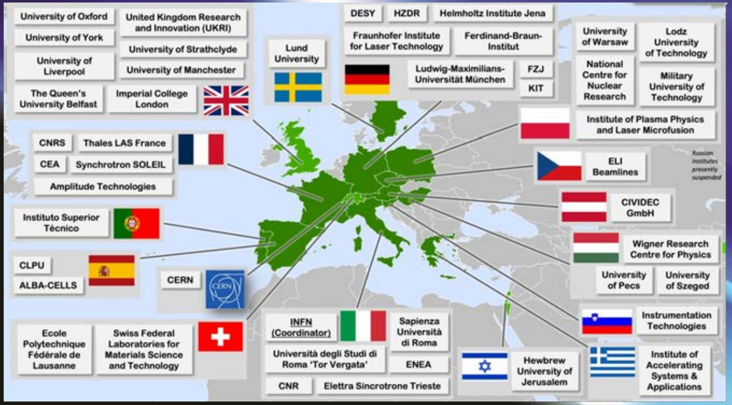
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

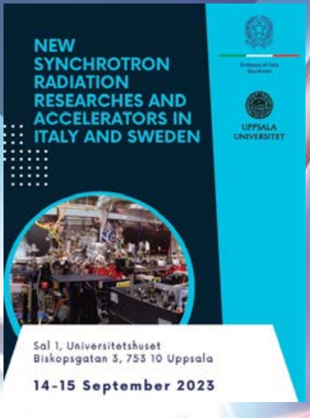
EuPRAXIA

The EuPRAXIA project

M. Ferrario, INFN-LNF

On behalf of the EuPRAXIA collaboration





NEW SYNCHROTRON RADIATION RESEARCHES AND ACCELERATORS IN ITALY AND SWEDEN

UPPSALA UNIVERSITET

Sal 1, Universitetshuset
Biskopsgatan 3, 753 10 Uppsala

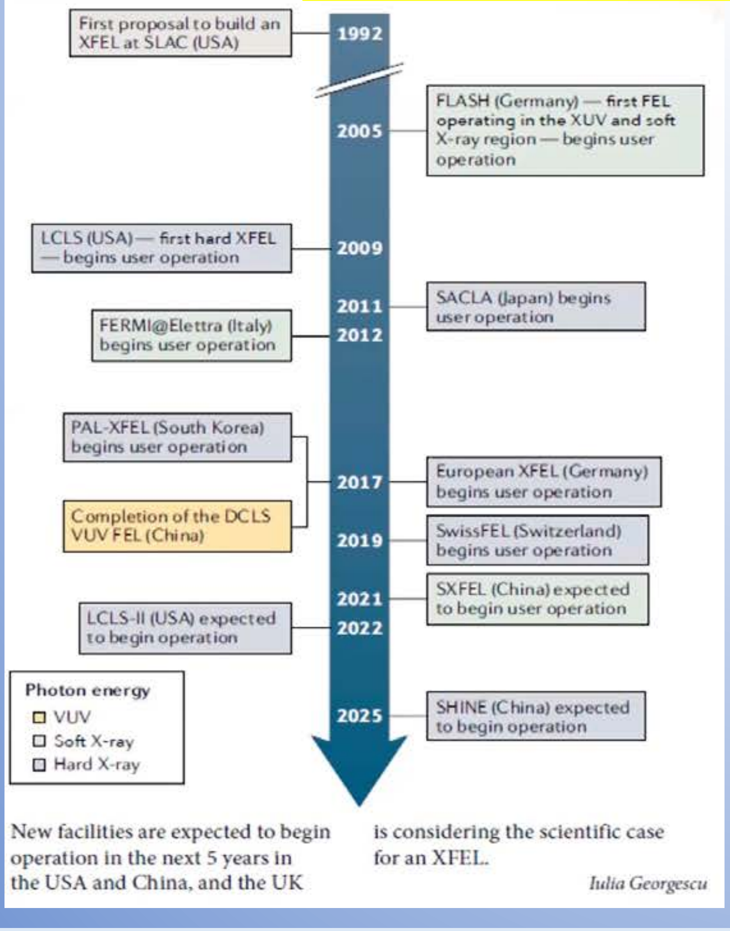
14-15 September 2023

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

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

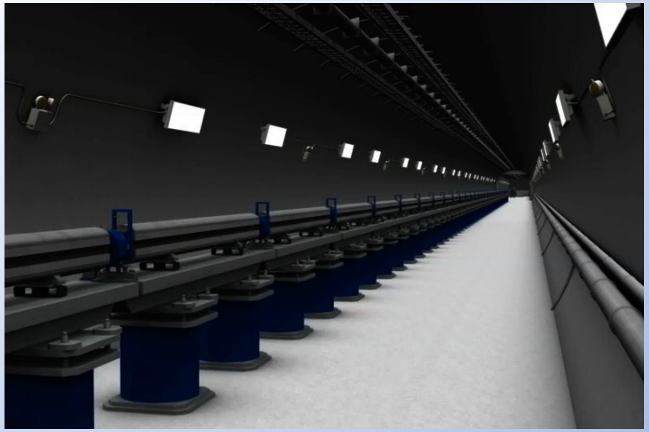


- 1992 — First proposal to build an XFEL at SLAC (USA)
- 2005 — FLASH (Germany) — first FEL operating in the XUV and soft X-ray region — begins user operation
- 2009 — LCLS (USA) — first hard XFEL — begins user operation
- 2011 — SACLA (Japan) begins user operation
- 2012 — FERMI@Elettra (Italy) begins user operation
- 2017 — PAL-XFEL (South Korea) begins user operation
- 2017 — Completion of the DCLS VUV FEL (China)
- 2017 — European XFEL (Germany) begins user operation
- 2019 — SwissFEL (Switzerland) begins user operation
- 2021 — SXFEL (China) expected to begin user operation
- 2022 — LCLS-II (USA) expected to begin operation
- 2025 — SHINE (China) expected to begin operation

Photon energy
- ☐ VUV
- ☐ Soft X-ray
- ☐ Hard X-ray

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



Linac Coherent Light Source (LCLS) Conceptual Design Report - SLAC–R–593 April 2002 UC-414

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

2

Producing particle and photon pulses to support several urgent and timely science cases

Enable frontier science in new regions and parameter regimes

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

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

Plasma accelerated beam driven FEL

It's a CHALLENGE: **the FEL is extremely sensitive to the beam quality.**

Low (geometric) emittances: $\epsilon_{x,y} < \frac{\lambda_0}{4\pi}$

Low relative energy spread σ_γ: $\sigma_\gamma < \frac{1}{2}\rho_{fel}$

Low emittances
Low energy spread
High current

where $$\rho_{fel} = \frac{1}{4\pi}\left[\frac{2\pi^2}{\gamma^3}\left(\lambda_u K\left[JJ\right]\right)^2 \frac{I_{peak}}{\Sigma_e I_A}\right]^{1/3}$$

Exponential growth

$$P(z) = \frac{1}{9}P_0 e^{z/L_g}$$

gain length

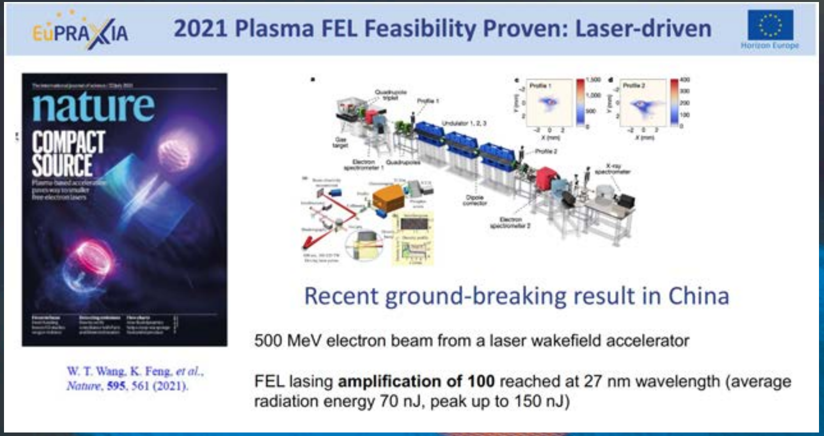
$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{fel}}$$

saturation

$$P_F \sim 1.6\,\rho_{fel} P_{beam}$$

=> A poor beam quality causes an increase of L_g and a reduction of P_F

Basic beam quality achieved in pilot FEL experiments



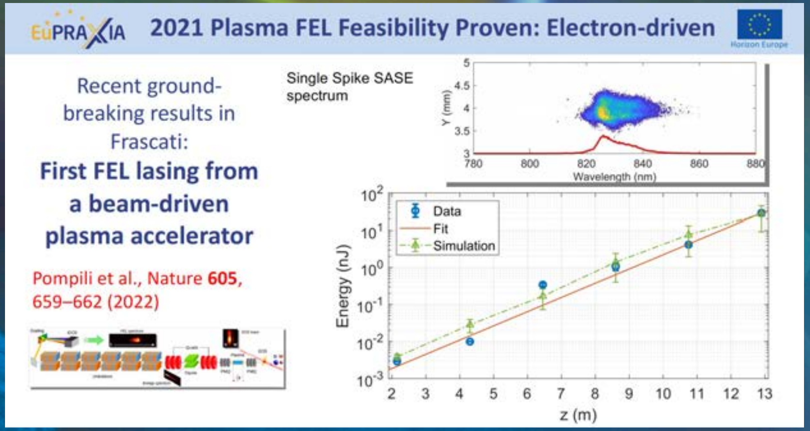
2021 Plasma FEL Feasibility Proven: Laser-driven

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)



