EUROPEAN
PLASMA RESEARCH
ACCELERATOR
WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

Status of EuPRAXIA@SPARC_LAB

and possible synergies with the CEPC/FCCee injectors

Massimo Ferrario (INFN-LNF)
On behalf of the EuPRAXIA@SPARC_LAB Team

Int. Workshop on CEPC
Shanghai – October 23, 2026

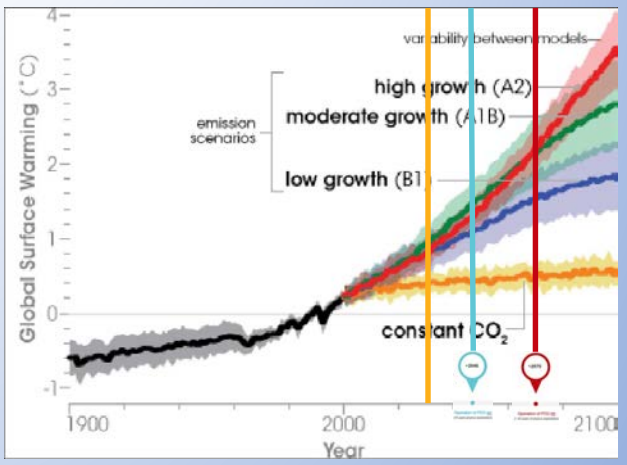
A New European High-Tech User Facility

Funded by the European Union

1

Building a facility with very high field plasma accelerators, driven by lasers or beams
1 – 100 GV/m accelerating field

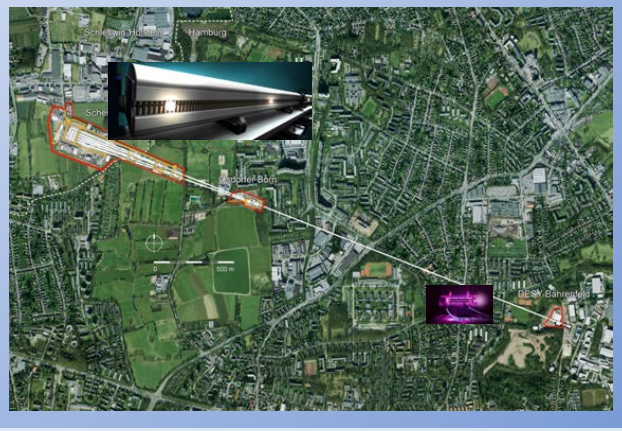
Shrink down the facility size
Improve Sustainability



2

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

Drive Advanced Acceleration Sources
Pave the way for future Linear Colliders



https://www.eupraxia-facility.org/

EuPRAXIA Consortium Networking

Funded by the European Union

2 Implementation Pillars
@ INFN – LNF & @ ELI-ERIC

Several National Nodes. Roles to be fully defined

Project Clusters



A large collection of European know-hows in accelerators, lasers and plasma technologies

Network organization
- **Sites (PWFA/LWFA): new users facilities**
- **National nodes**
- **Technology clusters**

The EuPRAXIA RI (ESFRI) ecosystem

Funded by the European Union

EuPRAXIA@SPARC_LAB	IT-pillar, funded by Ministry and ERDF Lazio Region
EuPRAXIA@ELI-ERIC	CZ-pillar, supported by ELI-ERIC
EuPRAXIA Advance Photon Sources – EuAPS	R&D funded by Recovery Funds, IT
EuPRAXIA Doctoral Network	EU grant, 2023
EuPRAXIA Preparatory Phase	EU grant, 2022, ESFRI PP
EuPRAXIA Early Implementation Phase	EU grant, 2025, ESFRI Implem.
PACRI	EU grant, 2024, R&D on plasma, laser and RF technologies



10 European countries involved

EuPRAXIA collaboration has diversified its portfolio of activities through different grants and funding lines (Ministry, ERIC, EU, Agencies, Uni & Labs, regional, …). Around **150 ME** raised so far + in-kind contributions

EuPRAXIA Scientific Goals

Funded by the European Union

- Free Electron Laser

***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

***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

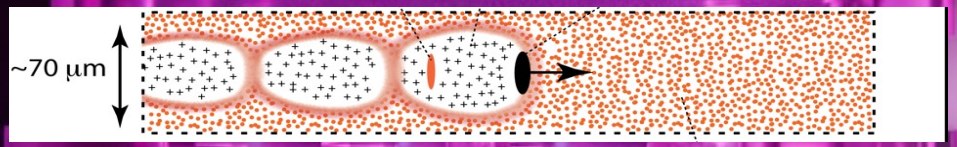
- High Rep. Rate Laser

***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

***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.*

Principles of Plasma Wakefield Acceleration

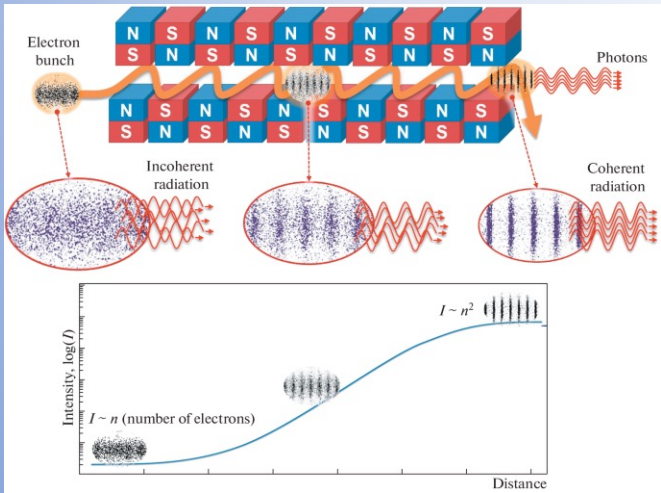


$$Q_w \Delta E_w \leq \eta Q_d \Delta E_d$$

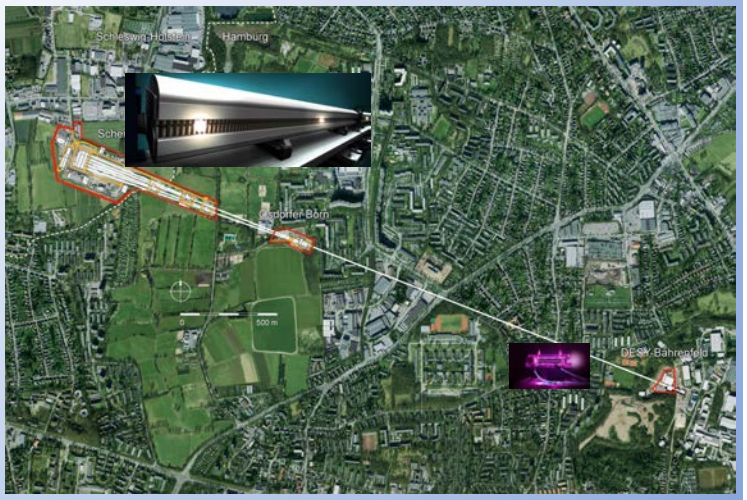
$$\Delta E_w \leq \eta \frac{Q_d}{Q_w} \Delta E_d.$$

FEL is a well established technology

(But a widespread use of FEL is partially limited by its size and costs)





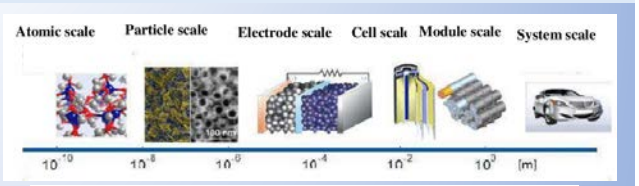


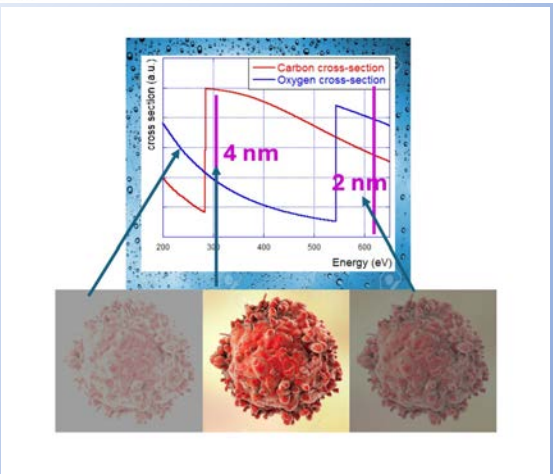
The choice of using a Free-Electron Laser (FEL) as the first application has been determined by the fact that FELs are extremely sensitive to the quality of the electron beam, making them an ideal testbed to demonstrate the capabilities of plasma-based accelerators. In addition a plasma-driven FEL is immediately attractive to a broad scientific user base, facilitating the transition from accelerator R&D to real-world applications and justifying further investment.

