EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

Status of EuPRAXIA

A plasma acceleration-based user facility

P. Campana (INFN-LNF)

ALEGRO 2025, SLAC, March 5th 2025

Funded by
the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from UK and Switzerland.

A New European High-Tech User Facility

Funded by the European Union

EuPRAXIA is the first European Research Infrastructure dedicated to particle accelerator R&D **based on novel plasma acceleration** concepts, **driven by innovative laser and linac technologies**

1

Building a FEL facility with very high field plasma accelerators, beam- or laser-driven (1 – 100 GV/m)

Shrink down the facility size
Improve Sustainability

Technology case

2

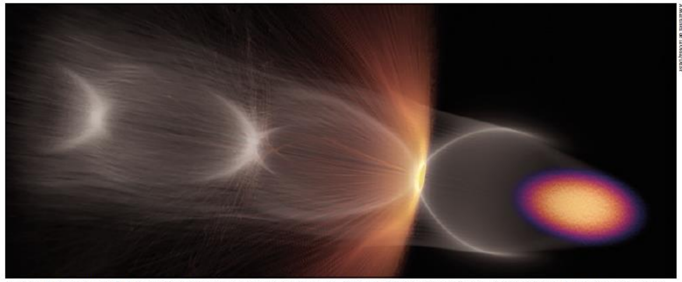
Producing particles and photons to support several urgent and timely science cases

Drive short wavelength FEL
Pave the way for future Linear Colliders

Science case

ESFRI has included EuPRAXIA in the 2021 Roadmap of EU Research Infrastructures: 10 year time to implement the facility (ready by ~ 2032)

FEATURE EuPRAXIA



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

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

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

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

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

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

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

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

EuPRAXIA storyboard

Funded by the European Union

EuPRAXIA EU Design Study 2015-19

ESFRI Roadmap approved VI.2021

EuPRAXIA_PP & DN EU grants XI.2022 → X.2026

PACRI EU grant III.2025 → II.2029

EuPRAXIA Consortium ESFRI RM submission IX.2020

ESFRI Preparatory Phase 2021→2026

ESFRI pre-implementation Phase 2026→2031

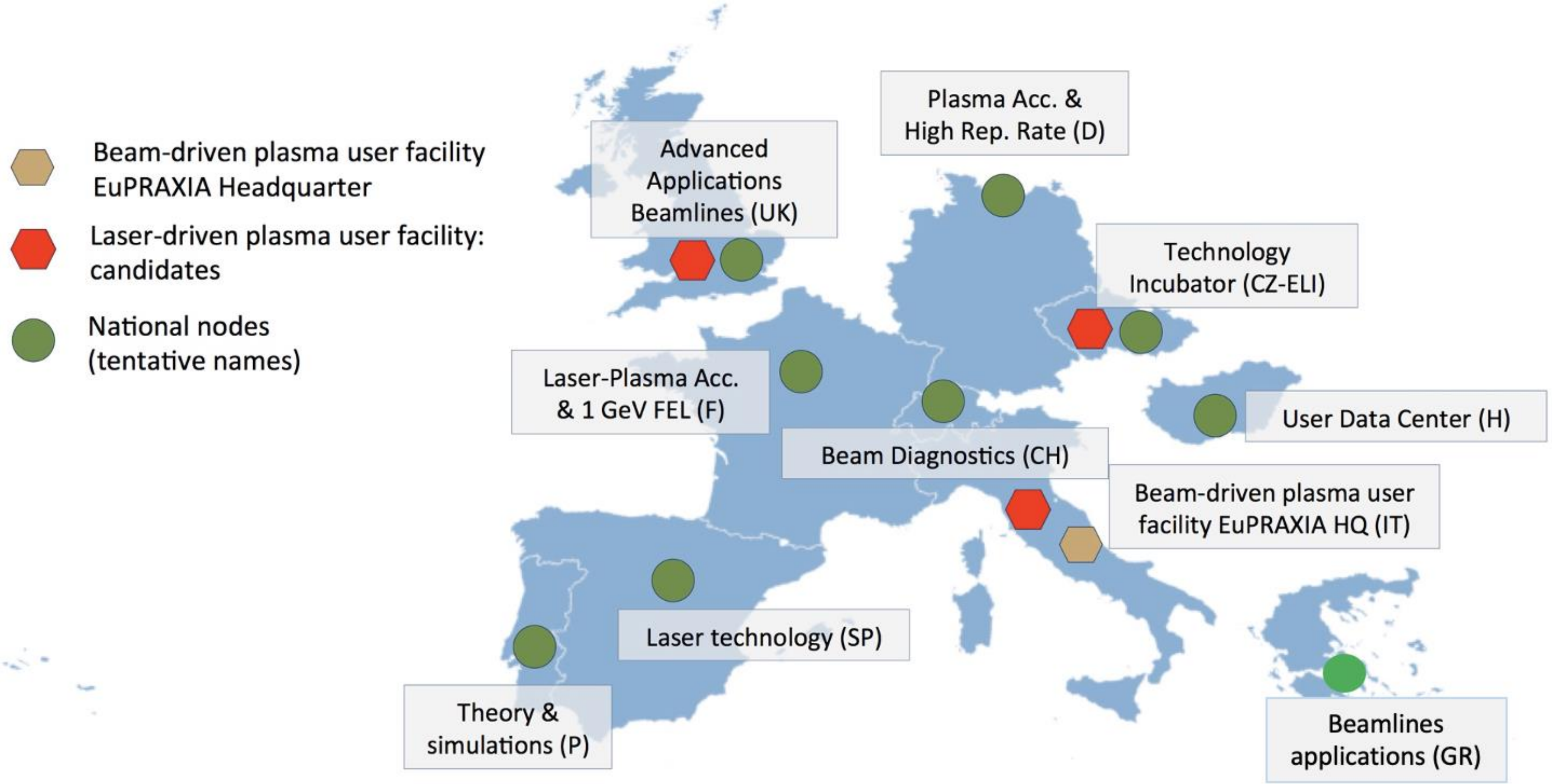
TO BE CONFIRMED

Original design (*R. Assmann et al.*): make EuPRAXIA similar to a HEP-style collaboration, able to setup and manage a Large European Network on Advanced Particle Acceleration Technologies (plasma et al.), on lasers, and on their academic, industrial and societal applications.
Based on two FEL user facilities (PWFA and LWFA), and several clusters, *valueing in-kind and cash national contributions*. ESFRI Roadmap provides opportunity to access national and EU-based calls for funds.

This design is being throughly pursued from the Design Phase (2015) to the current Preparatory Phase.

EuPRAXIA Consortium Networking

Funded by the European Union



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

Network organization:
- **2 Sites (PWFA/LWFA)**
- **National nodes**
- **Technology clusters**

3 candidates for LWFA:
- CNR-INO, Pisa
- ELI ERIC, Prague
- EPAC-RAL, UK

EuPRAXIA Preparatory Phase

- The EuPRAXIA Consortium Hub is located in Frascati (INFN), which is also PWFA site
- The LFWA site is under evaluation
- National nodes and technology clusters will support sites and R&D across the network

EuPRAXIA_PP Consortium & ancillary EU programs

Funded by the European Union

28 EU institutions, beneficiaries (3.7 M€)
10 ass. partners (CH & UK, w/matching funds**)**
8 Observers

Industrial companies involved

ANCILLARY SUPPORTING PROGRAMS

- EuPRAXIA Doctoral Network 3.1 M€

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement no. 101073480 and the UKRI guarantee fur

- EuAPS 22 M€

R&D on betatron plasma sources, based on IT Next-Gen. EU Recovery Funds (INFN, CNR, Rome TV Univ.)