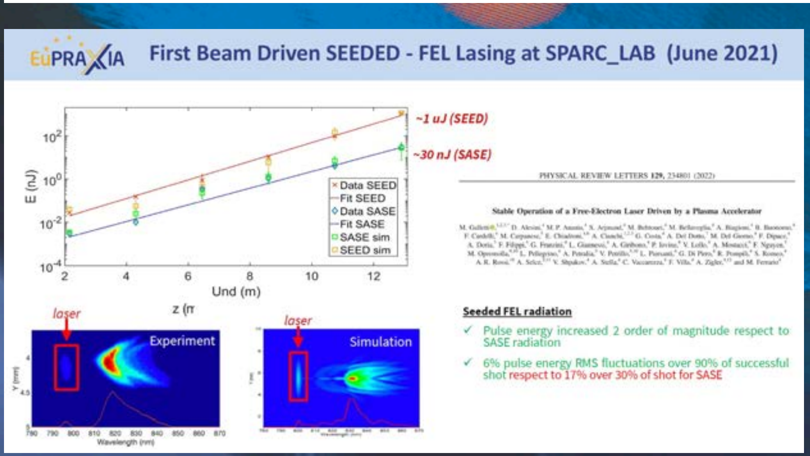
2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

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

Single Spike SASE spectrum



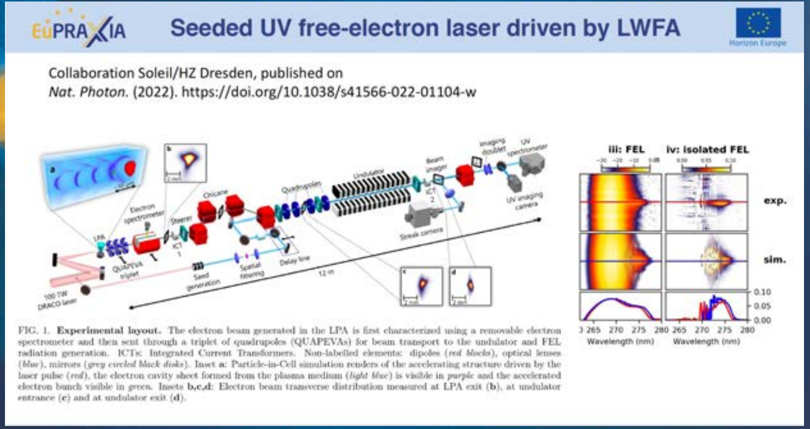
First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

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

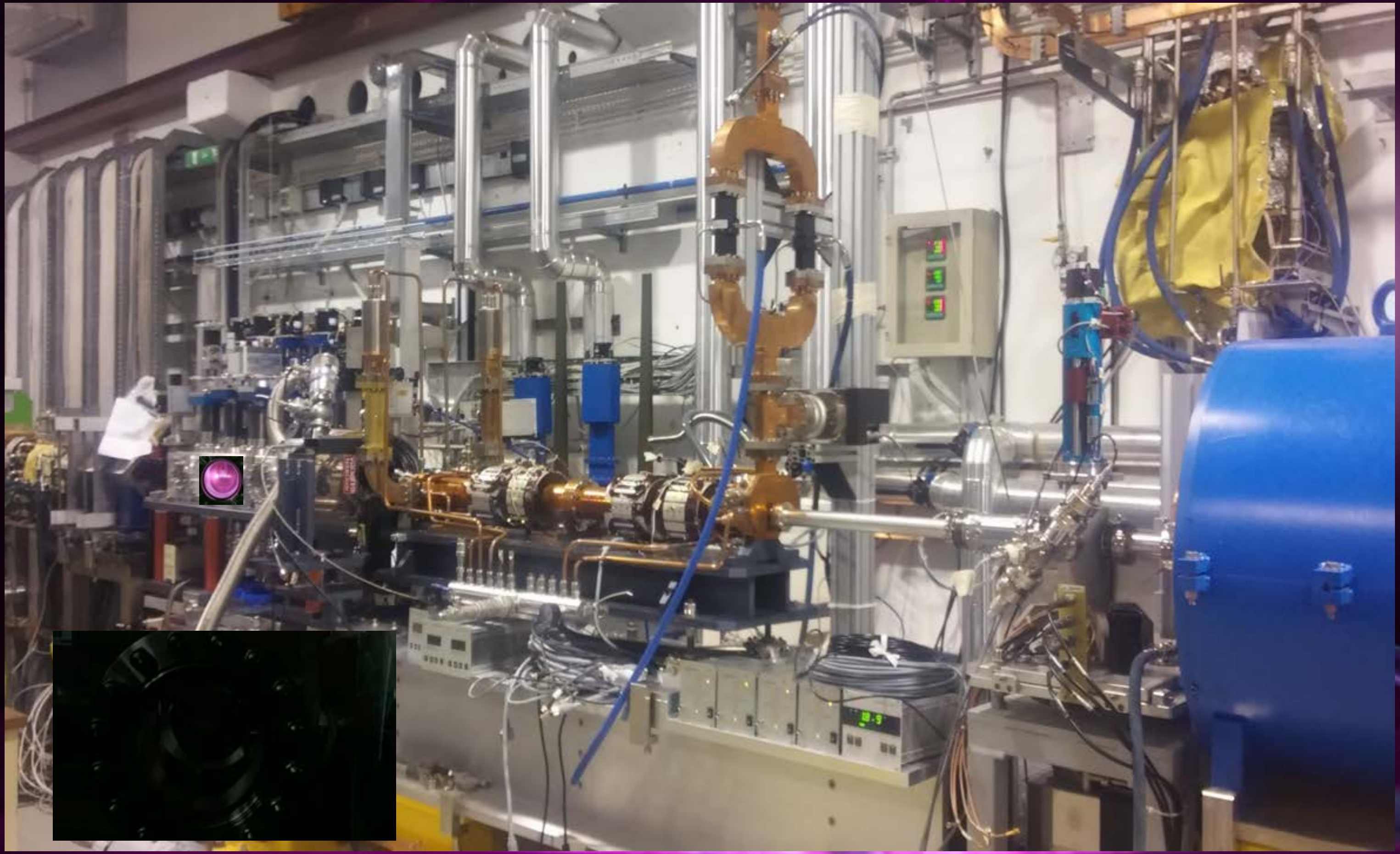


Seeded UV free-electron laser driven by LWFA

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**).

PWFA beam line at SPARC_LAB



Required Bunch Energy Stability

$$\frac{\Delta\lambda}{\lambda} \propto \frac{\Delta E}{E} \propto \rho \approx 10^{-3}$$

FEL requirement

$$E_z\left(\frac{\lambda_p}{2}\right) = \tilde{A}\sqrt{n_p I_d}$$

$$\left.\frac{\Delta E}{E}\right|_p = \frac{\Delta n_p}{n_p}$$

Plasma density

$$\left.\frac{\Delta E}{E}\right|_Q = \frac{\Delta I_d}{2(I_d)} + \frac{\Delta I_w}{2(I_w)}$$

