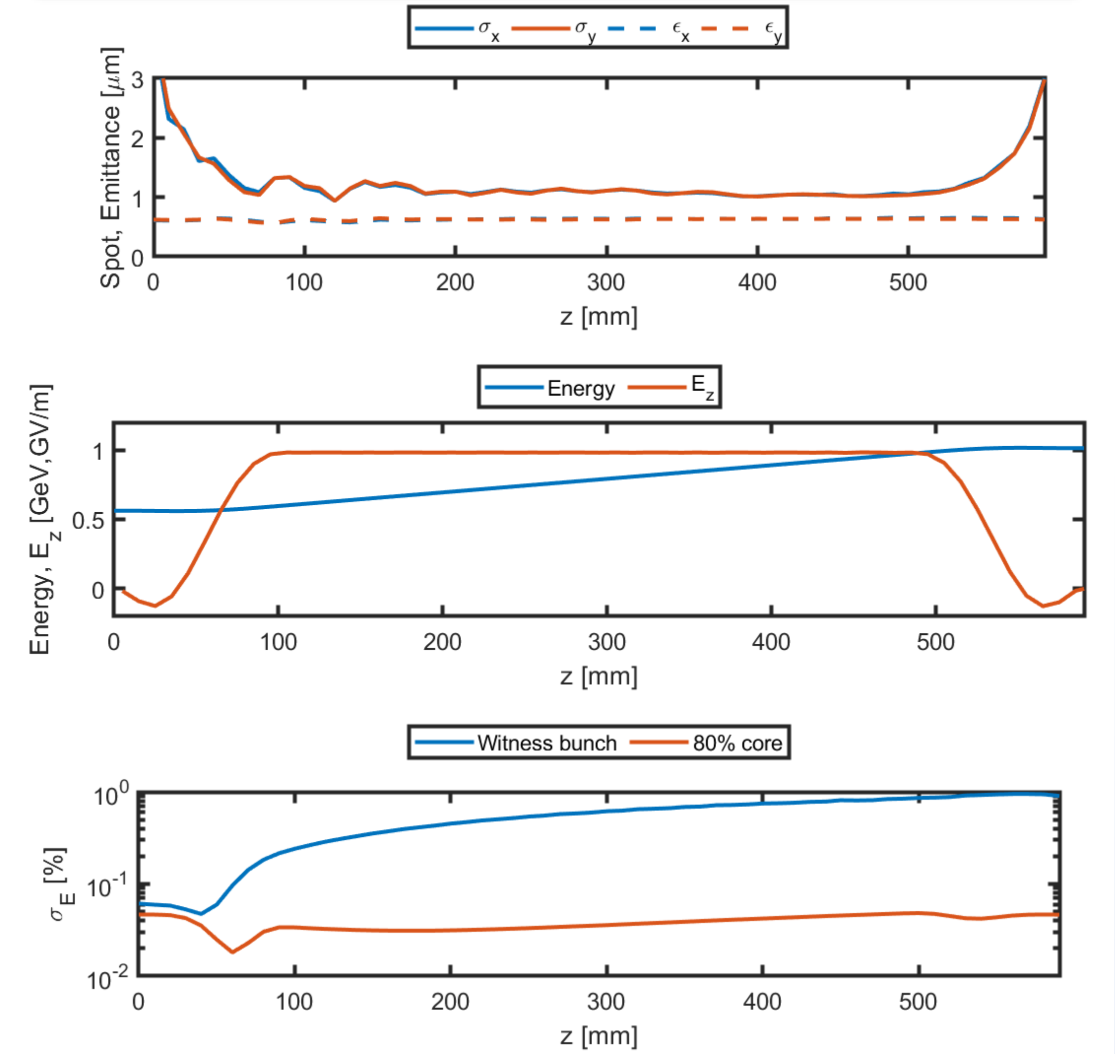
Nominal WP 200+30 pC: **Macroparameters evolution**

- Plasma ramp, 10 cm long, have been introduced in beam dynamics simulations following the numerical studies consistent with experimental results

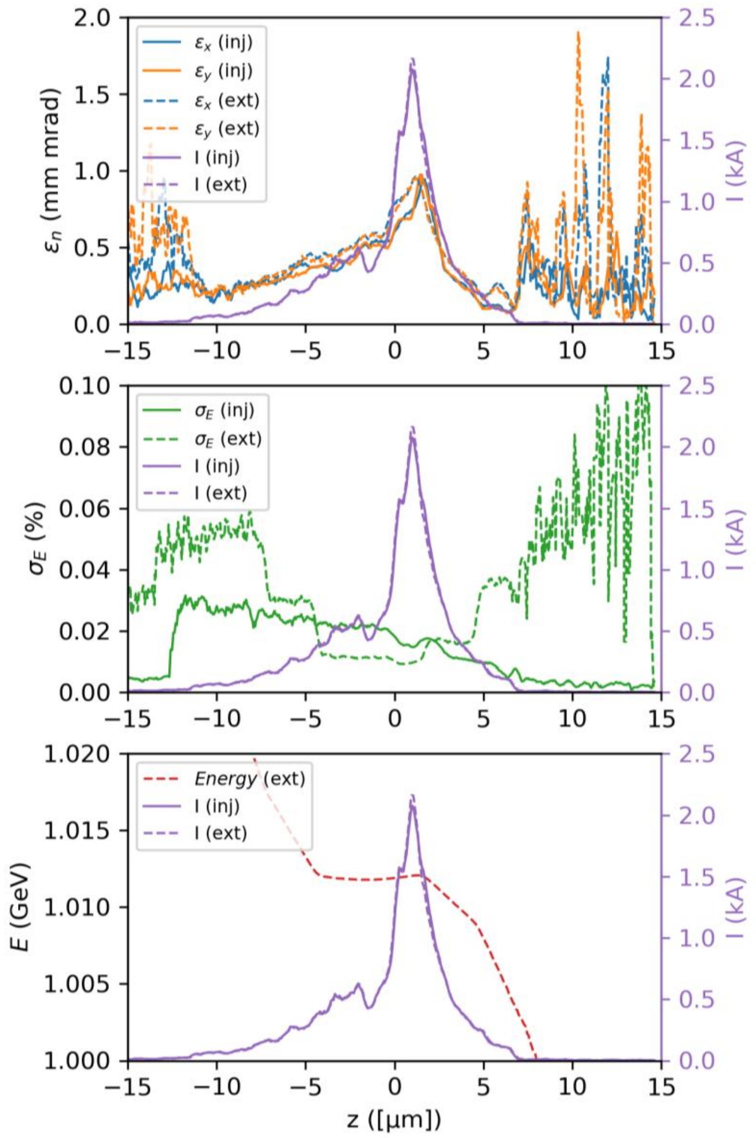


- **Reduction of core energy spread**
- **Energy spread minimum with $n_p = 10^{16}\mathrm{cm}^{-3}$**
- **Full preservation of emittance**
- **Final energy 1.01 GeV**
- **Maximum accelerating gradient 0.98 GV/m**
- **Average accelerating gradient ≈ 0.8 GV/m**

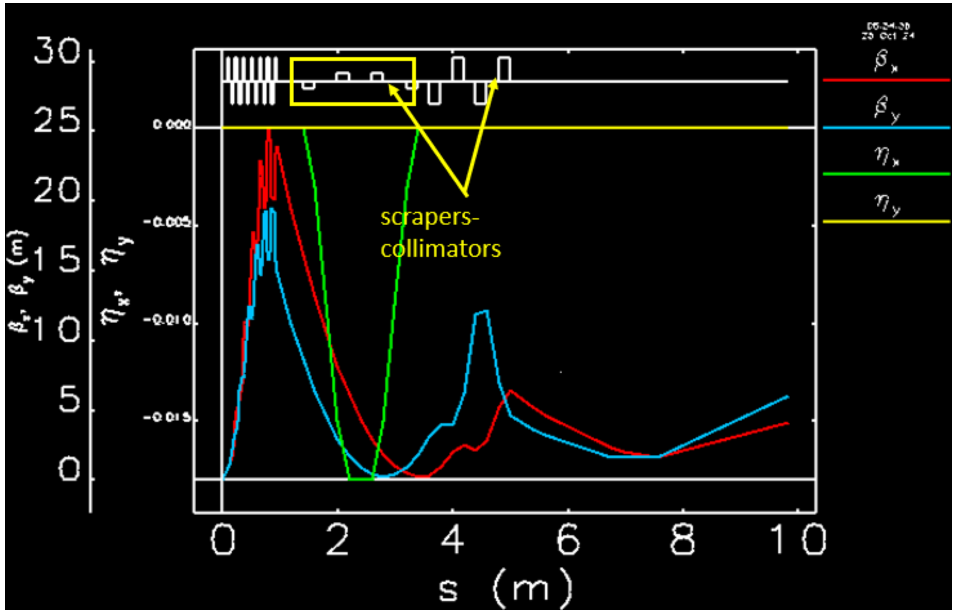
Nominal Working Point $n_p = 10^{16}\mathrm{cm}^{-3}$