- PACRI EU Horizon EU Grant 11 M€

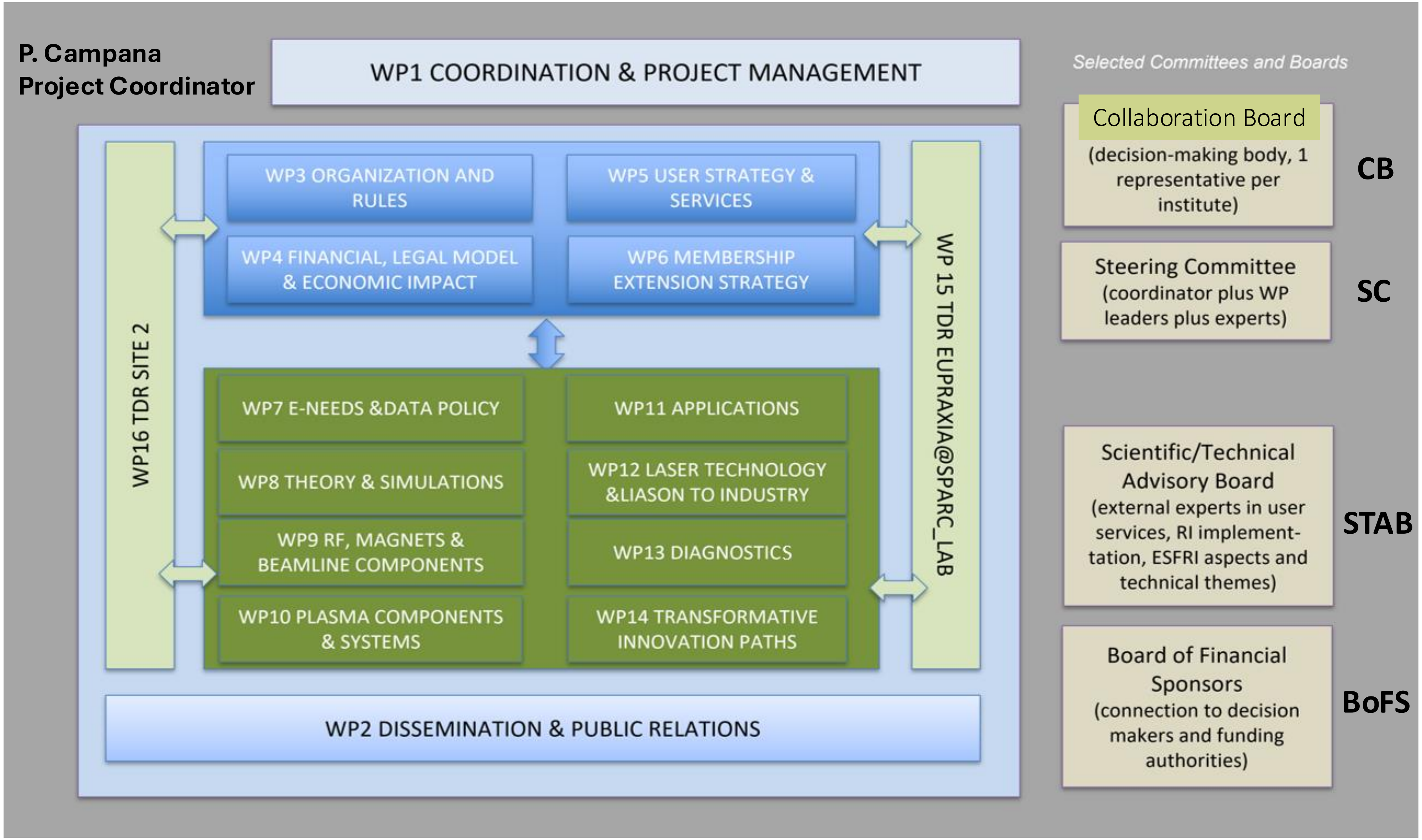
Program to develop plasma based sources (achieved thanks to EuPRAXIA framework). Starting March 2025

EMPA*	CH
EPFL*	CH
PSI*	CH
DESY	DE
FBH Berlin	DE
FHG-ILT Aachen	DE
FZ Julich	DE
HZ Dresden	DE
LMU Muenchen	DE
HHU Dusseldorf	DE
GSI-FAIR Darmstadt	DE
ELI Beamline ERIC	CZ
CEA	FR
CNRS	FR
THALES	FR
AMPLITUDE	FR
IASA Athens	GR
WIGNER	HUN
Uni. Szeged	HUN
Uni. Pecs	HUN

CERN	INT. ORG.
H. Univ. Jerusalem	ISR
CNR	IT
ELETTRA Trieste	IT
ENEA Frascati	IT
INFN	IT
U. Roma Sapienza	IT
U. Roma Tor Vergata	IT
IST Lisbon	P
ALBA Cells	SP
CLPU Salamanca	SP
IC London*	UK
QU Belfast*	UK
STFC*	UK
U. Liverpool*	UK
U. Oxford*	UK
U. Strathclyde*	UK
UCLA*	US

* associate partners

EuPRAXIA PP governance structure

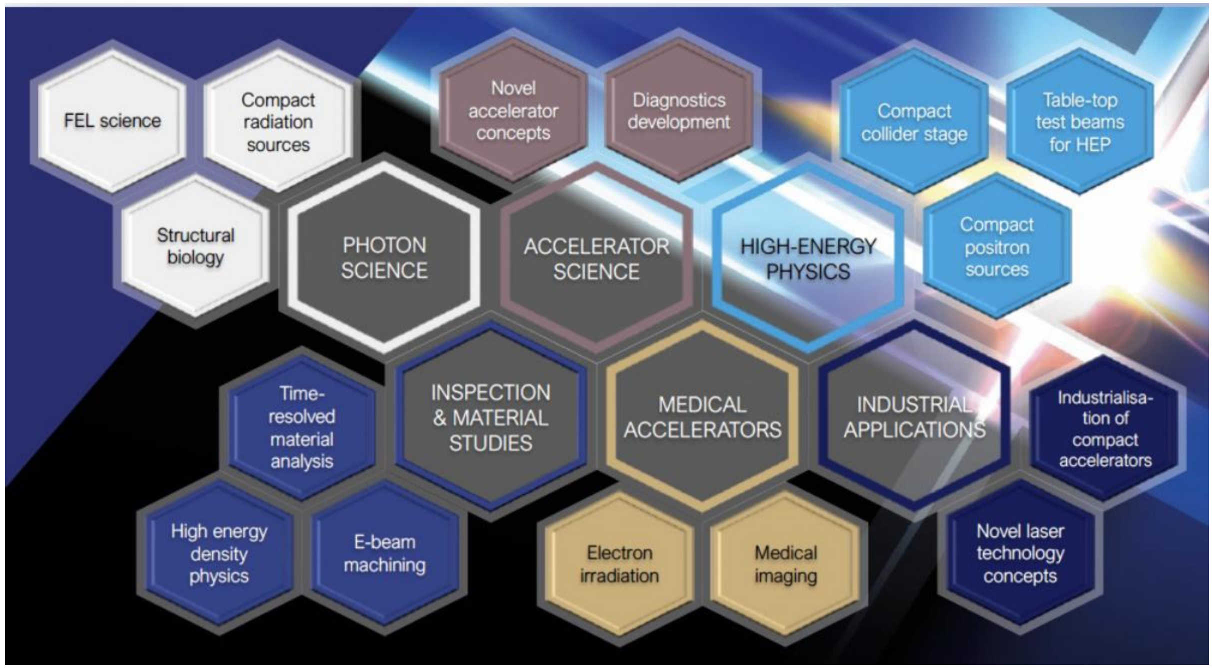


R&D of critical components / Implementation

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})