Bunch charge/length

$$\left.\frac{\Delta E}{E}\right|_{DW} = \frac{a\omega_p}{2\pi}\Delta t_{DW}$$

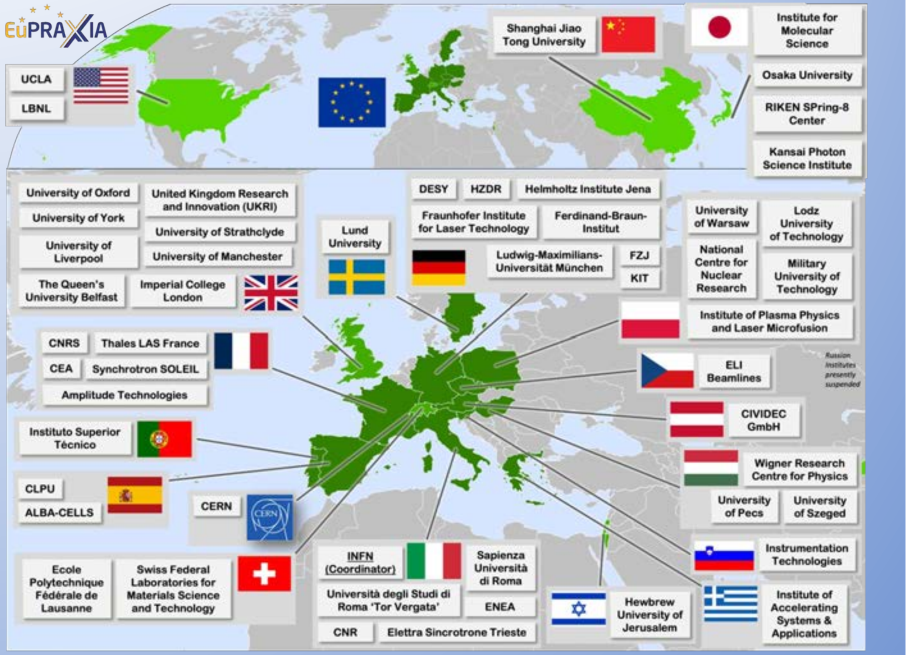
$$2 \le a \le 4$$

Driver/Witness separation

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

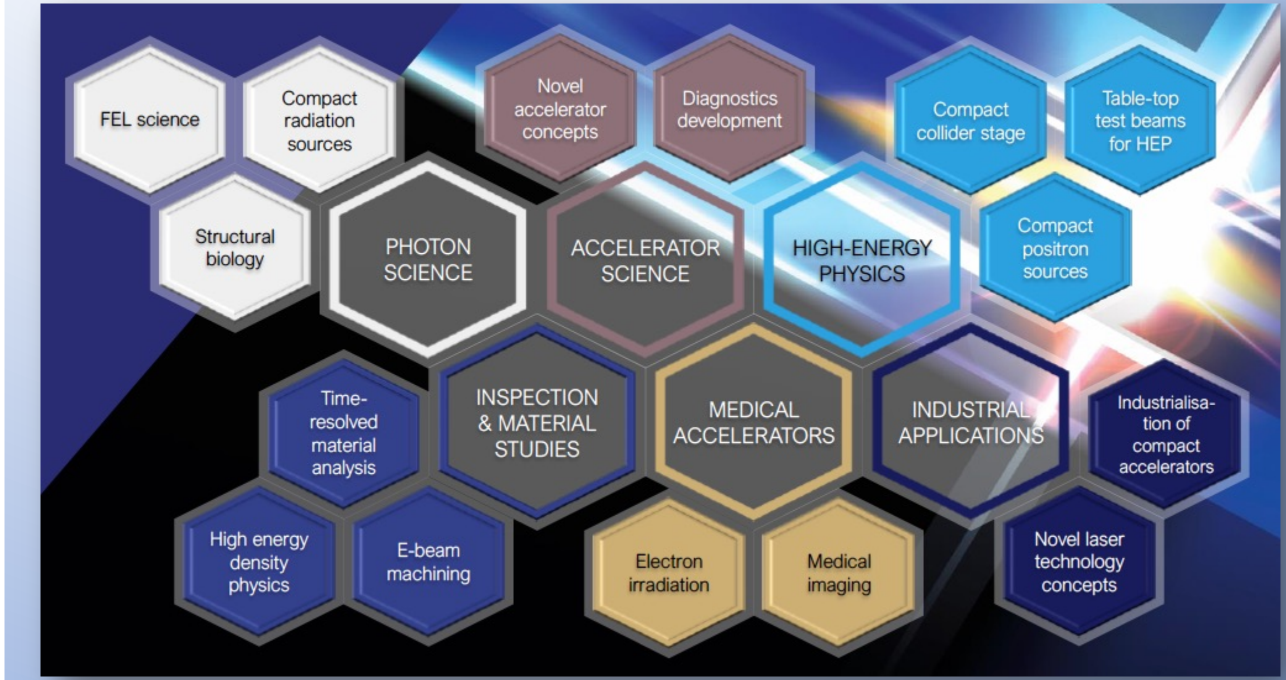


- **Efficient fund raising:**
  - –**Preparatory Phase** consortium (funding EU, UK, Switzerland, in-kind)
  - –**Doctoral Network** (funding EU, UK, in-kind)
  - –**EuPRAXIA@SPARC_LAB** (Italy, in-kind)
  - –**EuAPS Project** (Next Generation EU)

Intense R&D Program on critical components

Funded by the European Union

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



Distributed Research Infrastructure

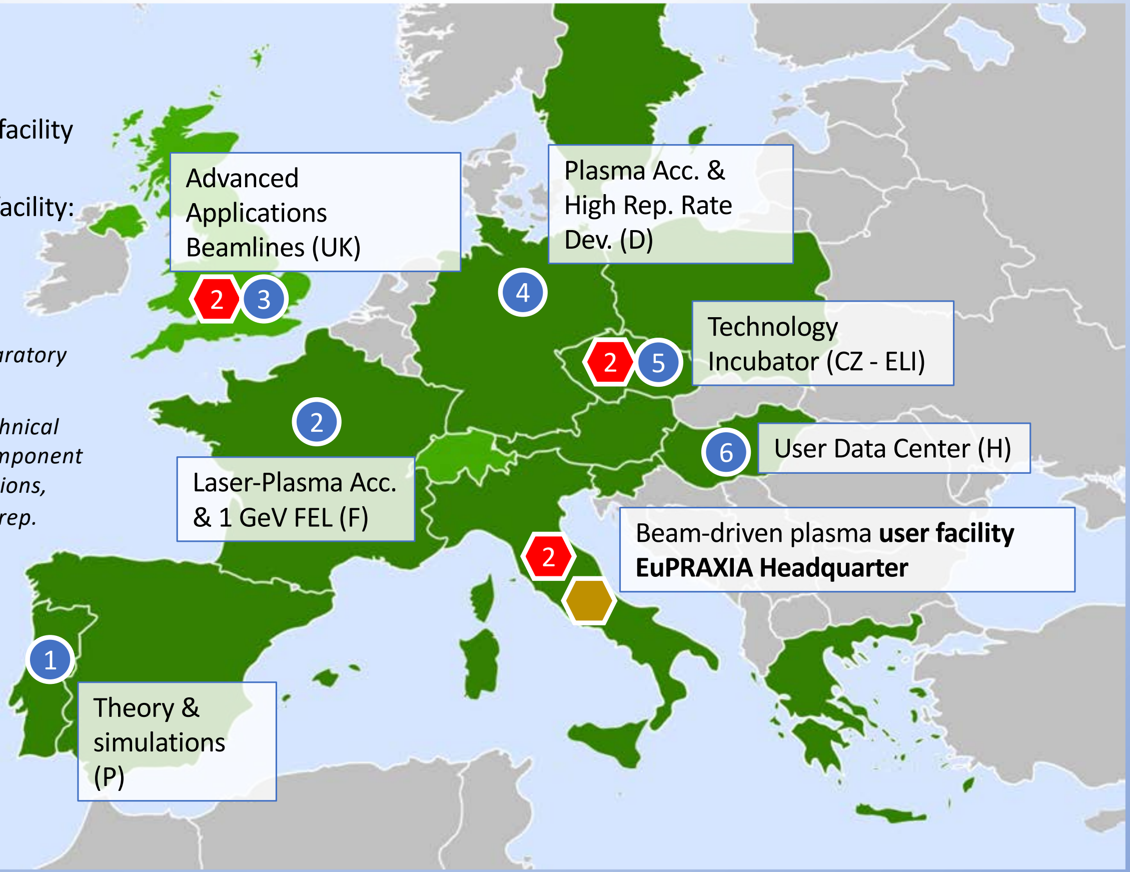
Funded by the European Union

- ⬢ Beam-driven plasma user facility EuPRAXIA Headquarter
- 2 Laser-driven plasma user facility: candidates
- ● Excellence Center

Second site will be decided in Preparatory Phase project.

Excellence centers (EC) perform technical developments, prototyping and component construction. Number of EC's, locations, roles, responsibilities reviewed in Prep. Phase.

Horizon Europe



Advanced Applications Beamlines (UK)

Plasma Acc. & High Rep. Rate Dev. (D)

Technology Incubator (CZ - ELI)

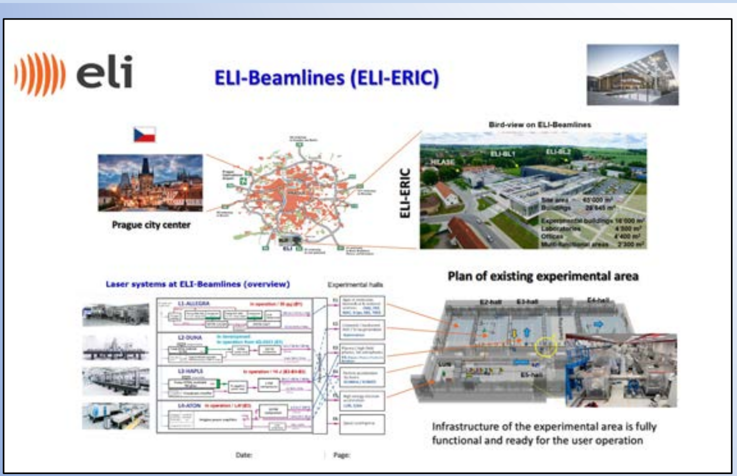
Laser-Plasma Acc. & 1 GeV FEL (F)

User Data Center (H)

Beam-driven plasma **user facility EuPRAXIA Headquarter**

Theory & simulations (P)

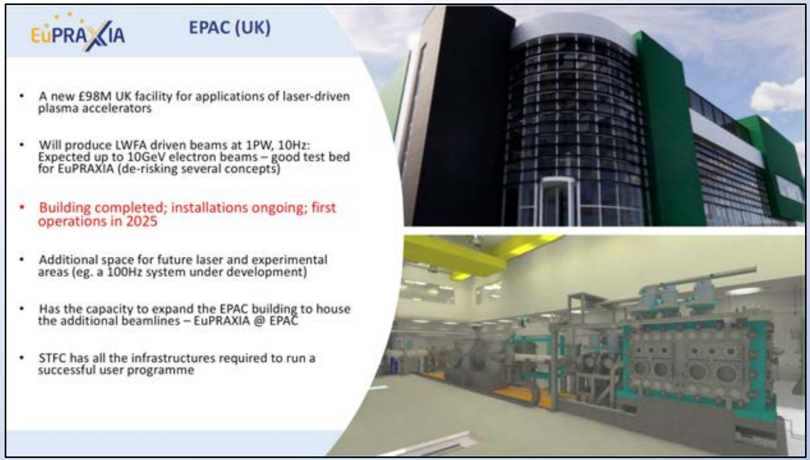
Current Candidates for EuPRAXIA Laser Site



ELI-Beamlines (ELI-ERIC)

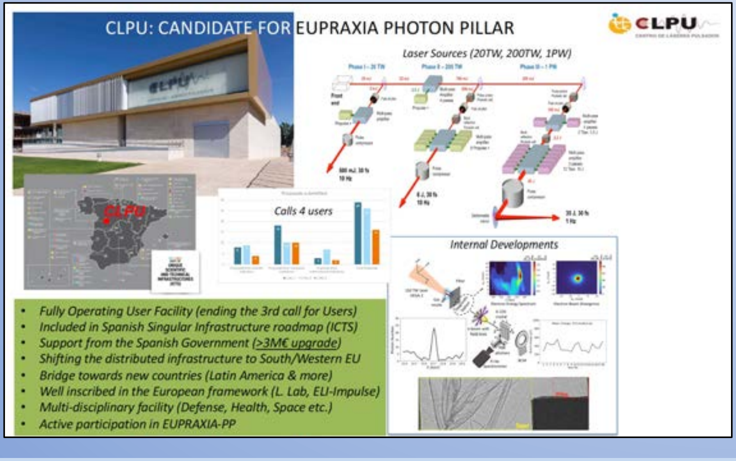
Plan of existing experimental area

Infrastructure of the experimental area is fully functional and ready for the user operation