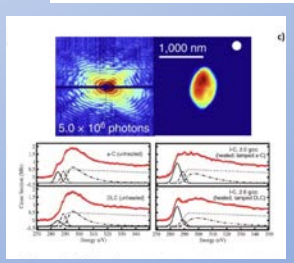
Scientific Case and Applications

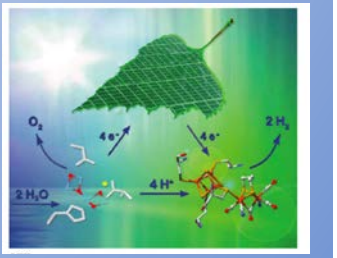
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Application Area	Scientific Focus	Techniques	Phase	Key Impact
Atomic, Molecular, and Optical (AMO) Physics	Ultrafast electron dynamics, core-level excitation, fragmentation pathways	Time-resolved photoabsorption, photoemission, ion/electron spectroscopy (TOF, VMI), Coulomb explosion imaging	P1	Fundamental insights into charge migration, excited-state dynamics, and molecular structure
Ion & Electron Spectroscopy (Gas Phase)	Ionization and fragmentation of molecules, clusters, aerosols; selected environmental and astrochemical model systems	PI-MS, TOF detectors, momentum imaging	P1	Proof-of-principle user experiments; benchmarking FEL performance and machine stability
Warm Dense Matter (WDM)	Non-equilibrium states, ultrafast structural transitions, electron–ion equilibration	Time-resolved XAS and XES	P2	Advances in planetary science, dense plasmas, and fusion-relevant materials
Structural Biology & Soft-Matter Imaging	CDI of hydrated biological specimens (viruses, macromolecular assemblies)	Coherent Diffraction Imaging, single-pulse "diffraction-before-destruction"	P2	High-resolution reconstructions in the water window; foundations for future bio-imaging program









Technical Design Report published on February 5, 2026

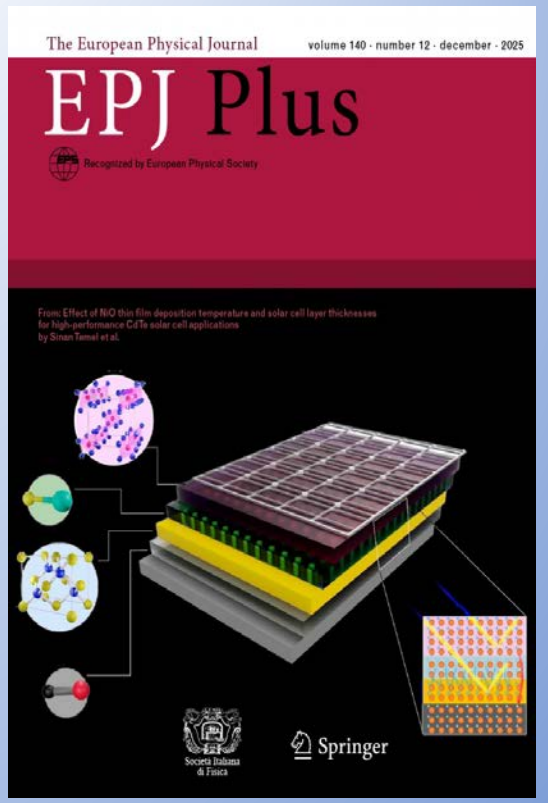
Accepted for publication in EPJ-Plus

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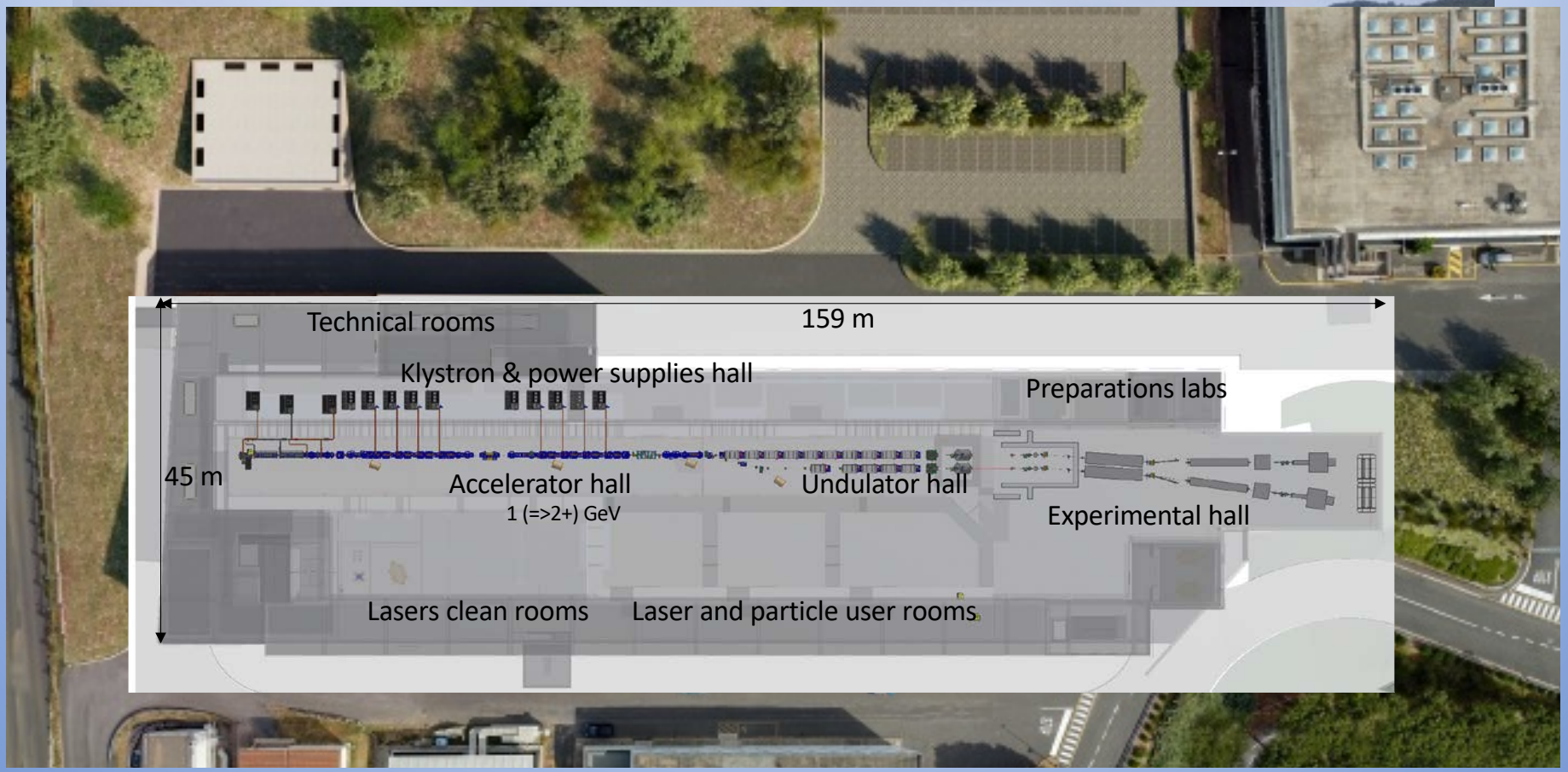
Authors

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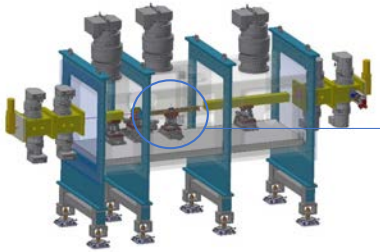


https://doi.org/10.15161/oar.it/k57qz-5qk09

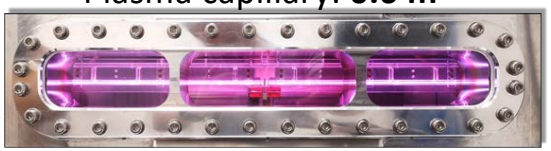
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Plasma capillary: **0.6 m**