W-D Separation beamline: from plasma module to FEL



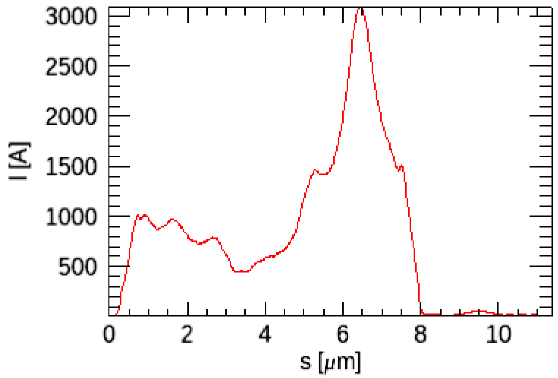
Witness slice analysis @plasma exit



Separation beamline matching

(fodo + chicane + collimators)

Simulation input file contains the **entire beam** (W+D)



Energy (GeV)	1
γ	1957.95
I_{peak} (kA)	3.07
dE/E (‰)	0.46
Proj. Emitt x	0.69
Proj. Emitt y	0.65

Witness slice analysis (upper) and rms parameters (lower) @FEL entrance

Accelerator sensitivity

- From the SPARC_LAB experience and **state of the art** are considered jitter as in table

S-band Gun and Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.10	*deg*
Cathode Laser System		
Charge [ΔQ] (max)	± 1	%
Laser time of arrival [Δt](rms)	± 20	fs
Laser Spot size [Δσ]	± 1	%

from simulations
for main working point
(VB - CF. 20)
@plasma injection

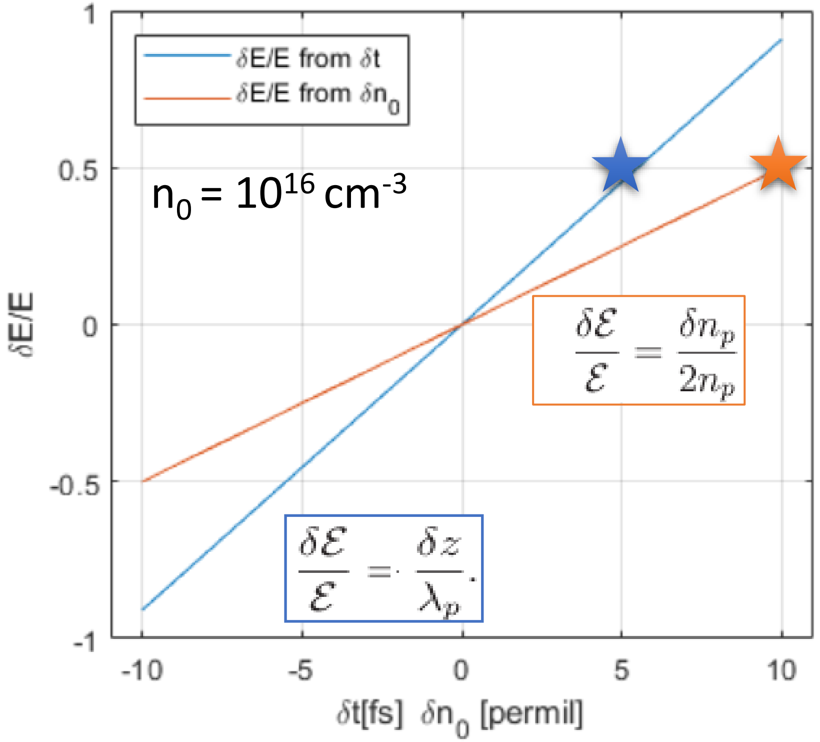
- *5 fs W-D distance jitter*

Plasma density		
n_0	± 1	%

adding plasma density jitter
@plasma exit

- *δE = 1 % rms <E> = 1 GeV*

Jitter contribution introduced in S2E simulations



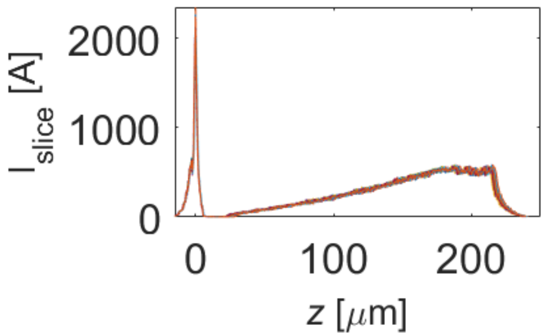
Analytical evaluation of plasma vs linac contribution to energy gain jitter @plasma exit

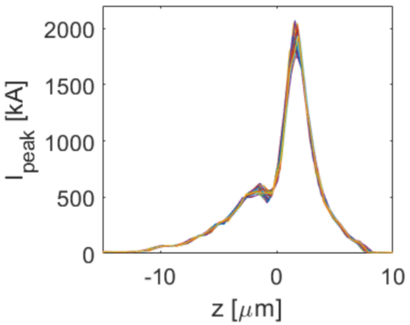
[*] S. Romeo *et al* 2024 *J. Phys.: Conf. Ser.* **2687** 042008**DOI** 10.1088/1742-6596/2687/4/042008

Sensitivity studies: from cathode to plasma exit

@linac exit	Witness	Driver	Units
Charge	30.00 ± 0.04	200.00 ± 0.30	pC
Energy	562.53 ± 0.32	563.86 ± 0.30	MeV
Energy spread	0.06 ± 0.0003	0.128 ± 0.0006	%
Bunch length	18.00 ± 0.22	151.5 ± 0.81	fs
I_{peak}	2.055 ± 101	-	kA
Δt	0.529 ± 0.004	-	ps
$\varepsilon_{n_{x,y}}$	0.77 ± 0.008	1.6 ± 0.018	mm mrad
$\sigma_{x,y}$	4.4 ± 0.3	8.9 ± 0.13	μm
$\beta_{x,y}$	25.8 ± 3.5	55.0 ± 1.4	Mm
$\alpha_{x,y}$	1.0 ± 0.15	0.70 ± 0.030	

Errors are intended as rms quantities

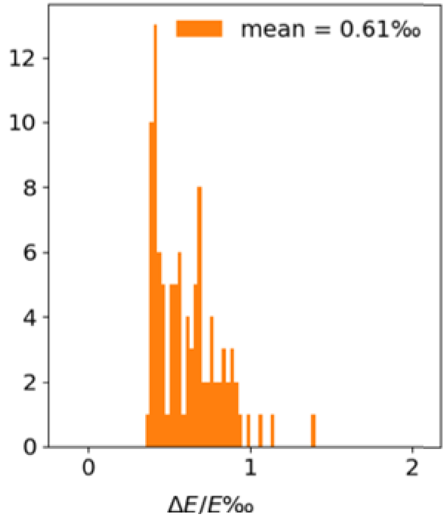


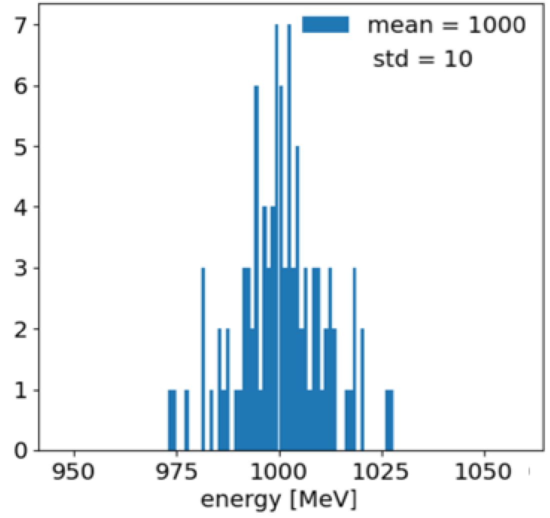


Comb beam current and witness slice analysis

@plasma exit

- 200 + 30 pC nominal working point affected by LINAC and plasma jitters
- plasma density is assumed to jitter 1% (one sigma) around the “nominal” longitudinal value

