EUROPEAN
PLASMA RESEARCH
ACCELERATOR
WITH
EXCELLENCE IN
APPLICATIONS

The EuPRAXIA project: goals and user facility

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On behalf of the EuPRAXIA@SPARC_LAB collaboration

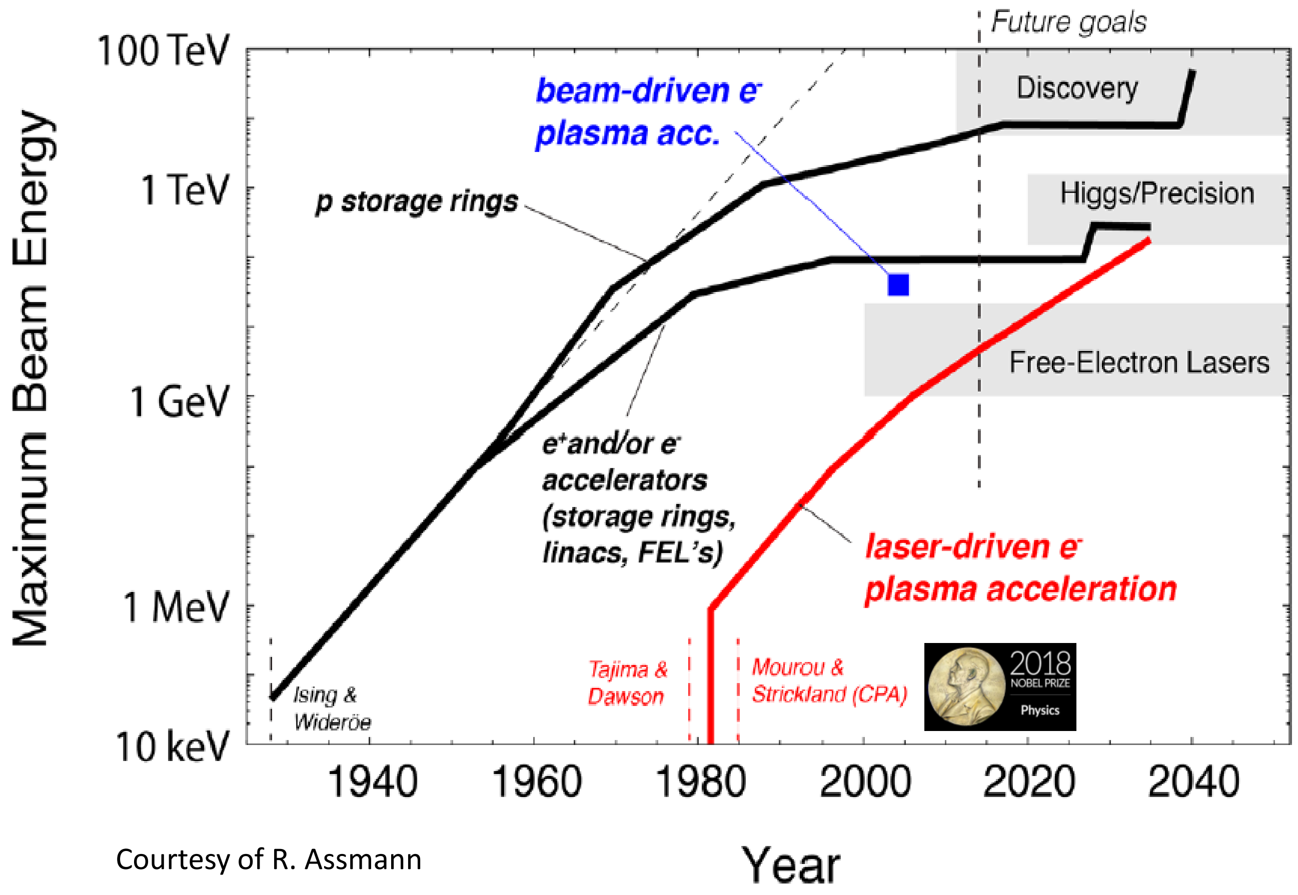
This project has received funding from the European Union´s Horizon Europe research and innovation program under grant agreement No. 101079773

2026 CIP
1° Conferenza Italiana Plasmi

Livingston diagram for accelerators

Funded by the European Union

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



Courtesy of R. Assmann

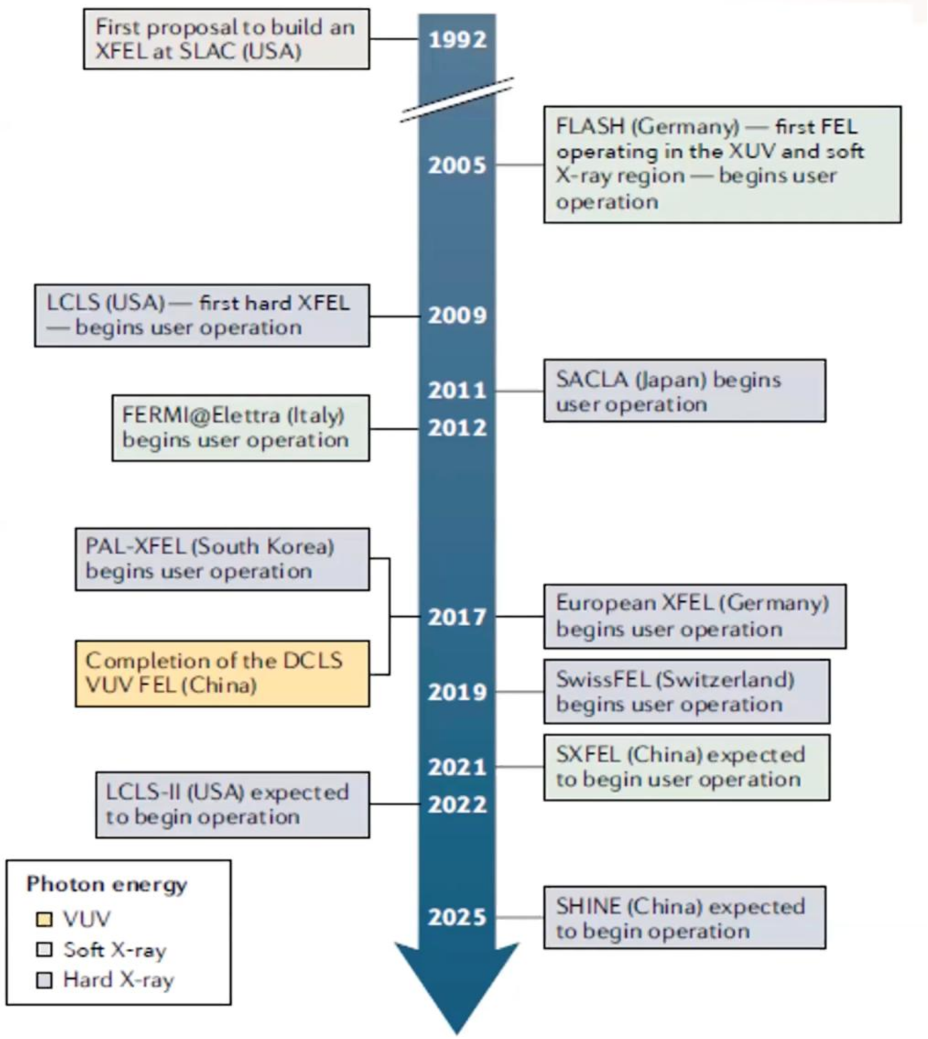
Plasma Accelerator Achievements

- Gradients up to **100 GV/m** vs **<100 MV/m** from RF structures
- Acceleration >10 **GeV** of electron beams
- Basic **beam quality for FEL** demonstrated

FEL is a well-established technology

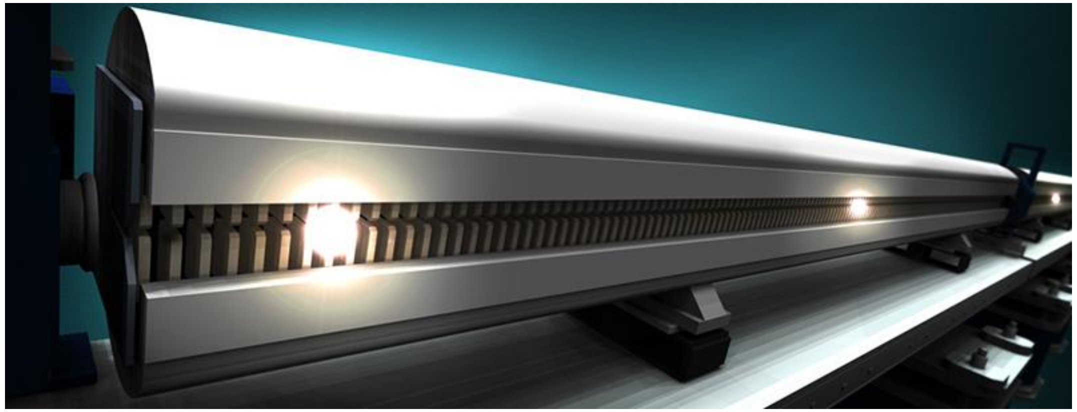
(But a widespread use of FEL is partially limited by its size and costs)

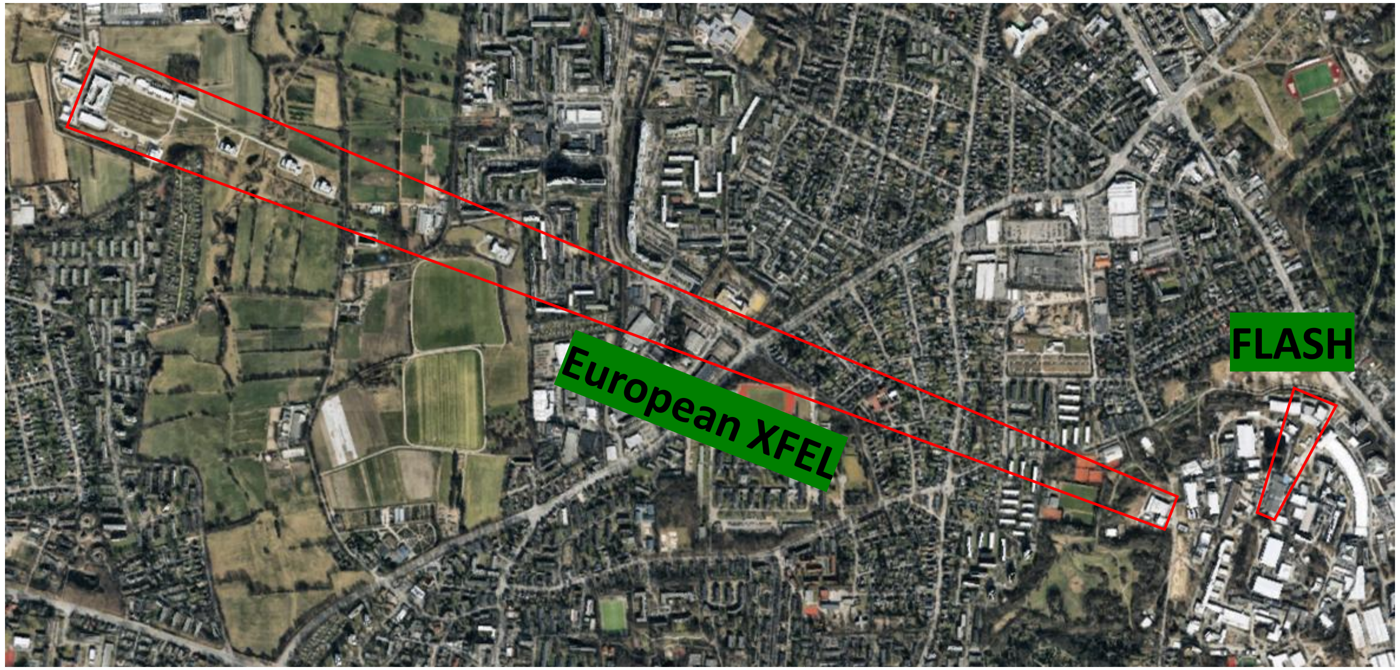
Funded by the European Union



New facilities are expected to begin operation in the next 5 years in the USA and China, and the UK is considering the scientific case for an XFEL.

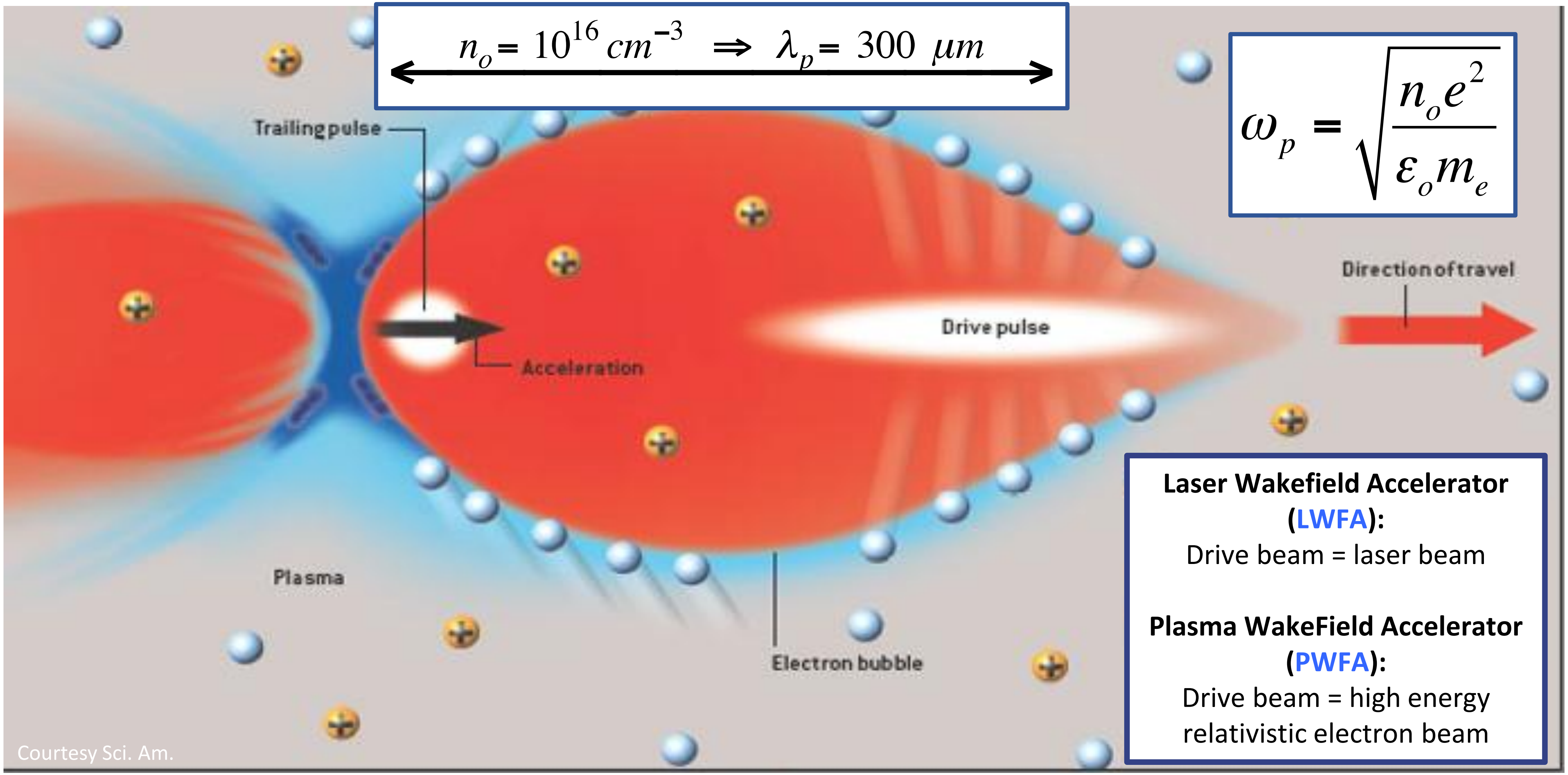
Iulia Georgescu





Principle of plasma acceleration

Funded by the European Union



$$n_o = 10^{16}\ cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$$

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy relativistic electron beam

- Tajima, T. and Dawson, J. M. *Phys. Rev. Lett.*, **43** (1979), 267.
- Chen, P., Dawson, J et al . *Phys. Rev. Lett.*, **54** (1985), 693.

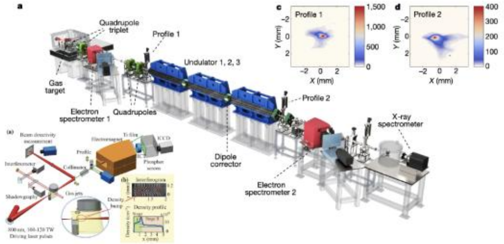
Plasma FEL pilot experiments

Funded by the European Union

2021 Plasma FEL Feasibility Proven: Laser-driven

Horizon Europe

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



Recent ground-breaking result in China

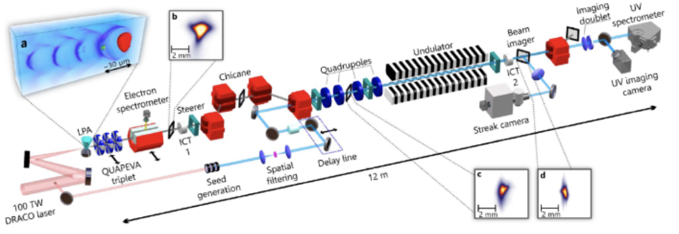
500 MeV electron beam from a laser wakefield accelerator

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

Seeded UV free-electron laser driven by LWFA

Horizon Europe

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



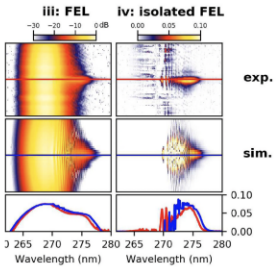


FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled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

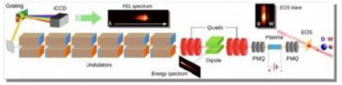
2021 Plasma FEL Feasibility Proven: Electron-driven

Horizon Europe

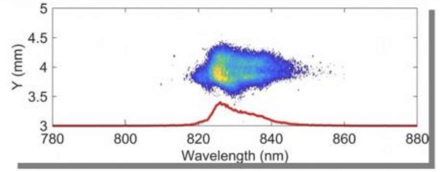
Recent ground-breaking results in Frascati:

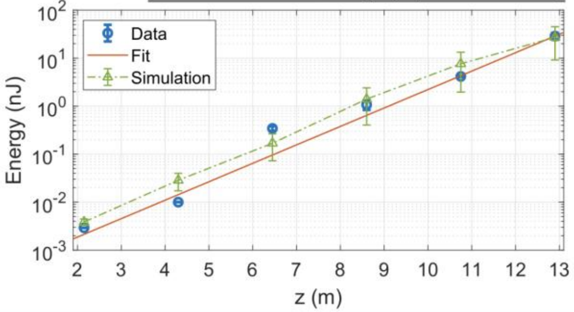
First FEL lasing from a beam-driven plasma accelerator

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

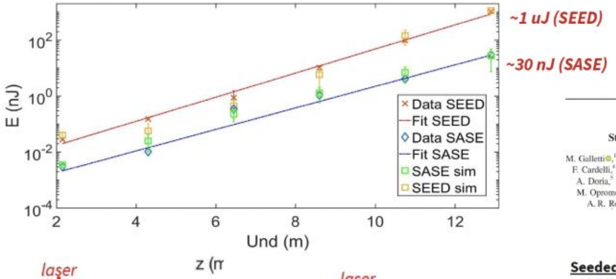


Single Spike SASE spectrum



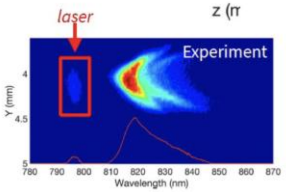


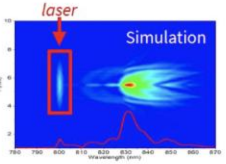
First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)



PHYSICAL REVIEW LETTERS 129, 234801 (2022)

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





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

A New European High-Tech User Facility

Funded by the European Union

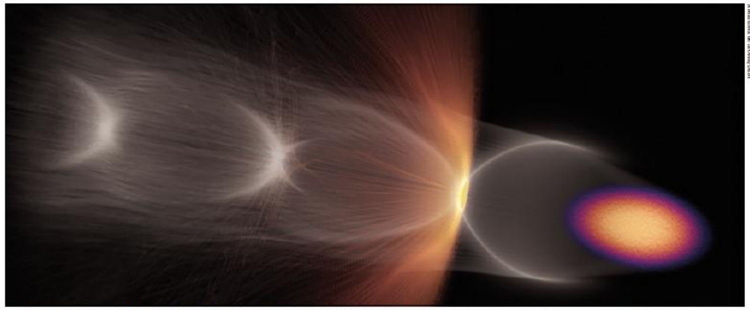
European Plasma Research Accelerator with Excellence In Applications

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

Building a facility with very high field plasma accelerators, driven by lasers or particle bunches
1 – 100 GV/m accelerating field
Reduce size and cost –> Improve Sustainability

Provide a practical path to more research facilities and ultimately to higher beam energies
Enable frontier science in new regions and parameter regimes
Future Linear Collider & Short wavelength FEL

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

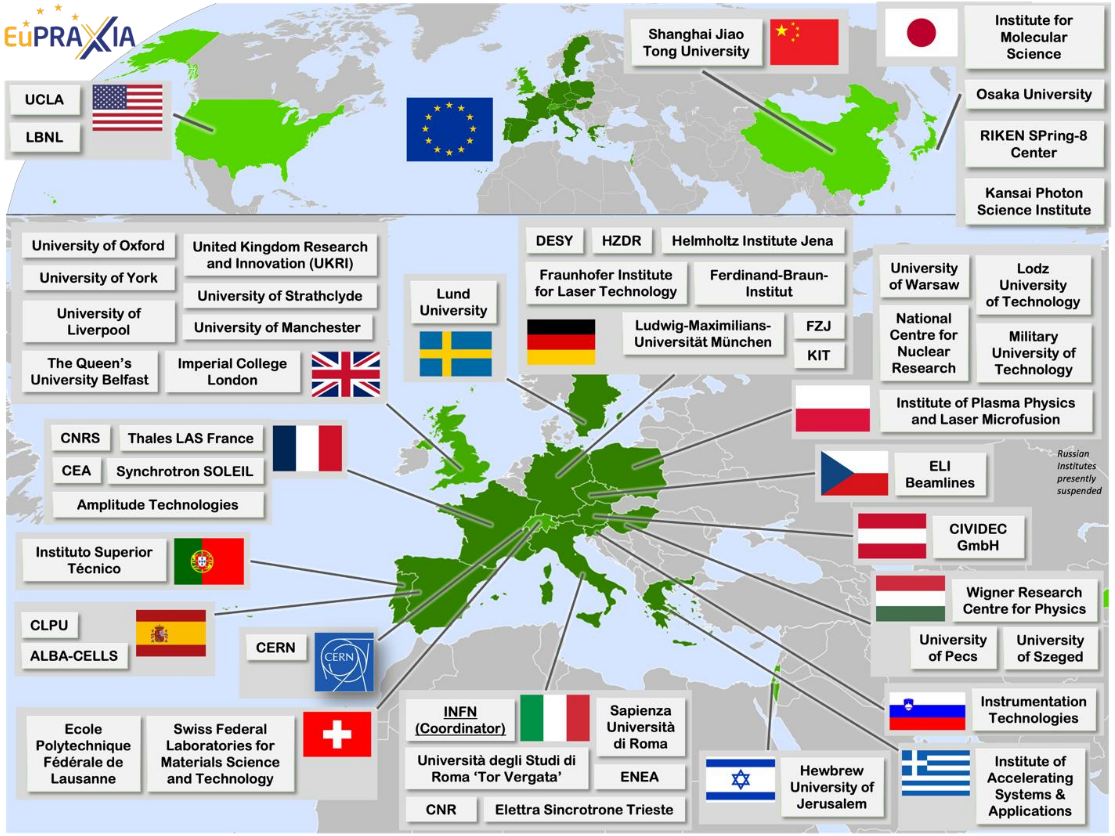
THE AUTHORS
Ralph Assmann *DESY and INFN,* **Massimo Ferrario** *INFN,* **Carsten Welsch** *University of Liverpool/INFN.*

CERN COURIER MAY/JUNE 2023 25

- Assmann, R. et al. EuPRAXIA conceptual design report. *Eur. Phys. J. Spec. Top.*, **229** (2020), 3675–4284.