54 m

AQUA Beamline

ARIA Beamline

Photon beamlines

28.5 m

Plasma chamber: **3.5 m**

9 m



33.5 m

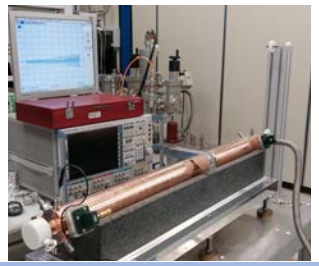
17.5 m

Undulators



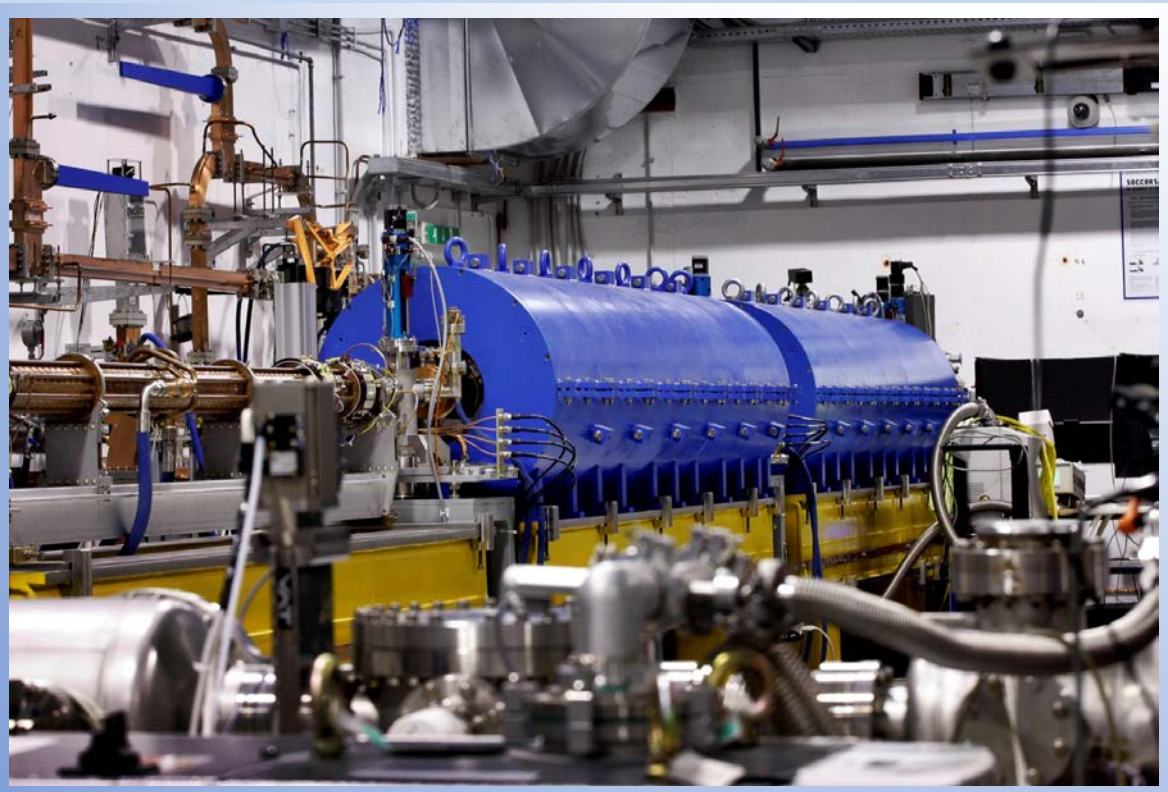
Plasma module

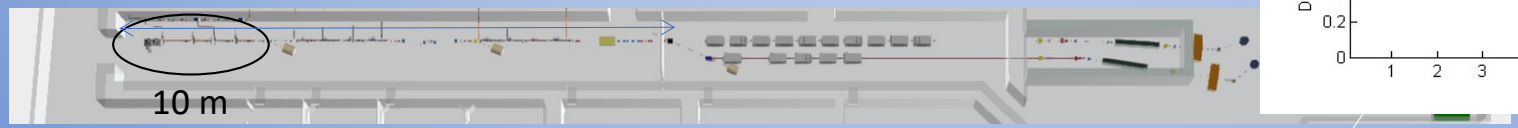
X-band Linac



S-band Injector

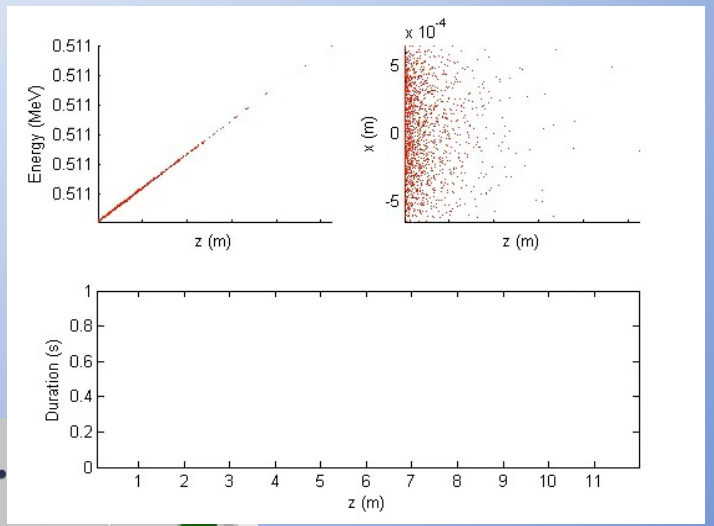
High Quality Electron Beams





Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

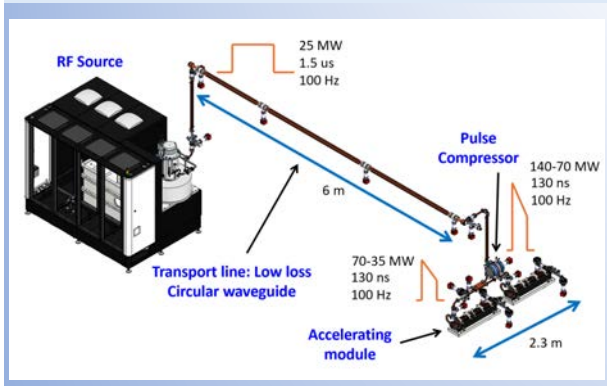
Table 7.2: Driver and witness beam parameters at the end of photo-injector.

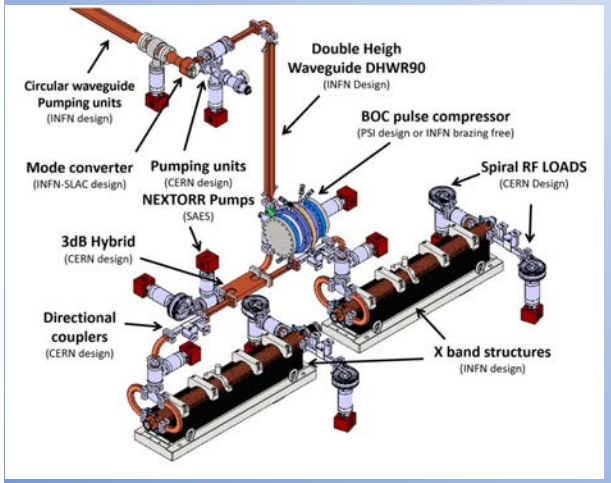


Courtesy E. Chiadroni/A. Giribono

L. Serafini and M. Ferrario. “Velocity bunching in photo-injectors”. AIP conference proceedings. Vol. 581. 1, 2001, pp. 87–106.

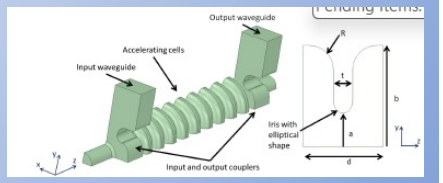
X-band linac structures

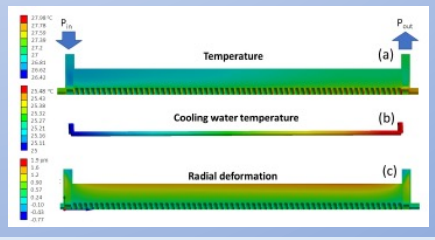


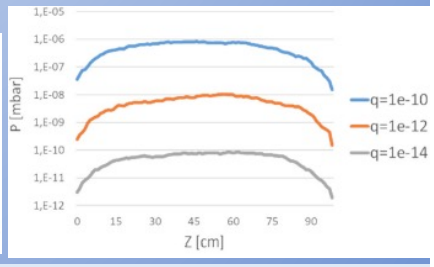


1. Describe the **X-band accelerating module** we want to implement in terms of:
   - RF structure **design and parameters** (electromagnetic design, cooling, etc.)
   - Waveguide **components** (DC, pumping, etc.)
   - Expected **performance** (RF, vacuum, etc.)
   - **Supports**
   - Parameters of the **power sources** (with reference to the dedicated chapter)
2. **Magnetic chicane** layout and main parameters.
3. **Quadrupoles and diagnostics**

Accelerating structures parameter	Symbol	Unit	Value
Frequency	f_{RF}	GHz	11.9942
Average accelerating field	E_{acc}	MV/m	60
Iris radius (linear tapered)	a	mm	3.85-3.15 (3.5)
Structure active length	L_s	m	0.94
Number of cells	N_{cell}		112
Shunt impedance per unit length	R	MΩ/m	93-107 (100)
Effective shunt impedance per unit length	R_s	MΩ/m	350 (347)
Peak input power per structure	P_{peak}	MW	70
Input power per structure averaged over the pulse	P_{in}	MW	51
P_{out}/P_{in}		%	25
Filling time	τ_F	ns	130
Peak mod. Poynting Vector	S_c	W/μm^2	3.6 (4.3)
Peak Surf. E field	E_P	MV/m	160 (190)
Quality factor	Q		6400
Phase advance per cell	ϕ		$2\pi/3$
Repetition rate	f_{rep}	Hz	100