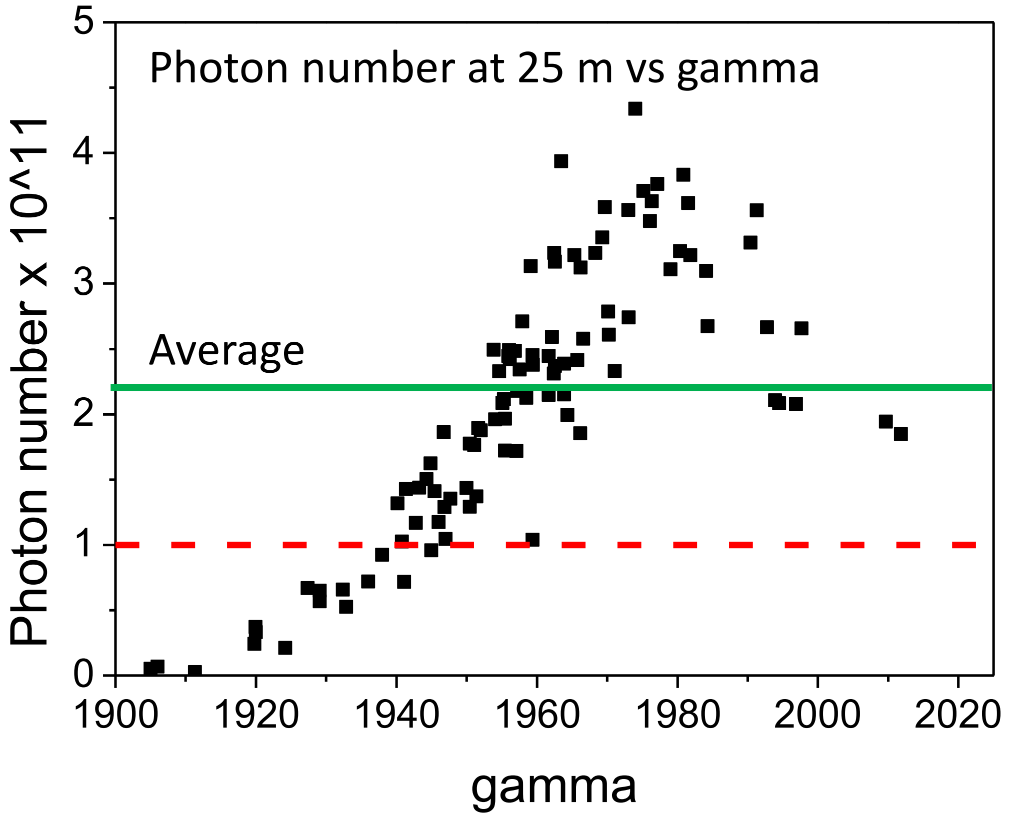




Courtesy of A. Del Dotto

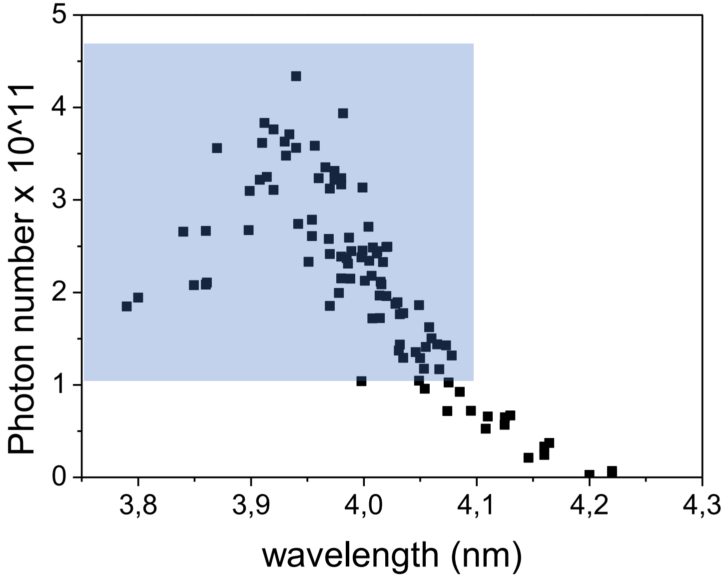
Sensitivity studies: FEL emission (statistics over 101 shots)

Funded by the European Union

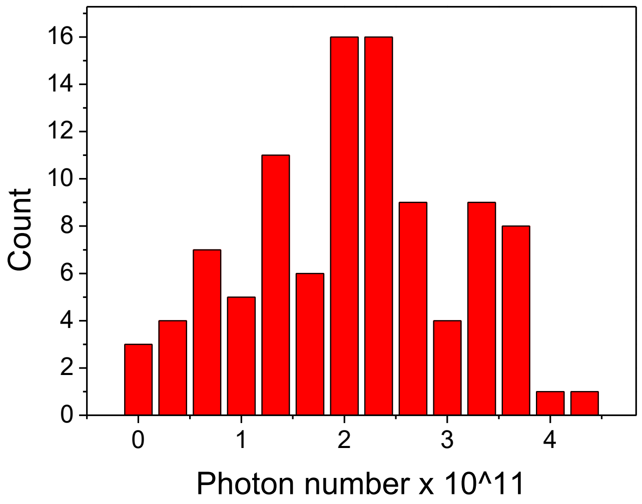


85/101 shots with

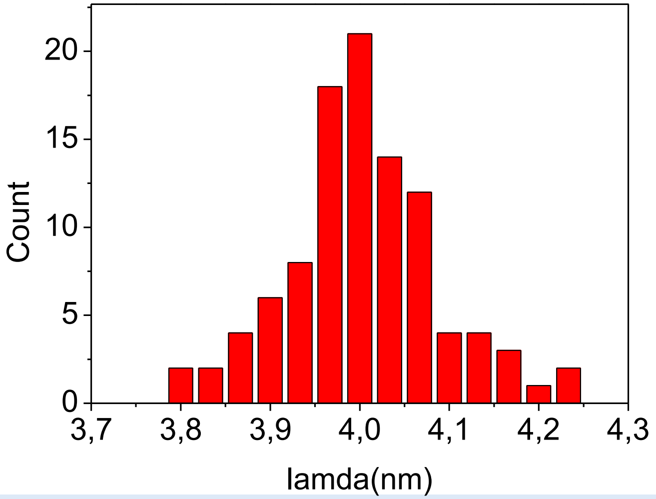
- Photon Number **> 10^{11}**
- Wavelength ∈ [3.8 : 4.05] nm



Photon number distribution



Wavelength distribution



	Unit	Average value	Error	Relative error
Wavelength	**nm**	**4.0037**	**0.084**	**0.02**
Energy (25 m)	**uJ**	**10.54**	**5.2**	**0.49**
Photon number	**x 10^{11}**	**2.092**	**1.01**	**0.48**

Courtesy of V. Petrillo – M. Opromolla

Static Errors Contributions

- Misalignments on input beam distribution at X-band linac entrance, accelerating and magnetic elements