EPAC (UK)

- A new £98M UK facility for applications of laser-driven plasma accelerators
- Will produce LWFA driven beams at 1PW, 10Hz: Expected up to 10GeV electron beams – good test bed for EuPRAXIA (de-risking several concepts)
- Building completed; installations ongoing; first operations in 2025
- Additional space for future laser and experimental areas (eg. a 100Hz system under development)
- Has the capacity to expand the EPAC building to house the additional beamlines – EuPRAXIA @ EPAC
- STFC has all the infrastructures required to run a successful user programme



CLPU: CANDIDATE FOR EUPRAXIA PHOTON PILLAR

- *Fully Operating User Facility (ending the 3rd call for Users)*
- *Included in Spanish Singular Infrastructure roadmap (ICTS)*
- *Support from the Spanish Government (>3M€ upgrade)*
- *Shifting the distributed infrastructure to South/Western EU*
- *Bridge towards new countries (Latin America & more)*
- *Well inscribed in the European framework (L. Lab, ELI-Impulse)*
- *Multi-disciplinary facility (Defense, Health, Space etc.)*
- *Active participation in EUPRAXIA-PP*

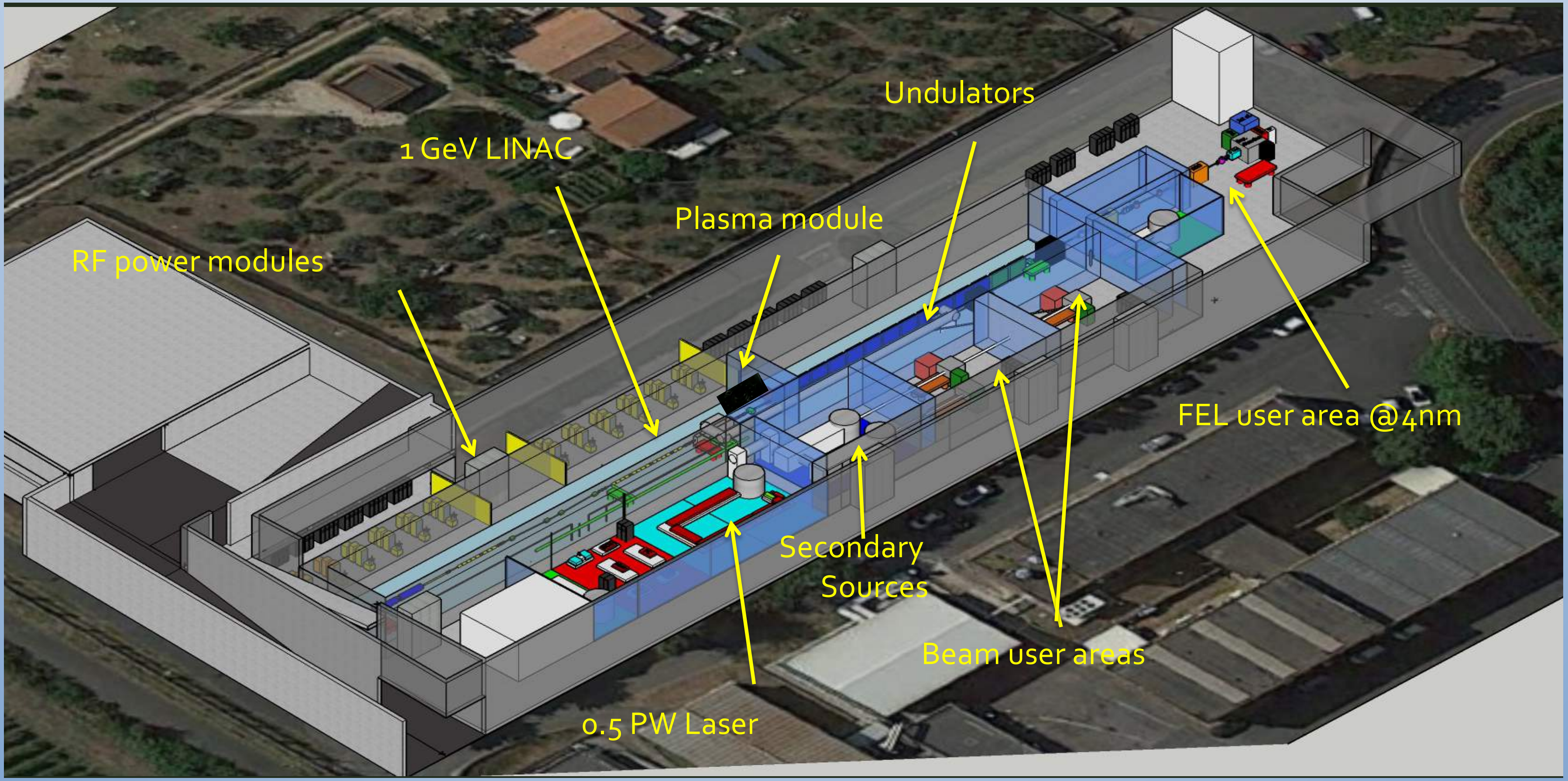
PISA for EuPRAXIA@CNR

- CNR campus in Pisa - home to the *Intense Laser Irradiation Laboratory (Est. 2000)*
- PW scale laser facility operational with user collaborative access
- Major upgrade (10 M€ funding) ongoing to enable EuPRAXIA 100 Hz laser milestone and user areas;
- Xtreme photonics node of the IPHOQS (CNR) and EuAPS (INFN) RI networks
- Pioneering group for access to EU Laser Infrastructures (30+ yrs)
- Unique link to multidisciplinary research and technology transfer on site
- Strong link with Pisa University system

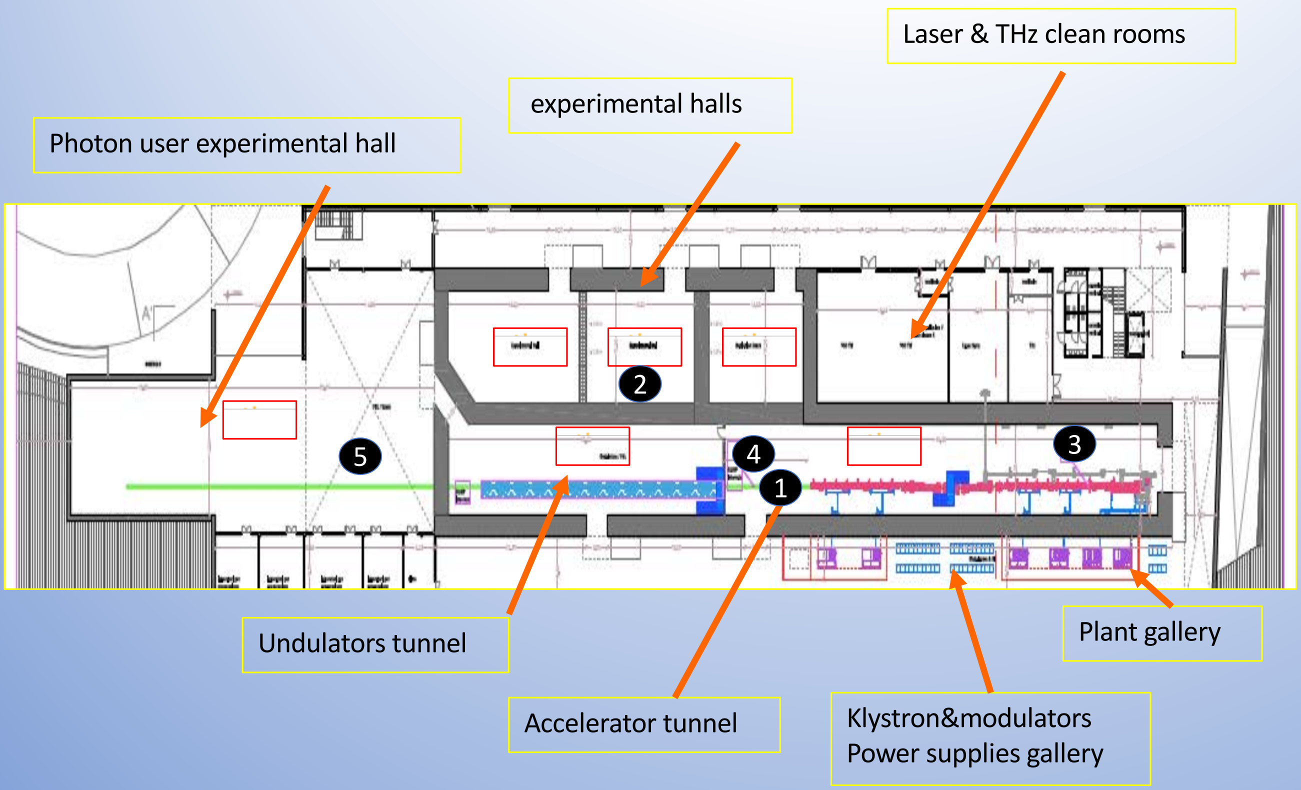
Headquarter and Site 1: EuPRAXIA@SPARC_LAB

- Frascati`s future facility
- > 130 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)

EuPRAXIA@SPARC_LAB



Opportunities for Collaboration



Laser & THz clean rooms

experimental halls

Photon user experimental hall

Undulators tunnel

Accelerator tunnel

Klystron&modulators
Power supplies gallery

Plant gallery

European interests & possible contributions to Frascati site:

① Plasma structure designs, devices

② Compact positron source

③ HQ 150 MeV laser plasma injector

④ HQ laser driver

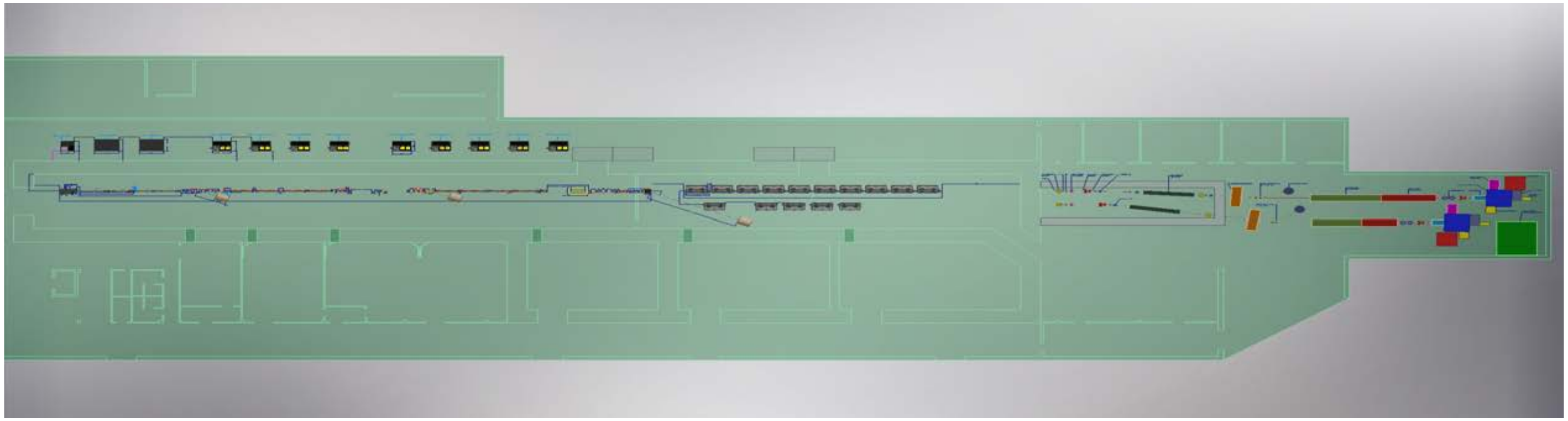
- Hybrid concepts
- Simulations

⑤ User experiments and lines

To be detailed in TDR phase.

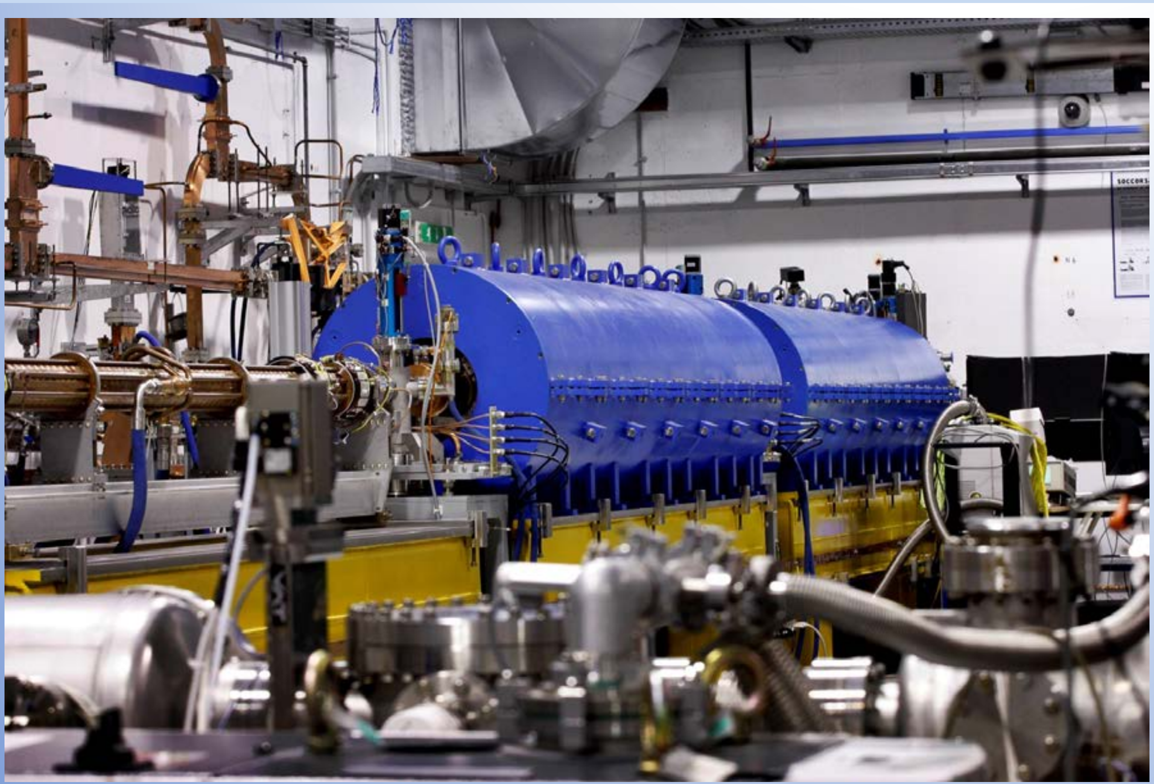
EuPRAXIA@SPARC_LAB Layout

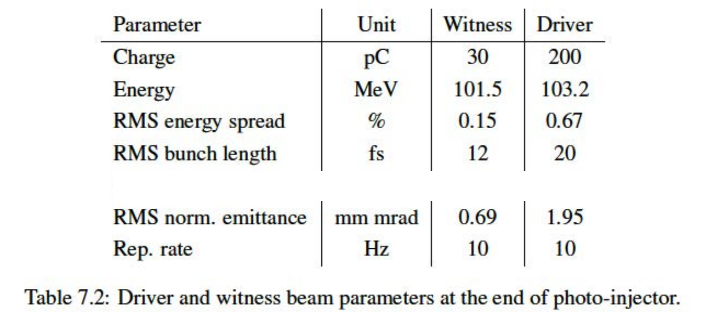
Funded by the European Union



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

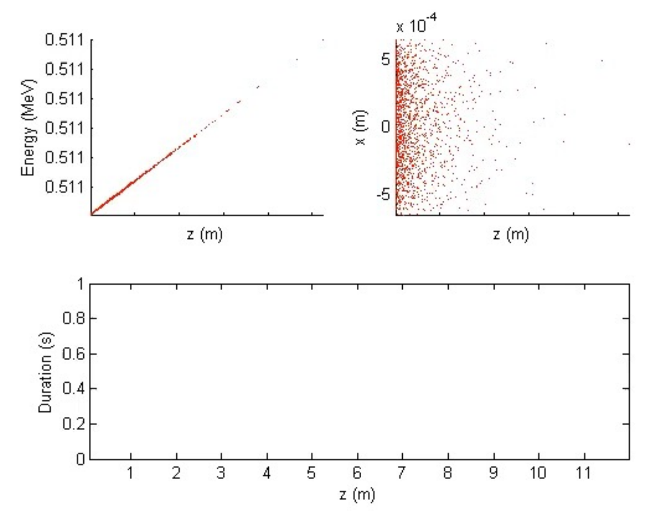
High Quality Electron Beams





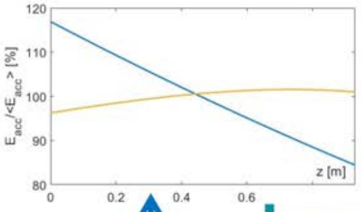
Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

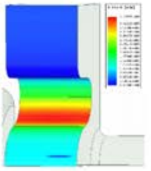
Table 7.2: Driver and witness beam parameters at the end of photo-injector.