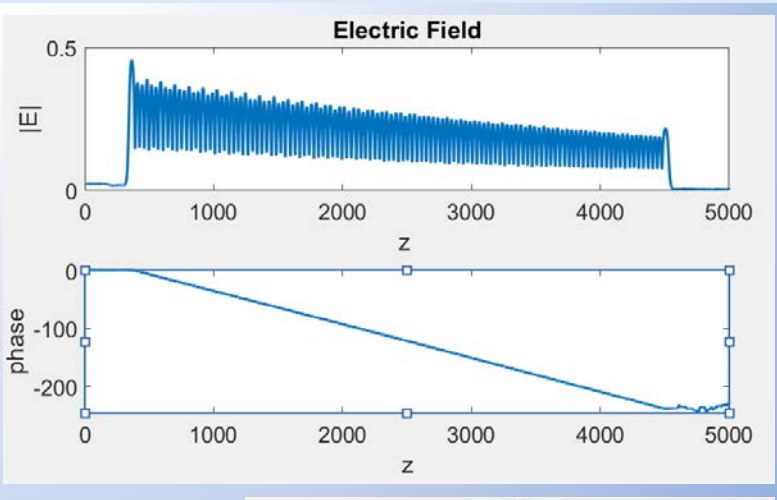


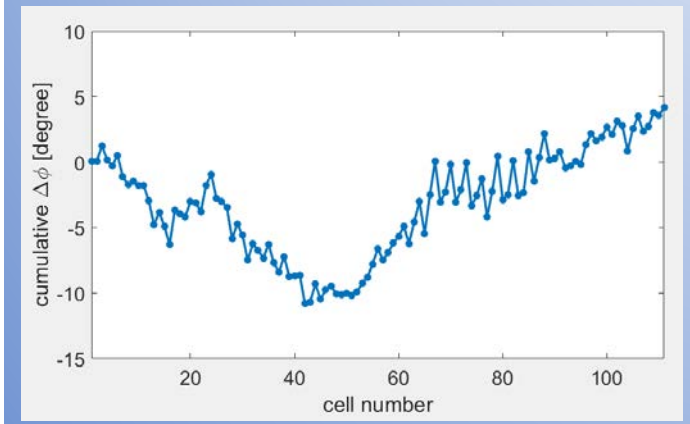


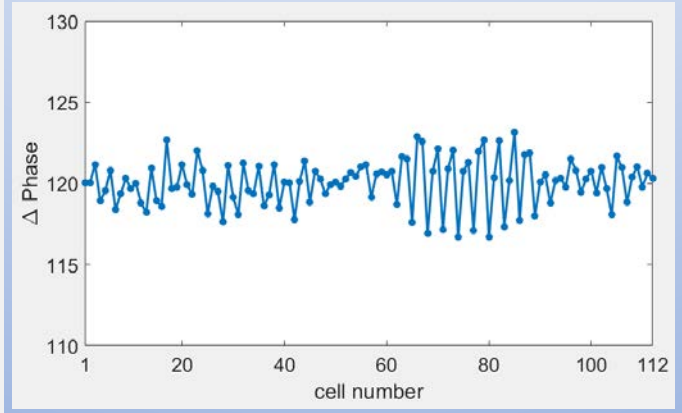


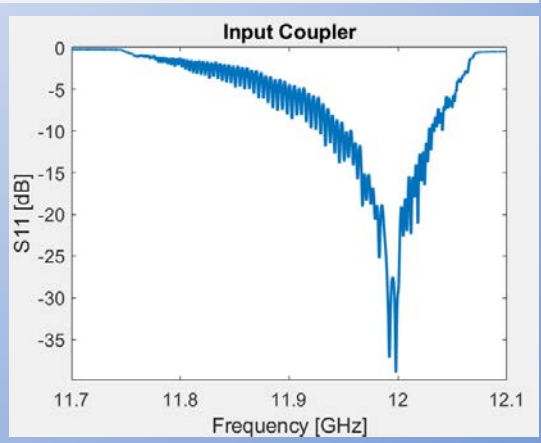
1st X band full scale structure ready for high power test









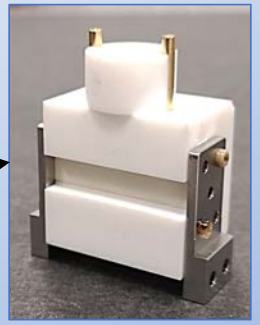


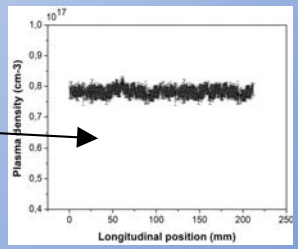
Plasma Accelerating Module

Key design parameters for the EuPAXIA@SPARC_LAB plasma source	
Source type	Gas-filled discharge capillary
Geometry	60 cm in length 2 mm in diameter variable inlets
Gas	Argon, Nitrogen, Hydrogen
Gas injection system	Continuous gas injection using a common service channel and several injectors with variable position and size
Repetition rate	100 - 400Hz
Discharge circuit parameters	Voltage: 10÷15 kV Current: 400÷500 A
Materials	Channel: Sapphire, Shapal Holder: Macor Electrodes: Tungsten
Plasma density	$10^{16} \div 10^{17}$ cm^{-3}
Lifetime	3×10^8 shots
Shot-to-shot stability	$< 1\%$ with laser stabilization



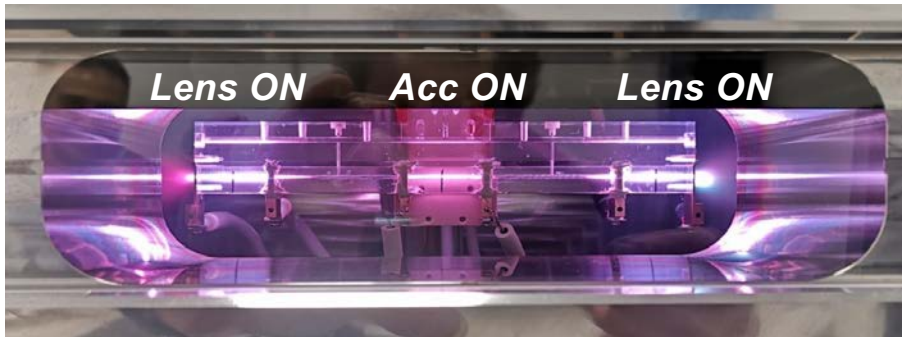


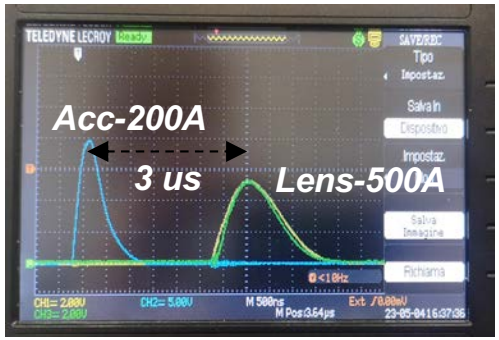




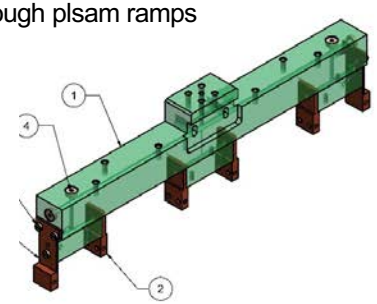
Courtesy A. Biagioni/L. Crincoli/R. Demitra

Integrated capillary

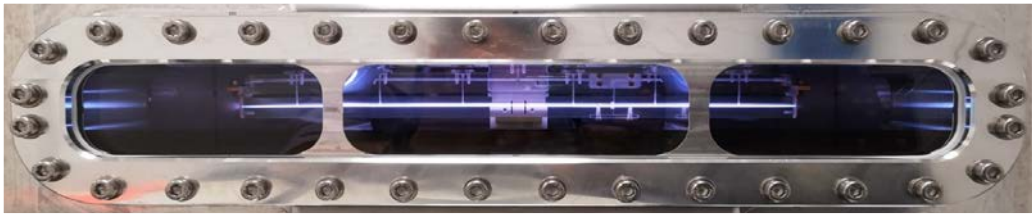




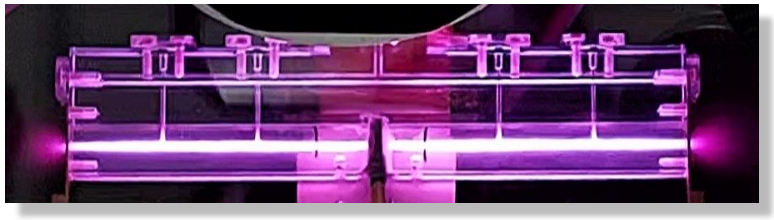
Studies on cross-talk effects:
Design of electrodes and HV-circuits to reduce the interaction among discharges through plsam ramps