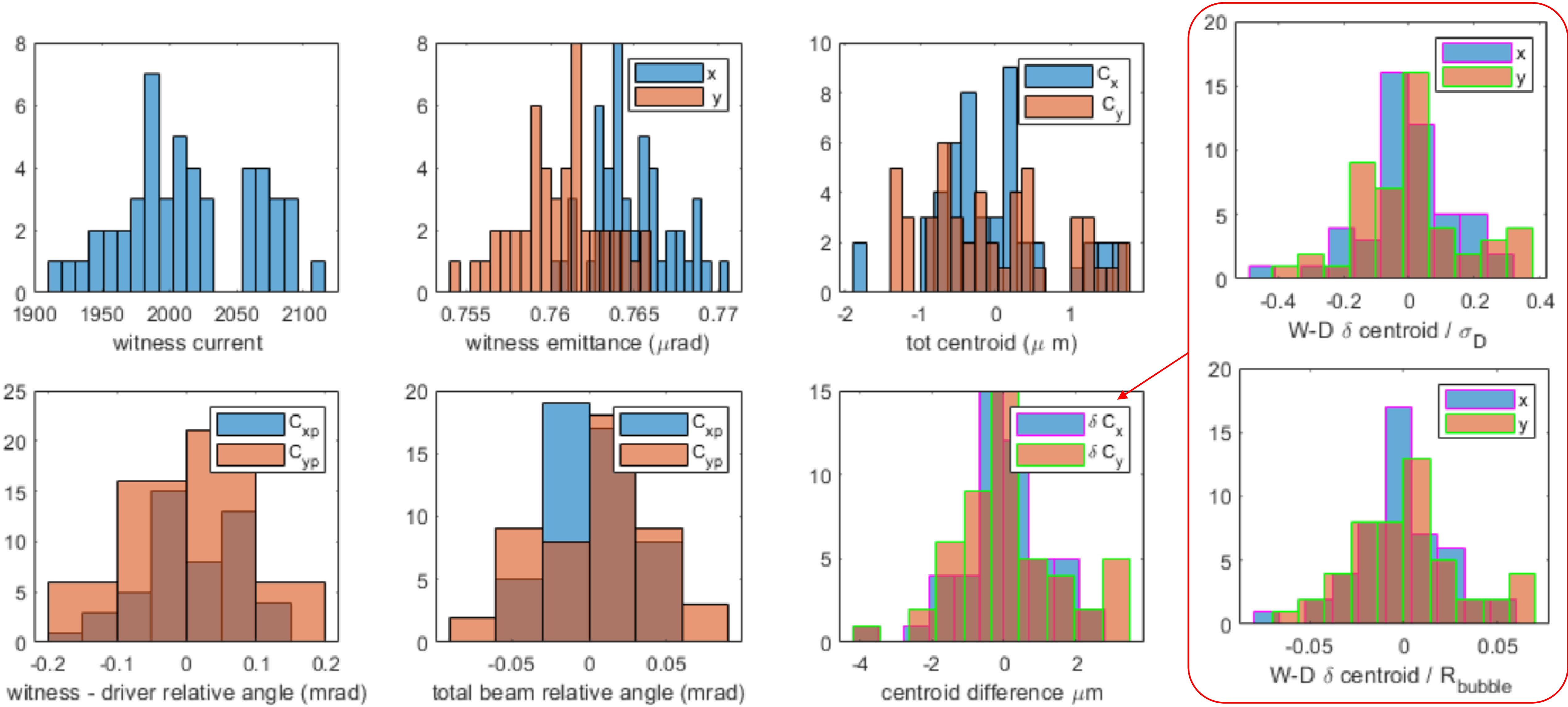
- The study has been performed with the Elegant code looking at the comb WP performances at the plasma entrance
  - Beam quality
  - Witness-driver transverse alignment

- Errors have been added as in table in according to following considerations:
  - All quantities are expressed as the rms values of a random Gaussian distribution, with a cutoff at 2σ
  - An initial offset is applied to the beam to simulate a potential off-axis trajectory in the upstream photoinjector
  - The X-band accelerating cavities are paired together in sets of two
  - **Bold values are intended as result of BBA technique**

Error type	Value	Units
Beam distribution @linac entrance		
X-Y Misalignment	**25,** 50	*μm*
X-band Accelerating Sections		
X-Y Misalignment	**25**, 70	*μm*
Quadrupoles		
X-Y Misalignment	**25**, 70	*μm*
Rotation about longitudinal axis	**25**, 70	*μrad*

30+200 pC (worst case – pre-BBA)

Funded by the European Union



EuPRAXIA Advanced Photon Sources (EuAPS)

- Supported by PNRR funding
- Collaboration among INFN, CNR, University of Tor Vergata
- EuPRAXIA → *laser-driven betatron radiation source @SPARC_LAB*
  → development of high power (up to 1 PW at LNS) and high repetition rate (up to 100 Hz at CNR Pisa) laser
  → pre-cursor for user-facility

1) **Ultrafast** - laser pulse duration tens of fs useful for **time resolved experiments** (XFEL tens of fs, synchrotron tens to 100 ps).
2) **Broad energy spectrum** - important for **X-ray spectroscopy**.
3) **High brightness** - small source size and high photon flux for **fast processes**
4) **Large market** - 50 synchrotron light sources worldwide, 6 hard XFEL's and 3 soft-ray ones (many accelerators operational and some under construction).

Electron beam Energy [MeV]	50-800
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^{6} – 10^{9}

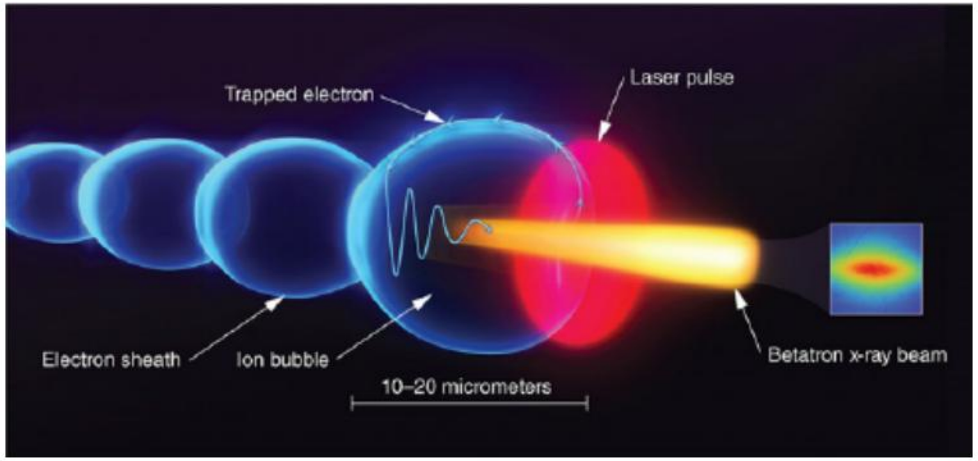


Figure 3: Principle of betatron X-ray emission from a LWFA. Electrons trapped at the back of the wakefield are subject to transverse and longitudinal electrical forces; subsequentlythey are accelerated and wiggled to produce broadband, synchrotron-like radiation in keV energy range [6].

Next Step: 'plasma-based compact undulators'

'EuPRAXIA Advanced Photon Sources PNRR_EuAPS Project', M. Ferrario et al. INFN-23-12-LNF (2023)

Conclusions

Funded by the European Union

- Plasma accelerators have advanced considerably in beam quality, **achieving FEL lasing**.
- EuPRAXIA is a design and an ESFRI project for a distributed European Research Infrastructure, **building two plasma-driven FEL´s in Europe**.
- **ELI-beamline** has been selected as Laser Driven Site EuPRAXIA FEL
- **EuPRAXIA@SPARC_LAB** in Frascati (LNF-INFN)
  - The **TDR is almost completed**
  - **Construction site opening:** September 2026
  - **First FEL user operation in 2029**
  - EuAPS will be the first application as user-facility of the EuPRAXIA project

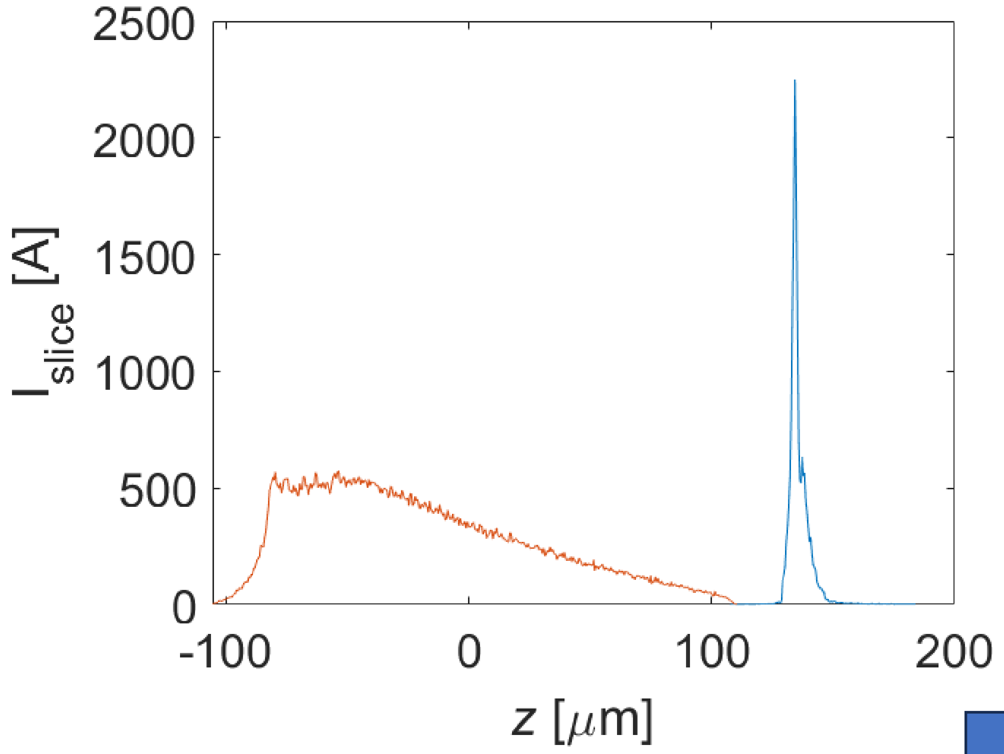
Thank you for your attention!