Application platform of plasma accelerators



Implementation strategy at EuPRAXIA sites

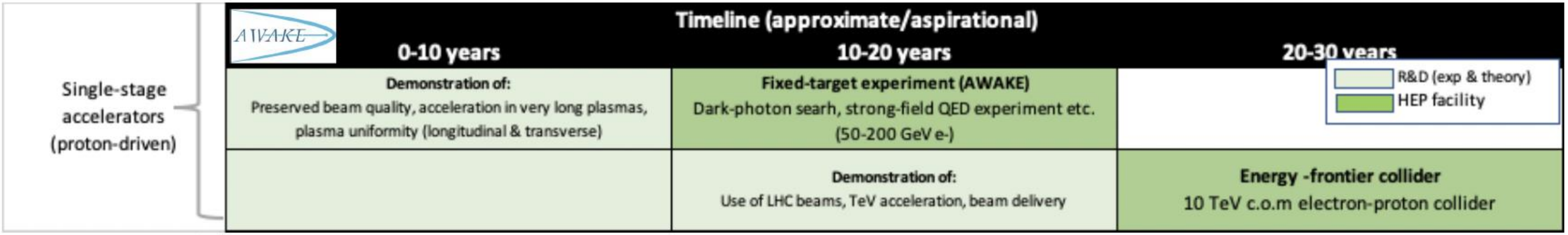
NEXT 10 Y

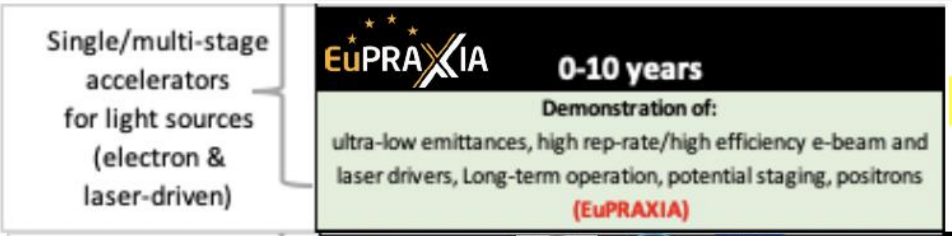
	Laser-driven	Beam-driven
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ Ultracompact positron source beamline + positron user area	✓ FEL beamline to 1 GeV + user area 1 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ X-ray imaging beamline + user area ✓ Table-top test beams user area ✓ FEL user area 2 ✓ FEL to 5 GeV	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ High-field physics beamline / user area ✓ Other future developments	✓ Medical imaging beamline / user area ✓ Other future developments

ESPP 2020 Strategy & EuPRAXIA

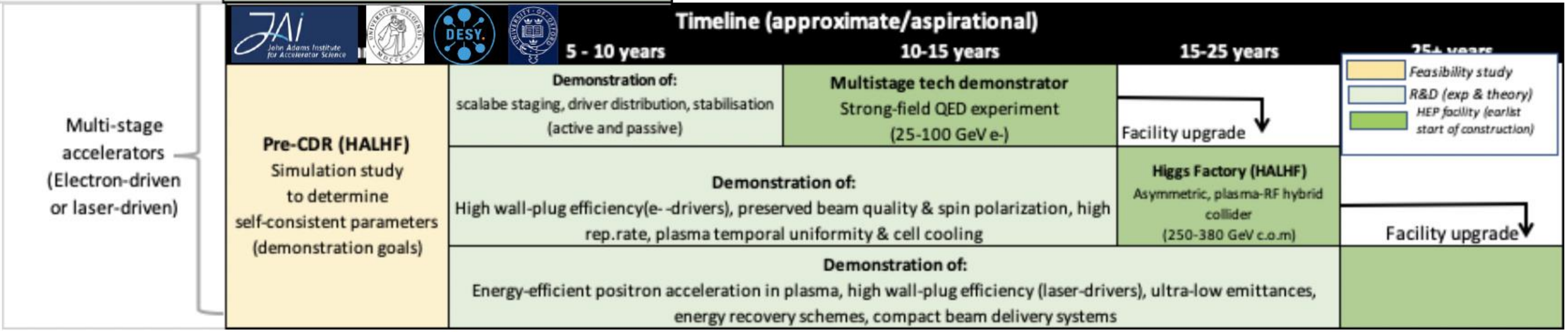
EuPRAXIA

Funded by the European Union





EuPRAXIA Paves the way to LC:
R&D on critical Components, High Rep. Rate,
Training, Shorter time perspective, Motivations,
Financial Support already on common interest components



Update on ESPP Roadmap – EAAC 2003 - Wim Leemans & Rajeev Pattathil

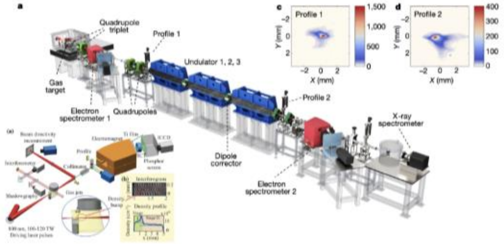
This role will be updated in the ESPP 2026 Strategy

Basic beam quality achieved in pilot FEL experiments

Funded by the European Union

Plasma FEL laser driven: feasibility proven

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)

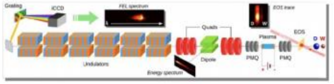
2021 Plasma FEL Feasibility Proven: Electron-driven

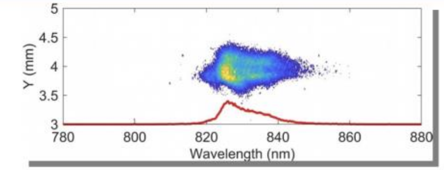
Horizon Europe

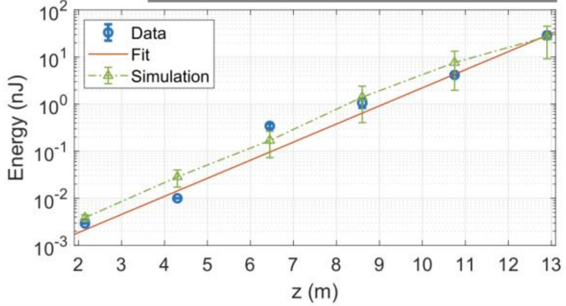
Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

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







Seeded UV-FEL laser driven

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

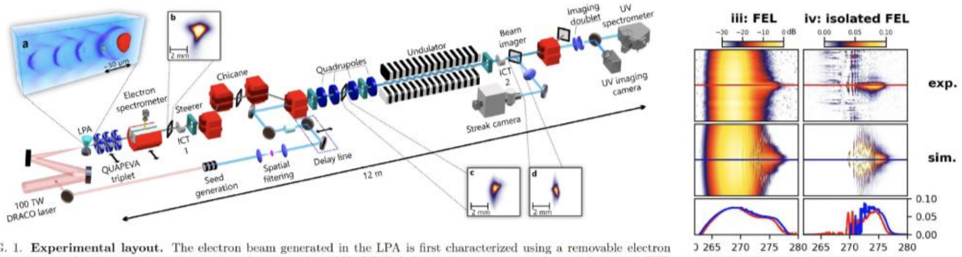
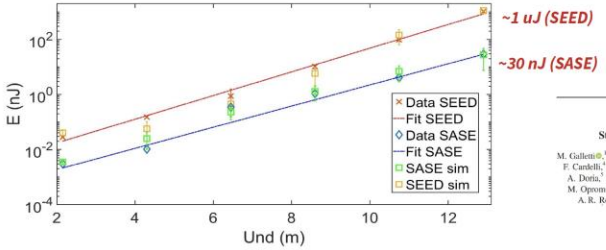
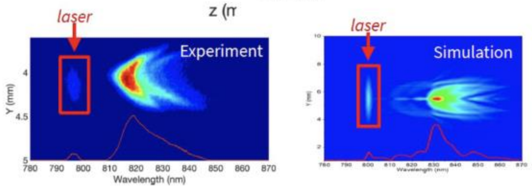


FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled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

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





PHYSICAL REVIEW LETTERS 129, 234801 (2022)

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

M. Galletti, D. Alesini, M. P. Anania, S. Arjmand, M. Behtouei, M. Bellaveglia, A. Biagioni, B. Buonomo, F. Cardelli, M. Carpanese, E. Chiadroni, A. Cianchi, G. Costa, A. Del Dotto, M. Del Giorno, F. Dipace, A. Doria, F. Filippi, G. Franzini, L. Giannessi, A. Giribono, P. Iovine, V. Lollo, A. Mostacci, F. Nguyen, M. Opromolla, L. Pellegrino, A. Petralia, V. Petrillo, L. Piersanti, G. Di Pirro, R. Pompili, S. Romeo, A. R. Rossi, A. Selce, V. Shpakov, A. Stella, C. Vaccarezza, F. Villa, A. Zigler and M. Ferrario