Very long capillary

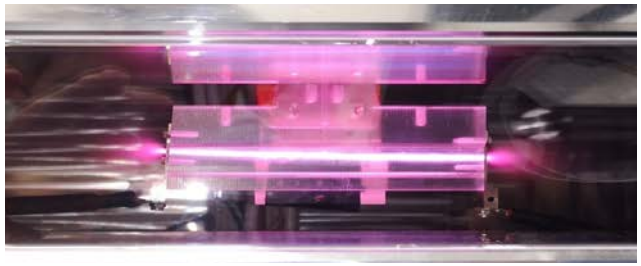


Design of m-scale capillaries for EuPRAXIA project by using segmented capillaries: design of HV-voltage circuits and discharge synchronization



Segmented capillary

Curved capillary for APD



Design of new geometries for curved channels:
HV-circuits to allow high current pulses

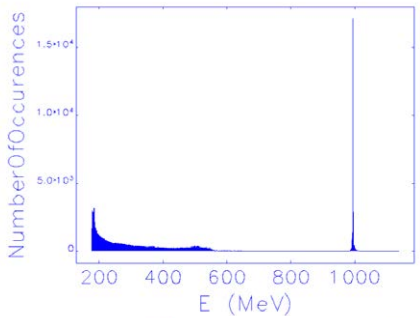
Pompili, Riccardo, et Al, Guiding of charged particle beams in curved capillary-discharge waveguides, AIP Advances 8.1 (2018)

EuPRAXIA at SPARC_LAB

Plasma Accelerating Module and Driver Separator

Funded by the European Union

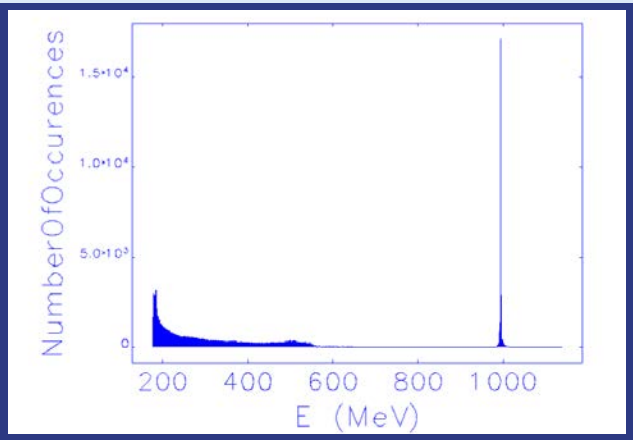
Vacuum chamber length	**2.7 m**
Plasma length	**0.6 m**
Density	**10^{16} cm^{-3}**
Capillary diameter	**2 mm**
Gas pressure	**10–20 mbar**
Plasma chamber pressure	**~10^{-3} mbar**
RF line vacuum requirement	**10^{-9} mbar**
Repetition rate	**100 Hz**



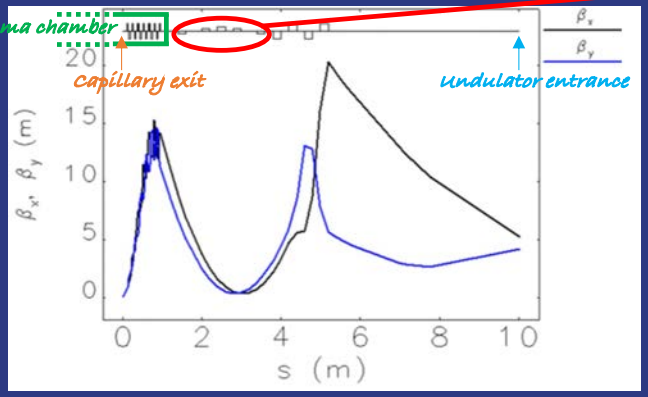


Separator total length	**2.4**	m
Dipoles	**4**	—
Dipole bend angle (1 GeV beam)	**2.5**	deg
Dipole field	**0.8**	T
R_{56}	**0.8**	mm
Dispersion at septum	**≈17**	mm
Driver–witness separation	**≈17**	mm
Septum deflection (driver)	**10**	deg
Arrival-time sensitivity	**≈27**	fs

Driver-Witness Separator - Septum Magnet



Energy distribution of the Comb beam at the plasma exit

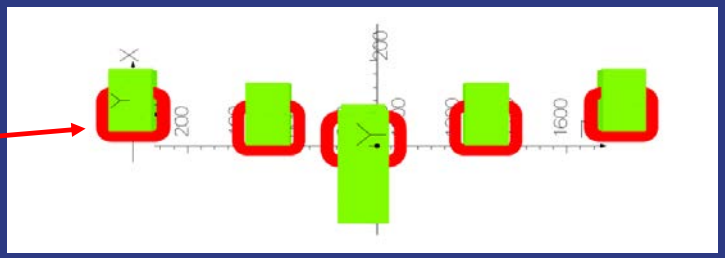


Twiss parameters for the witness beam along the capture/separation transfer line

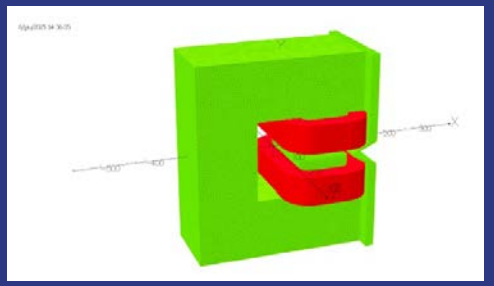
The separation of the driver and witness beams is achieved by exploiting their different energies, using a magnetic chicane and a septum dipole.

In the first dipole, the deflection angle differs for the two beams due to their energy difference, resulting in a transverse separation that is preserved through the second dipole. As a result, between the second and third dipoles, the two beams propagate parallel to each other with a transverse offset.

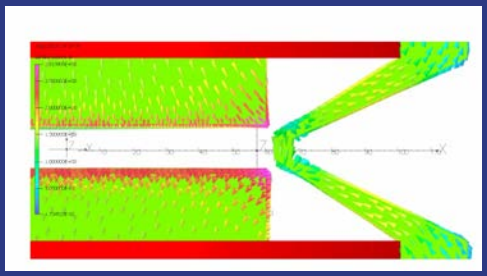
At this point, a septum C dipole is inserted, with the transverse geometry schematically shown in figure below.



The 3D design of the driver-witness separator chicane



The 3D design of the septum dipole



Details of the field in the septum

Radiation Generation: FEL

Funded by the European Union

Two FEL lines:

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

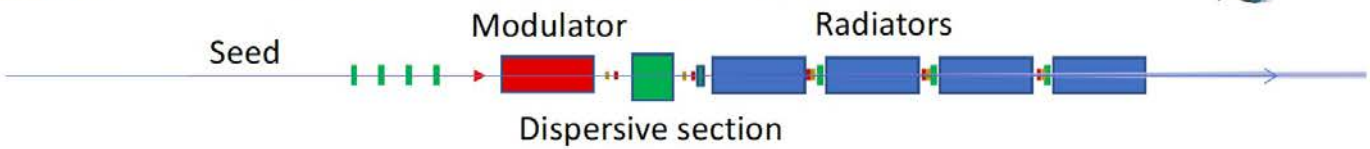


SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress



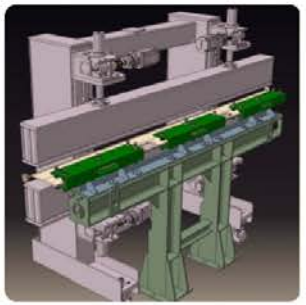


2) *ARIA*: VUV seeded HGHG FEL beamline for gas phase



SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 290 – 430 nm

FERMI FEL-1 Radiator



Courtesy of L. Giannessi, F. Stellato

EuPRAXIA@SPARC_LAB User Facility

Funded by the European Union

The facility aims to operate in two modes: a full-RF mode for initial commissioning, and a hybrid RF+PWFA mode that serves as a demonstrator for plasma-driven FELs user operation. Full-RF mode user operation is also possible.
The facility is expected to begin operations **in 2031**



•**Moderate Energy with High Impact:** Operating at around 1 GeV, will deliver Soft X-rays radiation in the "water window".

•**Compact Design:** With an accelerating length shorter than 50 meters, it is the most compact facility in the soft X-rays list, at least by a factor 3.

•**Technology Demonstrator:** it will be also a strategic testbed for integrating advanced acceleration schemes and short period undulators into user-oriented FELs marking a paradigm shift toward compact and cost-effective light sources.