Funded by the European Union

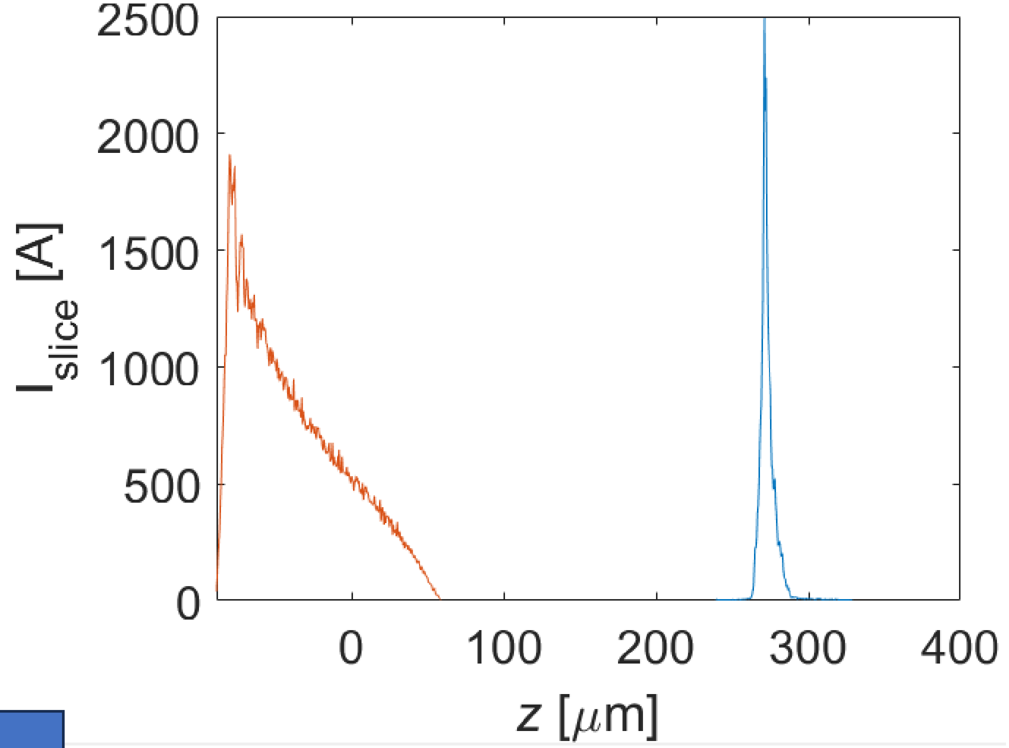
1 GV/m gradient in the plasma: two options considered

Funded by the European Union

200 + 30 pC , n_e = n x 10^{16} E_{acc} ≈ 1 GV/m



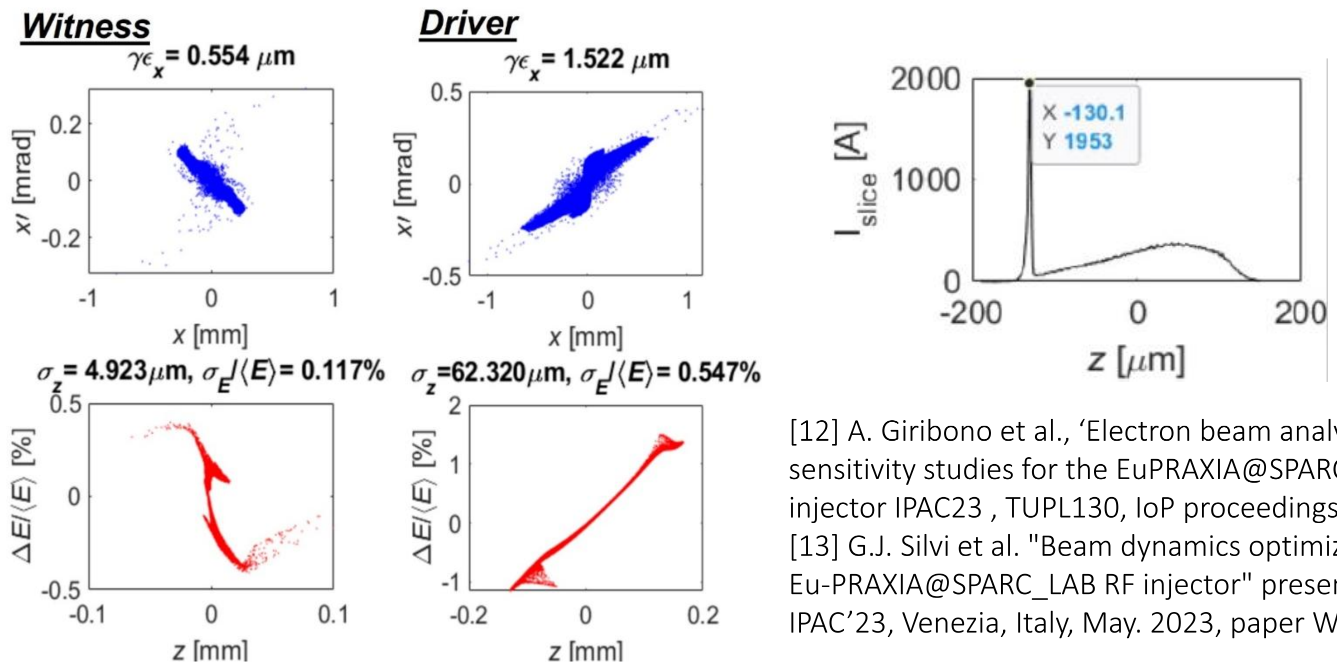
400 + 50 pC , n_e = n x 10^{15} E_{acc} ≈ 1 GV/m



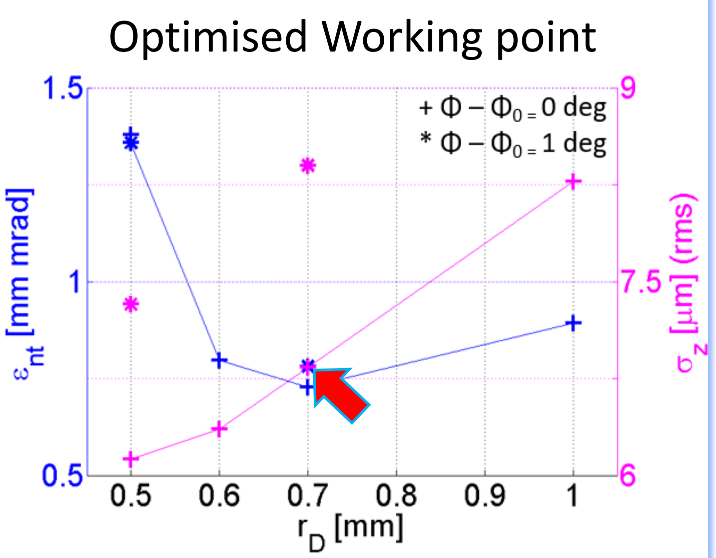
- Driver beam with higher charge and shorter length → higher gradients at lower plasma density → less sensitive to temporal jitter
- Driver beam with lower charge is less sensitive to wakefield and misalignments

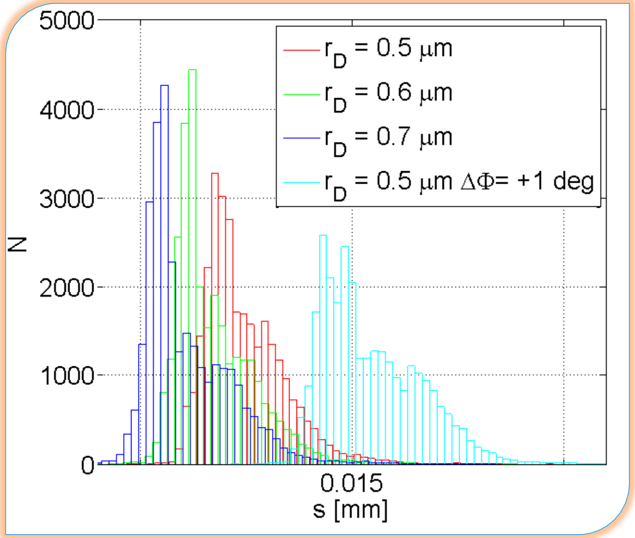
Beam generation for the PWFA case

- The beam dynamics has been studied by means of simulations with
  - TStep (and ASTRA) code →space charge regime
  - Elegant code → emittance dominated regime
  - The photoinjector sets the beam separation, emittance and current
  - The photoinjector is operated in the double hybrid RF compression scheme → this scheme ensures at same time up to 2 kA peak current and separation lower than 0.6 ps [8,9] and good flexibility