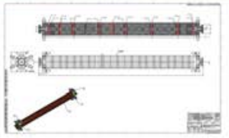


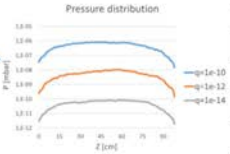
Courtesy E. Chiadroni

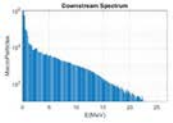
World`s Most Compact RF Linac: X Band





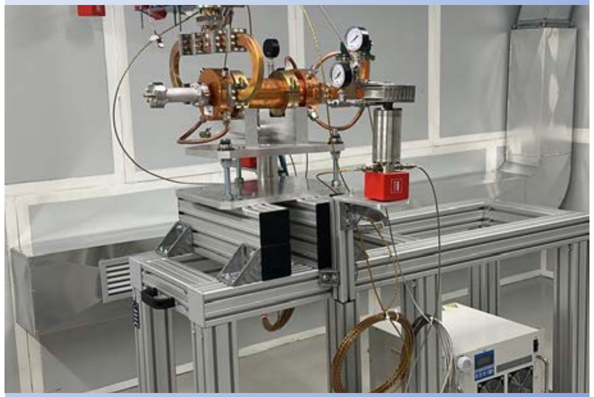


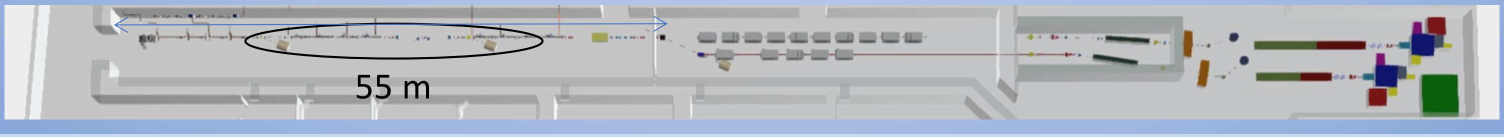




1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

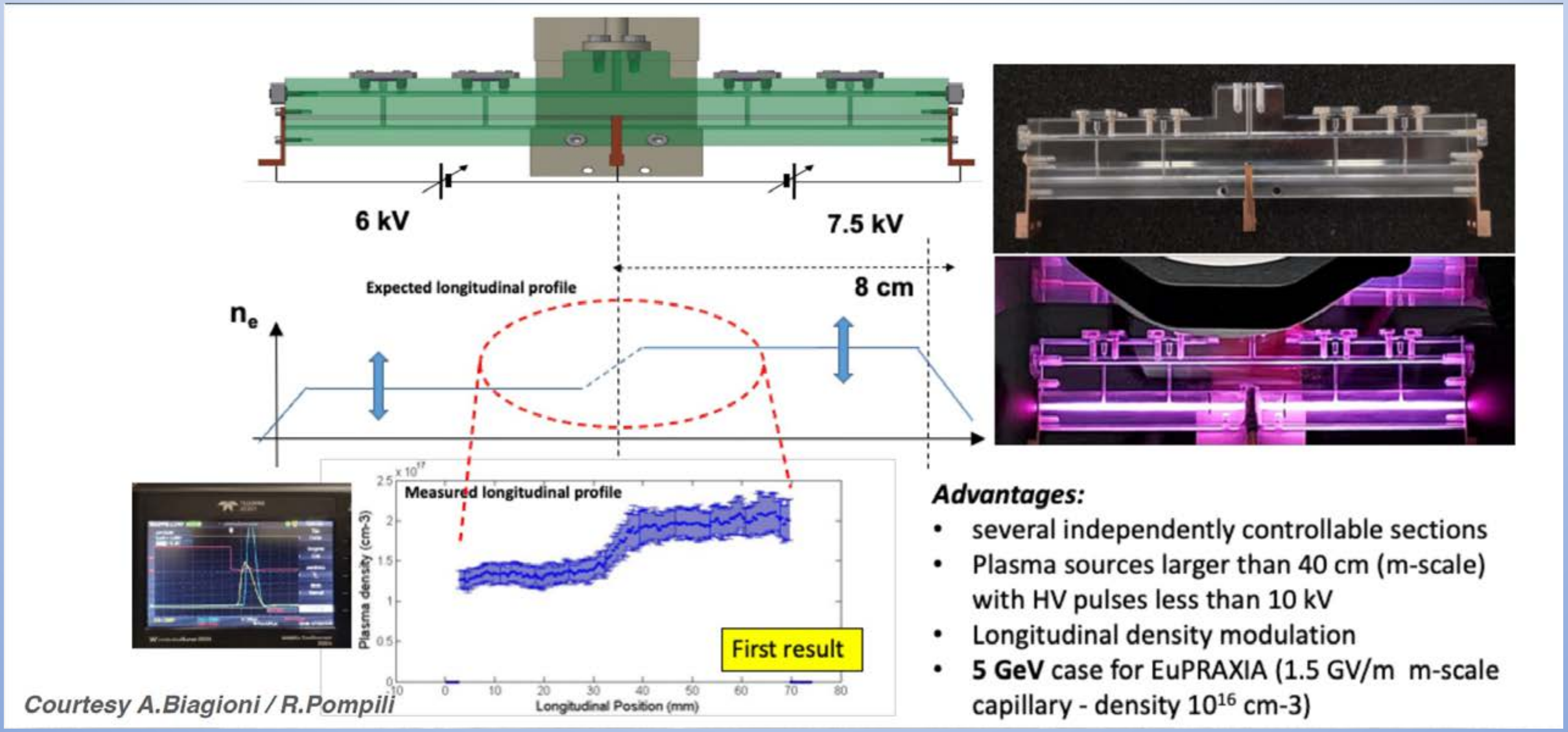
PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt 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**	





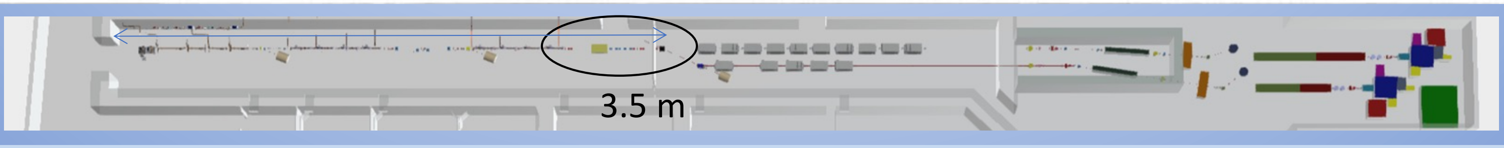
Courtesy D. Alesini

Plasma Module



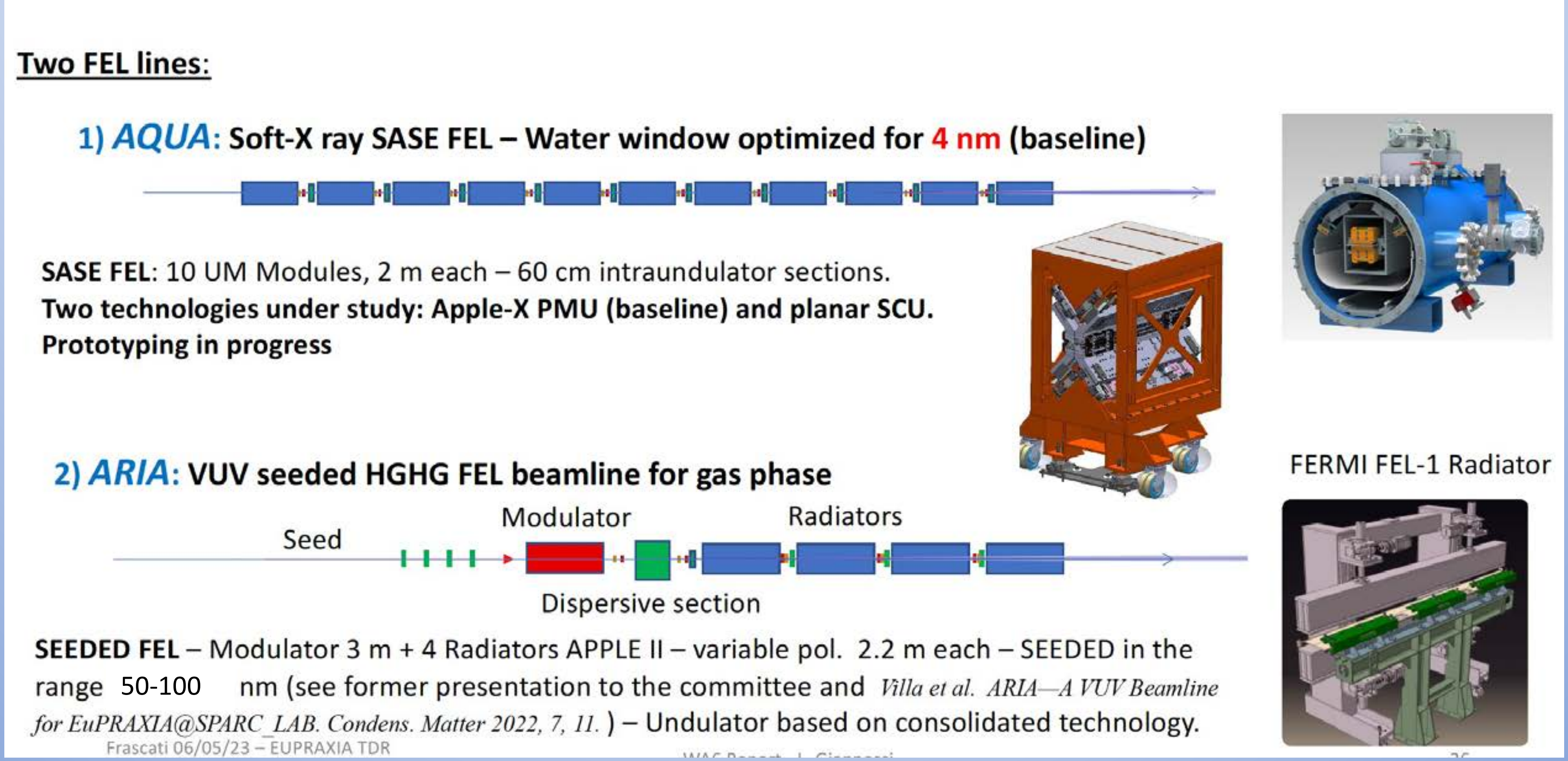
Advantages:

- several independently controllable sections
- Plasma sources larger than 40 cm (m-scale) with HV pulses less than 10 kV
- Longitudinal density modulation
- **5 GeV** case for EuPRAXIA (1.5 GV/m m-scale capillary - density 10^{16} cm-3)



Courtesy A. Biagioni, R. Pompili

Radiation Generation: FEL



Two FEL lines:

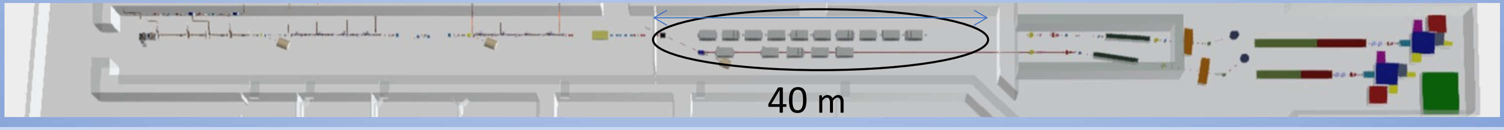
1) ***AQUA*****: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)**