	Units	PWFA	Full RF
		30 pC with tapering	Hybrid compression
Electron Energy	GeV	1	1
Repetition rate	Hz	100	100
Bunch charge	pC	30	200
Peak current at undulator entrance	kA	3.3	3.4
RMS bunch length at undulator entrance	μm	1.4	16.9
RMS normalized emittance (x,y)	$mm\ mrad$	0.7,0.6	2.1,1.0
RMS energy spread	%	0.5	0.2
Slice length	μm	0.5	0.5
Slice Normalized emittance (x,y)	$mm\ mrad$	0.7,0.6	0.3,0.3
Slice energy spread	%	0.04*	0.02
ρ (3D)	$\times 10^{-3}$	0.77	1.49
Radiation wavelength	nm	4.0	4.0
Saturation length	m	20.5	20.0
Photon Pulse Energy	μJ	16	150
Photon per pulse	$\times 10^{11}$	3.2	31.3
Photon Bandwith	%	0.4	0.5
Photon Brilliance per shot	$\times 10^{30}$	0.12	2.1

Funded by the European Union

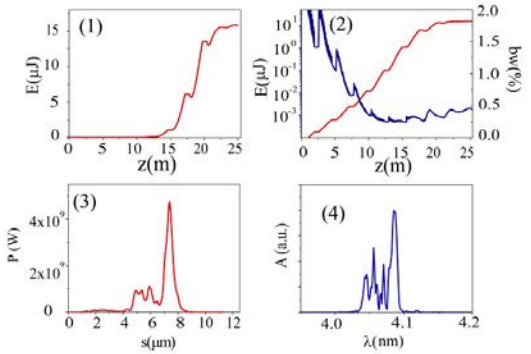


Figure 1.4: Genesis simulation results for PWFA working points with Undulator Tapering, Plot (1): energy growth in linear scale. Plot (2): energy growth in logarithmic scale and bandwidth in %. Plot (3): power distribution. Plot (4): amplitude of spectral distribution.

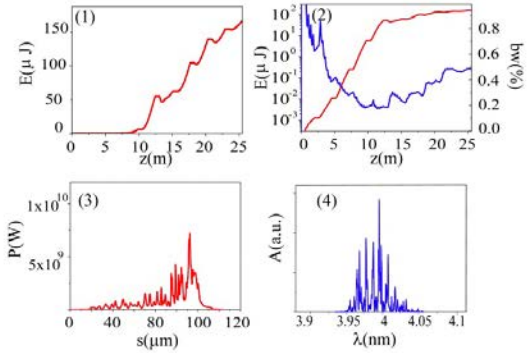


Figure 1.5: Genesis simulation results for Full RF working points with Undulator Tapering, Plot (1): energy growth in linear scale. Plot (2): energy growth in logarithmic scale and bandwidth in %. Plot (3): power distribution. Plot (4): a smplitude of spectral distribution.

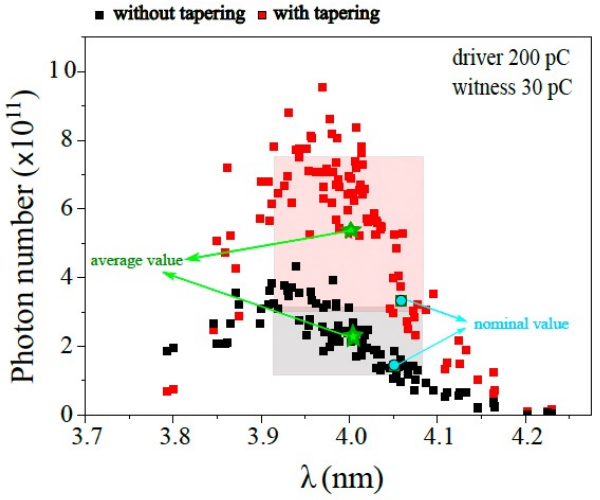
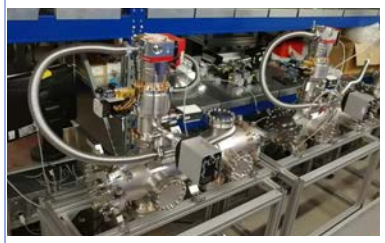
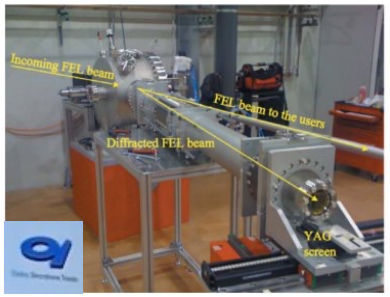
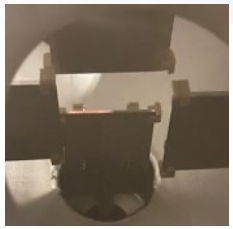


Figure 1.6: Photon number versus wavelength for 100 random events of the reference case at 1 GeV. Black squares: without tapering. Red squares: with a tapering with the K_{rms} values of Table 3.8. Green stars represent the average values. Cyan circles represent the values obtained with the reference beams. The shaded areas (light gray for the case without tapering and light pink for the case with tapering) around the average values have the half hight equal to the rms deviation of the photon number (1 and 2.33×10^{11}) and the half bases equal to the rms deviation of the peak wavelength (85 pm).

AQUA Beamline: Photon Beamline





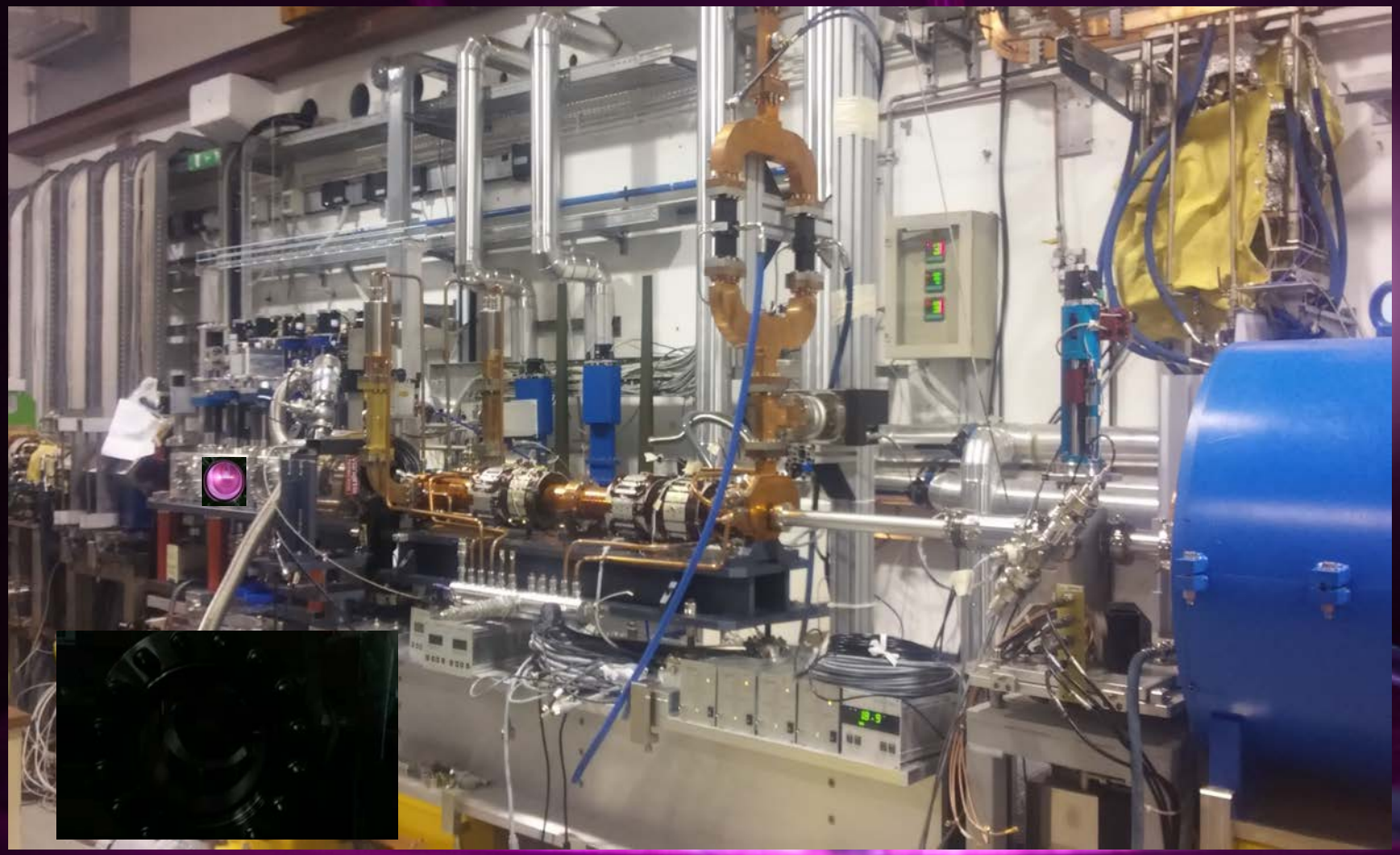




In the PWFA configuration, the larger shot-to-shot energy jitter is addressed through systematic single-shot photon diagnostics and energy tagging, enabling post-acquisition sorting and correlation-based data analysis.