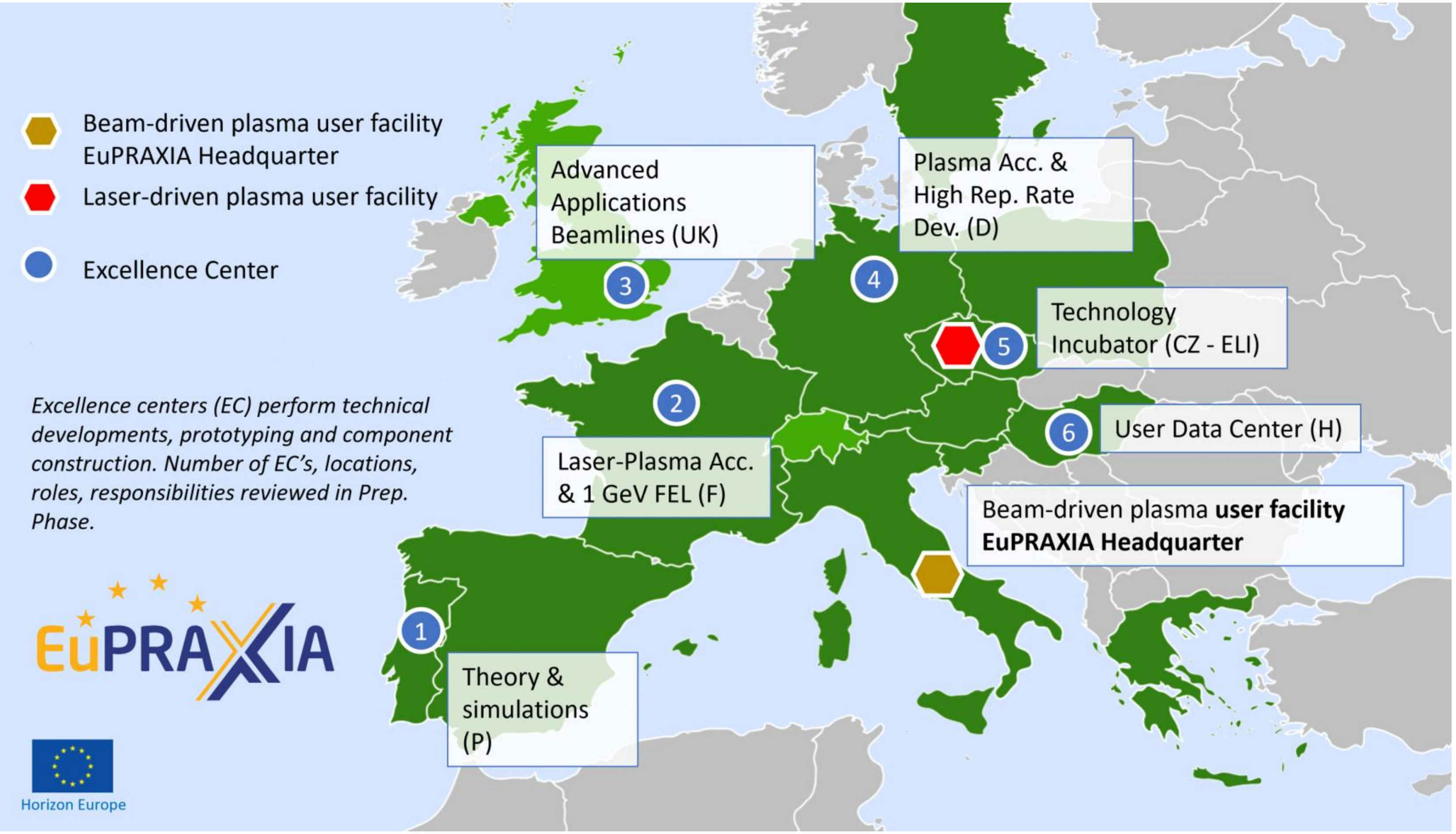
Wide International Collaboration

- **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:** Plasma Accelerator System for Compact Research Infrastructures (Horizon Eu)



Distributed Research Infrastructure

Funded by the European Union



Two EuPRAXIA pillars at LNF:

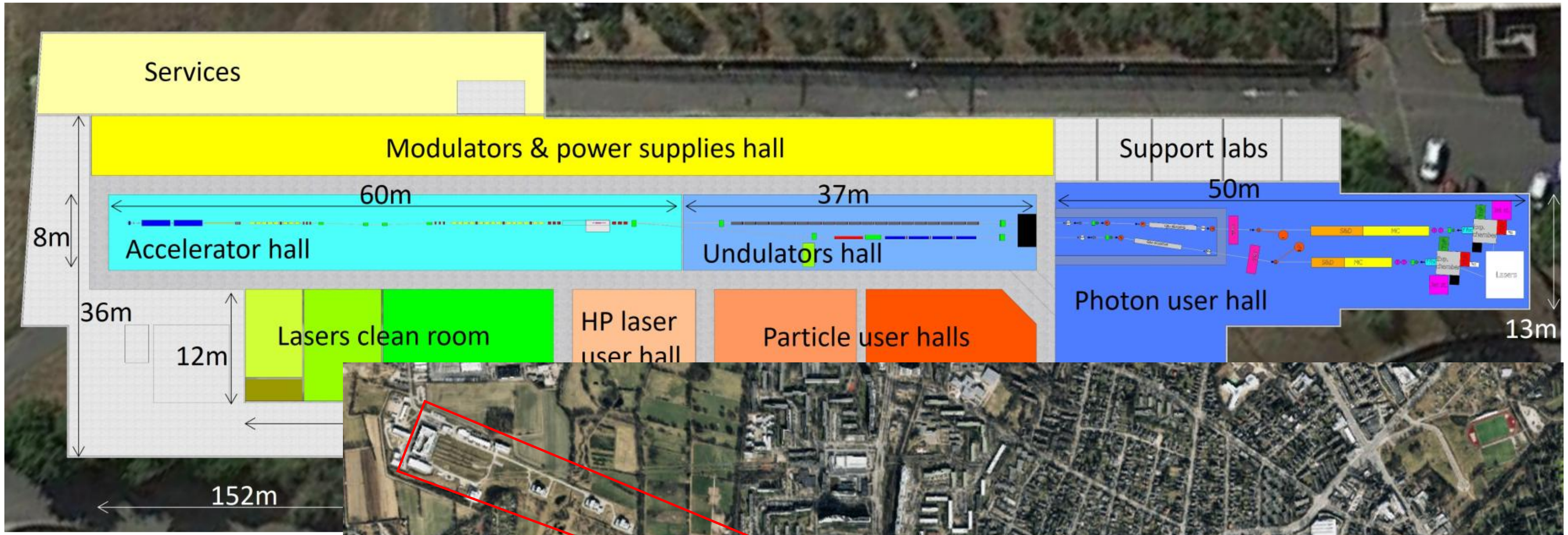
1. **EuPRAXIA@SPARC_LAB**
   - New infrastructure to host the facility
   - 1 GeV X-band linac
   - Multi-hundreds TW Laser
   - Two FEL lines guided by beam-driven plasma accelerator (4 nm and 50-180 nm)
2. **EuAPS** (Advanced Photon Sources)
   - Betatron radiation source
   - Cost-effective and Compact photon sources
   - For users applications

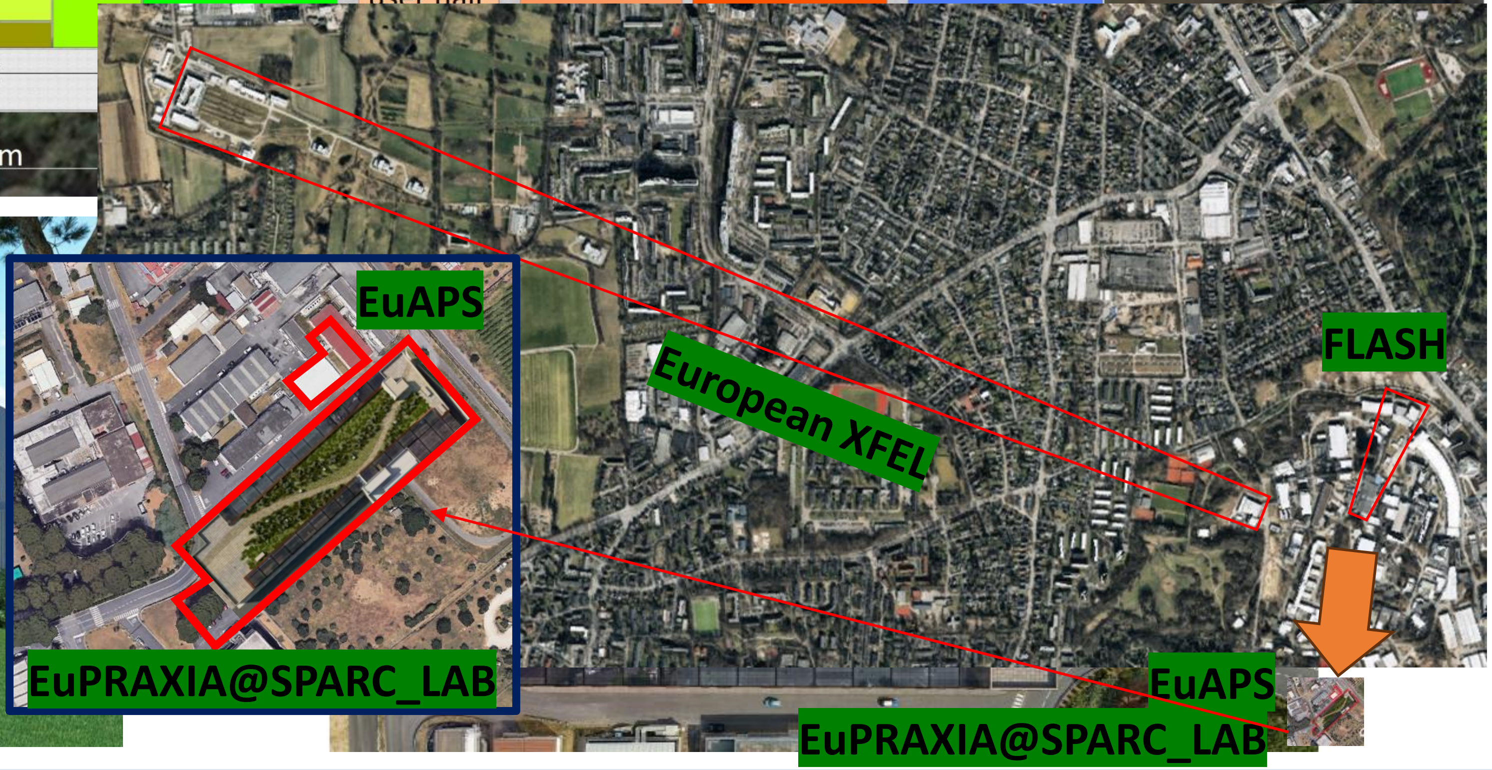
Headquarter and Site 1: EuPRAXIA@SPARC_LAB

Funded by the European Union

LNF future facility

- <120 M€ invest funding
- Beam-driven plasma accelerator
- The world`s most compact GeV class RF accelerator (X band with CERN)
- Europe`s most compact FEL

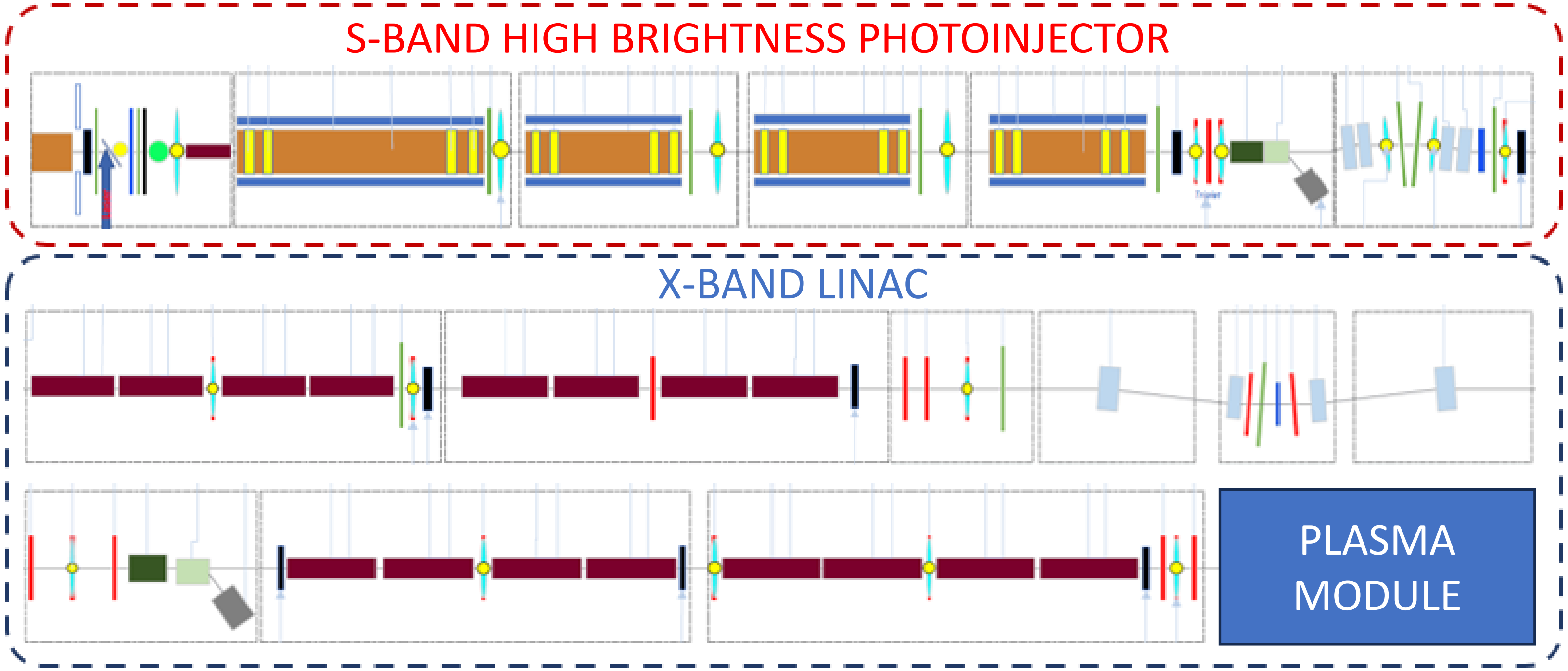




Courtesy F. Cioeta, E. Di Pasquale, A. Ghigo, A. Falone

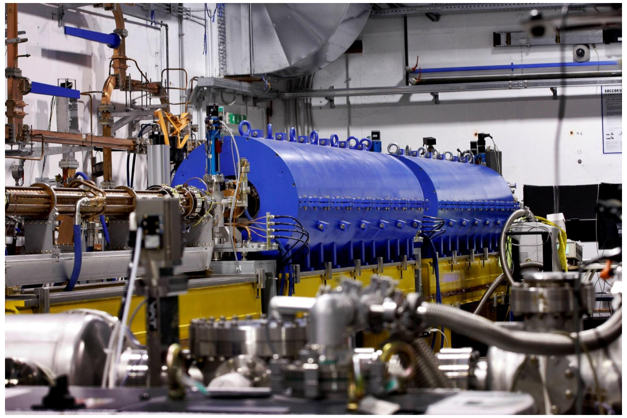
EuPRAXIA@SPARC_LAB Layout

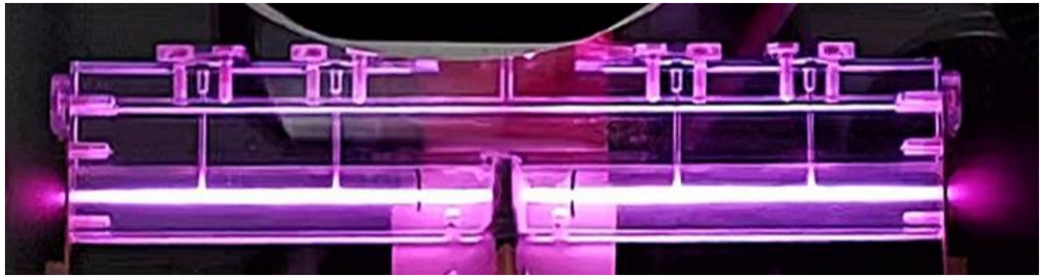
Funded by the European Union



A combination of **cutting edge technology**:

- High brightness RF injector
- X-band linac
- Plasma module for PWFA



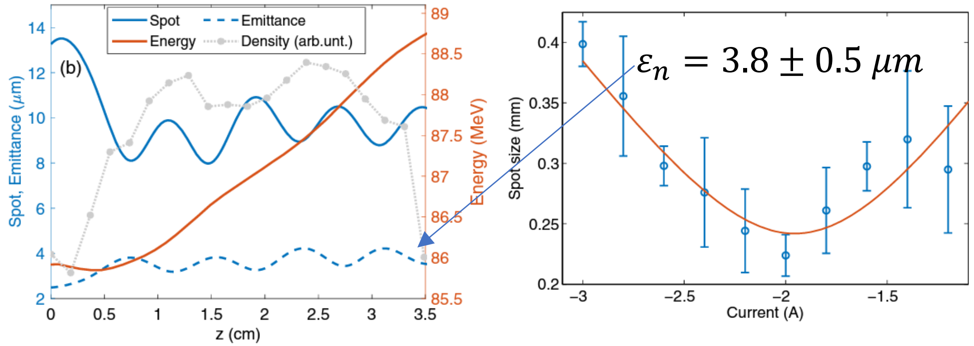


PWFA experiments at SPARC_LAB

Funded by the European Union

Emittance measurement

PHYS. REV. ACCEL. BEAMS **24,** 051301 (2021)

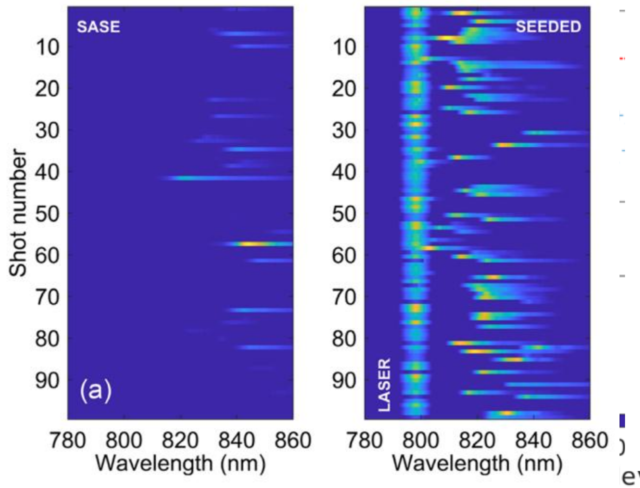


SASE FEL

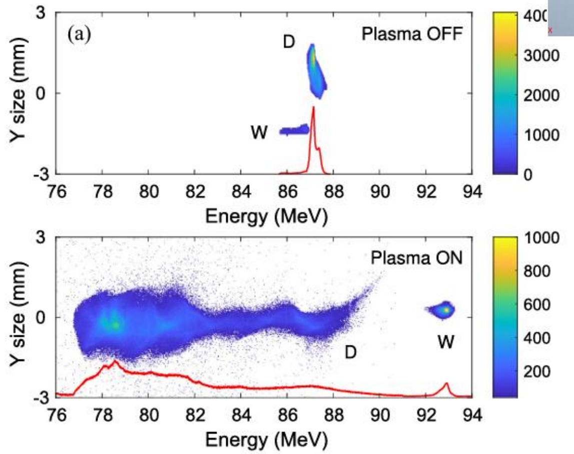
Energy spread measurement

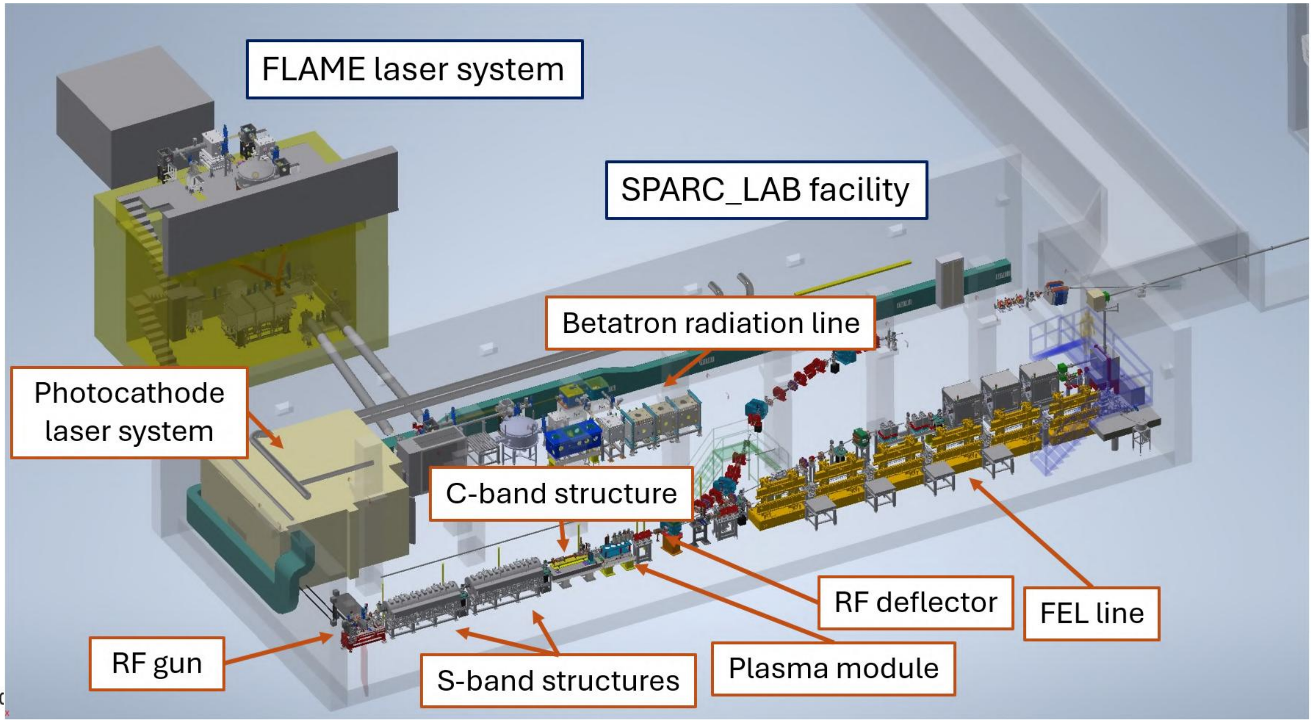
Seeded FEL

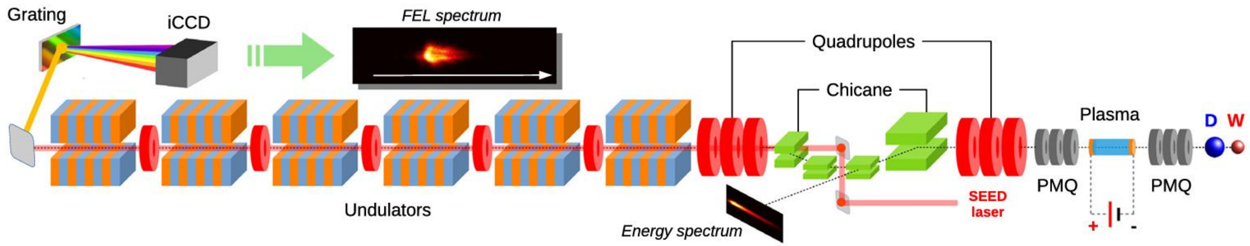
Nature | Vol 605 | 26 May 2022 | **659**