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

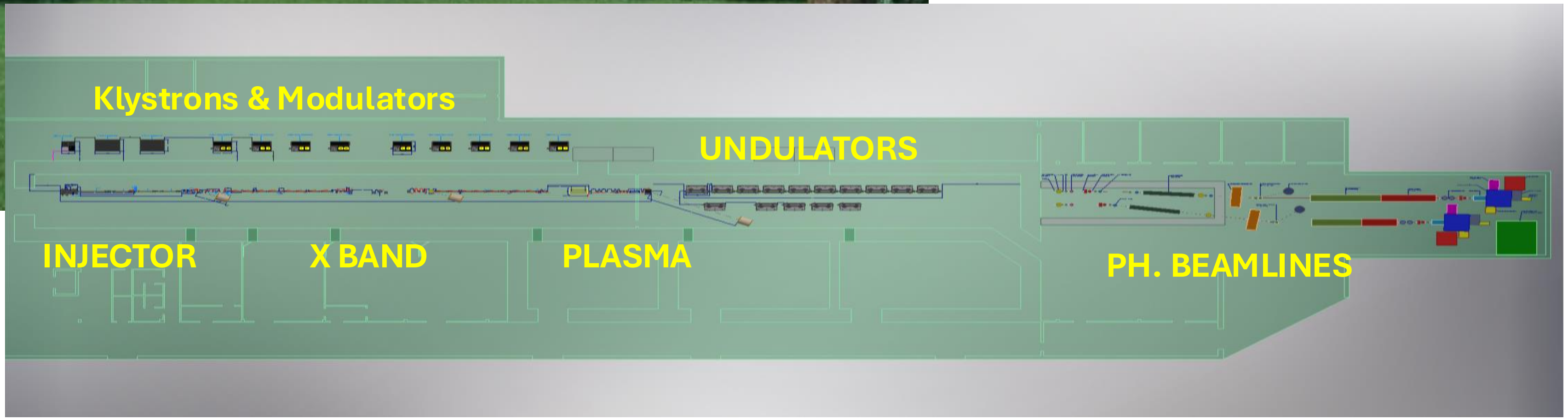
.. a lot of efforts and R&D needed to move from pilot experiments to real facilities (for HEP or FEL) ...

PWFA site (LNF): EuPRAXIA@SPARC_LAB

Funded by the European Union

BUILDING RENDERING
CONSTRUCTION STARTS 09.26

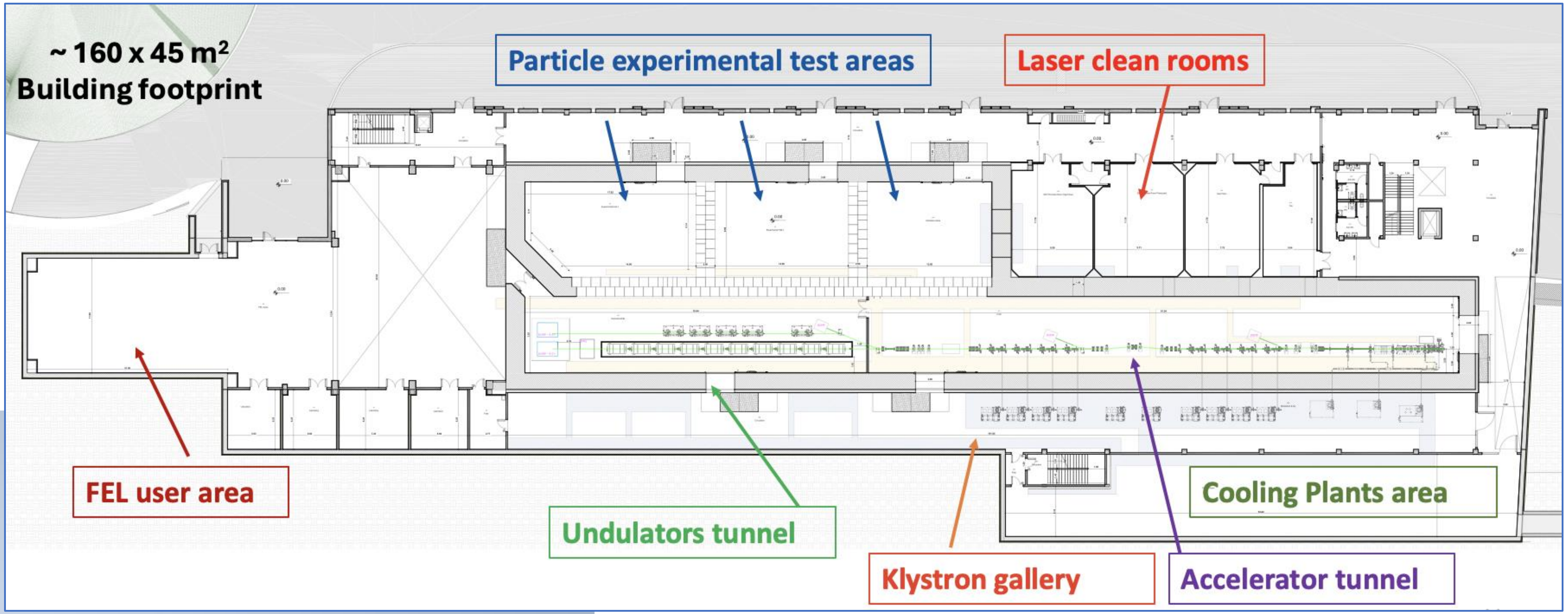
- EuPRAXIA HQ of ESFRI RI
- INFN Frascati future facility,
  fully funded (~ 120 ME)
- Beam-driven plasma acceleration
  1 GeV FEL, 4nm
- A compact 1 GeV RF accelerator
  (X-band, in collaboration with
  CERN, 60-100 MV/m)