Courtesy: F. Villa

PWFA beam line at SPARC_LAB

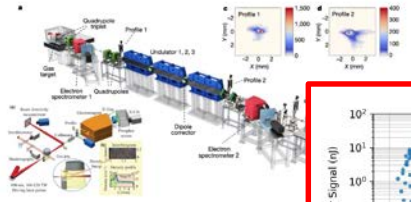


Basic beam quality achieved in pilot FEL experiments

EuPRAXIA 2021 Plasma FEL Feasibility Proven: Laser-driven



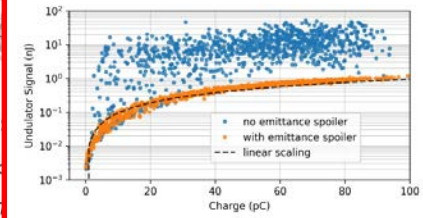
W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).



Recent ground-breaking re

500 MeV electron beam from a laser wakefiel

FEL lasing **amplification of 100** reached at 2
radiation energy 70 nJ, peak up to 150 nJ)



S. K. Barber *et al.*, *Phys. Rev. Lett.* **135**, 055001 (2025);
F. Kohrell *et al.*, PRAB (2026)

BERKELEY LAB

+ industry partners

> **Laser-driven plasma FEL (gain >1000)** for 1000s of shots per day, over 21 days

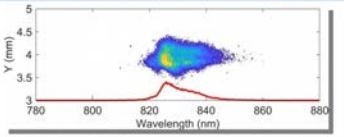
> **Emittance 0.25 μm** (inferred by gain length)

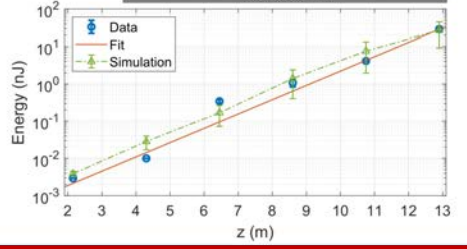
> **Community progress:** SIOM, Frascati, HZDR + Soleil also demonstrated FEL gain

EuPRAXIA 2021 Plasma FEL Feasibility Proven: Electron-driven

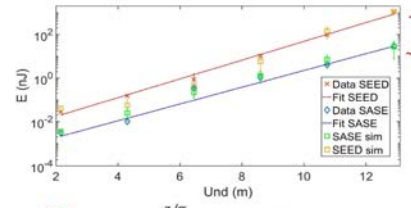
Recent ground-breaking results in Frascati:

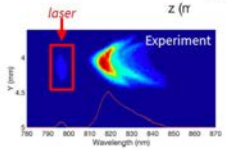
Single Spike SASE spectrum

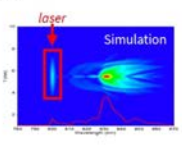




EuPRAXIA First Beam Driven SEEDED - FEL Lasing at SPAR







PHYSICAL REVIEW LETTERS 129, 234801 (2022)

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

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

ded UV free-electron laser driven by LWFA

resden, published on
s://doi.org/10.1038/s41566-022-01104-w

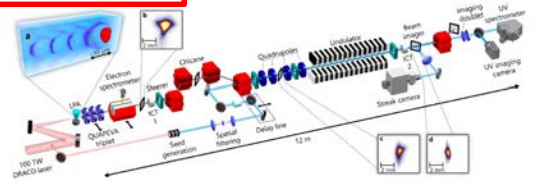
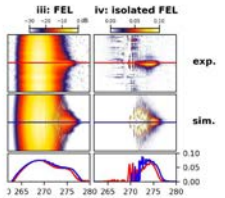


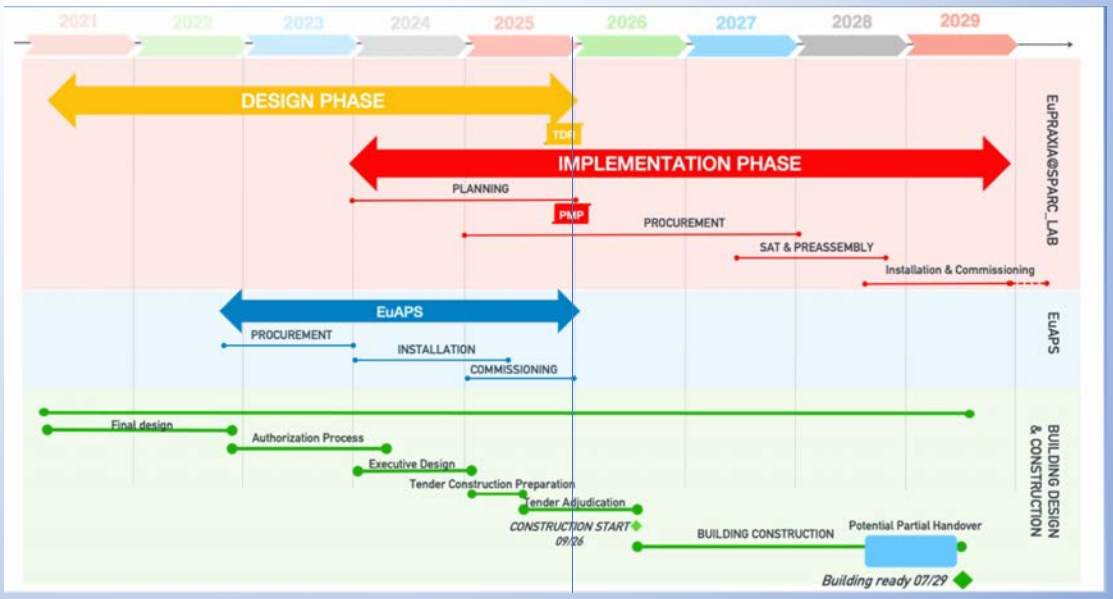
FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled 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**).



Project Cost, Timeline, and Management

Functional Area	Estimated Cost (€)
Injector	10.999.880
Low Energy Line	9.596.380
Bunch Compressor	1.180.400
High Energy Line	9.761.760
Plasma Module	2.222.600
AQUA FEL	12.062.000
AQUA Beam Lines	7.095.900
General Elements	3.940.740
Building	51.578.552
Hi-Tech utilities	6.000.000
TOTAL	**114.438.212**

Table 1.2: Aggregated cost per functional area



As expected, the cost of the **Plasma Module is significantly lower** than that of the High Energy Line, almost one fifth, despite delivering the same energy gain, underscoring the economic advantage of plasma-based acceleration technologies in comparison to conventional radio-frequency systems.

The implementation timeline targets **2029 for building readiness** and **2031 for minimum operational status**, aligned with ESFRI Landmark designation requirements. **EuAPS** is expected to run as User Facility **from 2026**

Courtesy A. Falone

Future Otlook => PACRI and EuPLASMAR

Funded by the European Union

Higher Repetition Rate

- Upgrade from **100 Hz → ~400 Hz operation**
- Possible implementation of a **C-band RF photoinjector**
- Higher average beam power enabling **high-flux photon science**

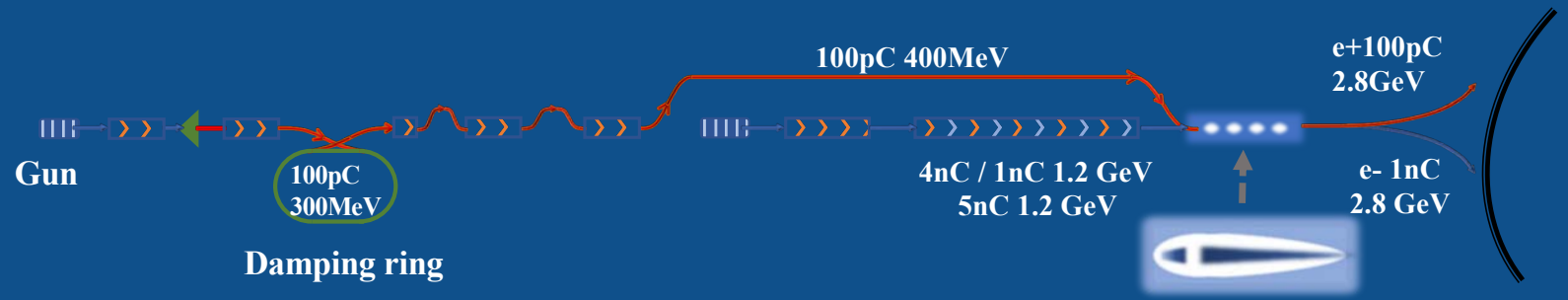
Higher Beam Energy

- Extension of the **PWFA plasma stage**
- Multi-GeV operation compatible with **future EuPRAXIA upgrades**
- Access to **shorter wavelength FEL radiation or Compton γ-ray sources**