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**

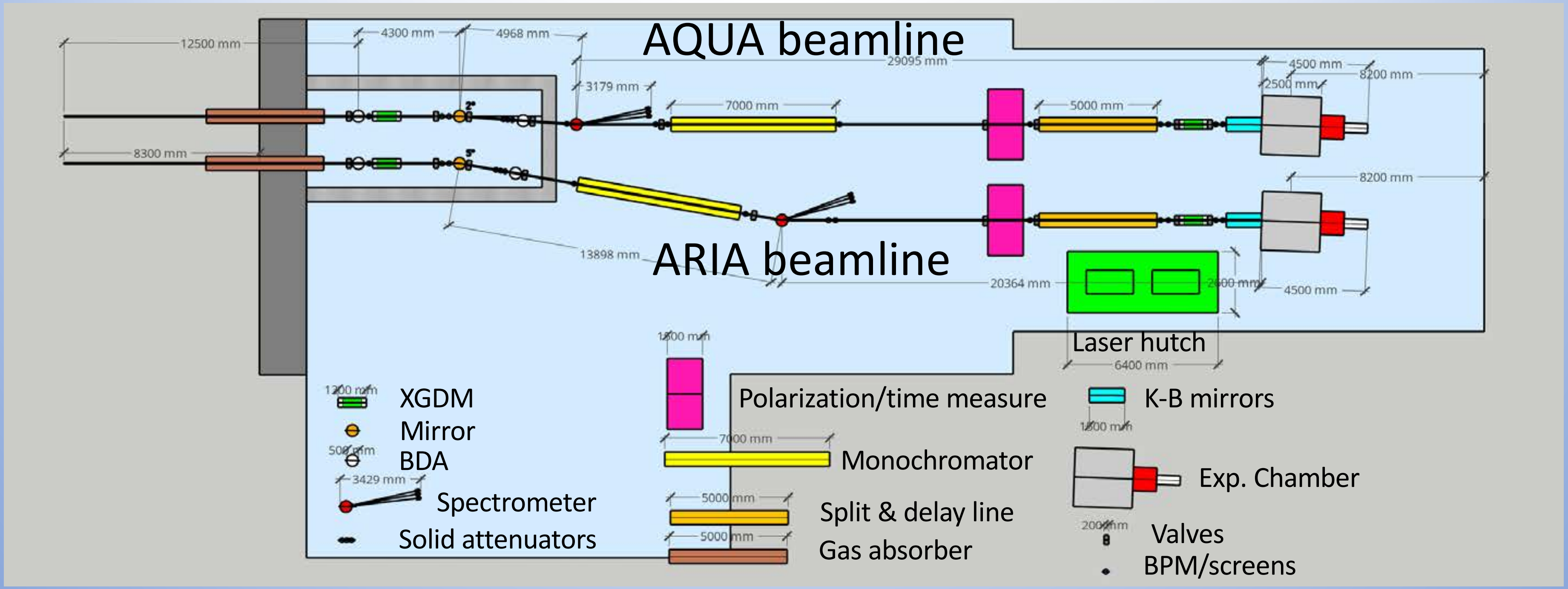
SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 50-100 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC_LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.

Frascati 06/05/23 – EUPRAXIA TDR



Courtesy L. Giannessi

FEL Beamlines

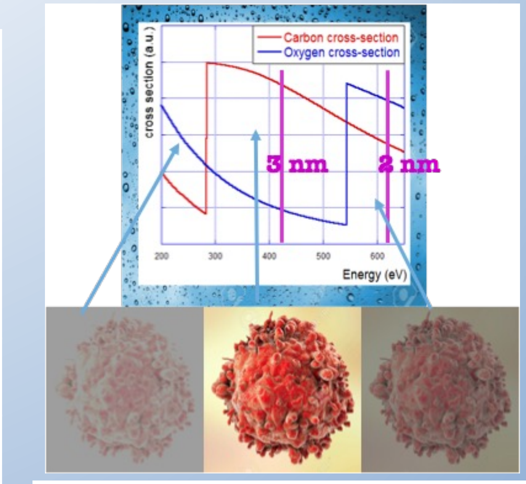


Expected SASE FEL performances

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

Parameter	Unit	PWFA	Full X-band
Radiation Wavelength	nm	3-4	4
Photons per Pulse	$\times 10^{12}$	0.1- 0.25	1
Photon Bandwith	%	0.1	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	2	2
Photon Brilliance per shot	$s\ mm^2 mrad^2$ $bw(0.1\%)$	$1{-}2 \times 10^{28}$	1×10^{27}

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)



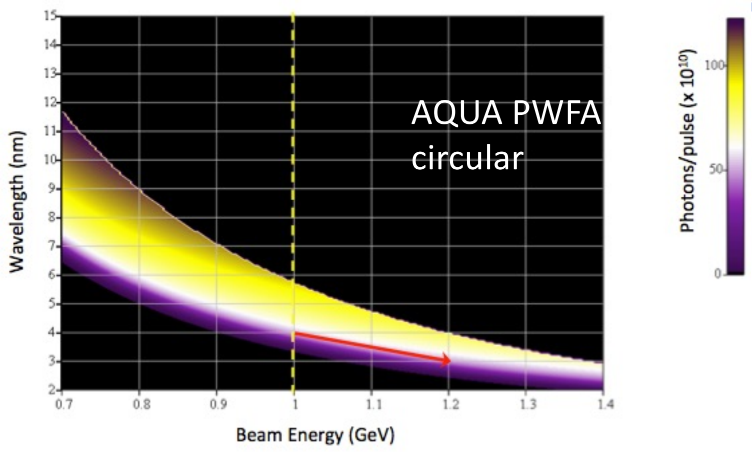
Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10 ^{11} photons/pulse needed

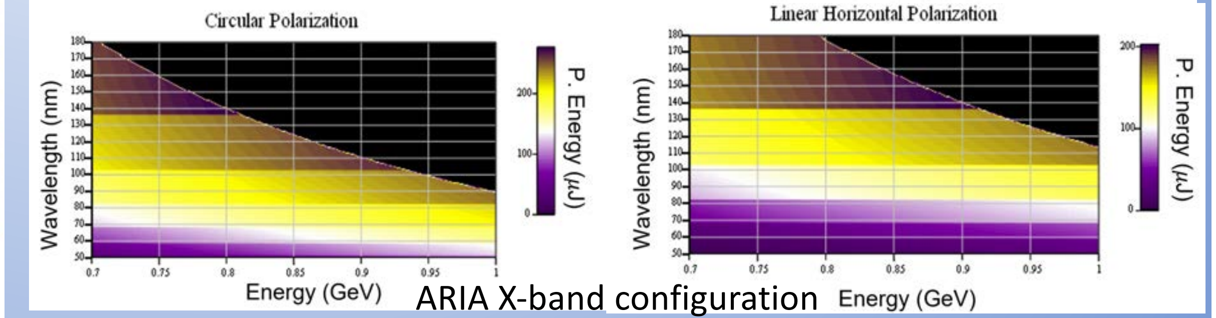
Courtesy F. Stellato, UniToV

Courtesy C. Vaccarezza/L. Giannessi

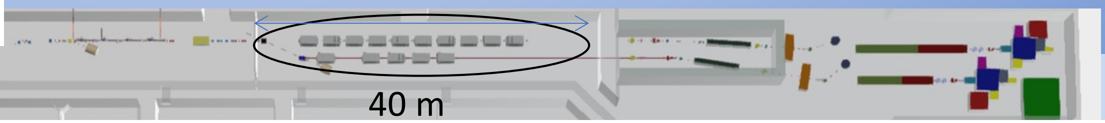
Expected FEL radiation at undulators end

Parameter	Unit	AQUA PWFA	AQUA X-band	ARIA PWFA	ARIA X-band
Radiation Wavelength	*nm* *eV*	3-10 415-120	4-10 310-120	50-150 25-8	50-150 25-8
Photons per Pulse	$\times 10^{12}$	0.25-1	0.25-1	10-60	12-150
Photon Bandwith	*%*	0.3	0.3	0.05	3
Configuration		SASE		HGHG seeding	