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

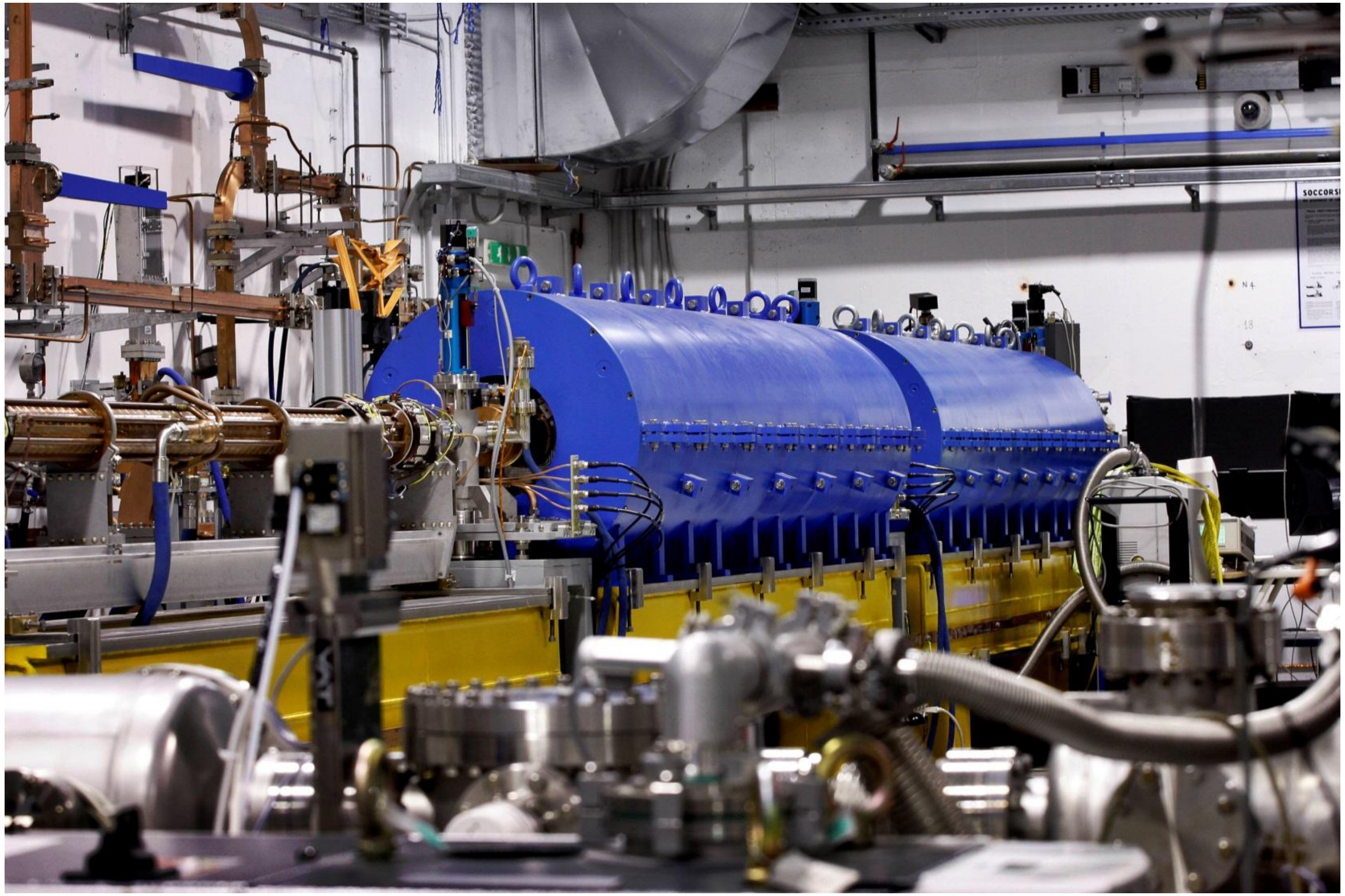






High Quality S-band Photoinjector R&D

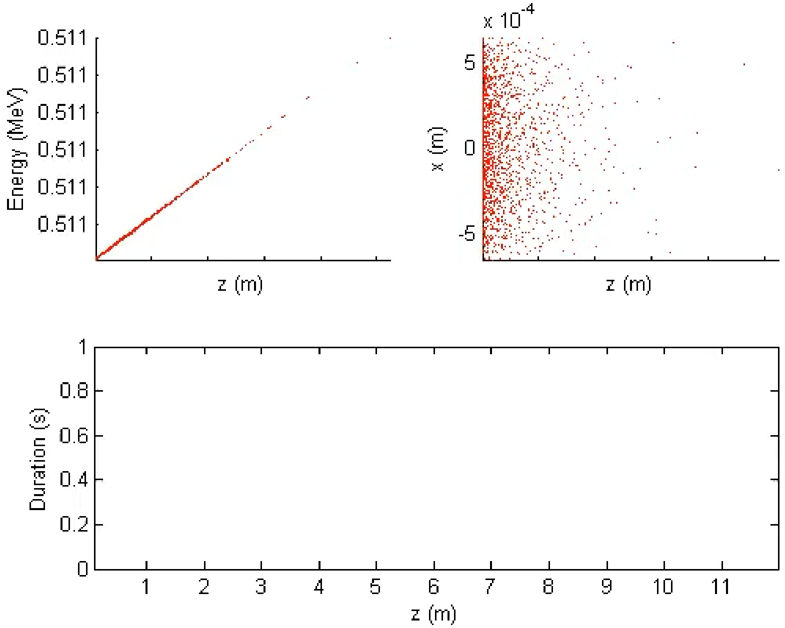
Funded by the European Union



Courtesy of E. Chiadroni

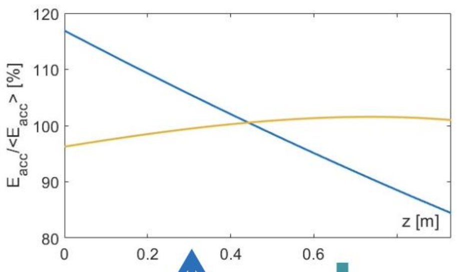
Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

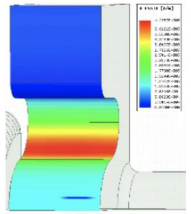
Table 7.2: Driver and witness beam parameters at the end of photo-injector.



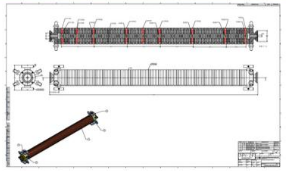
X-Band Booster R&D at TEX

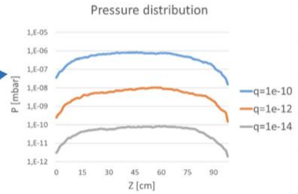
Funded by the European Union

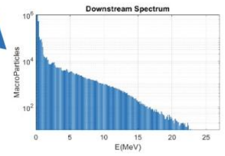




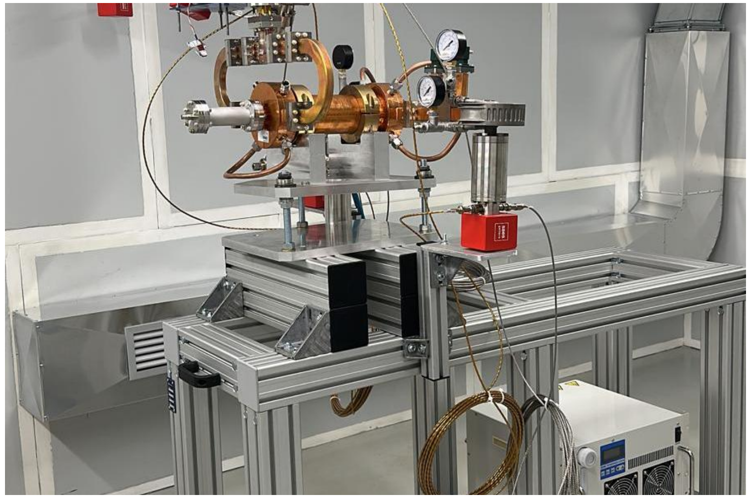
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*







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**	



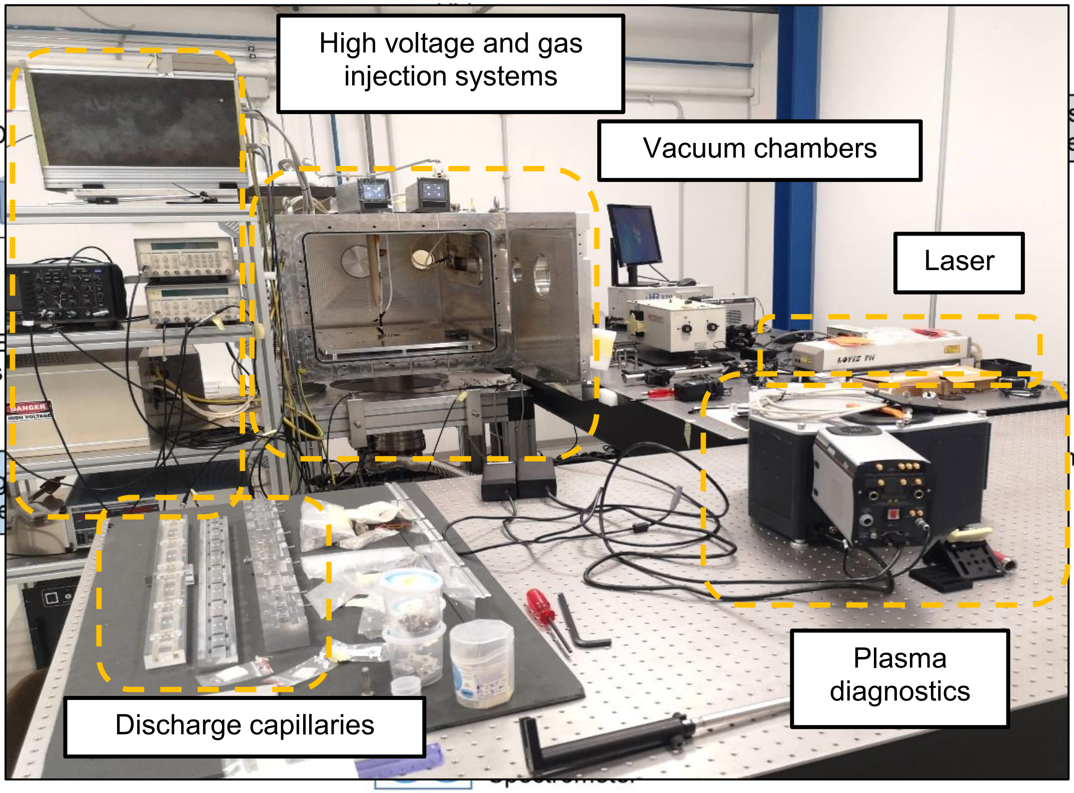
Courtesy of D.Alesini, F.Cardelli

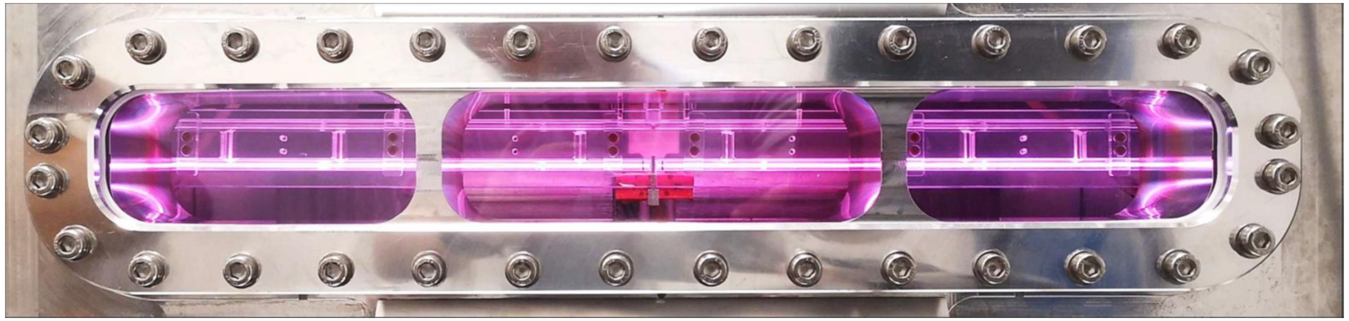
Plasma Module R&D at Plasma_lab

Plasma module components

- Gas-filled plasma discharge capillary
- Gas injection and high voltage systems
- Vacuum chamber and pumping system
- Plasma discharge diagnostics

Key design parameters for the plasma discharge capillary source	
Source type	Gas-filled discharge capillary
Geometry	60 cm in length 2 mm in diameter
Gas (continuous flow)	Nitrogen
Gas pressure	10-20 mbar
Discharge repetition rate	100 Hz
Discharge circuit parameters	15 kV, 500 A
Materials	Channel: Sapphire, Shapal Holder: Macor Electrodes: Tungsten
Plasma density	$10^{15} \div 10^{17}$ cm^{-3}
Lifetime	$> 1 \times 10^8$ shots
Shot-to-shot stability	$<$ 1% rms plasma density jitter with laser stabilization





Courtesy of A.Biagioni, L.Crincoli, R.Demitra, V.Lollo, R.Pompili

Plasma Module R&D at Plasma_lab

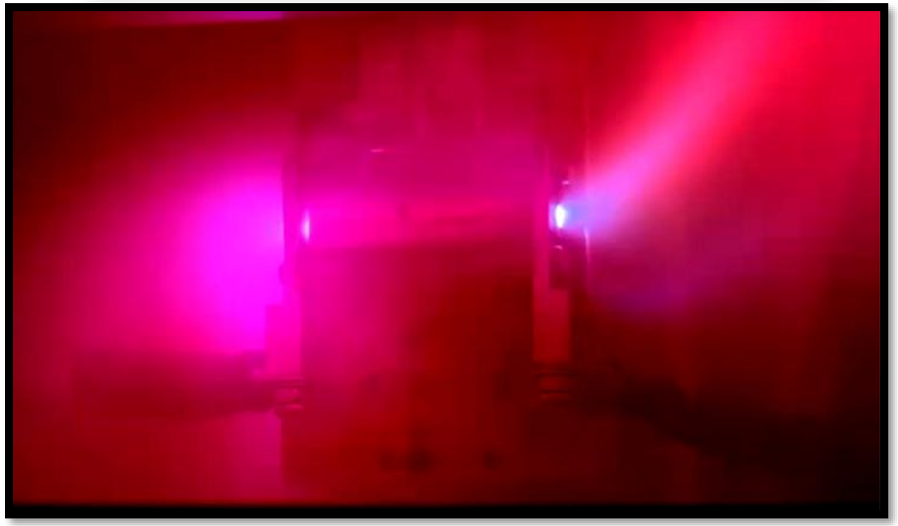
Funded by the European Union

Plasma module operation at high repetition rate

1. Solid-state high repetition-rate discharge system
2. Vacuum systems suitable for continuous flow gas injection (turbo and primary pumps cooling system)
3. High temperature-resistant materials capable of withstanding the plasma thermal load

- Crincoli, L. et al. *Scientific Reports* **15**, 12456 (2025)
- Biagioni, A., Crincoli, L., Demitra, R., et al. (2025). Link

100 Hz repetition rate discharges



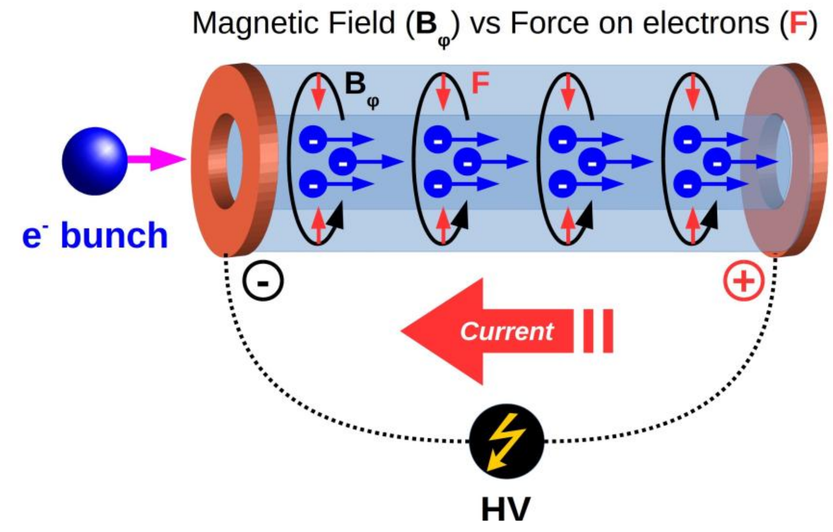
Plasma Module R&D at Plasma_lab

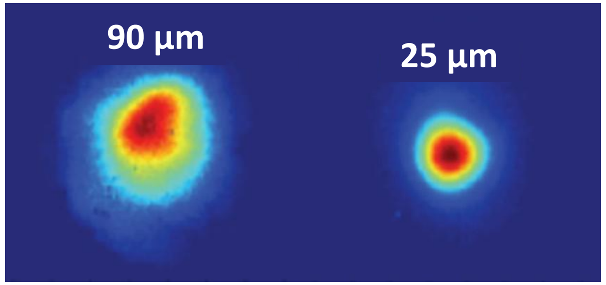
Segmented capillary

Integrated plasma module

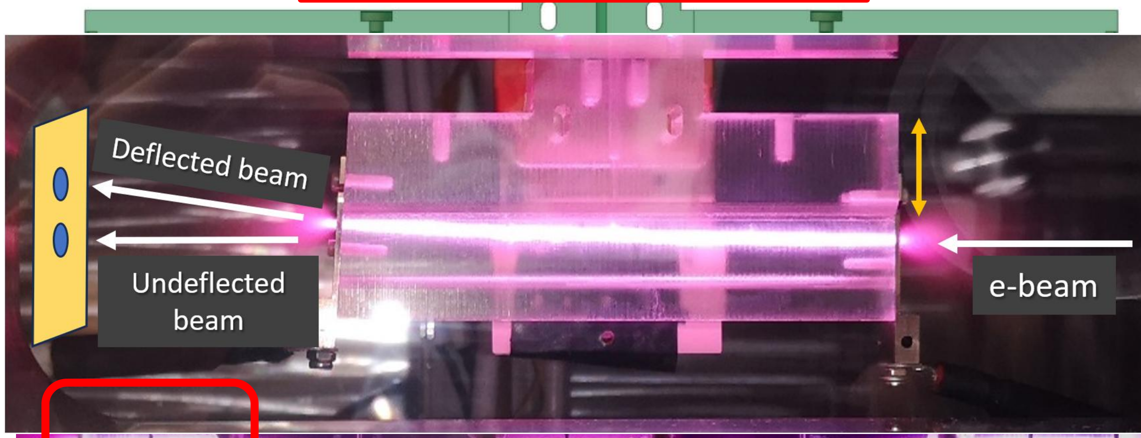
Active Bending Plasma

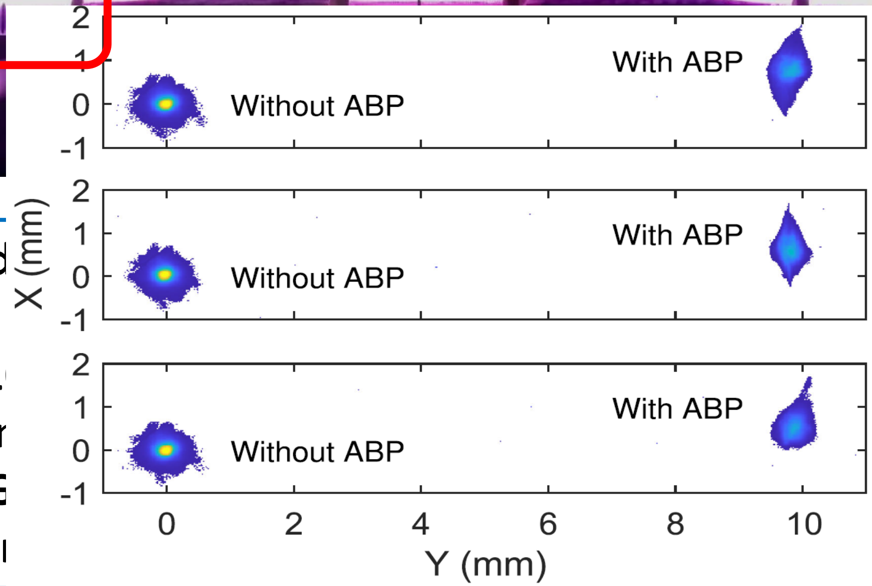
Active Plasma Lens





- Pompili, R., et al. *Applied Physics Letters*, **110** (2017), 104101.
- Chiadroni, E., et al. *Nuclear Instruments and Methods in Physics Research* **909** (2018), 16.





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- Pompili, R., et al. *Phys. Rev. E*, **109** (2024), 055202.
- Pompili, R., et al. *Phys. Rev. Lett.*, **132** (2024), 215001

Expected electron parameters

Funded by the European Union

Parameter	Unit	PWFA	Full X-band
Electron Energy	GeV	1	1
Bunch Charge	pC	30	200
Peak Current	kA	3.3	3.4
RMS Bunch length	μm	1.4	16.9
RMS Energy Spread	%	0.5	0.2
RMS norm Emittance	μm	1	1
Slice length	μm	0.5	0.5
Slice Energy Spread	%	≤0.05	≤0.05
Slice norm Emittance	mm-mrad	<0.8	0.3
Repetition rate	Hz	100-400	100-400

Courtesy of C. Vaccarezza

Two different configurations:

- ~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 (**5 GeV** case) in future with similar building occupancy ($\sim m$)
- ~**1 GeV** beam from the **X-band** linac (with additional RF power) w/o PWFA
  - ➢ Larger charge per bunch
  - ➢ Longer pulses
  - ➢ At the upper limit of RF technology (not easily upgradable without extending the occupancy)

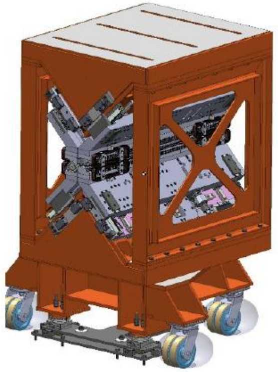
Radiation Generation: FEL

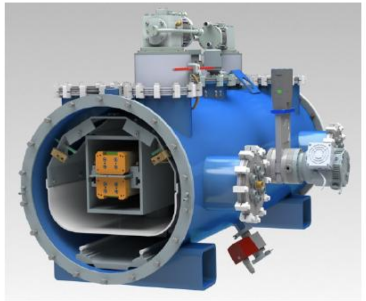
Funded by the European Union

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

Funded by the European Union

Two FEL lines:

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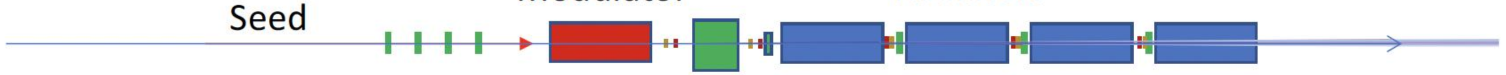
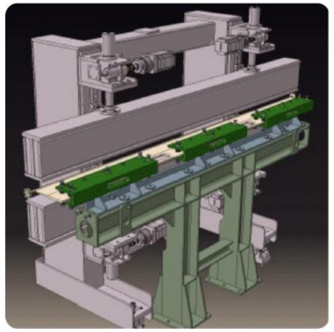


FERMI FEL-1 Radiator



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

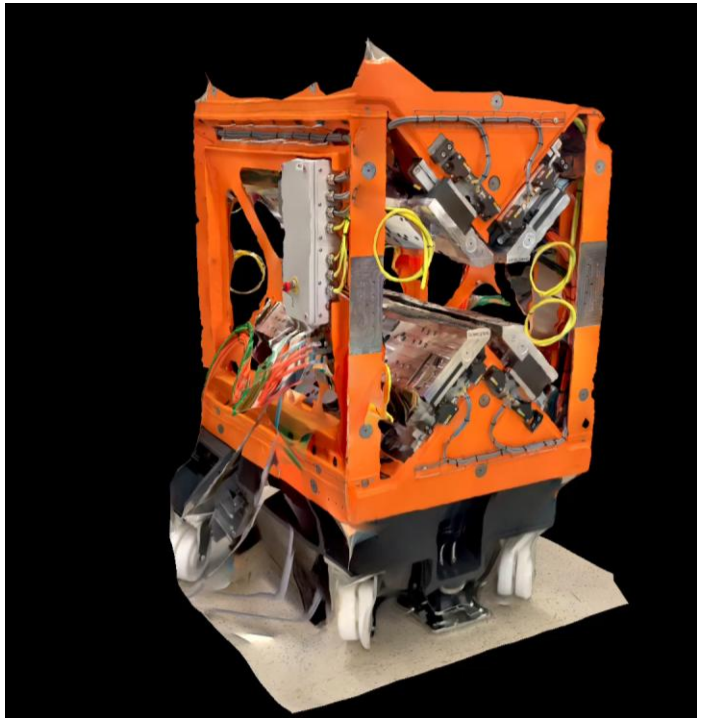
Courtesy of L. Giannessi, F. Stellato

Undulators design

Funded by the European Union

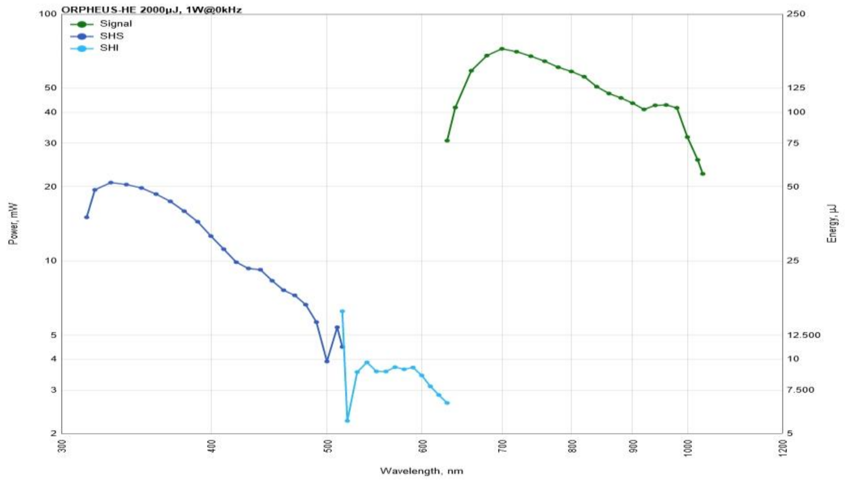
Undulator parameters	AQUA
Period (mm)	18
Maximum strength (k)	1.47
Minimum gap (mm)	1.5
Active length (m)	19.8