Contribution to Future Plasma-Based Linear Colliders

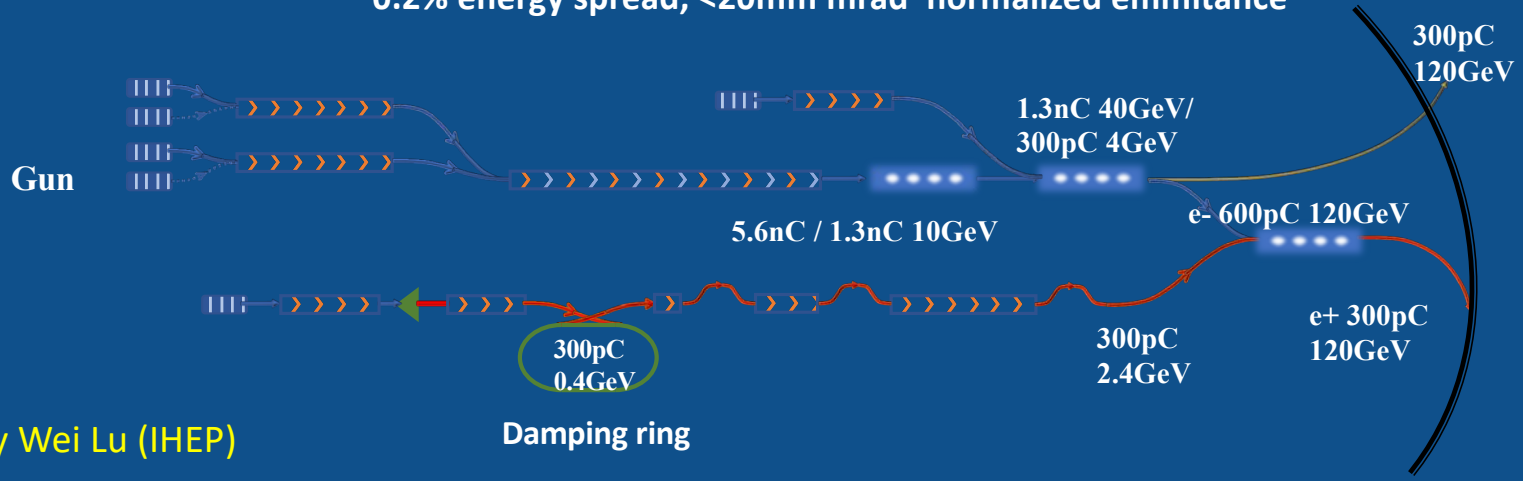
- Beam loading optimization and high transformer ratio regimes
- Stability and reproducibility of plasma accelerators
- Staging of plasma modules
- High-efficiency energy transfer from RF drivers to plasma wakefields

BEPCII and CEPC/FCC-ee full energy plasma injector

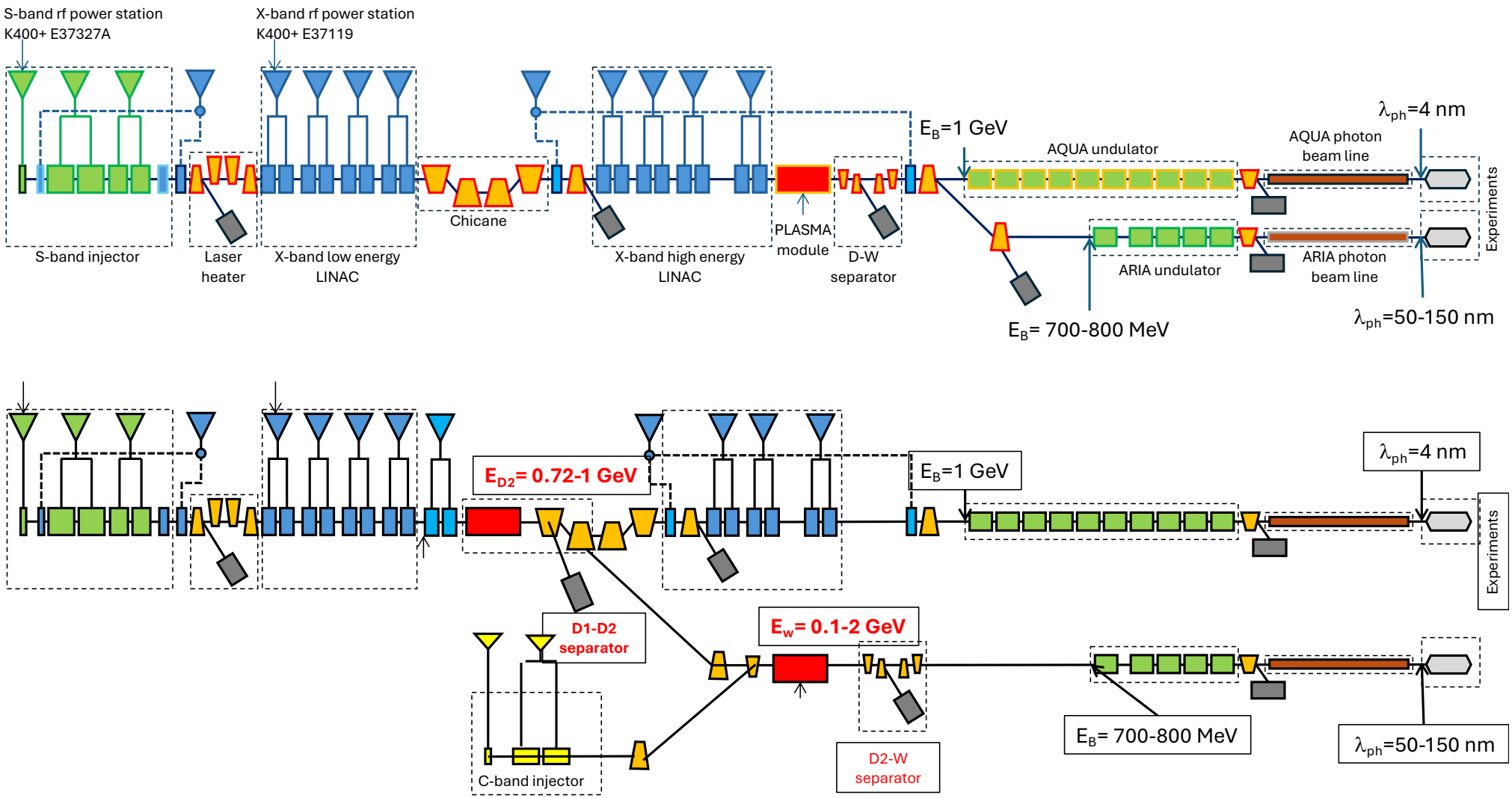


100Hz 300pC 120-180GeV e+/e-

0.2% energy spread, <20mm mrad normalized emmitance



Courtesy Wei Lu (IHEP)


S-band rf power station
K400+ E37327A
X-band rf power station
K400+ E37119
S-band injector
Laser heater
X-band low energy LINAC
Chicane
X-band high energy LINAC
PLASMA module
D-W separator
E_B=1 GeV
AQUA undulator
AQUA photon beam line
λ_{ph}=4 nm
Experiments
ARIA undulator
ARIA photon beam line
E_B= 700-800 MeV
λ_{ph}=50-150 nm
E_{D2}= 0.72-1 GeV
D1-D2 separator
C-band injector
E_w= 0.1-2 GeV
D2-W separator

Conclusions

Funded by the European Union

•The **EuPRAXIA@SPARC_LAB facility** represents the **first FEL user infrastructure based on beam-driven plasma wakefield acceleration (PWFA)** combined with compact **X-band RF technology**.

•The Technical Design Report demonstrates that the **baseline 1 GeV accelerator and FEL facility are technically feasible** within the proposed schedule and infrastructure framework.

•No critical showstoppers have been identified; the main technical challenges have **well-defined mitigation strategies and active R&D programs**.

•**Pulse-to-pulse beam energy stability** in PWFA remains the primary challenge for user-facility operation.
•Continued progress in:

- plasma source reproducibility
- RF phase and amplitude stability
- synchronization and diagnostics will enable **sub-percent energy stability compatible with FEL operation**.

EuPRAXIA@SPARC_LAB will evolve into a **European hub for advanced accelerator technology**, enabling a new generation of compact, high-brightness radiation sources for science, industry, and medical applications, while also providing a unique testbed for key technologies relevant to future plasma-based linear colliders.


Thank for your attention