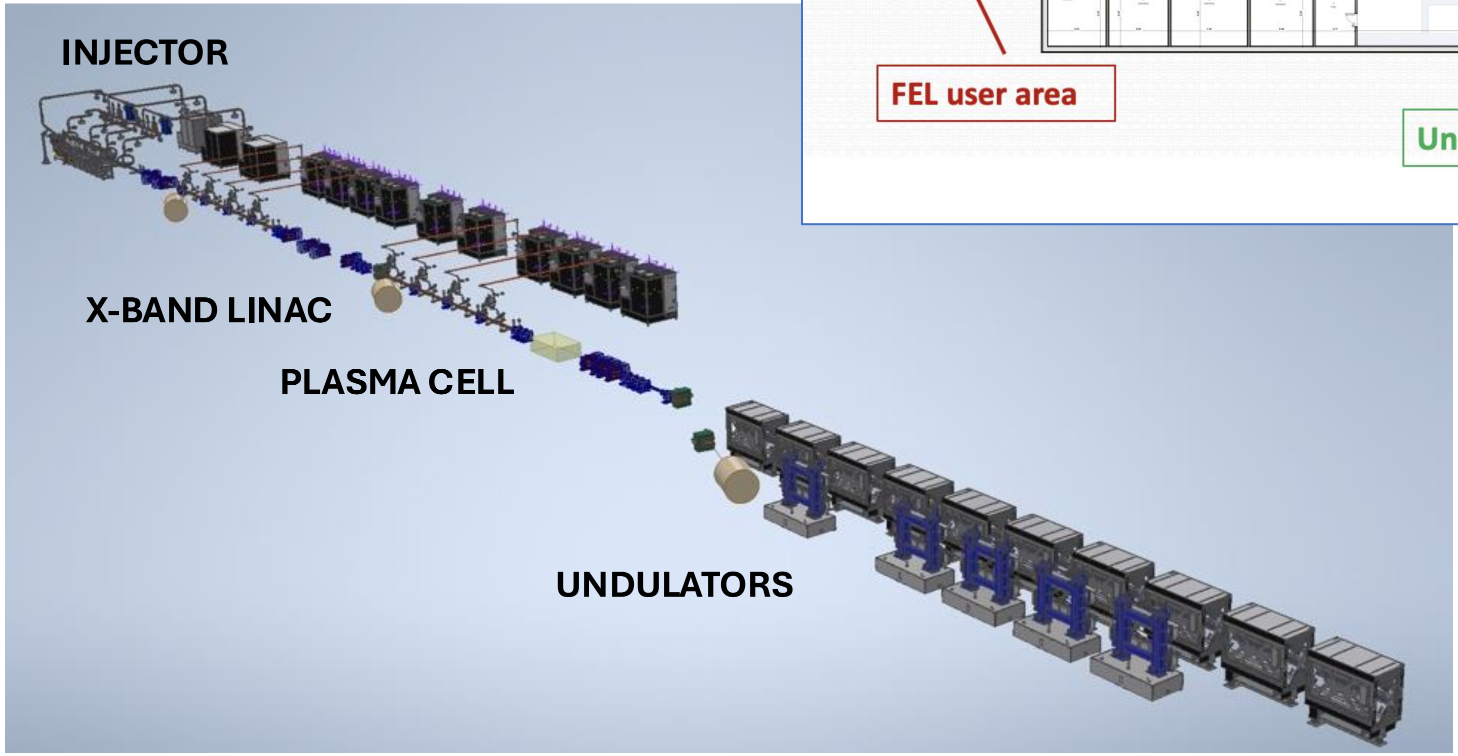


EuPRAXIA@SPARC_LAB layout

Funded by the European Union

- Layout completed: TDR to be submitted to International Review Committee by June 2025.
- Expected to be ready for procurements by early 2026.
- Commissioning in 2029

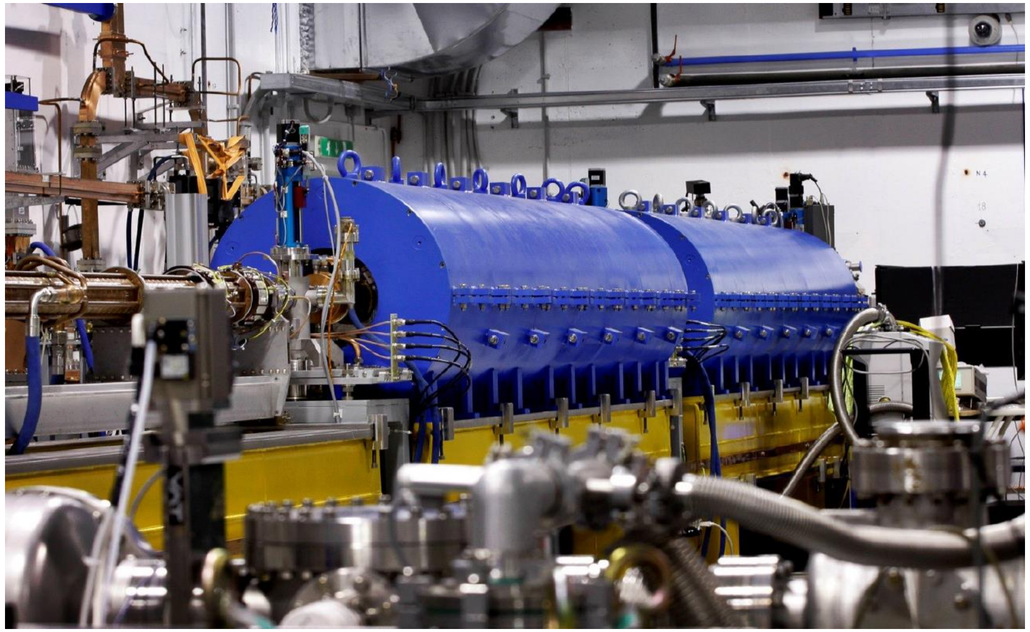


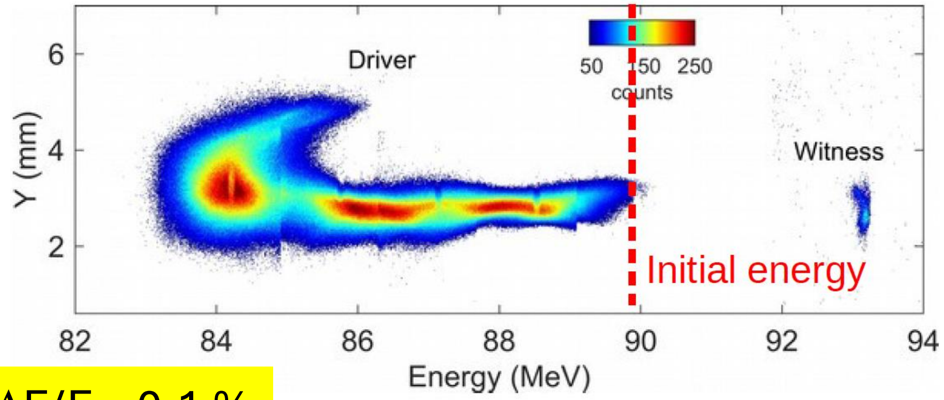


SPARC_LAB, a test facility for EuPRAXIA

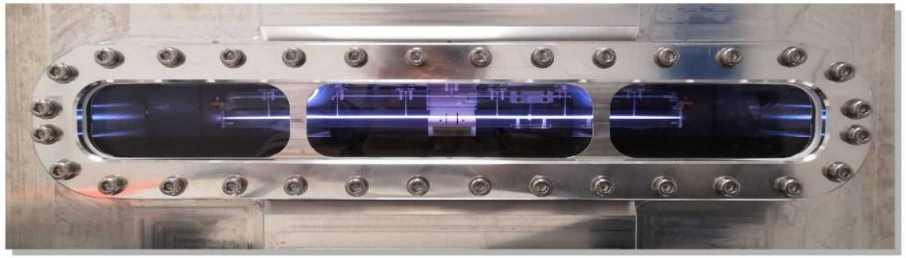
Funded by the European Union

The SPARC_LAB Linac (~ 150 MeV) is a test facility where R&D for the CRITICAL elements of EuPRAXIA can be tested:
- high brightness electron S-band injector;
- velocity bunching techniques;
- plasma modules (L, material, resilience);
- experimental test of complete S2E simulations;
- beam manipulation through plasma lenses;
- lasing through undulators;
- beam monitoring diagnostics;
- low-level RF synchronization techniques;
- R&D on Apple X & SC undulators.

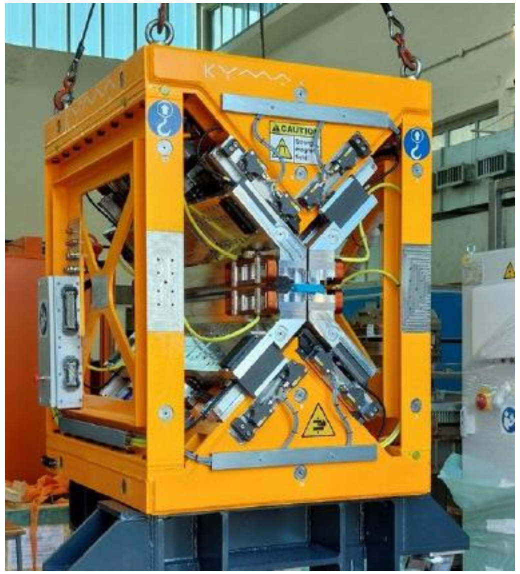




$\Delta E/E \sim 0.1$ %



40 cm long capillary → 1st prototype for the EuPRAXIA facility
- *Made with special junction to allow negligible gas leaks (<10^{-10} mbar)*
- *Next step is to extend its length to 60 cm as required by last studies*