[12] A. Giribono et al., 'Electron beam analysis and sensitivity studies for the EuPRAXIA@SPARC_LAB RF injector IPAC23 , TUPL130, IoP proceedings
[13] G.J. Silvi et al. "Beam dynamics optimization of Eu-PRAXIA@SPARC_LAB RF injector" presented at the IPAC'23, Venezia, Italy, May. 2023, paper WEPA040





[14] A. Giribono et al. EuPRAXIA@SPARC_LAB: The high-brightness RF photo-injector layout proposal, https://doi.org/10.1016/j.nima.2018.03.0

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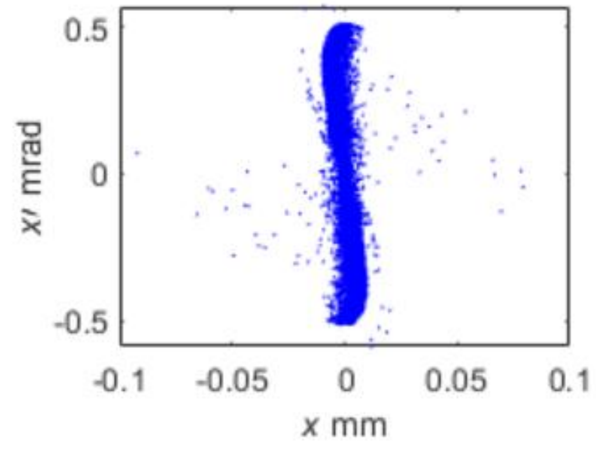
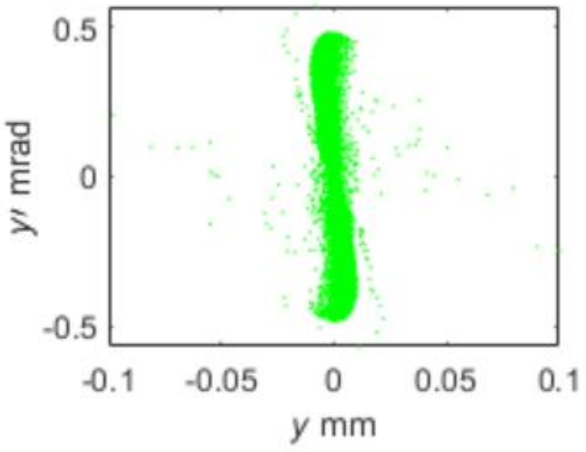
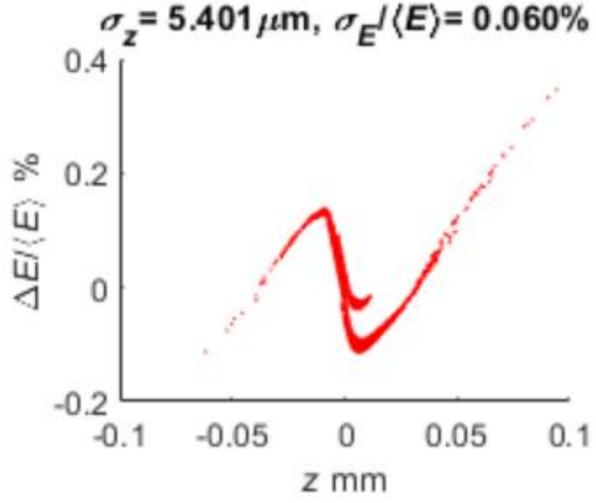
Electron beam phase space at linac exit 30+200 pC

Witness

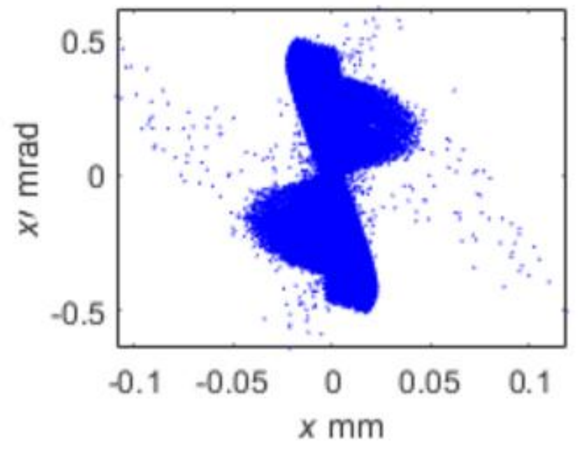


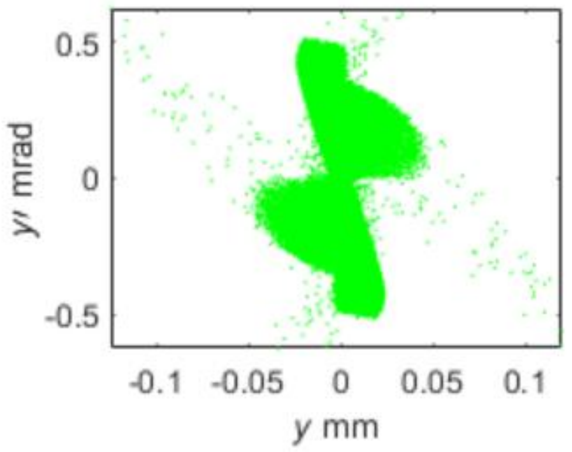


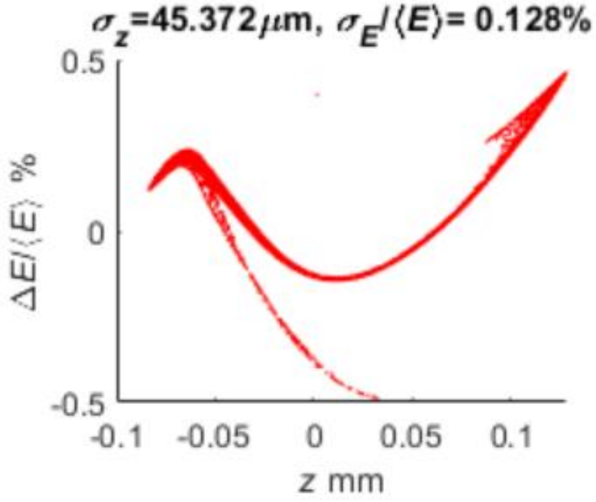


$N=$ 29999
$\langle E\rangle=$562.506MeV
$\sigma_x=$ 0.004 μm
$\beta_x=$ 0.025 m
$\alpha_x=$ 1.016
$\sigma_y=$ 0.004 μm
$\beta_y=$ 0.026 m
$\alpha_y=$ 0.964

Driver







$N=$ 200000
$\langle E\rangle=$563.827MeV
$\sigma_x=$ 0.009 μm
$\beta_x=$ 0.054 m
$\alpha_x=$ 0.663
$\sigma_y=$ 0.009 μm
$\beta_y=$ 0.056 m
$\alpha_y=$ 0.707

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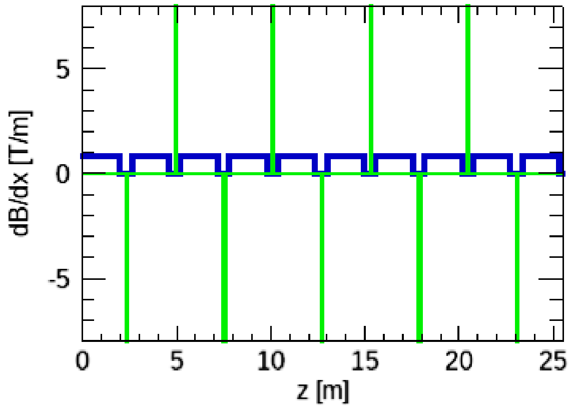
FEL matching and performances