Undulator parameters	ARIA	
	Modulator	Radiator
Period (mm)	100	55
Active length (m)	3.0	8.4
Seeding laser	OPA configuration	
Seeding wavelengths (nm)	320-400 + 600-800	
Seeding energy	>20 μJ	
Seeding duration	200-400 fs	



APPLE X undulator
allow for polarization tuning
(from linear to circular)

Seed laser
tunability

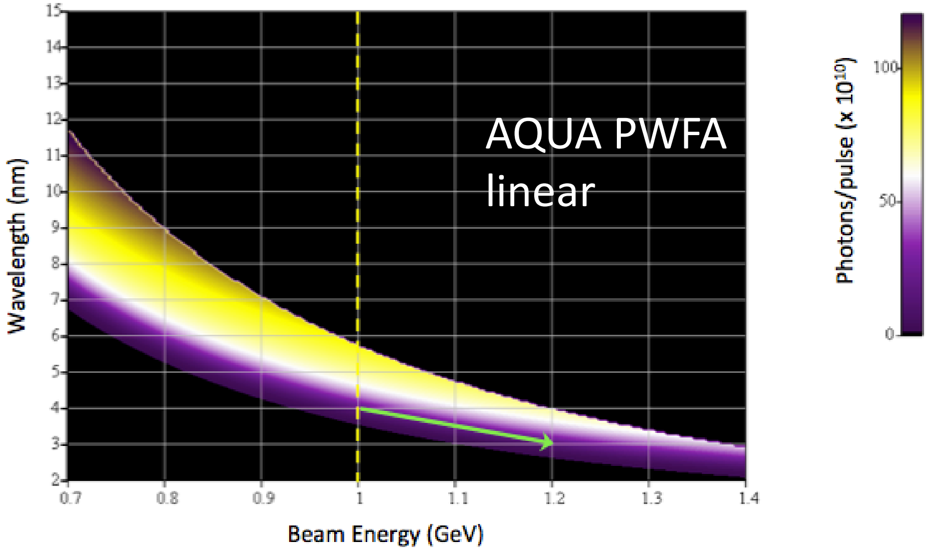


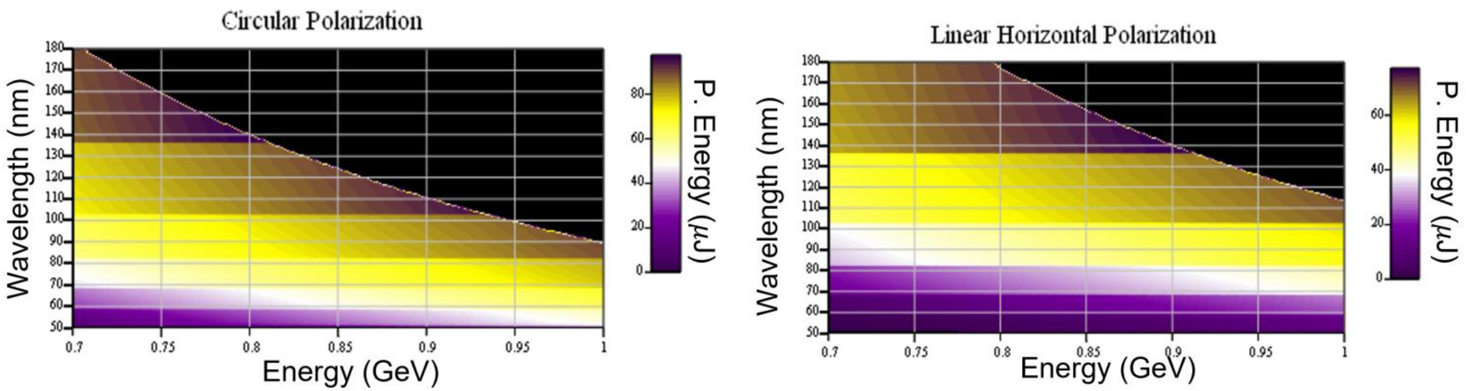
Courtesy of L. Giannessi, M. Opromolla

Expected FEL radiation at undulators end

Funded by the European Union

Parameter	Unit	AQUA PWFA	AQUA X-band	ARIA PWFA	ARIA X-band
Radiation Wavelength	*nm* *eV*	4 310	4 310	50-150 25-8	50-150 25-8
Photons per Pulse	$\times 10^{11}$	3.2	31.3	10-60	12-150
Photon Bandwith	*%*	0.4	0.5	0.05	3
Configuration		SASE		HGHG seeding	

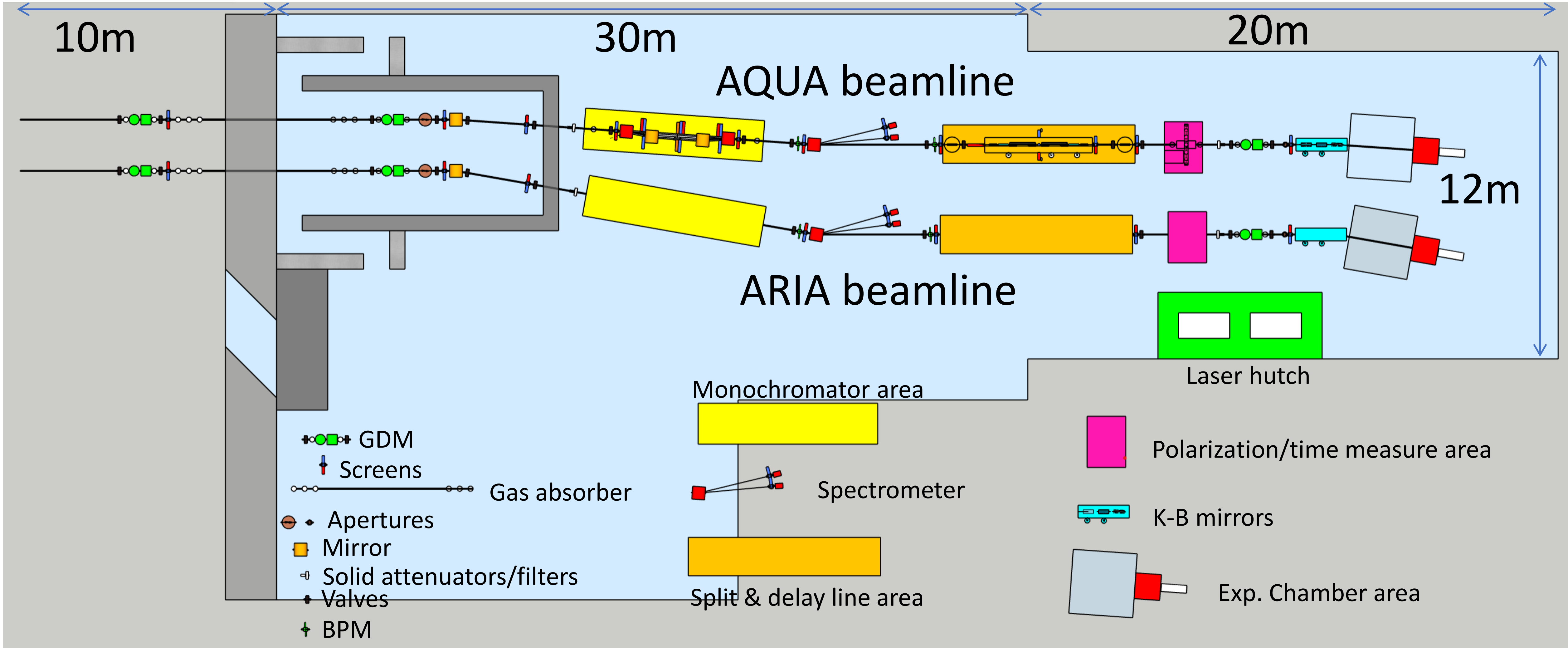




ARIA PWFA configuration

Courtesy of L. Giannessi, F. Stellato

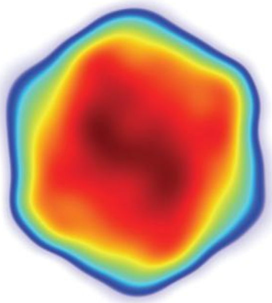
FEL Beamlines



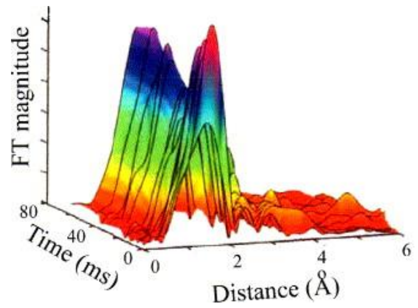
Courtesy of F. Villa

Experimental techniques and typology of samples

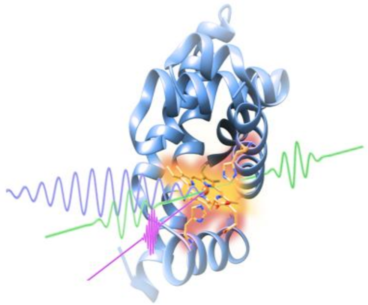
- Coherent imaging



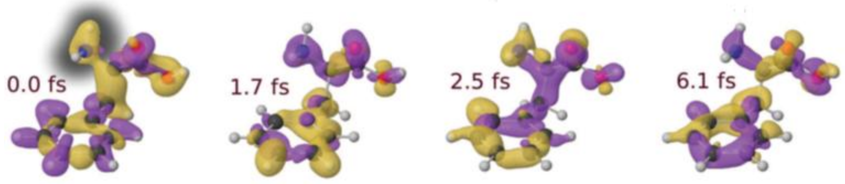
- X-ray spectroscopy



- Raman spectroscopy



- Photo-fragmentation of molecules

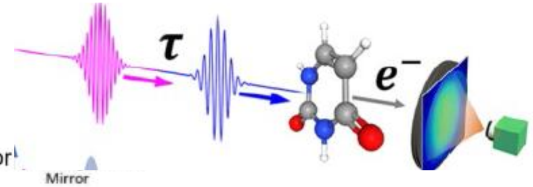


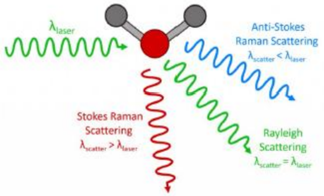
(Large) Viruses
Organelles
Bacteria/Cells
Metals
Semiconductors
Superconductors
Magnetic materials
Organic molecules

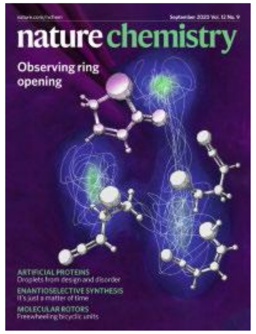
Courtesy of F. Stellato

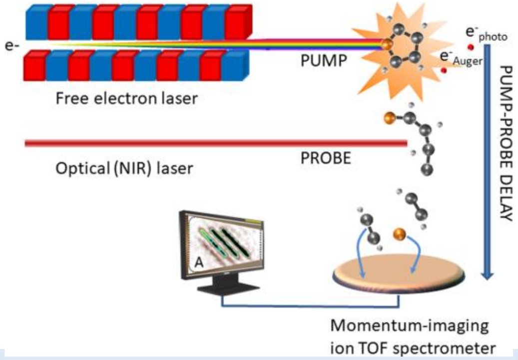
Experimental techniques and typology of samples

- Photoemission spectroscopy
- Photoelectron Circular Dichroism
- Raman spectroscopy
- Photo-fragmentation of molecules
- Time of Flight Spectroscopy









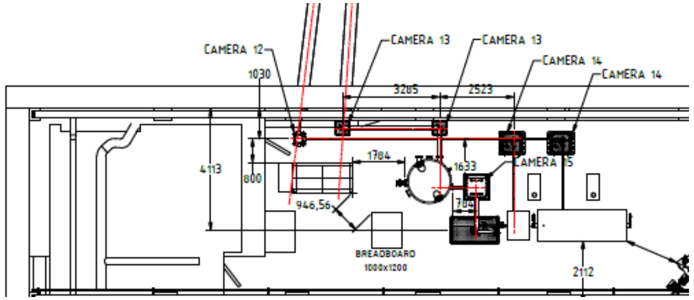
Gas phase & Atmosphere
(Earth & Planets)
Aerosols
(Pollution, nanoparticles)
Molecules & gases
(spectroscopies, time-of-flight)
Proteins
(spectroscopies)
Surfaces
(ablation & deposition)

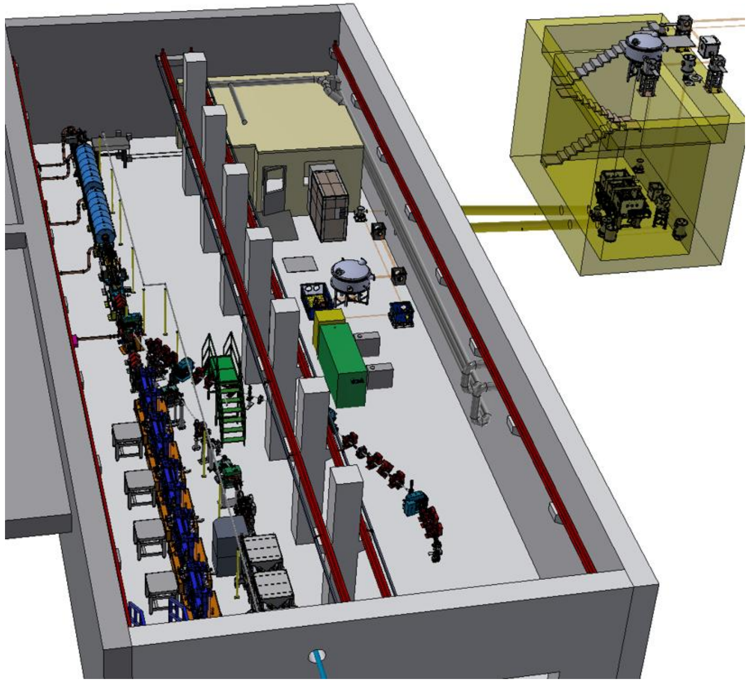
Courtesy of F. Stellato

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources

EuPRAXIA Advanced Photon Sources (EuAPS)

- Supported by PNRR fundings
- Collaboration among INFN, CNR, University of Tor Vergata
- EuPRAXIA framework:
  - ➢ Laser-driven betatron radiation source @SPARC_LAB - FLAME
  - ➢ High repetition rate laser (up to 100 Hz) @CNR Pisa
  - ➢ High power laser (up to 1 PW) @LNS

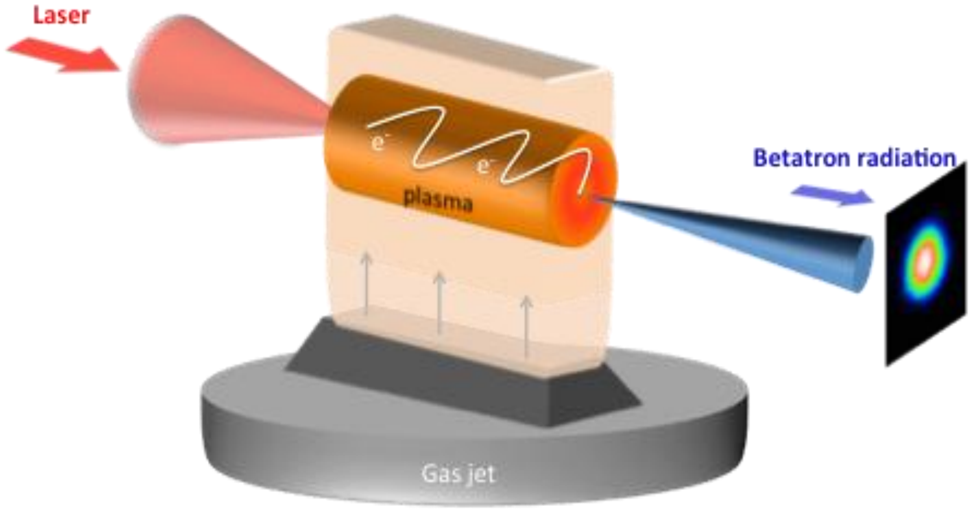


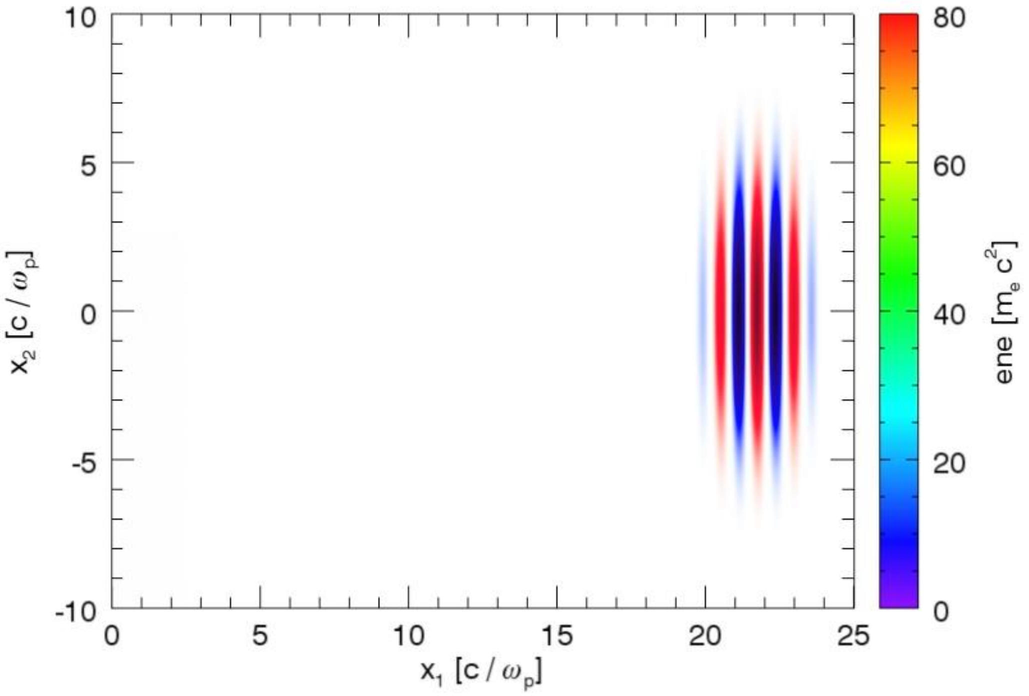


Courtesy of A. Cianchi

Betatron radiation

Betatron radiation is emitted by electrons accelerated in a plasma wakefield due to their **wiggling motion**





Courtesy J. Vieira, R. Fonseca/GoLP/IST Lisbon

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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources

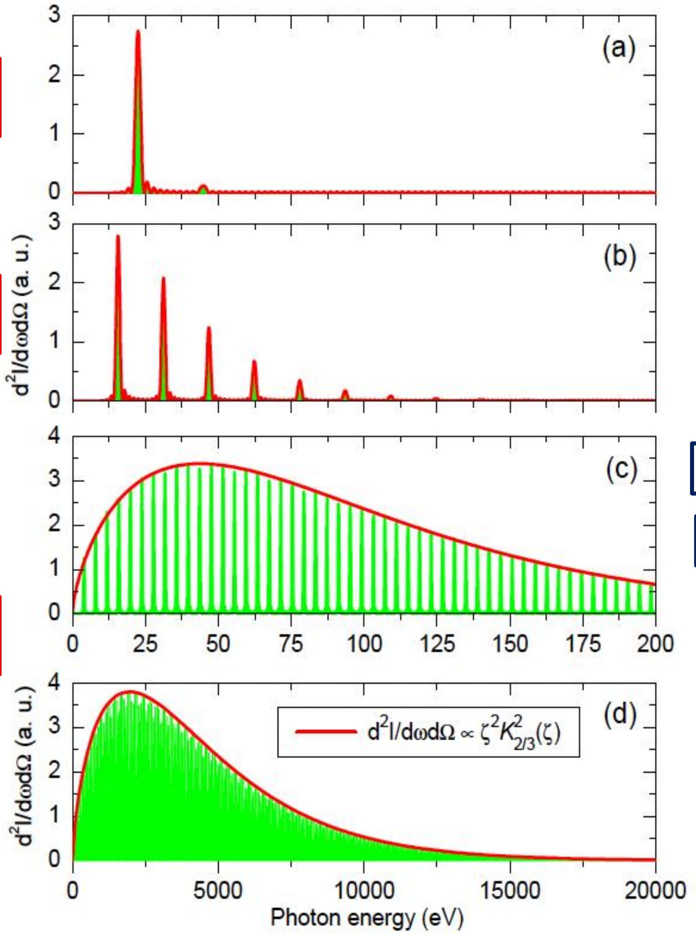
Betatron radiation

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).