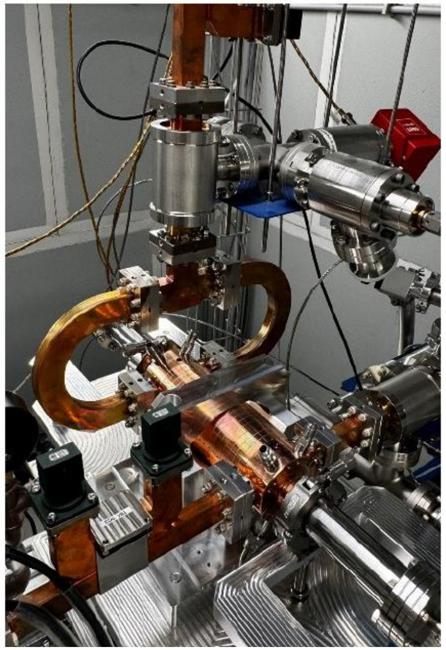


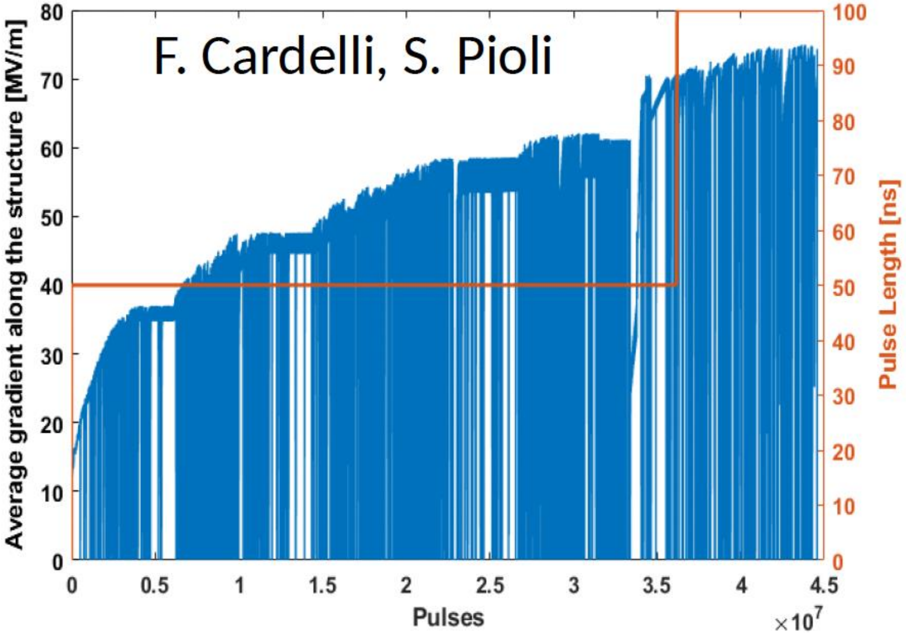
EuPRAXIA

TEX, a test facility for X-band

Funded by the European Union

- A dedicated LAB (TEX) is hosting C- and X- band testing facility (in collaboration with CERN CLIC team)
- The 1st EuPRAXIA RF cavity prototype (L=20 cm) has been successfully tested
- Input pulse 35 MW, 100 ns, 50 Hz, provided in 10 days an average gradient of 74 MV/m (80 MV/m peak)
- Final X-band RF module, L=1 m, under test in few months





Control Room

LLRF system

RF Source

VKX8311A Klystron

PWFA site: EuPRAXIA goal parameters

Funded by the European Union

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

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

Values obtained with full S2E simulation

Velocity bunching 200+30 pC case fully exploited
400+50 pC case studies on-going
Full X-band still to be studied
Implementing strategies to reduce E jitter of witness

Experimental driver-witness Temporal jitter < 5 fs from SPARC_LAB, reflects on ≈ 1% for the PWFA setup

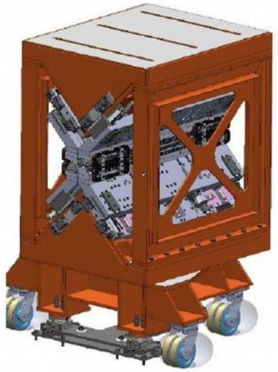
A. Giribono, C. Vaccarezza

PWFA site: FEL beam lines & scientific case

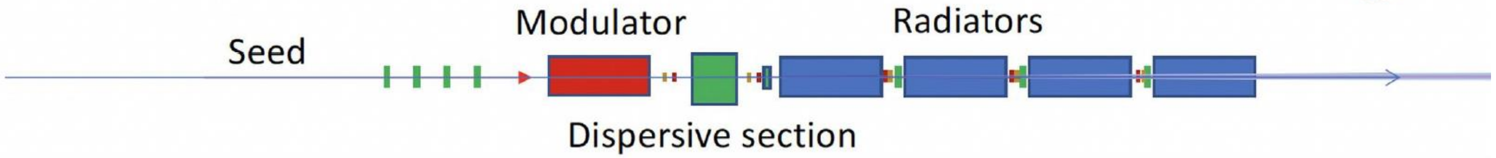
Funded by the European Union

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 50-150 nm

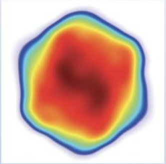


SEEDED FEL : Modulator 3 m + 4 Radiators – variable pol. – 2 m each – Seeded in the range 290-430 nm. **Final layout still in progress**

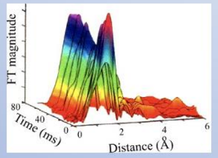
Parameter	Unit	AQUA PWFA	AQUA X-band	ARIA PWFA	ARIA X-band
Radiation Wavelength	*nm* *eV*	3-10 415-120	4-10 310-120	50-150 25-8	50-150 25-8
Photons per Pulse	$\times 10^{12}$	0.25-1	0.25-1	10-60	12-150
Photon Bandwith	%	0.3	0.3	3	0.05
Configuration		SASE		HGHG seeding	

AQUA

Coherent imaging



X-ray spectroscopy



Raman spectroscopy

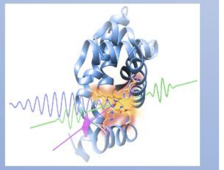
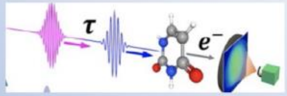


Photo-fragmentation of molecules

ARIA

Photoemission Spectroscopy



Photoelectron Circular Dichroism

Raman spectroscopy

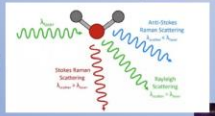
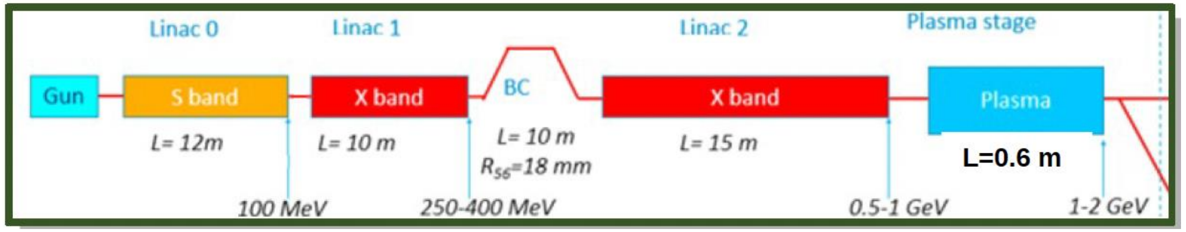
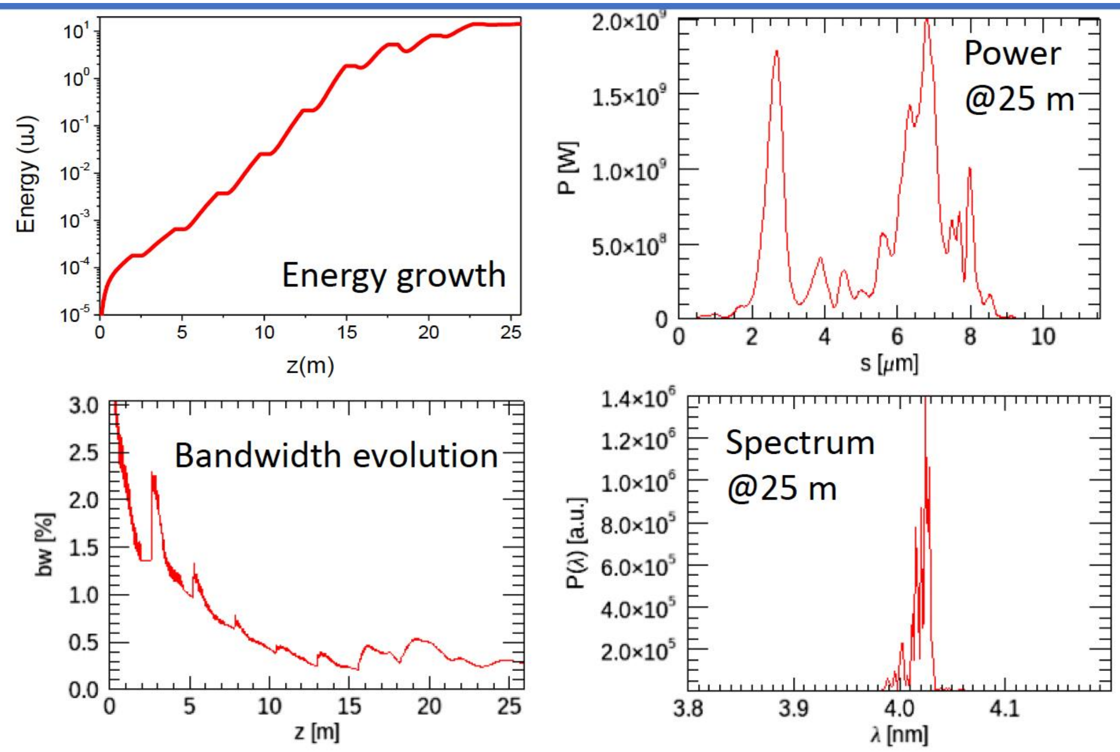


