Trieste
Stazione Marittina
27 | 28 giugno 2023

Istituto Nazionale di Fisica Nucleare
Piano Triennale
2024 | 2026

INFN

EuPRAXIA
e le sue Infrastrutture

Anna Giribono, Ricercatrice INFN-LNF

A New European High-Tech User Facility

Funded by the European Union

European Plasma Research Accelerator With Excellence In Applications

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

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

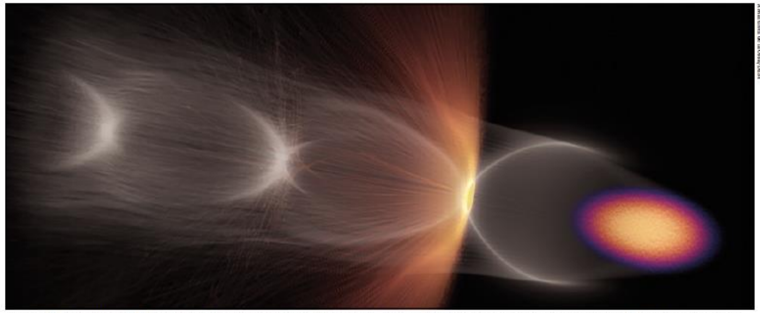
1 – 100 GV/m accelerating field

Shrink down the facility size

Provide a practical path **to more research facilities** and ultimately to **higher beam energies** for the same investment in terms of size and costs

Enable frontier science in new regions and parameter regimes

FEATURE EuPRAXIA



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

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

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

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

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

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

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

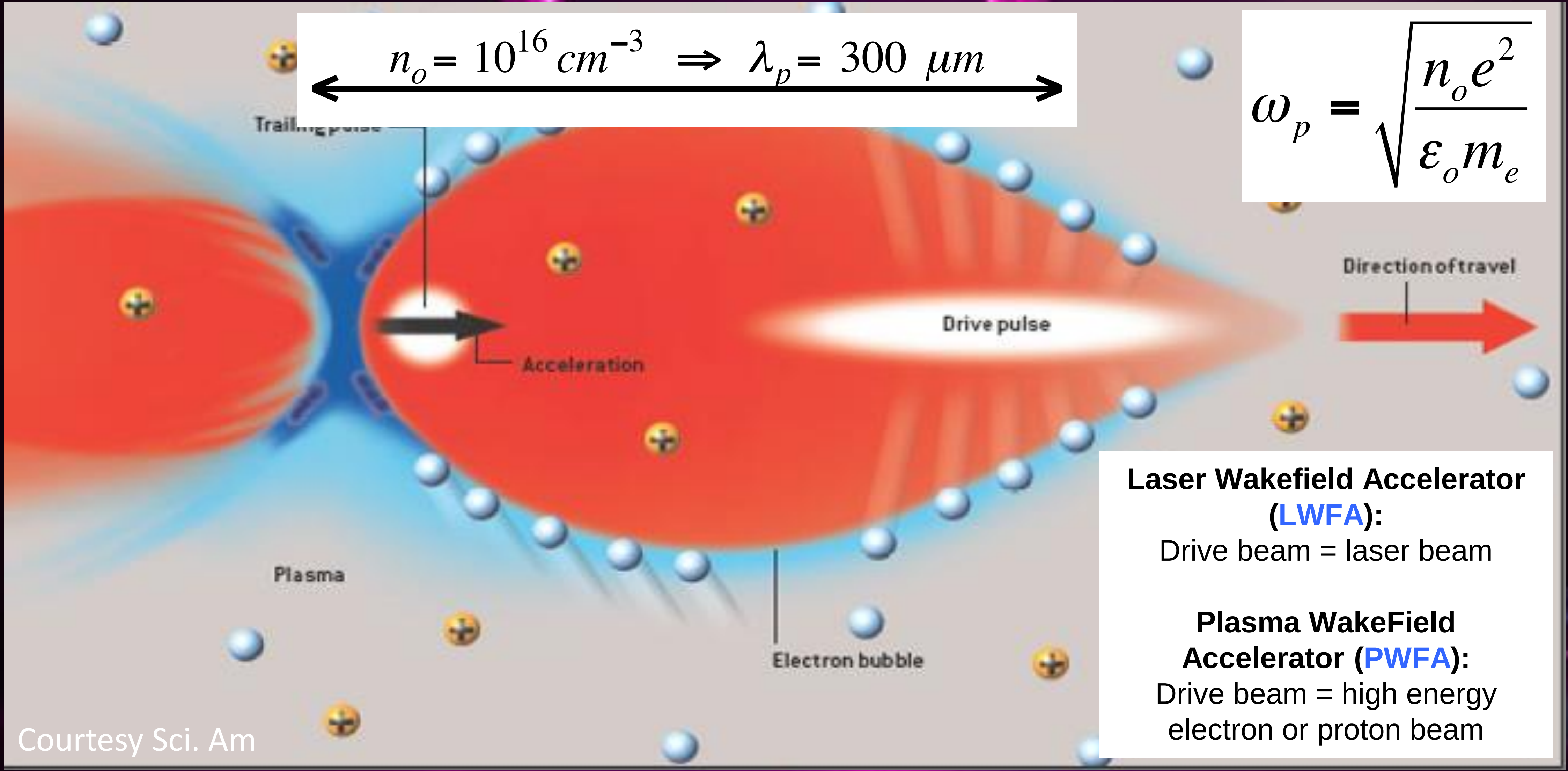
https://cerncourier.com/a/europe-targets-a-user-facility-for-plasma-acceleration/