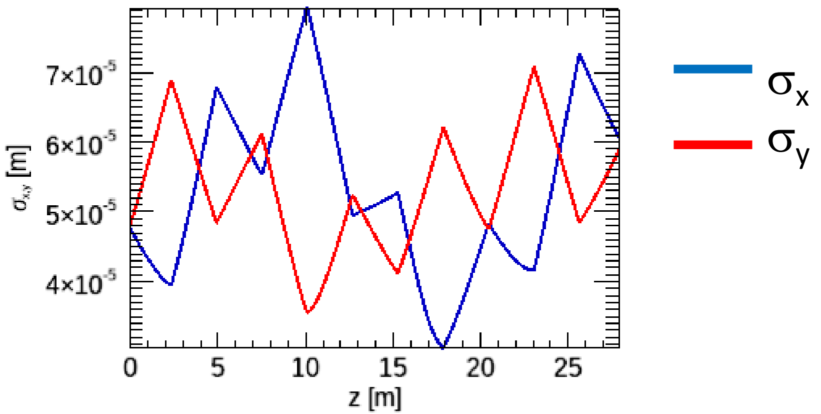
Matching

Undulator structure

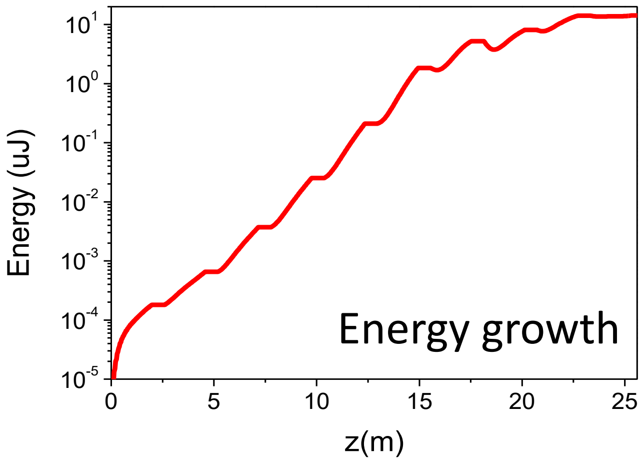


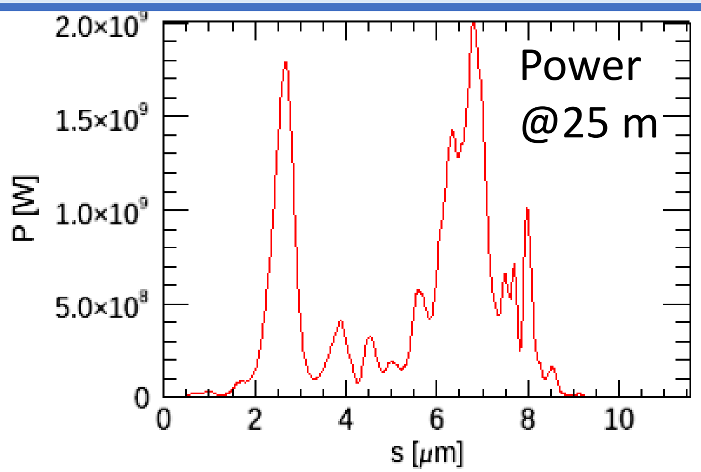
λ_w=1.8 cm
a_w=0.84
dB/dz=8 T/m

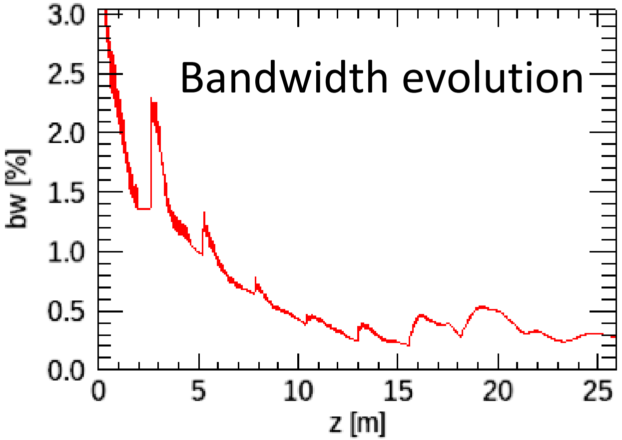
Average matching

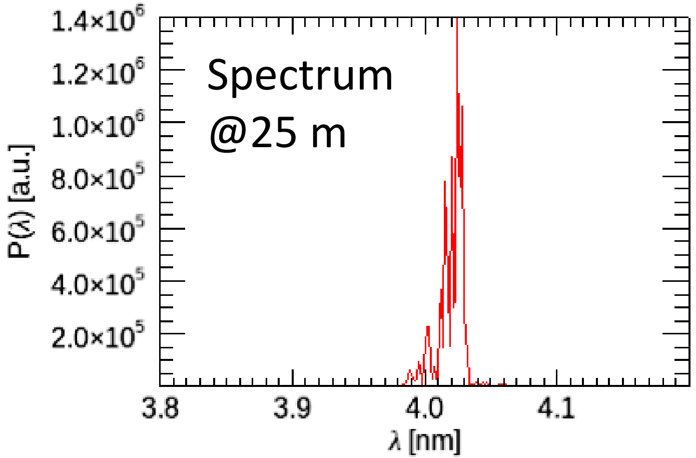


Performances









Energy (μJ)	λ (nm)	BW (‰)	Photon number	Size (μm)	Div (μrad)	L_sat (m)	L_rad (μm) FWHM
13.54	4.004	3	$2.71\ 10^{11}$	170	27	23	4.5

High transformer ratio PWFA for EuPRAXIA@SPARC_LAB: the 5 GeV WP

Funded by the European Union

In perspective of the draft of EuPRAXIA@SPARC LAB technical design report, we have explored through numerical simulations two ideal scenario suitable for the 5 GeV case trying to maximize the

$$R_T = \frac{|E^+_{max}|}{|E^-_{max}|}$$

- Quasi non-linear regime to exceed $R_T = 2$ and preserve beam quality

$$\tilde{Q} = \frac{N_b k_p^3}{n_p} \leq 2 \qquad n_b/n_p \gg 1$$

→

- Two bunches operation
- Resonant scheme

- The simulations have been performed in 2D by means of the Hybrid Fluid Kinetic code Architect [2]

- Plasma accelerating module → 2.4 m long flat top plasma profile with a background density $n_p = 2.5\ 10^{16}$ cm^{-3}, preceded by a 1 cm long injection ramp
  → beam energy at injection 1.2 GeV

[1] S. Romeo et al - High transformer ratio resonant PWFA ideal working point design for EuPRAXIA@SPARC_LAB - 2020 J. Phys.: Conf. Ser. 1596 012061
[2] F Massimo, S. Atzeni and A. Marocchino 2016 Journal of Computational Physics 327 841–850

High transformer ratio PWFA for EuPRAXIA@SPARC_LAB

Funded by the European Union

Two scenarios have been explored consisting in

a) Two bunches: 150 pC + 30 pC

b) Train of bunches → 40 – 140 – 270 pC + 30 pC

Same results in terms of final beam energy

Table 1. Driver(s) and witness parameters at the injection

	Driver(s)	Witness
Q [pC]	150/40-140-270	30
γ	2348	2348
ϵ_n [mm mrad]	1	0.7
σ_E [%]	0.1	0.1
$\beta_{x,y}$ [mm]	22	22
$\alpha_{x,y}$ [mm]	1	1
σ_z [μm]	33	16 (3.8 rms)

- Driver-driver separation of around $\lambda_p/2$ (105.6 μm)
- Driver-witness separation of around $\lambda_p/2$ (97 μm)