$K_u<1$

$K_u>1$

$K_u>>1$



$\omega_c = 3K_u\gamma^2\omega_\beta$

$N_{ph} \propto N_e N_\beta K_u$

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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources

EuAPS expected parameters

FLAME laser system

Parameter	Value	unit
Laser power	250	TW
Pulse duration	25	fs
Laser energy	7	J
Spot diameter RMS	4	um

Betatron radiation

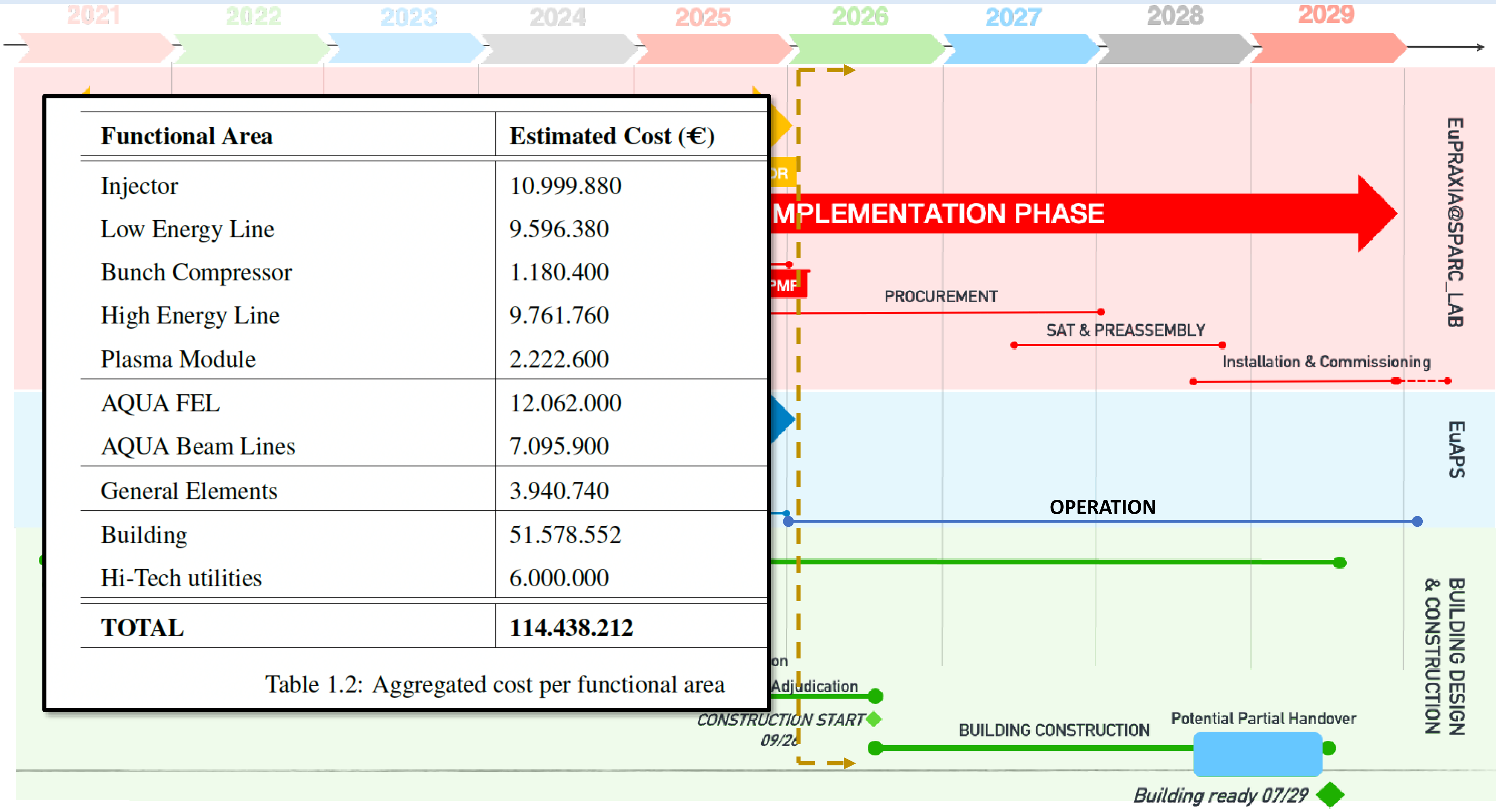
Parameter	Value	unit
Electron beam Energy	100-500	MeV
Plasma Density	10^{18}-10^{19}	cm^{-3}
Photon Critical Energy	1 -10	keV
Number of Photons/pulse	10^{6}-10^{9}	
Repetition rate	1-5	Hz
Beam divergence	3-20	mrad

EuAPS Scientific case

In order of increasing complexity:

1. Static imaging
2. Static X-ray absorption spectroscopy
3. Static X-ray emission spectroscopy
4. Time-resolved pump-probe X-ray absorption spectroscopy
5. Time-resolved pump-probe X-ray emission spectroscopy
6. Time resolved imaging (plasma dynamics)

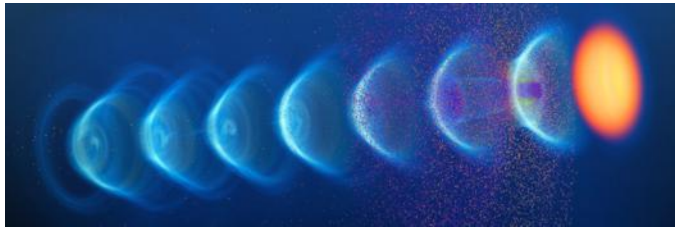
Timelines and costs



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

Conclusions & Acknowledgements



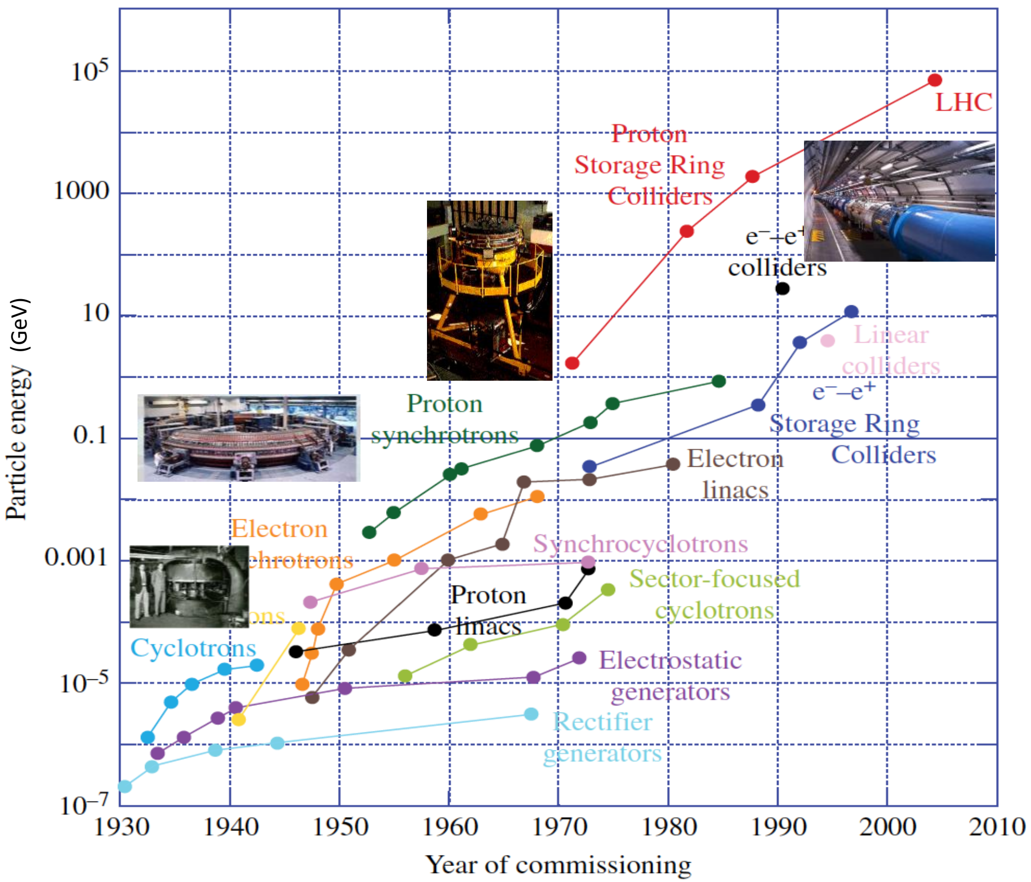
- Plasma accelerators have advanced considerably in beam quality, **achieving FEL lasing**.
- EuPRAXIA is a design and an **ESFRI project** for a distributed European Research Infrastructure, **building two plasma-driven FELs in Europe**.
- EuPRAXIA FEL site in Frascati LNF-INFN is sufficiently funded for **first FEL user operation in 2031**.
- EuAPS is in installation phase, first pilot experiment foreseen for **April 2026**
- Aim at making EuPRAXIA an **example of European innovation:** new science to new applications and new areas in particle and photon physics
- **Greatly appreciate slides from and discussions with:** the entire EuPRAXIA@SPARC_LAB and EuAPS teams

Funded by the European Union

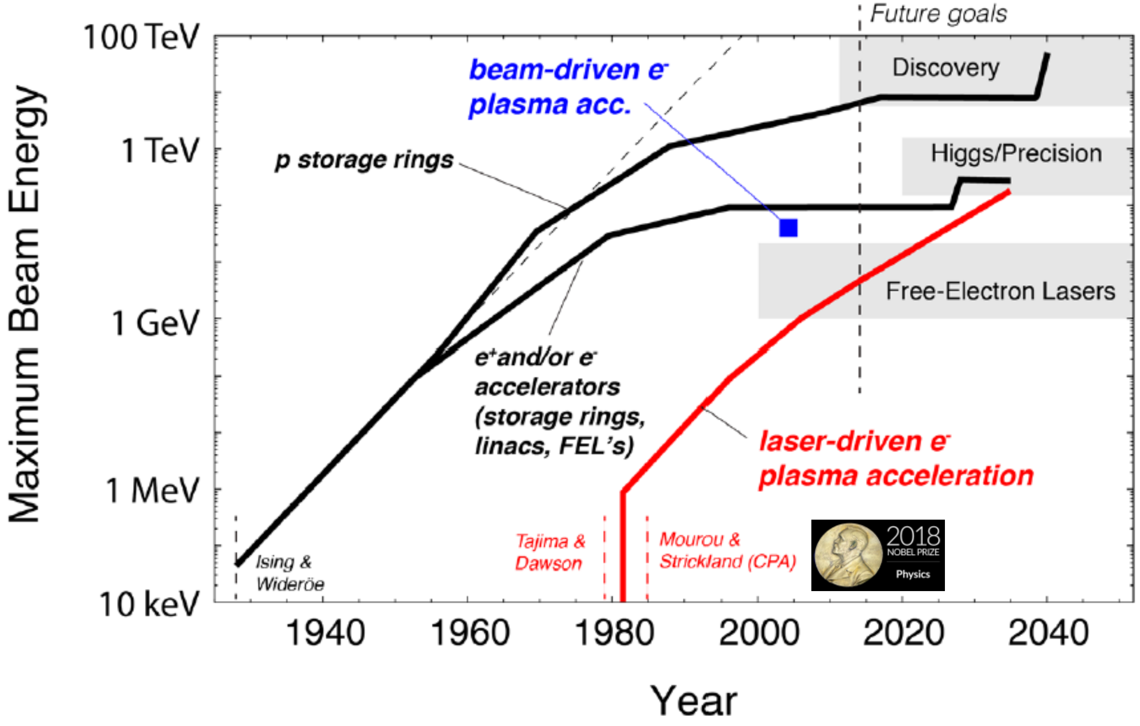
Thank for your attention

Livingston diagram for accelerators

Funded by the European Union



(Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.)

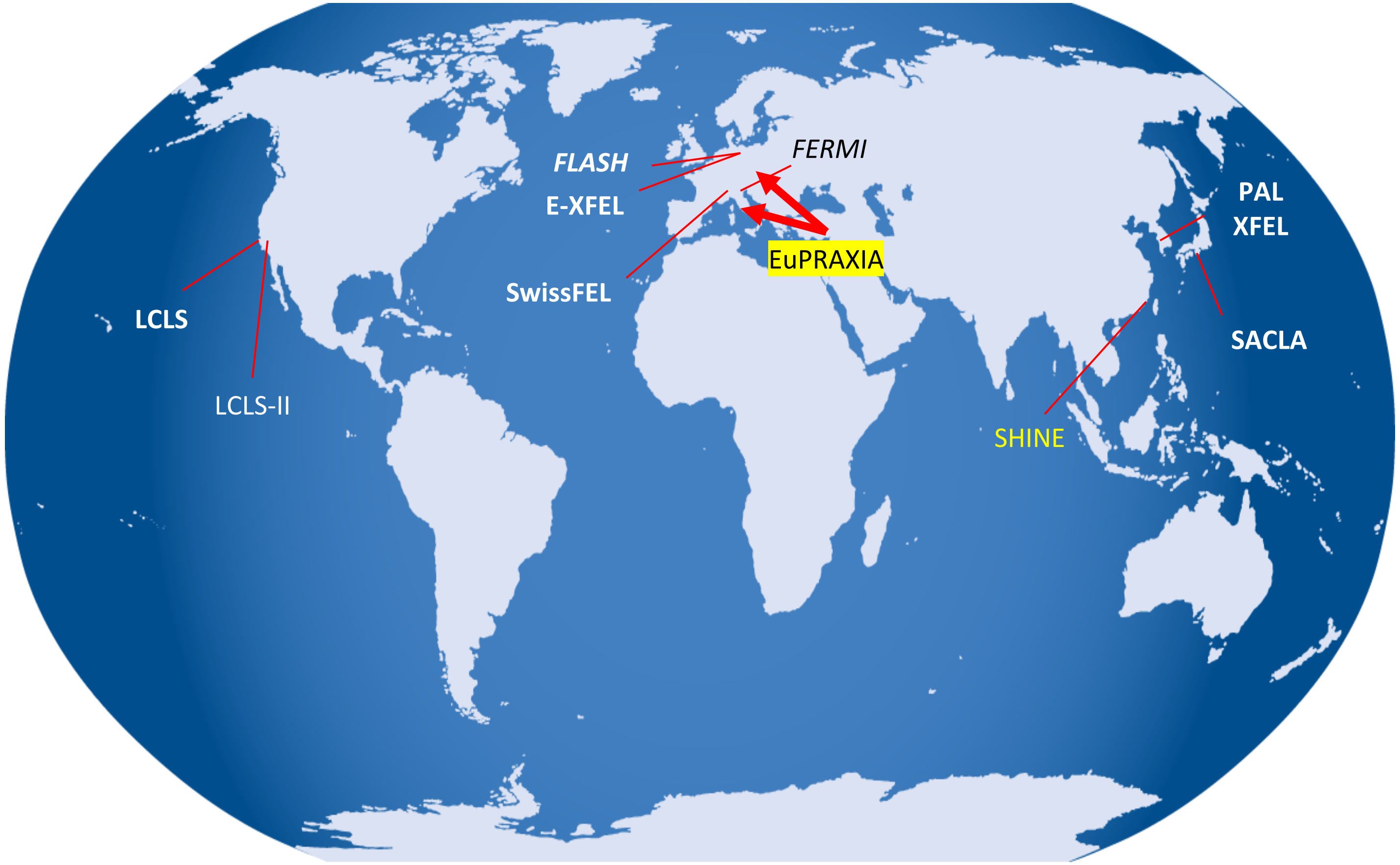


Plasma Accelerator Achievements

- Gradients up to **100 GV/m**
- Acceleration >10 **GeV** of electron beams
- Basic **beam quality for FEL** demonstrated

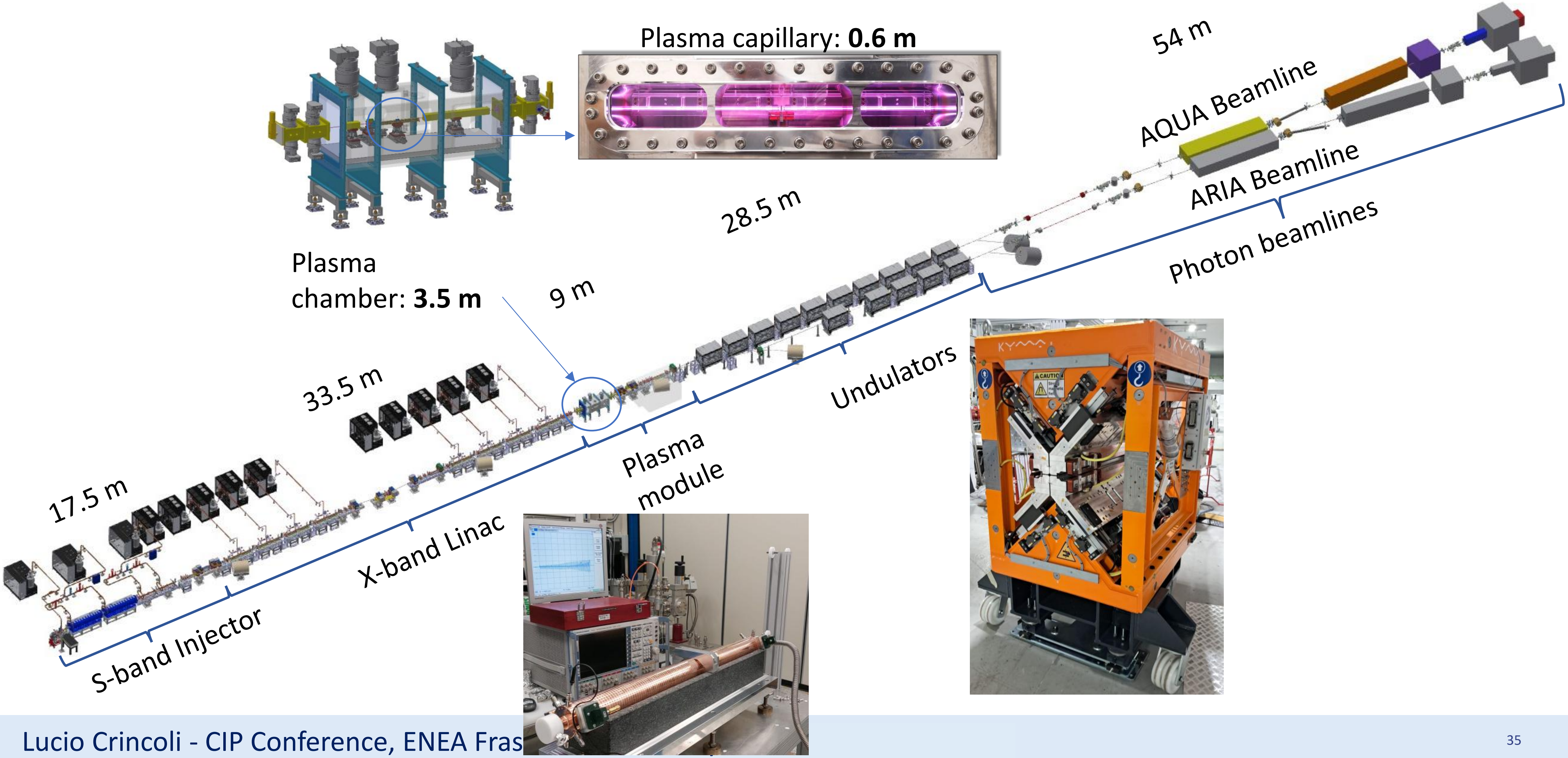
The Italian Pillar: EuPRAXIA@SPARC_LAB User Facility

Facility	Location	Wavelength Range [nm]	Linac Length [km]	Electron Energy [GeV]	RF Band And Gradient [MV/m]	Key Features
Soft X-rays radiations						
	Frascati, Italy	4–10	< 0.05	1.0 – 1.2	X/Plasma 60/1000	Compactness. Targets the water window; 3D bio-imaging.
FLASH	Hamburg, Germany	4.1–45	0.2	1.25	L 30	Pioneering SASE FEL; test facility for RF Super-Conductivity and FEL technologies.
FERMI	Trieste, Italy	10–100	0.15	1.67	S 28	Seeded FEL; high spectral purity in VUV–soft X-ray range.
Hard X-rays radiation						
LCLS 1	SLAC, USA	0.13–6.2	1	14	S 25	First hard X-ray FEL; ultrafast imaging capabilities.
European XFEL	Hamburg, Germany	0.05–4.7	2.1	17.5	L 24	High repetition rate; multiple beamlines.
SACLA	Harima, Japan	0.06–0.2	0.4	8.5	C 38	More compact design; operates in hard X-ray regime.
SwissFEL	Villigen, Switzerland	0.1–5.0	0.5	5.8	C 28	Two beamlines covering hard and soft X-rays.
PAL-XFEL	Pohang, South Korea	0.06–4.5	0.78	10	S 27	Covers both hard and soft X-rays.



EuPRAXIA@SPARC_LAB

Funded by the European Union



AQUA beamline: Undulators

Funded by the European Union

10 **Apple X** undulators for **SASE** FEL in the **water window** with **variable polarization**

	Units	PWFA	Full RF
ρ (3D)	$\times 10^{-3}$	0.77	1.49
Saturation length	m	20.5	20.0
Radiation wavelength	nm	4.0	4.0
Photon Pulse Energy	μJ	**16**	**156**
Photon per pulse	$\times 10^{11}$	3.2	31.3
Photon Bandwidth	%	0.4	0.5
Photon pulse length (rms)	fs	**1.0**	**14.1**
Photon brilliance per shot	$\times 10^{30}$	**0.12**	**2.1**

Parameter	Quantity	Units
Number	10	Undulators
Period length	18	mm
Number of periods	110	
Minimum gap	1.5	mm
Aperture at min. gap	6	mm
K_{RMS}at min. gap	1.11	
Peak Field error	0.5	%
Max. phase error	5	deg
1^{st}Field Integral (res LH,CR)	$2 \cdot 10^{-6}$	$T \cdot m$
1^{st}Field Integral (res LV)	10^{-5}	$T \cdot m$
2^{nd}Field Integral (res LH,CR)	10^{-6}	$T \cdot m^2$
2^{nd}Field Integral (res LV)	10^{-5}	$T \cdot m^2$
Max. Trajectory offset (@1GeV)	8	μm
Max. Trajectory angle (@1GeV)	15	μrad
Quadrupole (x,y)	$5 \cdot 10^{-2}$	T
Sextupole (x,y)	1	T/m
Transverse positioning system range (x/y)	1	mm
Transverse positioning system accuracy (x/y)	5	μm
Temperature stability	± 0.5	C°

Technological Readiness Level

Funded by the European Union

Sub - systems	TRL	Comments
Injector	9	S-Band injectors are widely used in many facilities including SPARC_LAB. S-Band technology is fully available in the market.
X-Band Linac	6	X-Band Linacs are relatively new. Impressive progress has been made and the final testing of the acc. section full prototype will upscale the corresponding TRL level in the upcoming months.
Plasma Module	5	Extensive R&D has been made to validate the plasma capillary technology and solid results have proved the validity of the technical choice. A full system proven in a real environment is expected to be done in the next year
AQUA Undulators	7	Technology demonstrated in other facilities (FERMI, SwissFEL, etc.)
FEL Beamline	8	Most of the components of the photon beamline are implemented at other facilities are commercially available, few systems (needed only for a subset of possible experiments) are still in development
RF power system	8	X-Band RF power system has been already tested and operated in normal condition in the test-stand. The final operational test will prove the validity and reproducibility of the technical choices in the real setting
Laser system	9	Photocathode laser is now a proven technology tested in real facilities (including SPARC_LAB). The systems are full available in the market almost as off-the shelf products
General elements	9	Other elements (Control, mechanics etc) are based on standardized components daily used in other facilities and in other context (e.g. industrial context)

TRL LEVEL	TRL Description
TRL 1	Basic principles observed – Scientific research begins to be translated into applied research and development (R&D).
TRL 2	Technology concept formulated – The basic principles are explored and practical applications are identified.
TRL 3	Experimental proof of concept – Active R&D is initiated, including analytical and laboratory studies to validate predictions.
TRL 4	Technology validated in lab – Basic technological components are integrated to establish that they work together.
TRL 5	Technology validated in relevant environment – The technology is tested in a simulated or relevant environment
TRL 6	Technology demonstrated in relevant environment – A prototype system is tested in an environment similar to the operational one.
TRL 7	System prototype demonstration in operational environment – A working prototype is demonstrated in a real operational setting.
TRL 8	System complete and qualified – The technology is proven to work in its final form and under expected conditions.
TRL 9	Actual system proven in operational environment – The technology is fully commercialized and operational in its intended setting.

Risk Mitigation: Two dedicated test facilities, SPARC_LAB and PLASMA_LAB, are actively supporting the development and validation of plasma acceleration concepts, while the TeX facility is dedicated to high power testing of X-band performance. Achieving a Technology Readiness Level (TRL) above 7 for these subsystems will only be possible following the successful operation of the EuPRAXIA@SPARC_LAB facility.

The Building

Funded by the European Union

Figure 1.4: 3D view (North-West side) of the EuPRAXIA@SPARC_LAB facilities.

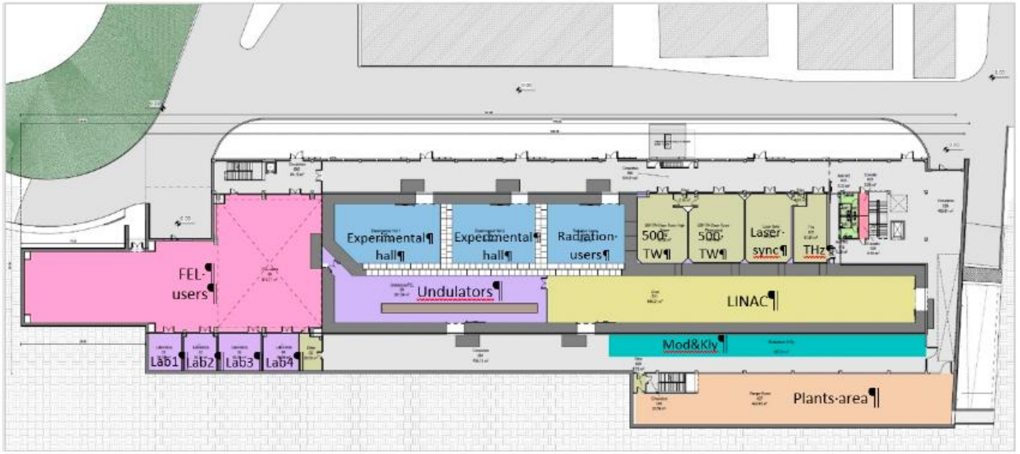


Figure 1.5: EuPRAXIA@SPARC_LAB building functional layout - Level 0

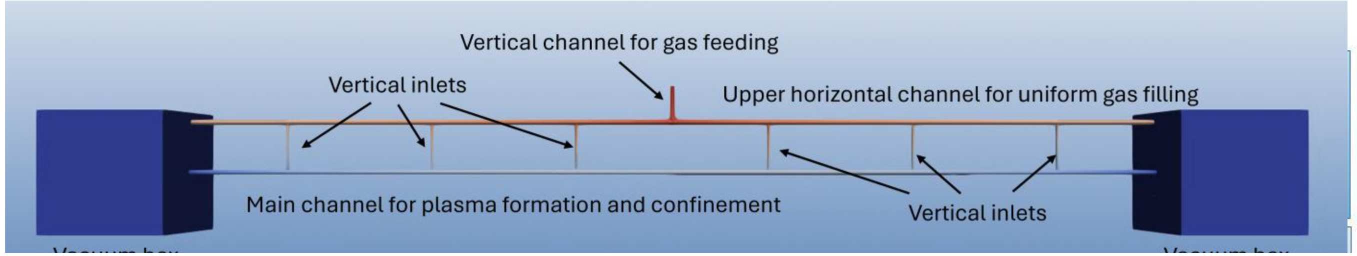
The **maximum expected power demand** of the project, used for the electrical installation design, **is about 2.8 MVA** for all the site.