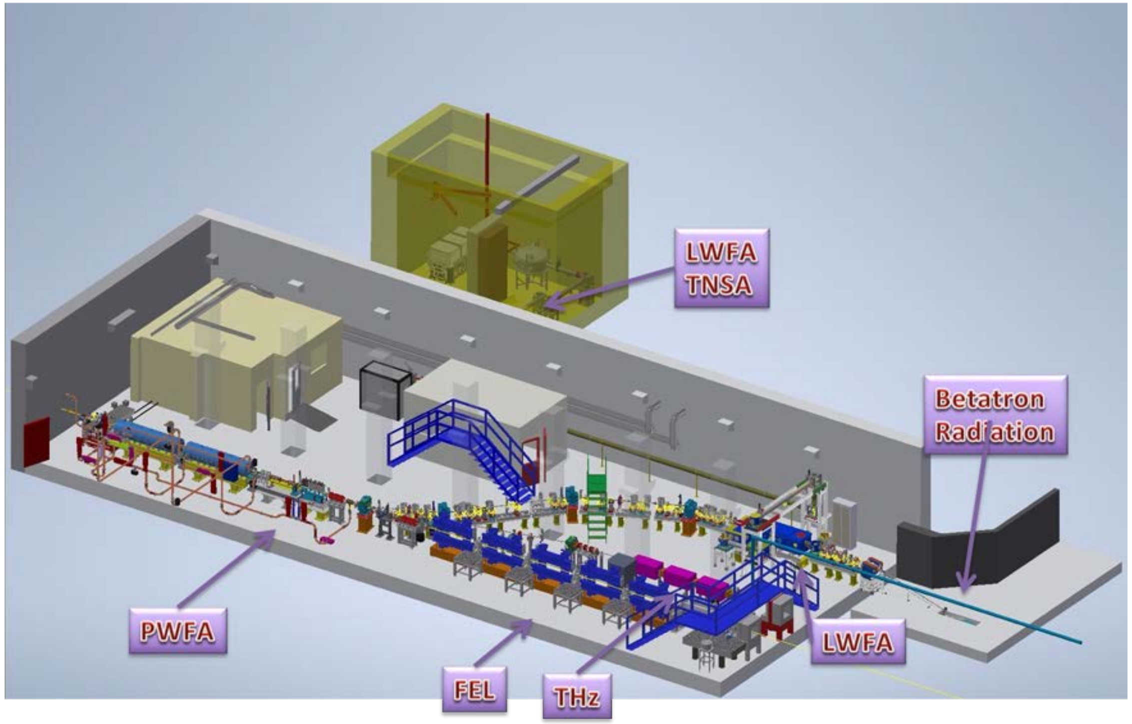


ARIA X-band configuration



SPARC_LAB Facility at LNF

SPARC_LAB is the test and training facility at LNF for Advanced Accelerator R&D



M. Ferrario et al. SPARC_LAB present and future. Nucl. Instrum. Methods B 309, 183– 188, (2013).

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NextGenerationEU

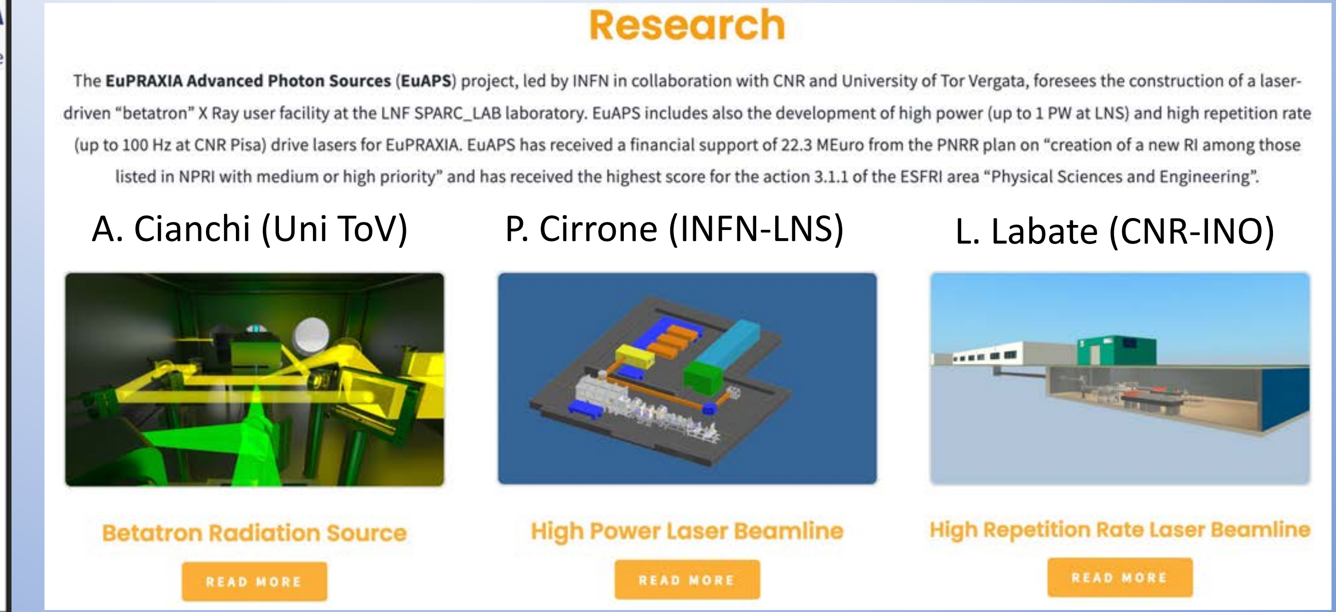
Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

EuPRAXIA Advanced Photon Sources

EuAPS: EuPRAXIA Advance Photon Sources

- Principal Investigator: M. Ferrario,
- Infrastructure Manager: C. Bortolin,
- Management and Dissemination: A. Falone



Research

The **EuPRAXIA Advanced Photon Sources** (**EuAPS**) project, led by INFN in collaboration with CNR and University of Tor Vergata, foresees the construction of a laser-driven "betatron" X Ray user facility at the LNF SPARC_LAB laboratory. EuAPS includes also the development of high power (up to 1 PW at LNS) and high repetition rate (up to 100 Hz at CNR Pisa) drive lasers for EuPRAXIA. EuAPS has received a financial support of 22.3 MEuro from the PNRR plan on "creation of a new RI among those listed in NPRI with medium or high priority" and has received the highest score for the action 3.1.1 of the ESFRI area "Physical Sciences and Engineering".

A. Cianchi (Uni ToV)

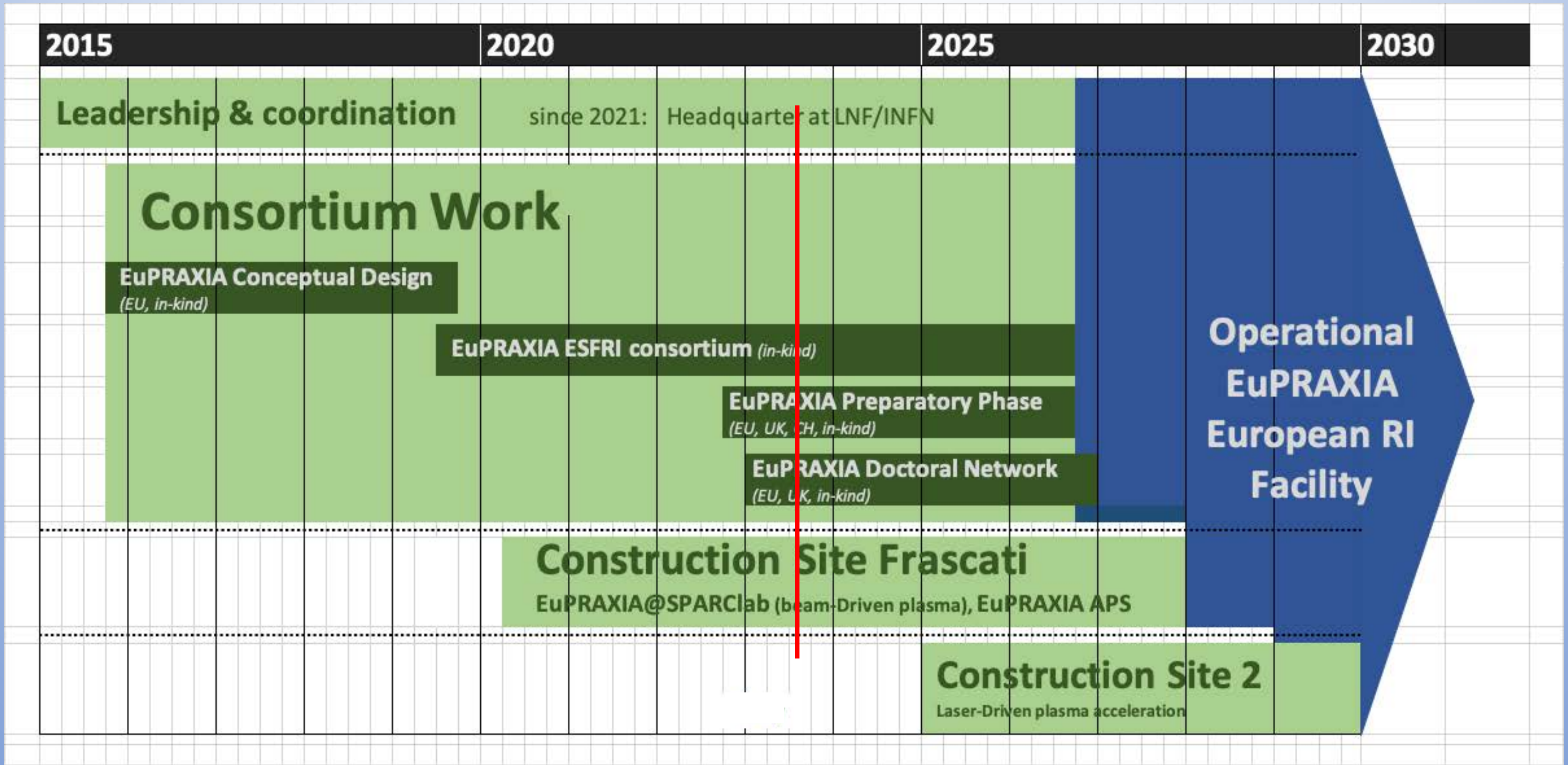
P. Cirrone (INFN-LNS)

L. Labate (CNR-INO)

M. Ferrario et al. INFN-23-12-LNF (2023)

EuPRAXIA Project Timeline

Funded by the European Union



2015 | 2020 | 2025 | 2030

Leadership & coordination since 2021: Headquarter at LNF/INFN

Consortium Work

EuPRAXIA Conceptual Design *(EU, in-kind)*

EuPRAXIA ESFRI consortium *(in-kind)*

EuPRAXIA Preparatory Phase *(EU, UK, CH, in-kind)*

EuPRAXIA Doctoral Network *(EU, UK, in-kind)*

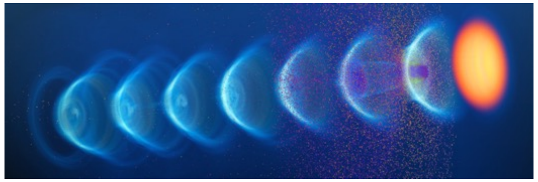
Construction Site Frascati
EuPRAXIA@SPARClab (beam-Driven plasma), EuPRAXIA APS

Construction Site 2
Laser-Driven plasma acceleration

Operational EuPRAXIA European RI Facility

Courtesy A. Falone

Conclusions & Acknowledgements



- EuPRAXIA is the **first ever plasma accelerator project with a CDR** and **first ever plasma accelerator project on the ESFRI roadmap**.
- **EuPRAXIA-PP project** will establish a **fully European project**, with European shareholders.
- Highly attractive for funding: **160 M€ secured**, > 25% of full implementation.
- Frascati construction project EuPRAXIA@SPARC_LAB making strong progress.
- Aim at making EuPPRAXIA an **example of European innovation:** new science to new applications and **new areas** while advancing towards Particle Physics.
- **Greatly appreciate slides from and discussions with: Ralph Assmann**, Enrica Chiadroni, Cristina Vaccarezza, Andrea Ghigo, David Alesini, Riccardo Pompili, Antonio Falone, Alessandro Cianchi, Luca Giannessi, Alessandro Gallo, Francesco Stellato, Leo Gizzi, Giancarlo Gatti, Molodozhentsev Alexander, Rajeev Pattathil AND THE ENTIRE EUPRAXIA@SPARC_LAB TEAM

Thank for your attention