Photo-fragmentation of molecules
Time of Flight Spectroscopy

FEL matching and performances

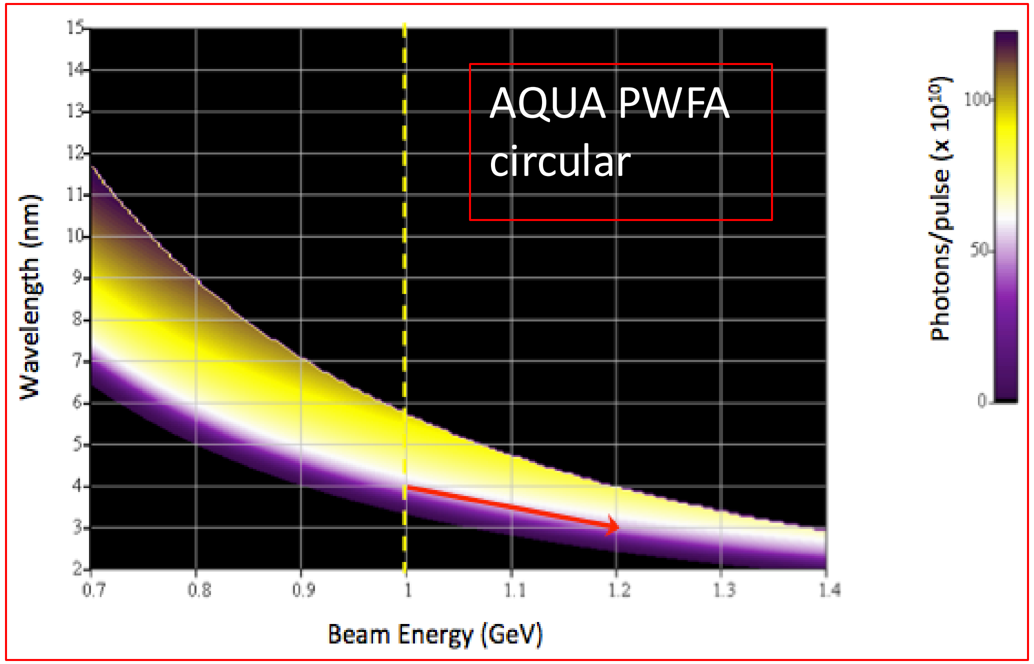


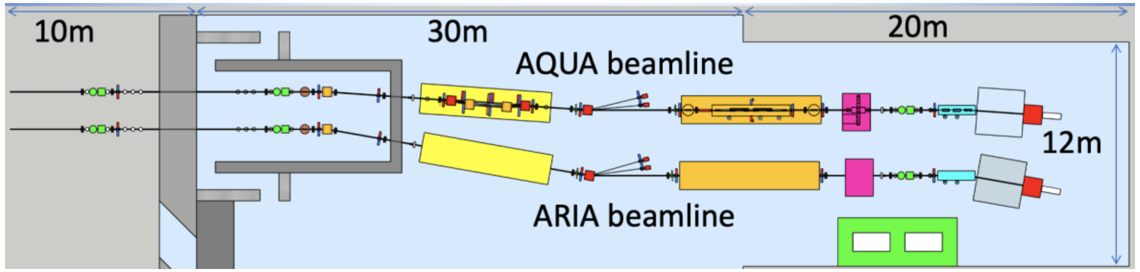
Performances



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

Analytic FEL phase space (preliminary)





User beamlines layout

Procedure for LWFA site choice (1)

- EuPRAXIA 2nd site internal panel setup.
- Preparation of template for 3 site bid-books. (informal support from respective Funding Agency expected as key element)
- Bid-books evaluation by panel (Jan-Feb).
- Ranked proposal submitted to Collaboration Board for approval

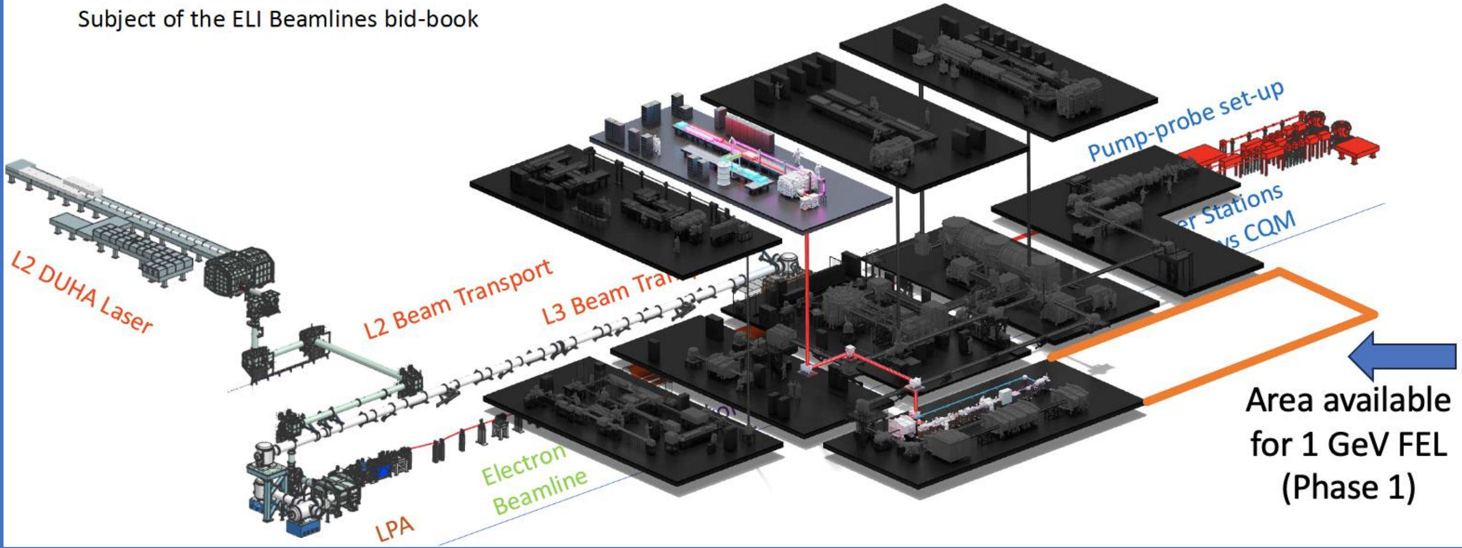
- *Existing infrastructure towards delivering the LPA-based EuPRAXIA pillar (Phase1)*
- *Technology readiness for LPA-based EuPRAXIA pillar (Phase1)*
- *Existing Safety and Control Systems*
- *Teaming and Management*
- *User-oriented operation experience*
- *Identification of pre-investment relevant for the EuPRAXIA development*
- *Identification of required funding to accomplish EuPRAXIA LPA-pillar Phase1*
- *Strategy to implement the EuPRAXIA LPA-pillar Phase-2*
- *Collaboration needed (wish-list from each candidate)*