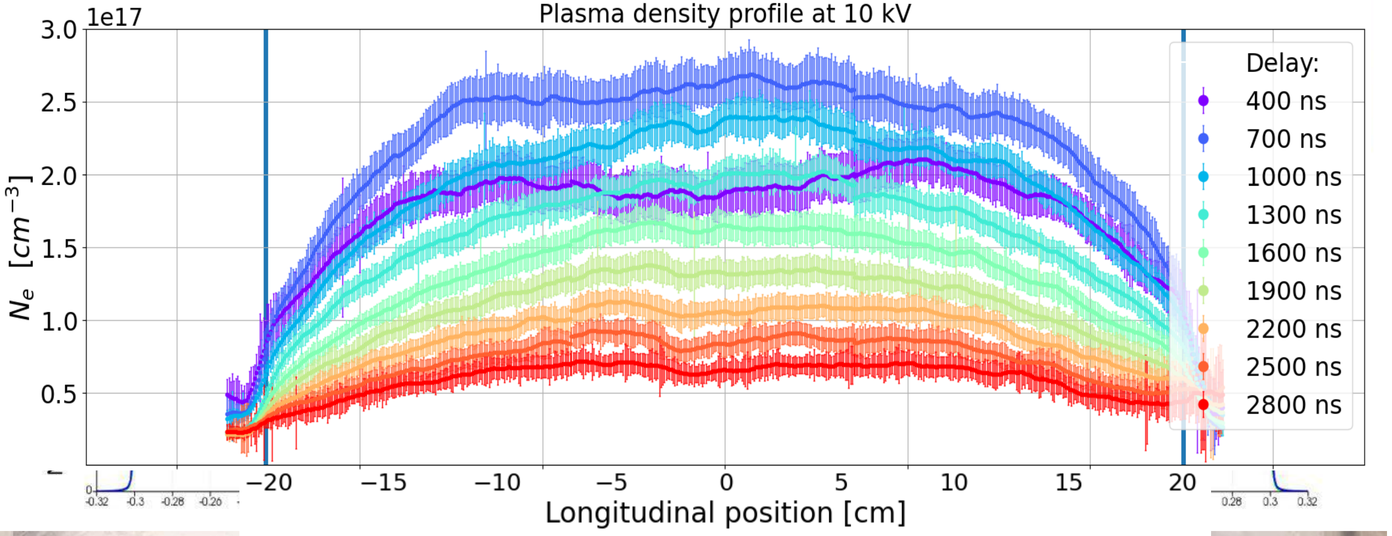
The **expected power consumption** for the AQUA operation at 100 Hz repetition rate, delivering up to 1.2 GeV electron beams **is 1.32 MW**

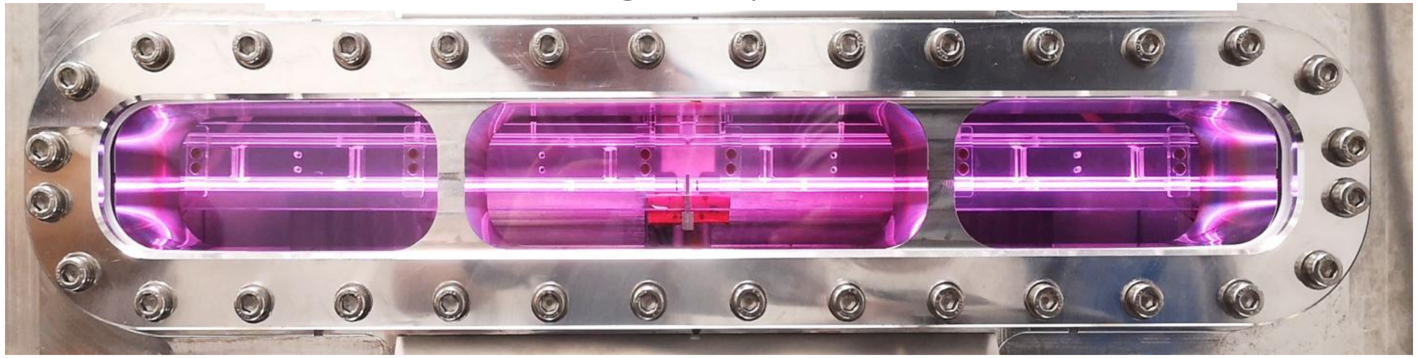
Electrical loads	kW
RF Modulators	575
Magnet PSU	360
Laser	15
Experimental users	10
Vacuum, electronics and controls	30
Cooling magnet + RF	180
HVAC	150
Total Expected power consumption	1320

Plasma density modulation

- Tapered capillaries allow tailoring the plasma density profile:
  - ➢ Flat-top profile with cigar-shape channels
  - ➢ Controlled density ramps with conical shape a extremities
- Segmented capillaries provide m-scale plasma channels with density modulation:
  - ➢ Gas injection channels for uniform neutral density
  - ➢ Independent voltage and delay tuning in the discharge segments
  - ✓ Cheap and compact m-scale sources





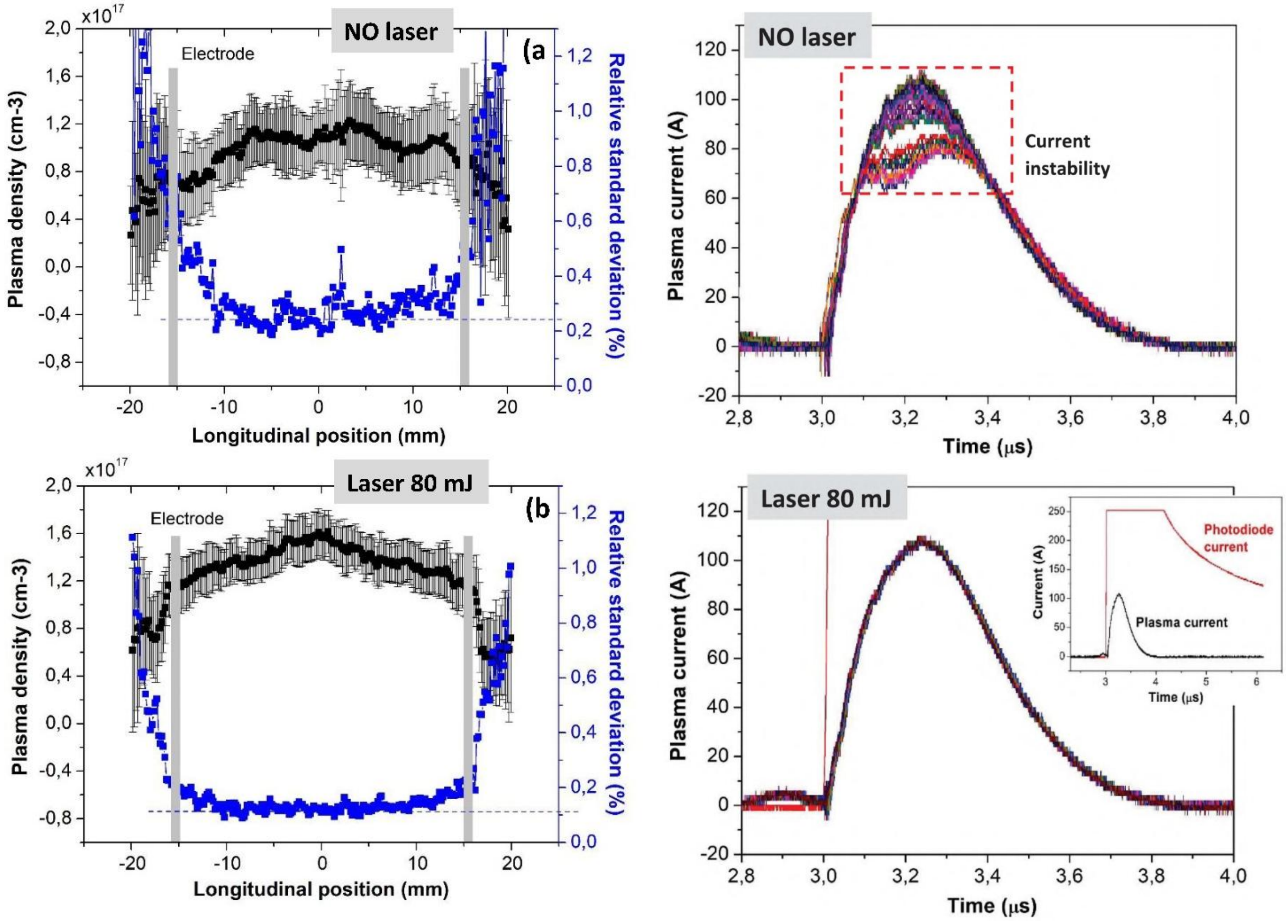


- Crincoli, L. *et al.* Characterization of plasma-discharge capillaries for plasma-based particle acceleration. *J. Phys.: Conf. Ser.* **2687** (2024).

Plasma discharge stabilization

- Intrinsic time jittering due to stochastic behaviour of discharge breakdown:
  - ➢ Shot-to-shot variation in the plasma density
- Low intensity laser pulses control the production of first free electrons, providing stabilization to the discharge formation:
  - ➢ 10s mJ IR laser pulses trigger the arc-discharge
  - ➢ Reduced variation in plasma density
  - ➢ Reduction in time and amplitude jitter

✓ Laser-induced pre-ionization allows to reduce the time jitter of the discharge current, thus improving the shot-to-shot plasma stability



- Biagioni, A. et al. Plasma Phys. Control. Fusion 63 (**2021**)

Analytical estimate

Sta

Ohmic heating inside the plasma channel:

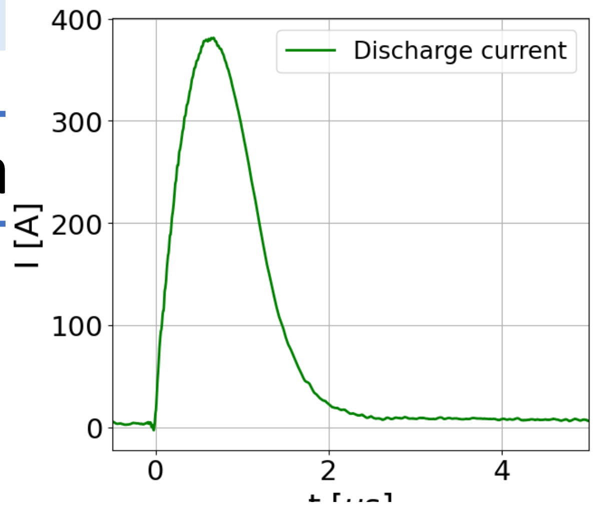
$$P(t) = R_p(t) I_p^2(t)$$

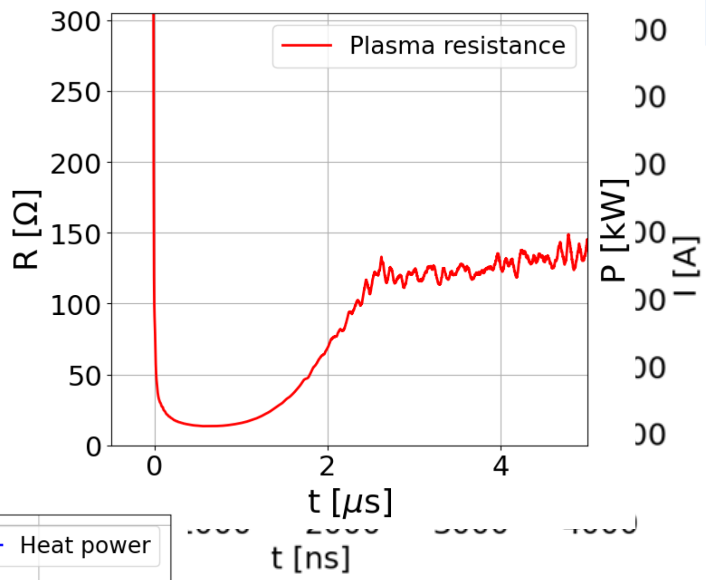
3 cm → 30 cm

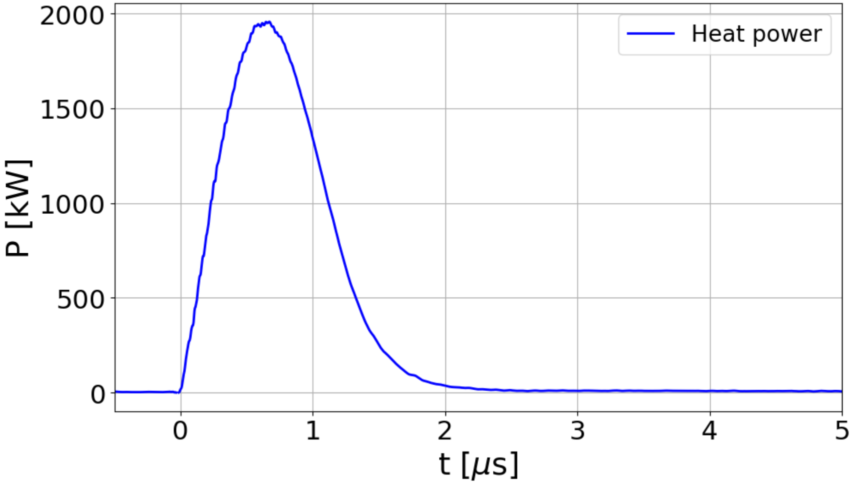
100 mJ → 1 J

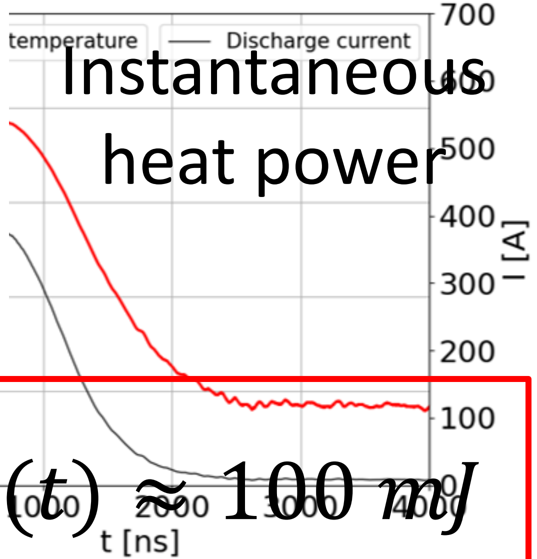
$T_e(t)$

- $R_p(t) = \rho_{ei}(t) \frac{L}{S}$
- $\rho_{ei}(t) = \frac{m_e}{n_e(t) e^2} \nu_{ei}(t)$
- $\nu_{ei}(t) = \frac{4}{3} \sqrt{\frac{2\pi}{m_e}} \frac{e^4 n_e(t) \ln\lambda_{ei}(t)}{(4\pi\varepsilon_0)^2 (k_B T(t))^{3/2}}$
- $\ln\lambda_{ei} = \ln\left[\frac{3}{2\sqrt{2\pi}} \frac{(4\pi\varepsilon_0)^{3/2}(k_B T(t))^{3/2}}{e^3 n_e^{1/2}(t)}\right]$









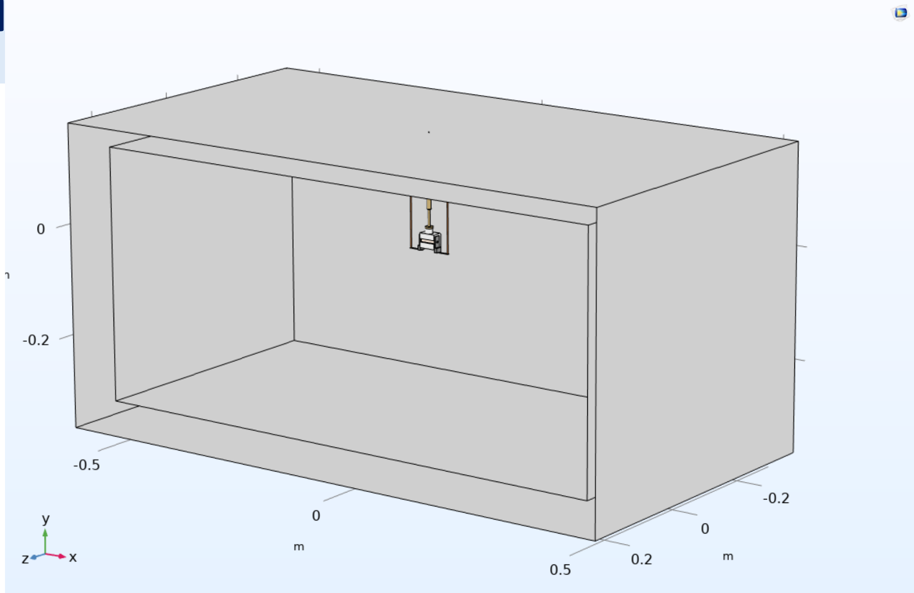
Instantaneous heat power

Heat per pulse

$$Q = \int_0^{\tau} P(t) \approx 100\ mJ$$

Gonsalves, A. J. et al. J. Appl. Phys. 119, 033302, 10.1063/1.4940121 (2016).
Bobrova, N. et al. *Phys. Rev. E: Stat. Nonlin. Soft Matter Phys.* (2002).

Numerical simulations



$$Q_p \approx 100\ mJ$$

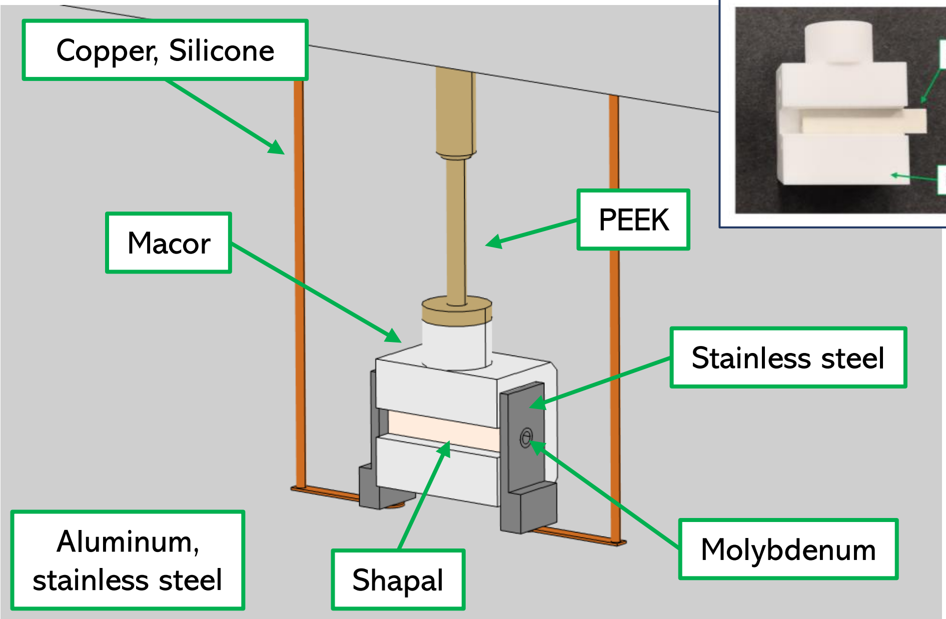
$$f = 10, 100, 1000\ Hz$$

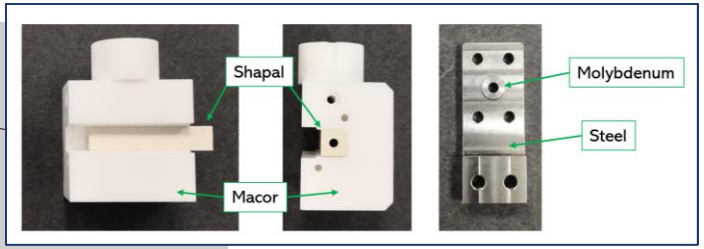
$$P_{avg} = 1, 10, 100\ W$$

- Fourier's Law for heat conduction:
  - ➢ $\vec{q} = -k(T)\nabla T$
- Capillary channel walls
  - ➢ Heat source P_{avg}
- External surfaces and vacuum chamber
  - ➢ Surface-to-surface radiation

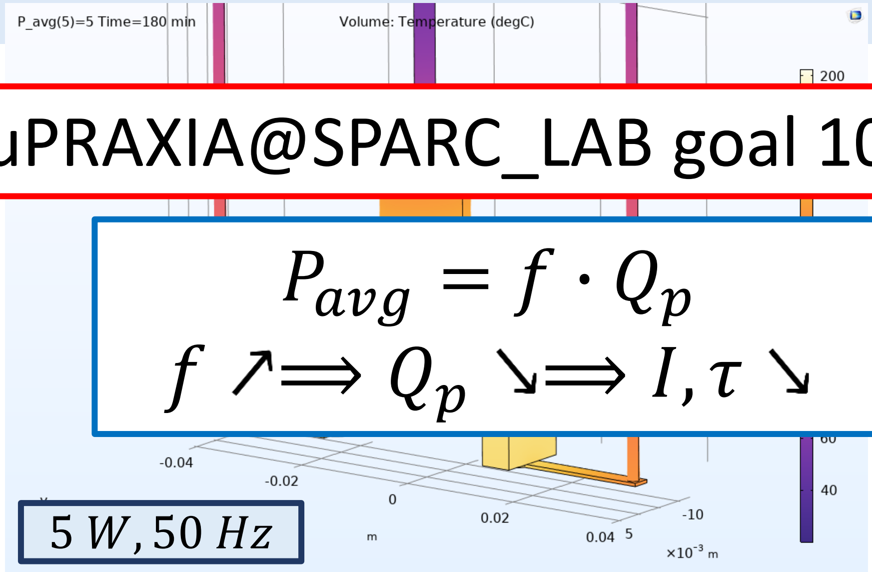
$$J = \varepsilon\sigma_B T^4 + \rho_d G$$

- Ext vacuum chamber
  - ➢ Room temperature





Numerical simulations

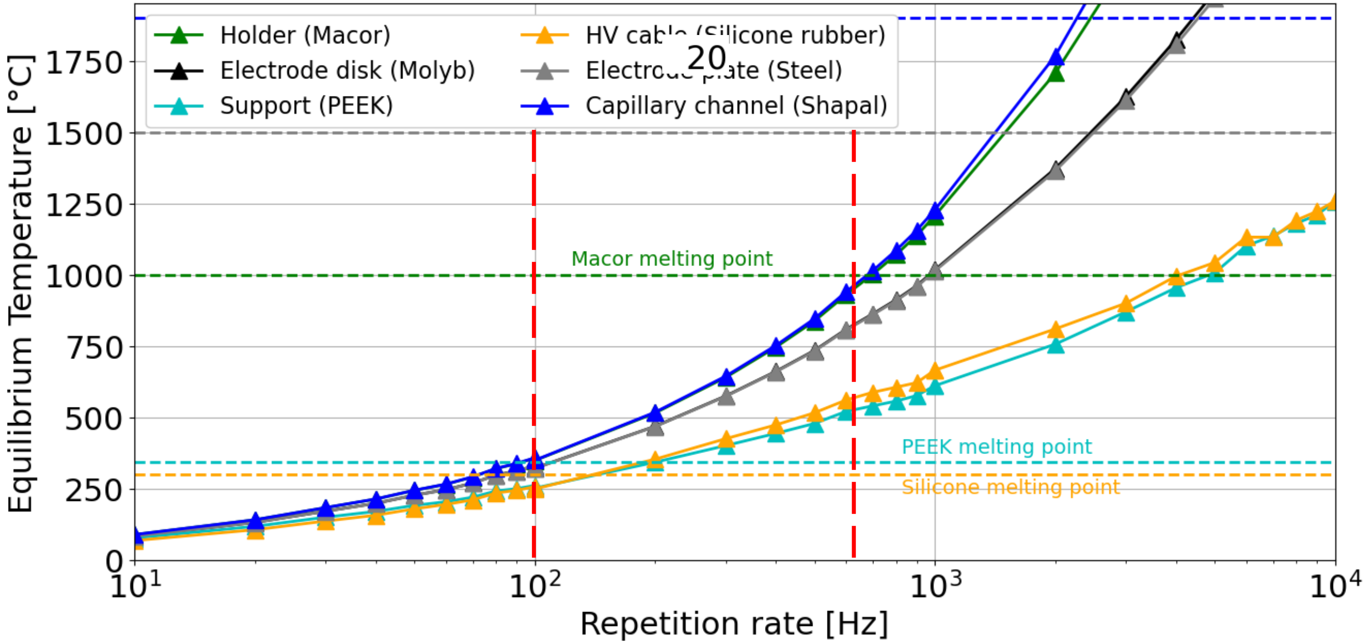


✓ EuPRAXIA@SPARC_LAB goal 100 Hz

$$P_{avg} = f \cdot Q_p$$
$$f \nearrow \Longrightarrow Q_p \searrow \Longrightarrow I, \tau \searrow$$