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

Principle of plasma acceleration

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

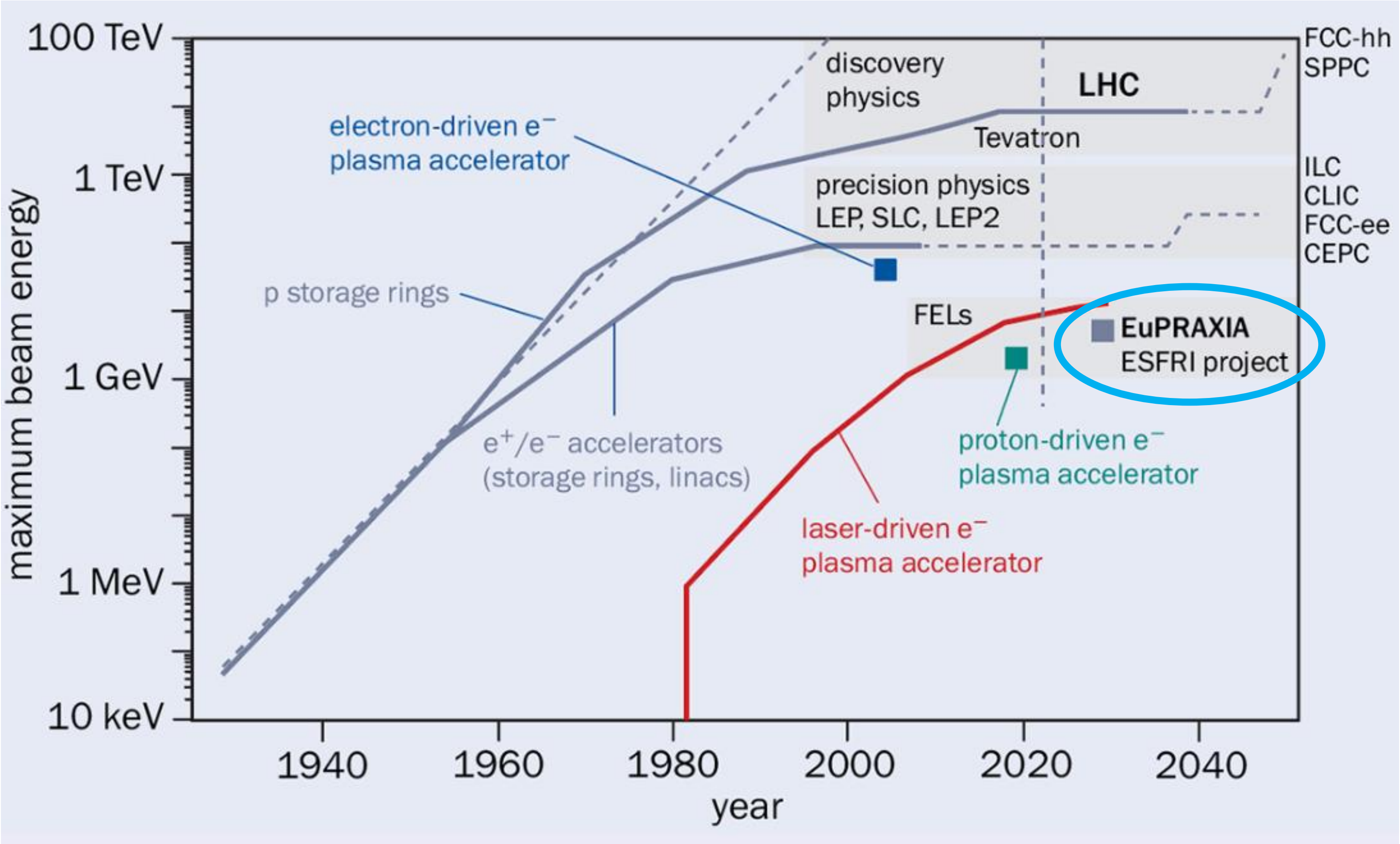
$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$