ELI ERIC Beamlines

eli

- Institutional Capability to Host the Site
- Technical Overview of the Laser-Driven Site Proposal
- Required and Available Resources
- Project Phases and Budget Timeline
- Support from EuPRAXIA Partners
- Political Endorsement
- Alignment with EuPRAXIA Governance

Conceptual model of the EuPRAXIA Phase-1
1GeV electron LPA scheme
Subject of the ELI Beamlines bid-book



Procedure for LWFA site choice (2)

STFC EPAC
Large size infrastructure in RAL STFC campus.
EPAC operation to start in 2026, EuPRAXIA can be part of laser & plasma accelerator facility.
Strong expertise at STFC and in UK academia (lasers and accelerators)
Application-oriented programs can be of help to EuPRAXIA.
RAL, hub for UK-EuPRAXIA research groups.
STFC strategy includes LPWA, while UK qualifies again for Horizon EU funding.

CNR INO – Medium size infrastructure in Pisa, long tradition in laser technology.
Already strong engagement with ELI, EPAC and industrial partners.
Management supports a stronger link with ELI Beamline activities:
discussion ongoing to setup a National RI dedicated to R&D and industrial laser development (to become EuPRAXIA National Node)

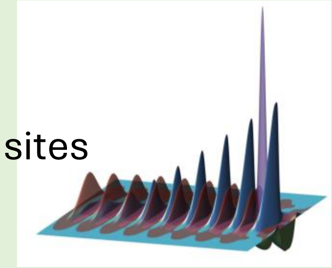
Decision on 2nd site to be taken at next EuPRAXIA Collab. Board on next March 25th

Status of EuPRAXIA national node network

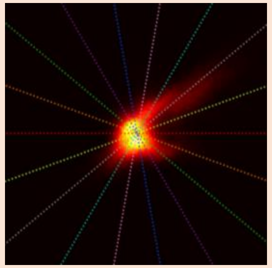
Funded by the European Union

National node activities under coalescence progress: National Roadmaps, definition of in-kind contribution, bids to Funding Agencies. **Non exhaustive examples follow:**

IST Lisbon
S2E simulation for LFWA and PWFA sites
E-needs, Open Data, FAIR, etc ...

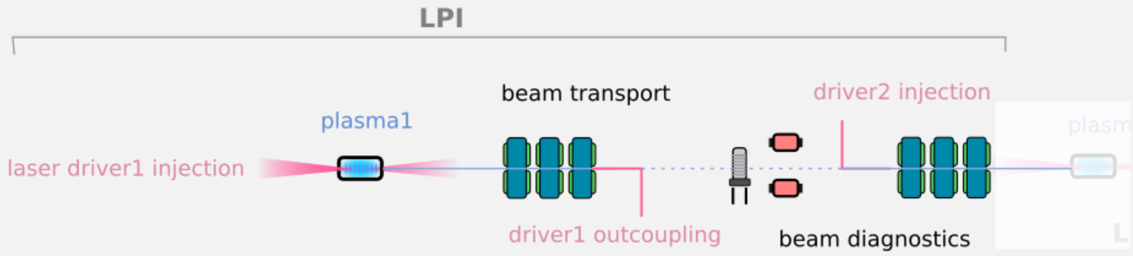


PSI - EPFL
Development of beam and photon diagnostics for PWFA & LFWA sites

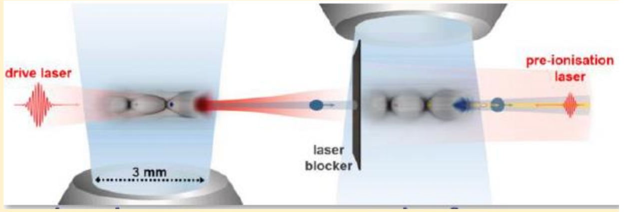


CERN
R&D on high efficiency X-band Klystrons & RF cavities

CNRS (vv. Institutes)
Preparatory design phase and future high gradient accelerator R&D at IJClab
10 Hz, 150-250MeV LPI test facility to improve **quality and stability of e- beam generated by LP accelerator**.



LMU, HZDR, HHU (and others)
Hybrid laser and particle driven wake-field acceleration (LPWFA)
Plasma photocathode injector
Plasma targetry and diagnostics



EuPRAXIA

General Ingredients of Future RI Governance

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Key inputs to the EuPRAXIA RI eco-system:

- Cooperative-oriented consortium with light legal framework (AISBL ?)
- Supported by Funding Agencies & accepted by ESFRI
- Flexible structure and based on MoUs (or Service agreements)
- Accounting in-kind contributions and fresh resources: assets remains to stakeholders
- Operating coherently as a Network of nodes + 2 sites + techological clusters
- Coordinated user access to EuPRAXIA facilities, under ESFRI regulation (OA, FAIR, etc…)
- <u>Centralized capability to participate to EU calls as “EuPRAXIA” legal entity</u>
- Operational costs: relying on host Institution (other schemes possible, although difficult)
- <u>Nodes and clusters are expected to contribute to specific technical parts of sites</u>

Summary

- EuPRAXIA is a challenging ESFRI European Research Infrastructure with several "non standards" aspects:
  - Effort to merge three very different communities: accelerators, plasma, lasers experts
  - Network with real sites, nodes and technological clusters: HEP-like collaboration guidance
  - Effort to have nodes/clusters contributing to sites
  - Un-conventional way of funding (multi-stakeholders: EU, FA, Universities, etc…), and substantial use of in-kind (HW, personnel, operation costs)
- PWFA Frascati site well advanced, resources fully pledged. Several technical challenges to obtain a FEL quality electron beam, stable over time, useful for users.
- LFWA site under selection, three strong site candidates. Decision by end of March. LFWA R&D ongoing at Labs
- In the medium term (2-3 years), EuPRAXIA should adopt a light legal framework to profit of EU calls, together with MoU to enhance operation and collaboration among sites, nodes, clusters
- By early 2030's, target of having PWFA and LFWA sites operational for users
- EuPRAXIA can be a test bed for many of the technical issues of various plasma-based projects, including future HEP Linac colliders
- **Considering the many challenges, future large size, plasma-based HEP infrastructures should follow the strategy of forming strong International Collaborations ("a la" LHC experiments)**

Funded by the European Union

EuPRAXIA

EuPRAXIA-PP Consortium

Coordinator

INFN
Istituto Nazionale di Fisica Nucleare

Consiglio Nazionale delle Ricerche

Elettra Sincrotrone Trieste

ENEA
Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

SAPIENZA
Università di Roma

Università di Roma
Tor Vergata

Imperial College London

Queen's University Belfast

UK Research and Innovation

University of Liverpool

University of Oxford

University of Strathclyde Glasgow

CERN

DESY.

FBH Leibniz Ferdinand Braun Institut

Fraunhofer ILT

GSI

hhu Heinrich Heine Universität Düsseldorf

HZDR
Helmholtz Zentrum Dresden Rossendorf

Jülich Forschungszentrum

LMU Ludwig-Maximilians-Universität München

Amplitude

cea

cnrs

THALES

eli

Técnico Lisboa

ALBA

CLPU Centro de Láseres Pulsados

Empa
Materials Science and Technology

EPFL

Paul Scherrer Institut PSI

The Hebrew University of Jerusalem

IASA

Pécsi Tudományegyetem
University of Pécs

SZTE
University of Szeged

Wigner

The University of California
UCLA