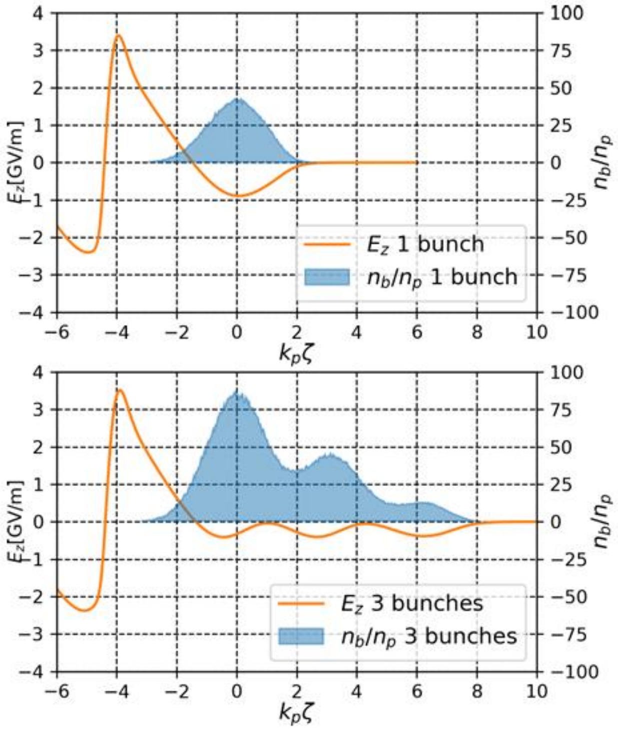
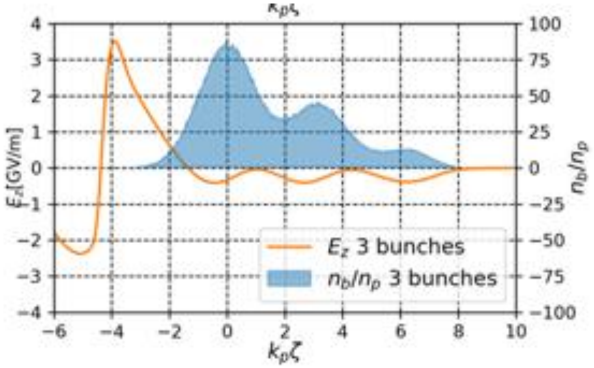


Figure 1. Longitudinal field on axis and longitudinal current profile for single bunch scheme (top) and 3 bunch train scheme (bottom) at $z = 0$.

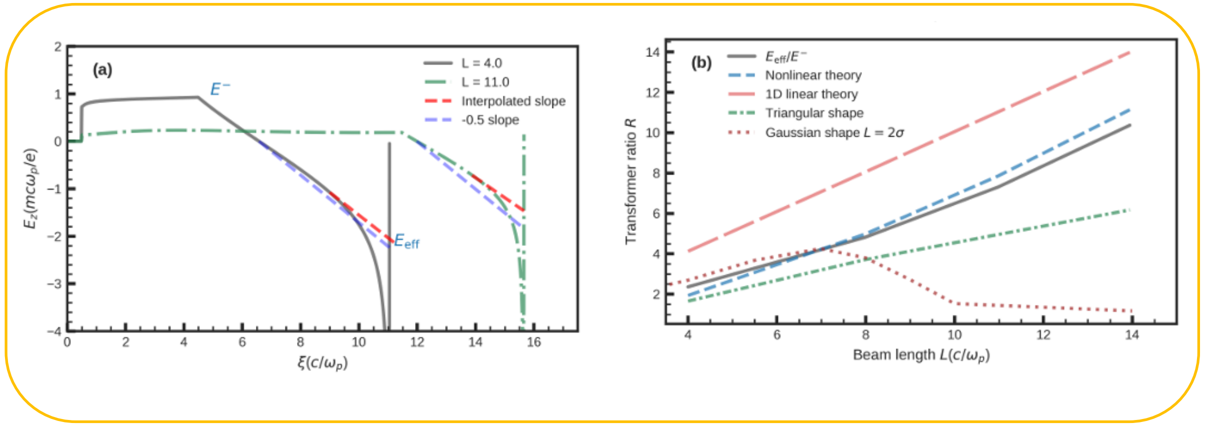
High transformer ratio PWFA for EuPRAXIA@SPARC_LAB: beam tailoring

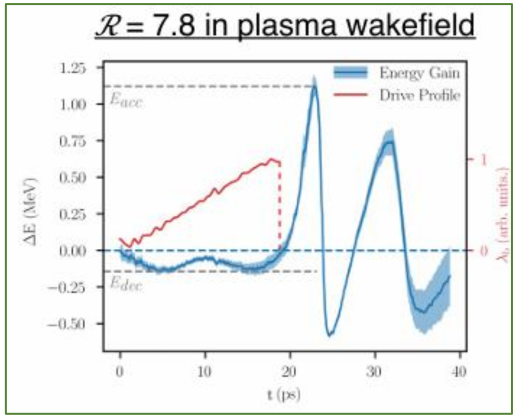
Funded by the European Union

- Driver:
  - train of three bunches with the same shape
  - final design that is in between a single bunch with ***triangular shape*** and a train of bunches
- *Witness:*
  - *Triangular current shape in order to minimize the energy spread growth* [3]



- Moderate beam quality
  - Higher accelerating gradients in the non-linear blow-out regime → smaller footprint
  - Hybrid LWFA + PWFA
- Further optimisation methods also suggest that customised tailoring exists to produce much higher R_T (for example up to 10 in [4,5])





[3] M. Tzoufras, W. Lu, F. Tsung, C. Huang, W. Mori, T. Katsouleas, J. Vieira, R. Fonseca and L. Silva 2008 Physical Review Letters 101 145002
[4] Q. Su et al. Optimization of transformer ratio and beam loading in a plasma wakefield accelerator with a structure-exploiting algorithm (2023)
[5] Roussel, R., et al. PRL 124 (2020): 044802 - Gao, Q., et al. PRL 120 (2018): 114801 - Loisch, G., et al. PRL 121 (2018): 064801

High transformer ratio PWFA for EuPRAXIA@SPARC_LAB

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- The average accelerating gradient is E_z = 1.65 GV/m and the effective transformer ratio is R_T = 3.65 → 5 GeV in 2.4 meter long plasma channel

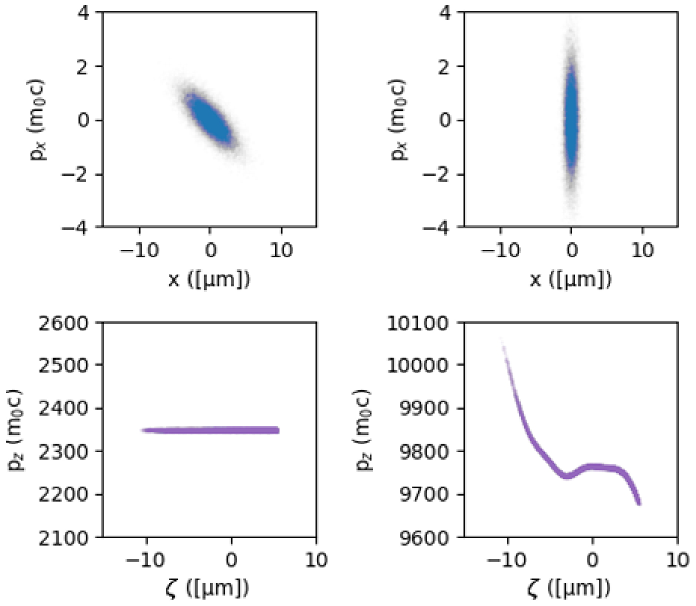

Figure 3. Witness phase space at the initialization (left) and at the end of the simulation (right). The transverse phase space is perfectly matched while the longitudinal phase space presents an energy spread growth mostly located on bunch tail.

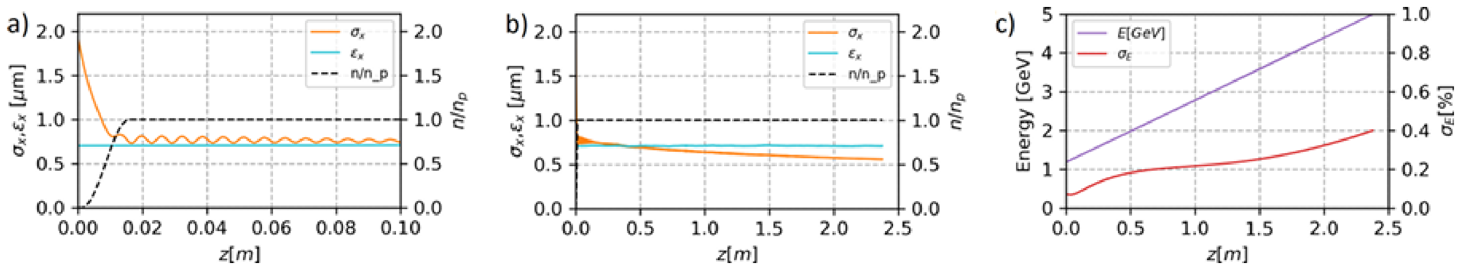

Figure 2. Integrated parameters evolution of Witness bunch. We report the evolution of the transverse spot size and emittance in a) (for the first 10 cm) and in b) (for the entire channel) along with the density of the plasma channel. We report in c) the evolution of energy and energy spread.

The emittance of the witness is preserved along the entire plasma channel and the energy spread grows up to 04%