$5\ W, 50\ Hz$

- 100 Hz:
  - ➢ Each component remains below critical Temperature
- 100-400 Hz:
  - ✓ Capillary (ceramic)
  - ✓ Electrodes (metals)
  - X PEEK support and HV cables
- 700 Hz:
  - ➢ Macor limit
- >2 kHz:
  - ➢ Shapal and steel limit

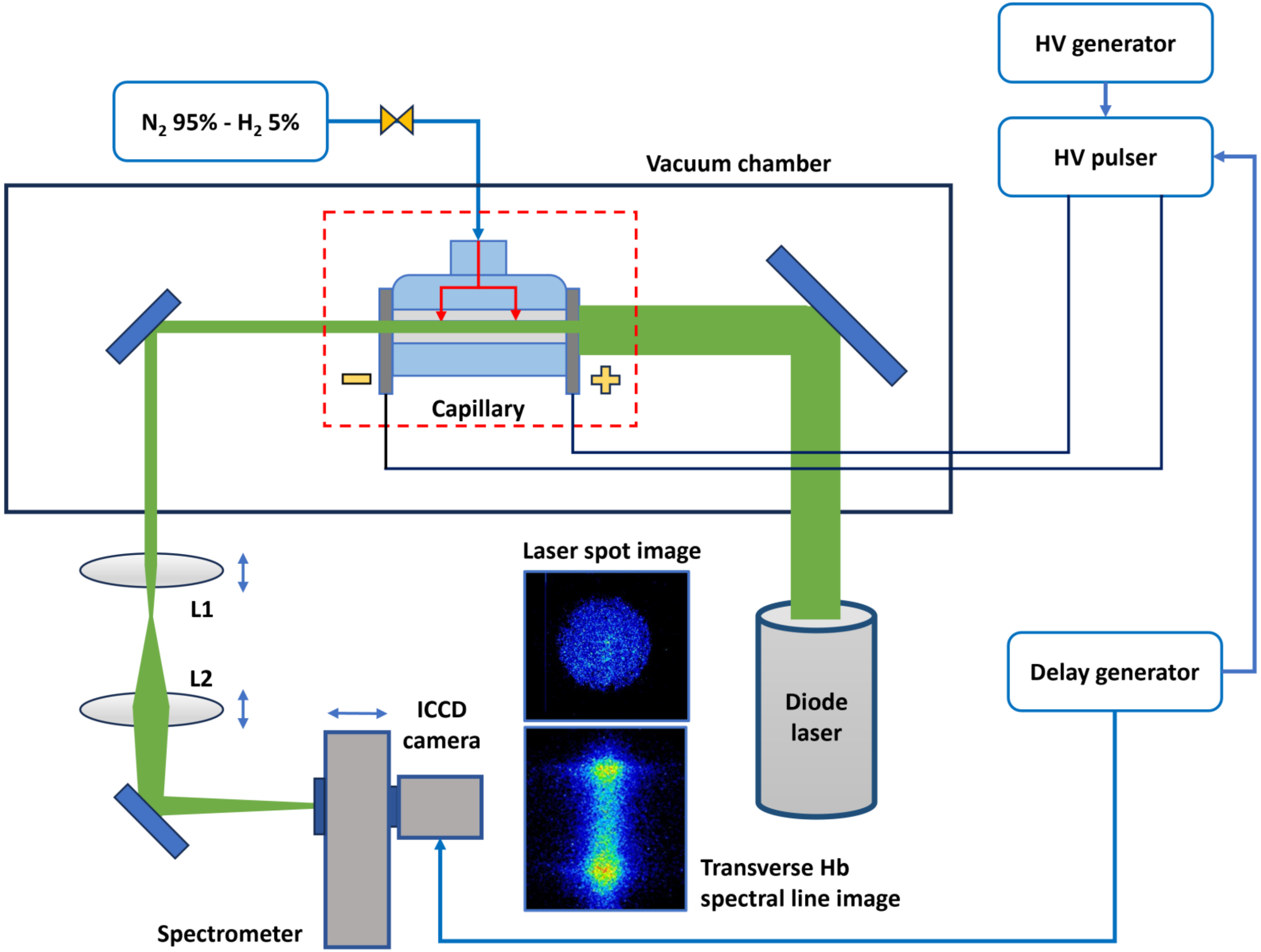


Experimental testing

- Gas filled discharge settings:
  - N_2 80-100 mbar in continuous flow
  - 5 kV – 400 A
  - 10-150 Hz operation

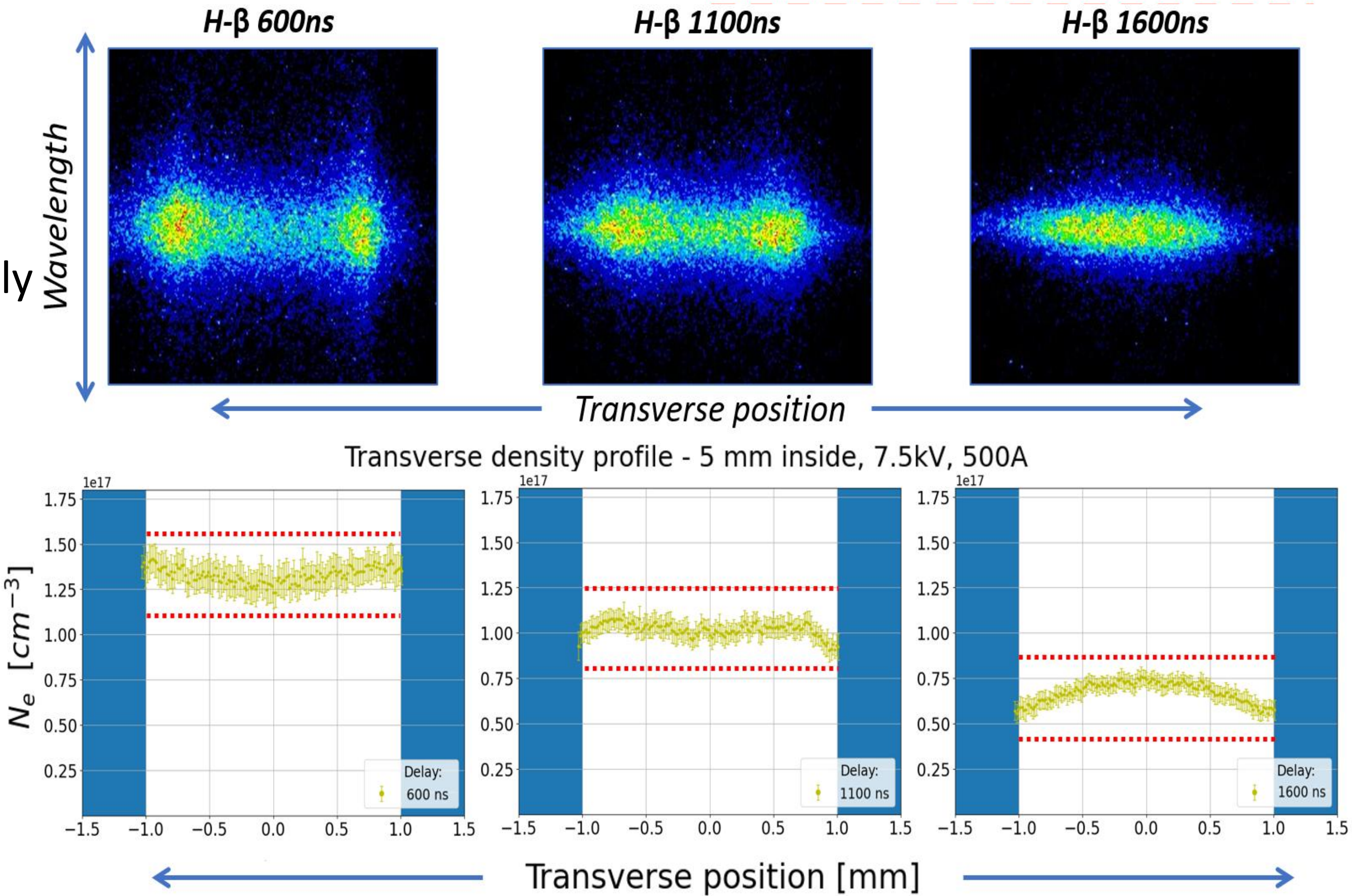
- Diagnostics for plasma and capillary geometry
  - Stark broadening method
  - Laser spot imaging
  - Microscopic analysis

100 Hz repetition rate discharges



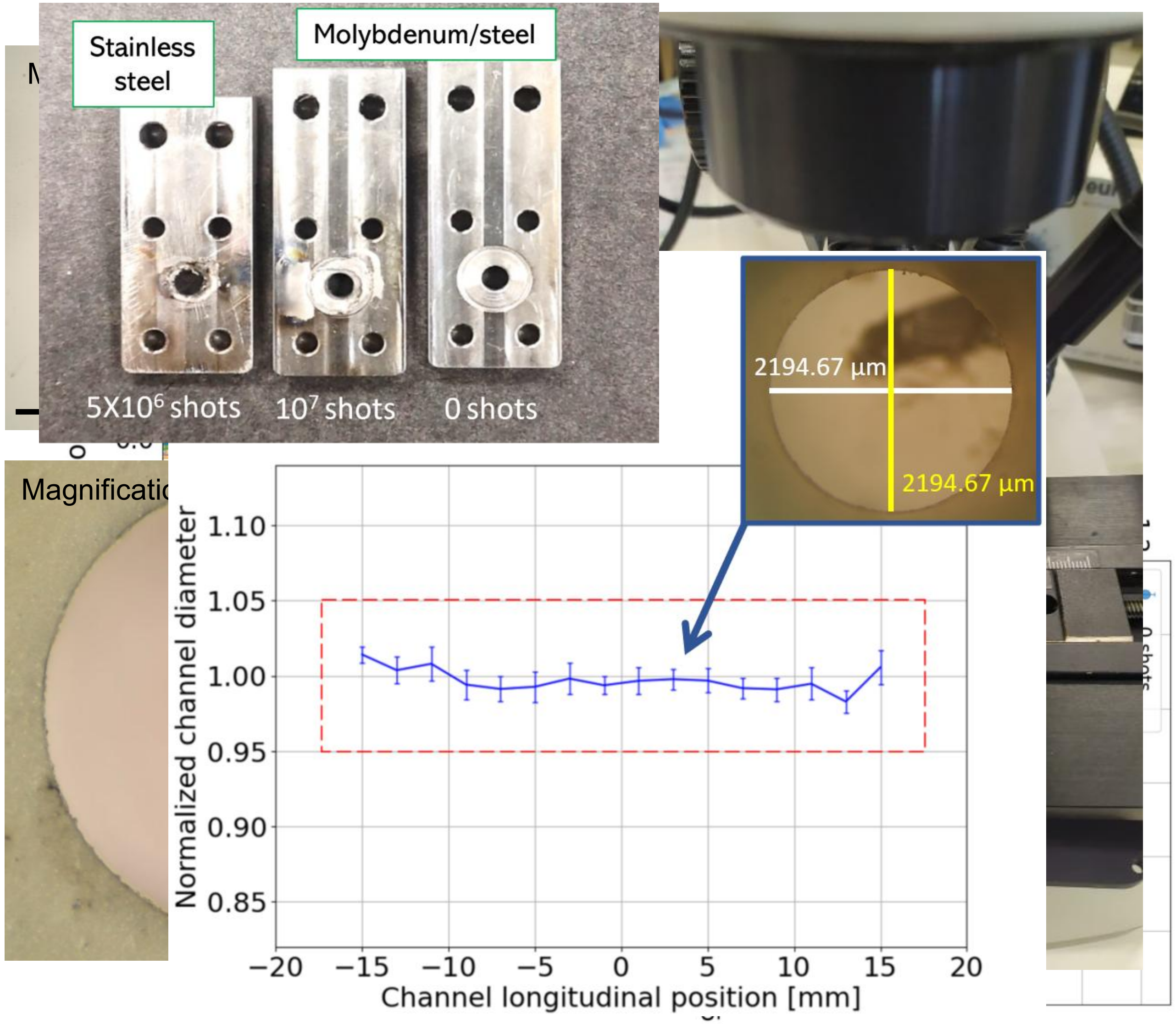
Plasma density measurements

- H_2 Balmer line broadening to determine transverse (vertical) plasma density profiles
- Optical line shift to longitudinally scan the plasma channel
- Camera acquisition gated to discharge trigger for time-resolved measurements
- Experimental settings:
  - ➢ 1 Hz operation
  - ➢ H_2 80-100 mbar in pulsed injection
  - ➢ 7.5 kV – 500 A



Preservation of the capillary channel

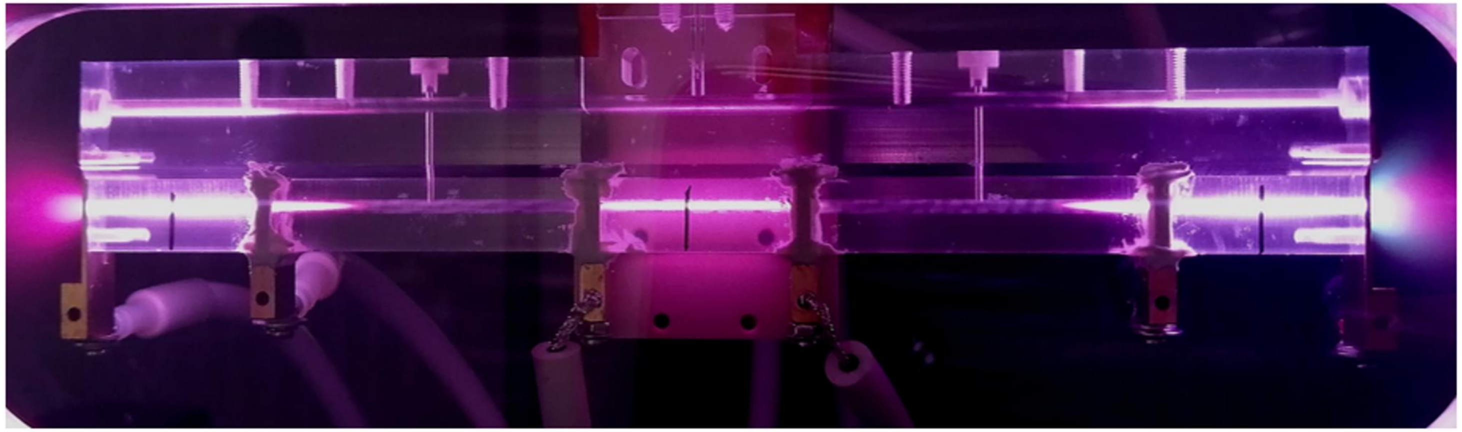
- Laser spot size lineouts measured at different number of shots
  - ✓ No alteration is observed
- Microscopic analysis of the capillary channel with a stereomicroscope
  - ✓ The geometrical profile is not altered after the experimental campaign
  - ✓ Molybdenum disk preserves the electrode integrity

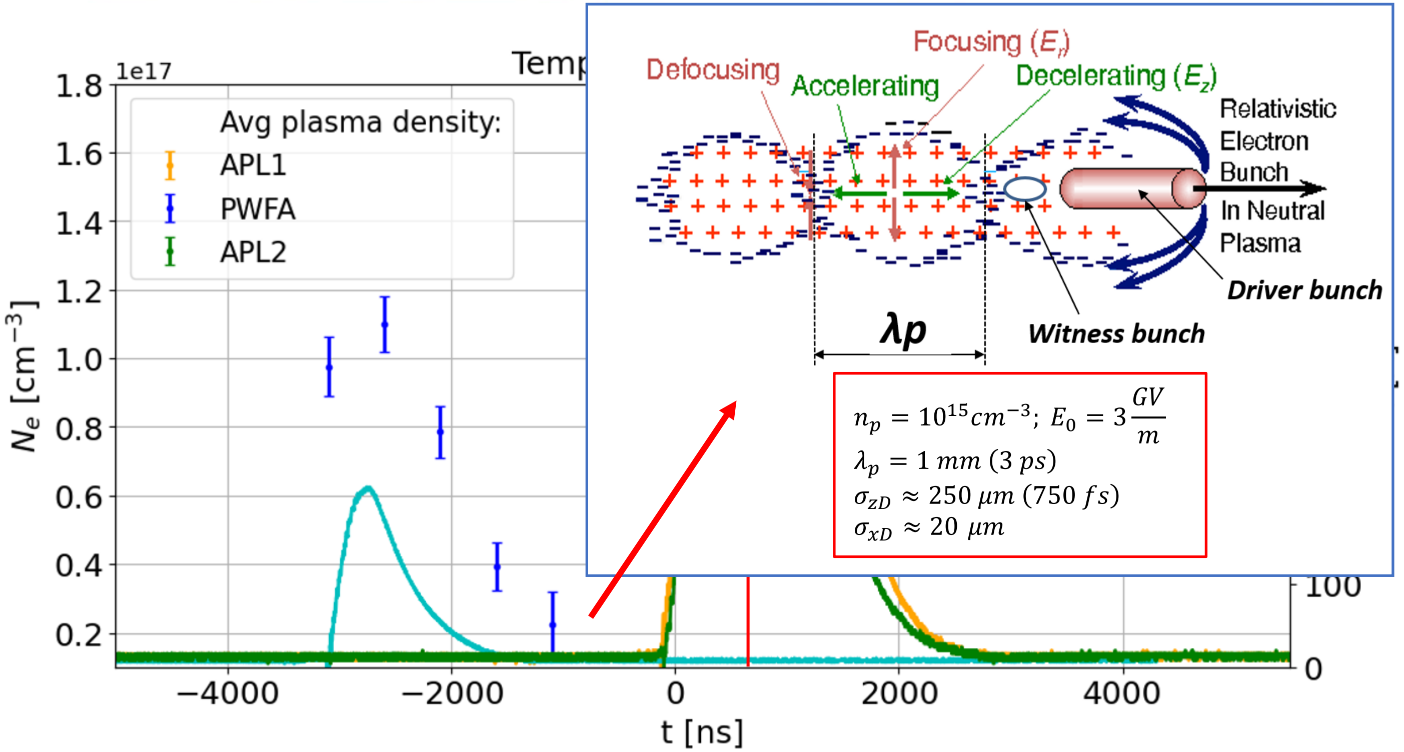


Integrated plasma discharge capillary

Operating properties

- Discharges synchronization
  - Lenses synchronized with the beam entrance
  - Central discharge applied 3 µs before for plasma acceleration
- 10 kV voltage resulting in:
  - 500 A on the lenses
  - 250 A in the accelerator
- Internal drifts behave like spacers



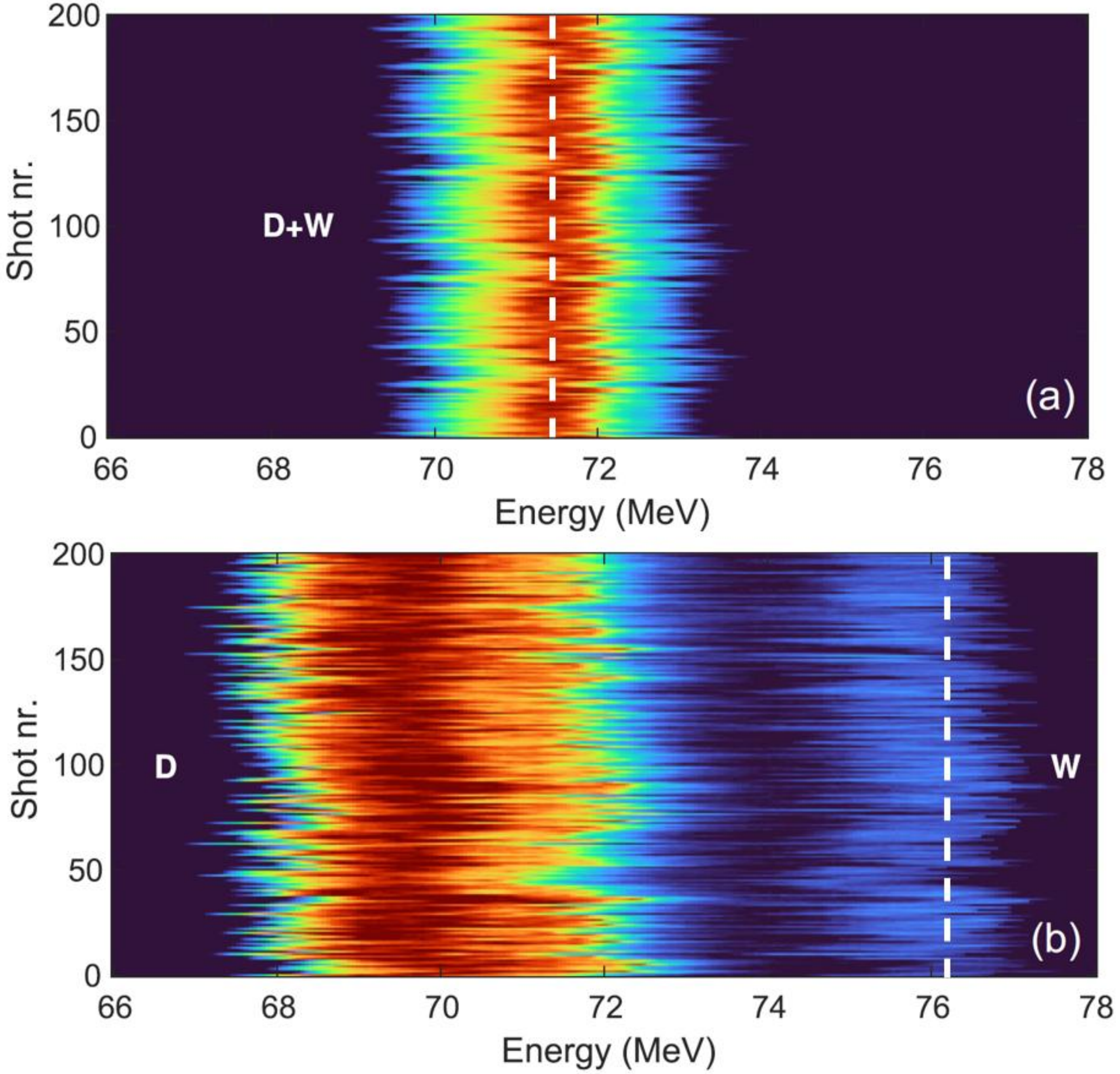


Electron beam focusing and acceleration at SPARC_LAB

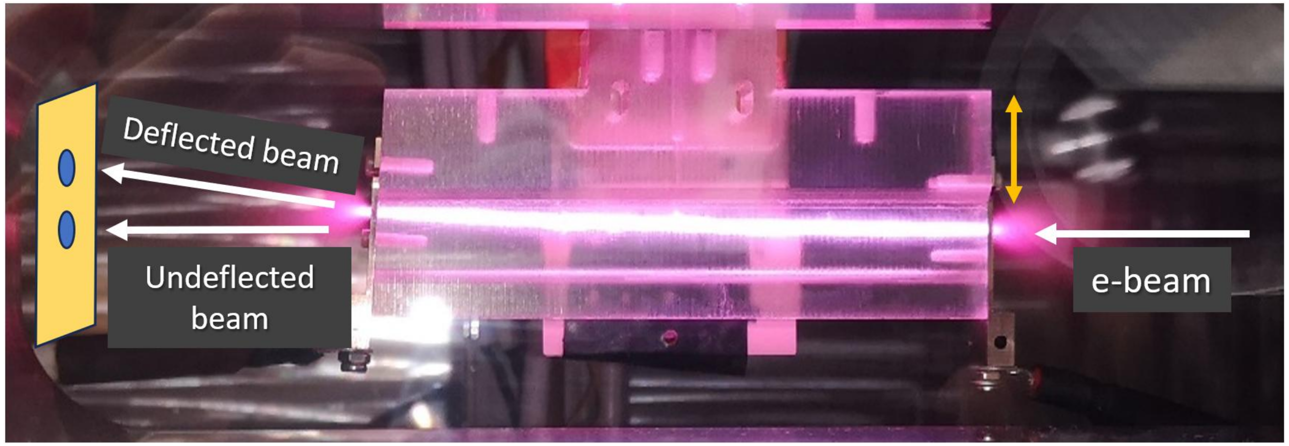
Parameter	Unit	Driver	Witness
Electron energy	MeV	71.6 ± 0.1	71.9 ± 0.1
RMS energy spread	MeV	0.49 ± 0.03	0.72 ± 0.04
Bunch charge	pC	200	50
RMS bunch duration	fs	185 ± 39	55 ± 32
Driver-witness delay	ps	1.15 ± 0.03	
RMS normalized emittance	μm	6.2 ± 0.7	4.8 ± 0.4

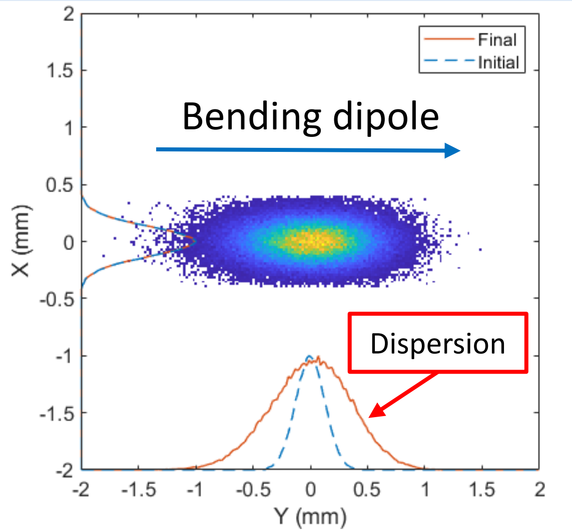
- 4.5 MeV gain over 3 cm (150 MV/m gradient)
- Proof of principle of staged plasma-based focusing-acceleration of electron beams within a compact integrated plasma source

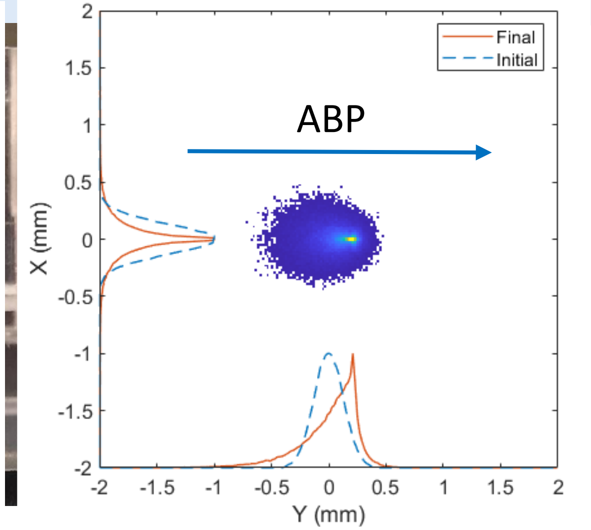
200 consecutive shots taken with accelerated beam

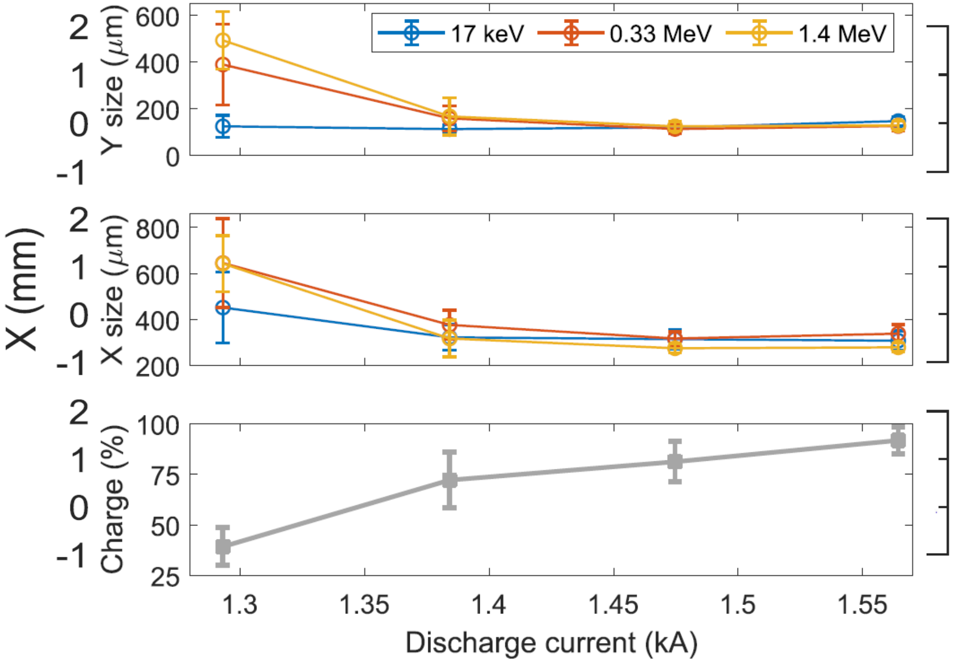


Curved capillary for plasma bending



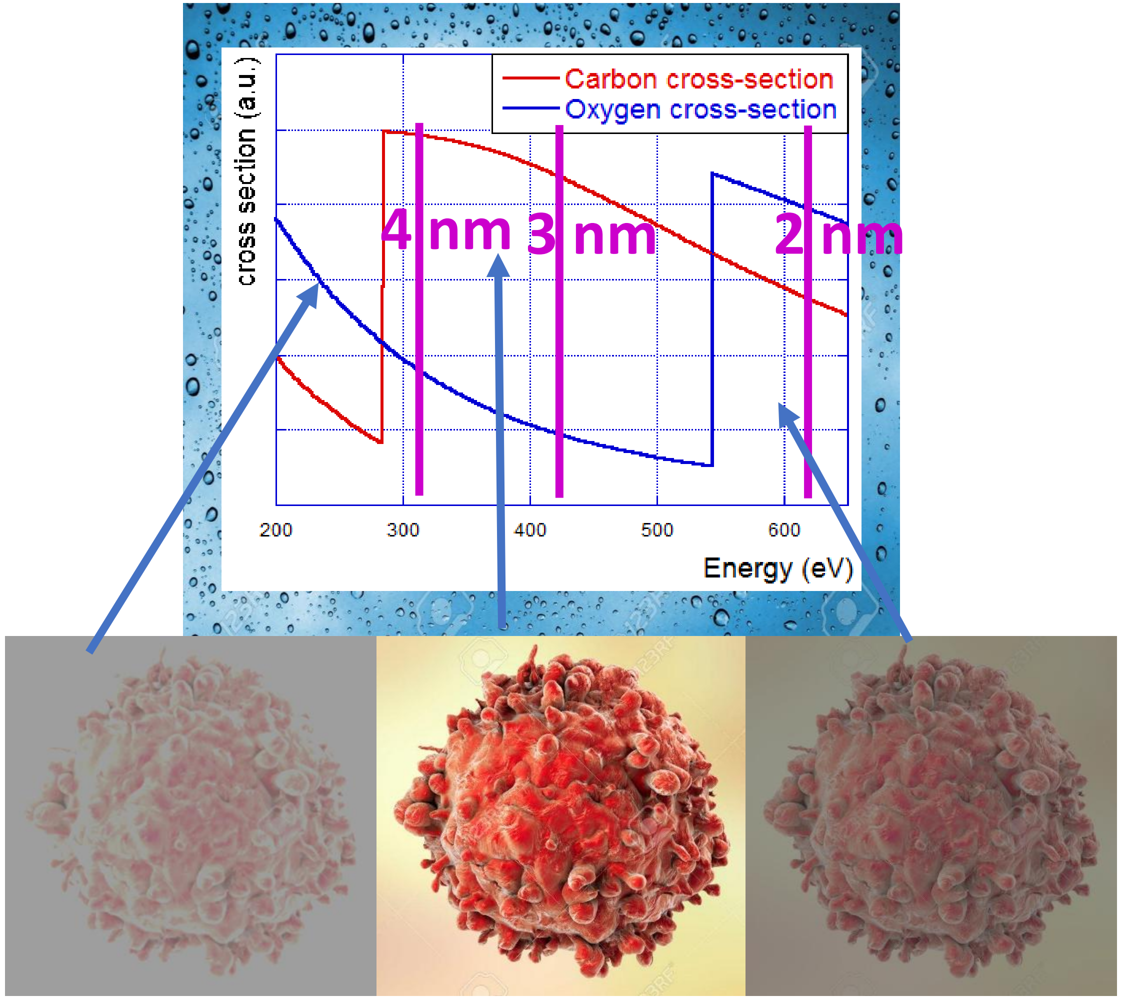






- 60 MeV 50 pC bunch with three energy spread configurations
- 4° trajectory bending with 10 mm offset on screen
- No dispersion observed

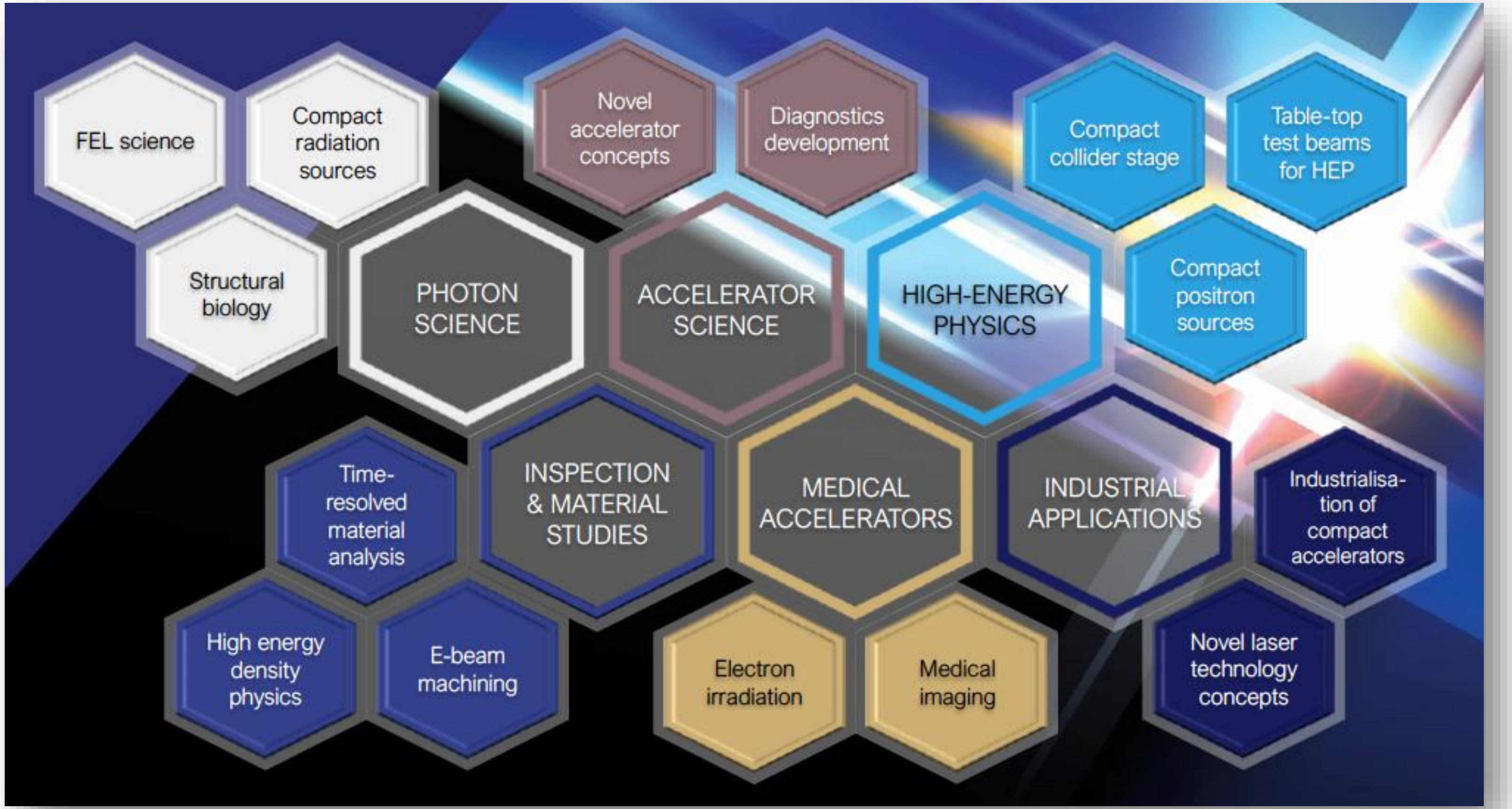
Water window wavelength range



Intense R&D Program on critical components

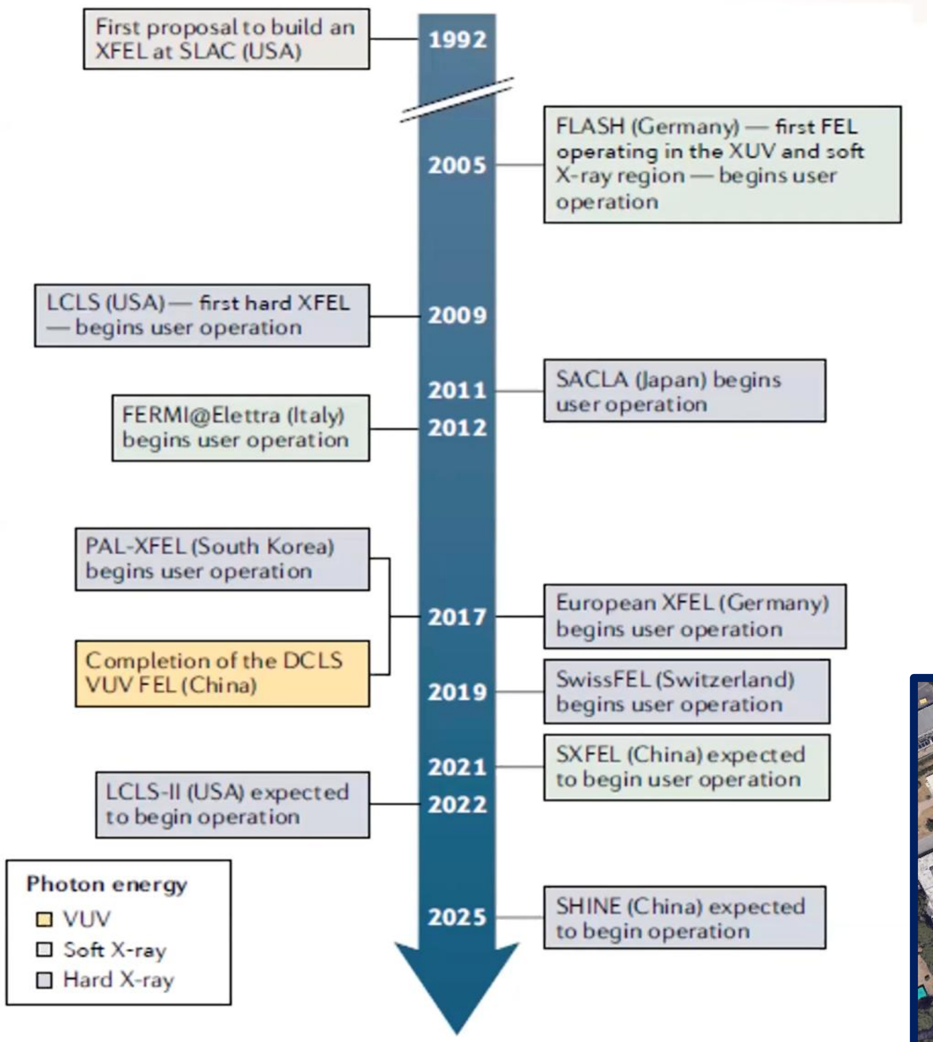
Funded by the European Union

- **Plasma Targets**
- **X-band RF Linac**
  (60 MV/m , up to 400 Hz)
- **Lasers**
  (100 J, 50 fs, 10-100 Hz)
- **Electrons**
  (0.1-5 GeV, 30 pC)
- **Positrons**
  (0.5-10 MeV, 10^6)
- **Positrons** (GeV source)
- **<u>FEL light</u>**
  (0.2-36 nm, 10^9-10^{13})
- **<u>Betatron X rays</u>**
  (1-10 keV, 10^{10})



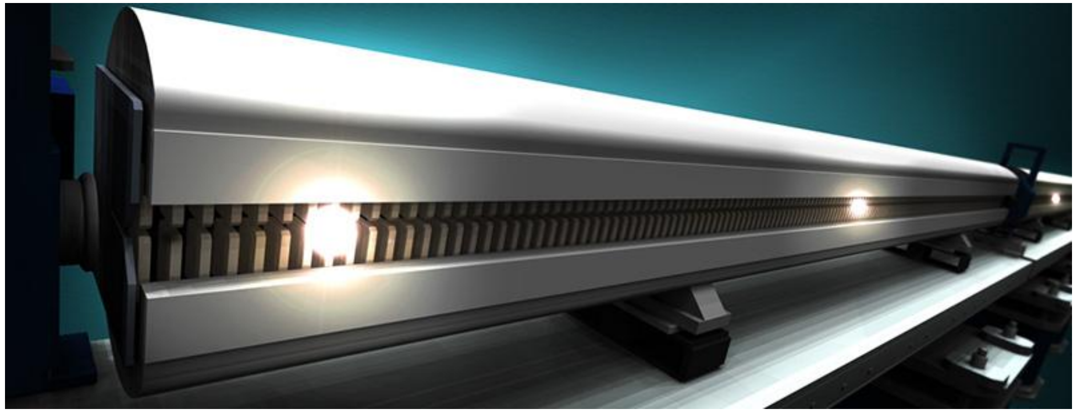
FEL from PWFA reduces costs and dimensions

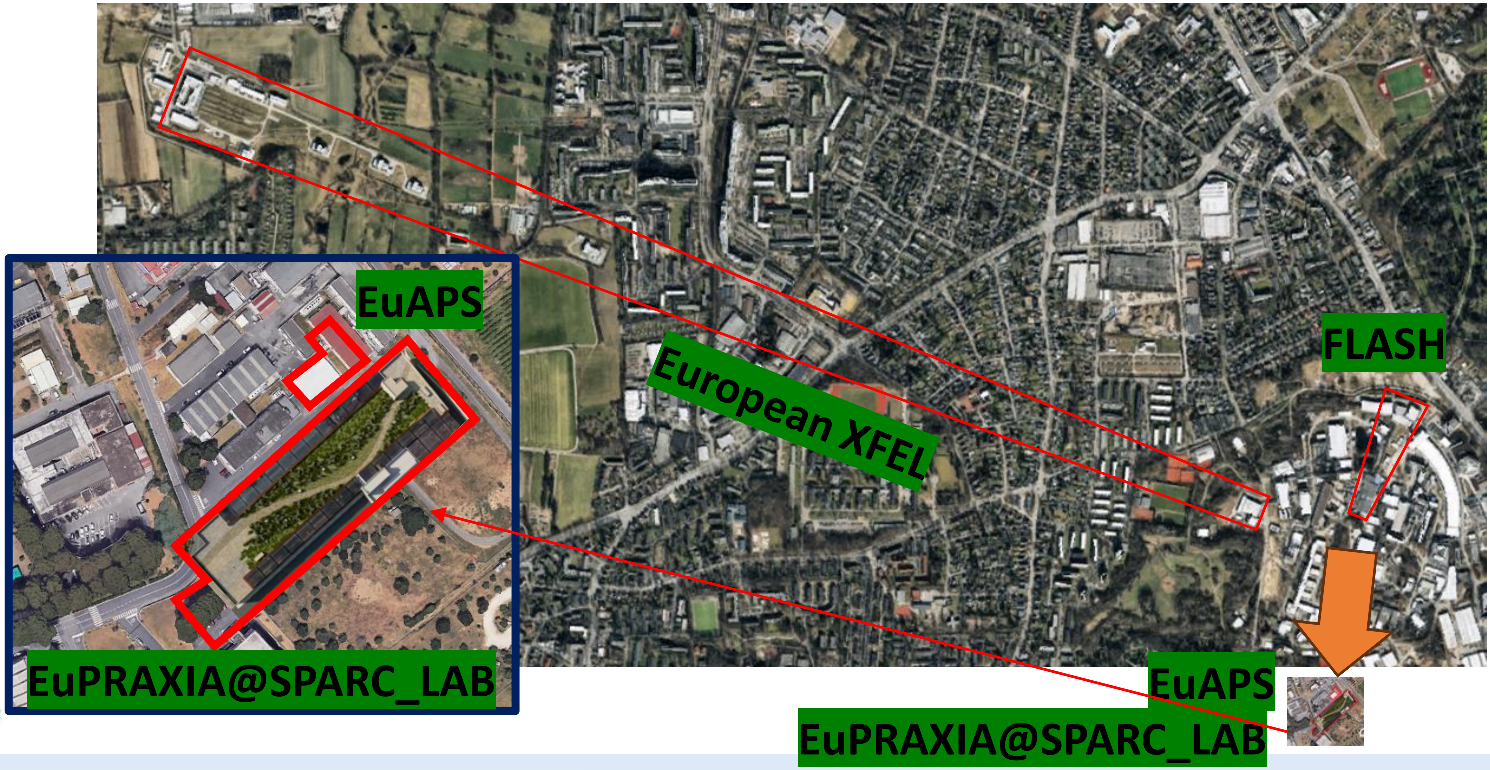
Funded by the European Union



New facilities are expected to begin operation in the next 5 years in the USA and China, and the UK is considering the scientific case for an XFEL.

Iulia Georgescu





Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

EuPRAXIA Advanced Photon Sources

Betatron radiation

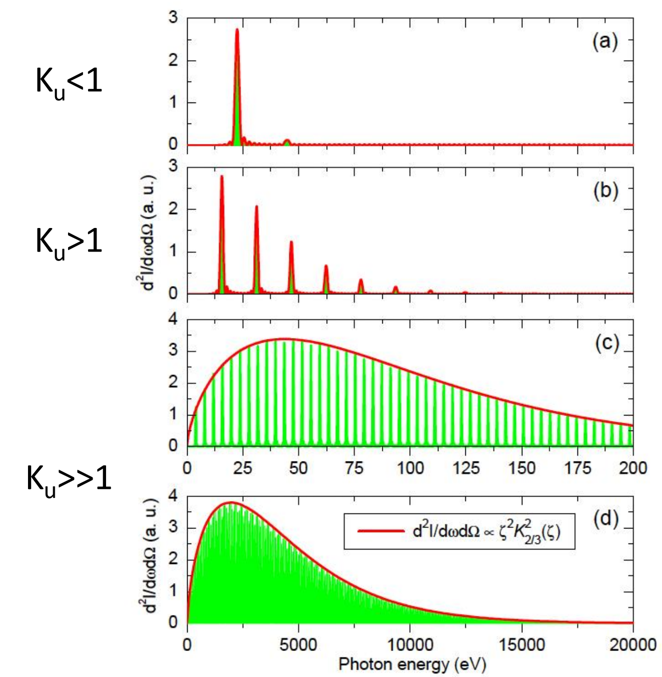


Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 μm, (b) 0.5 μm, and (c) 1.6 μm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 μm.*

$$\omega_c = 3K_u\gamma^2\omega_\beta$$

$$N_{ph} \propto N_e N_\beta K_u$$

$$\lambda_\beta = \sqrt{2\gamma}\lambda_p$$

Laser pulse

Betatron x-ray beam

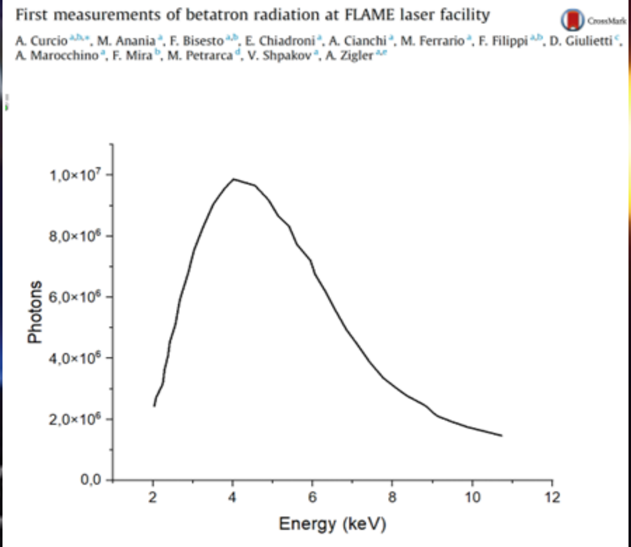
$$\lambda_r(\theta) = \lambda_\beta/2\gamma^2 \cdot \left[1 + \frac{1}{2}K_u^2 + (\gamma\theta)^2\right]$$

Betatron wavenumber

$$K_u = \gamma k_\beta r_\beta$$

$$r_\beta = \frac{2\sqrt{a_0}c}{\omega_p}$$

Oscillation amplitude


First measurements of betatron radiation at FLAME laser facility

A. Curcio, M. Anania, F. Bisesto, E. Chiadroni, A. Cianchi, M. Ferrario, F. Filippi, D. Giulietti, A. Marrocchino, F. Mira, M. Petrarca, V. Shpakov, A. Zigler