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

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

The Livingstone Diagram



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

Plasma Accelerator Achievements

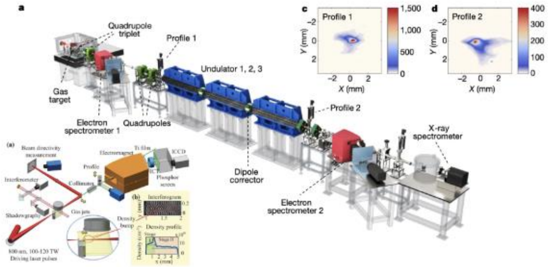
- Gradients up to **100 GV/m**
- Acceleration > 10 **GeV** of electron beams
- Basic beam **quality for FEL** demonstrated

The most demanding in terms of beam brightness, stability and control

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

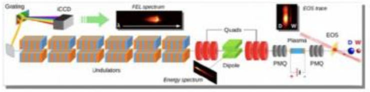
FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)

2021 Plasma FEL Feasibility Proven: Electron-driven

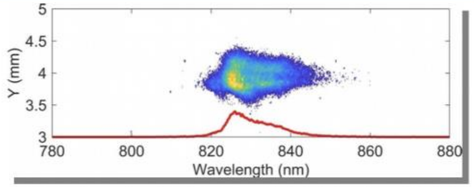
Recent ground-breaking results in Frascati:

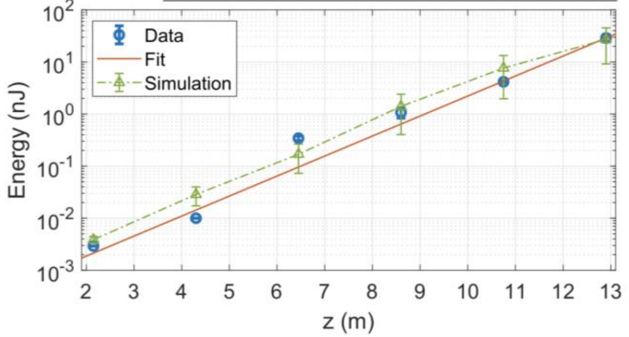
First FEL lasing from a beam-driven plasma accelerator

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



Single Spike SASE spectrum





Seeded UV free-electron laser driven by LWFA

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

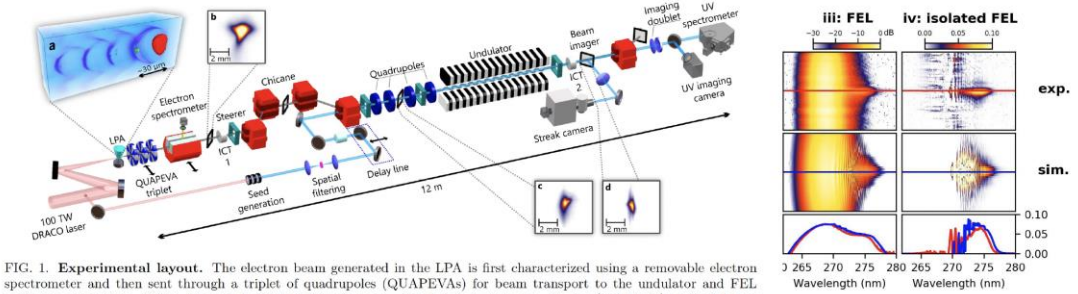
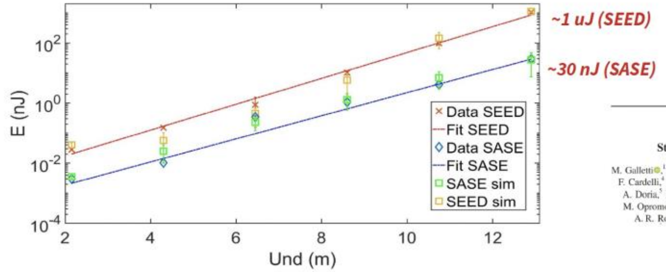


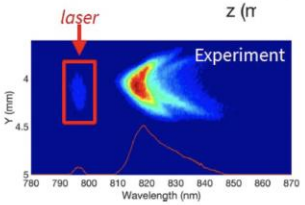
FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled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

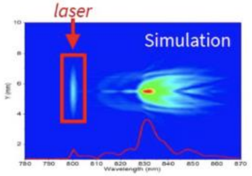
First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)



PHYSICAL REVIEW LETTERS 129, 234801 (2022)

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





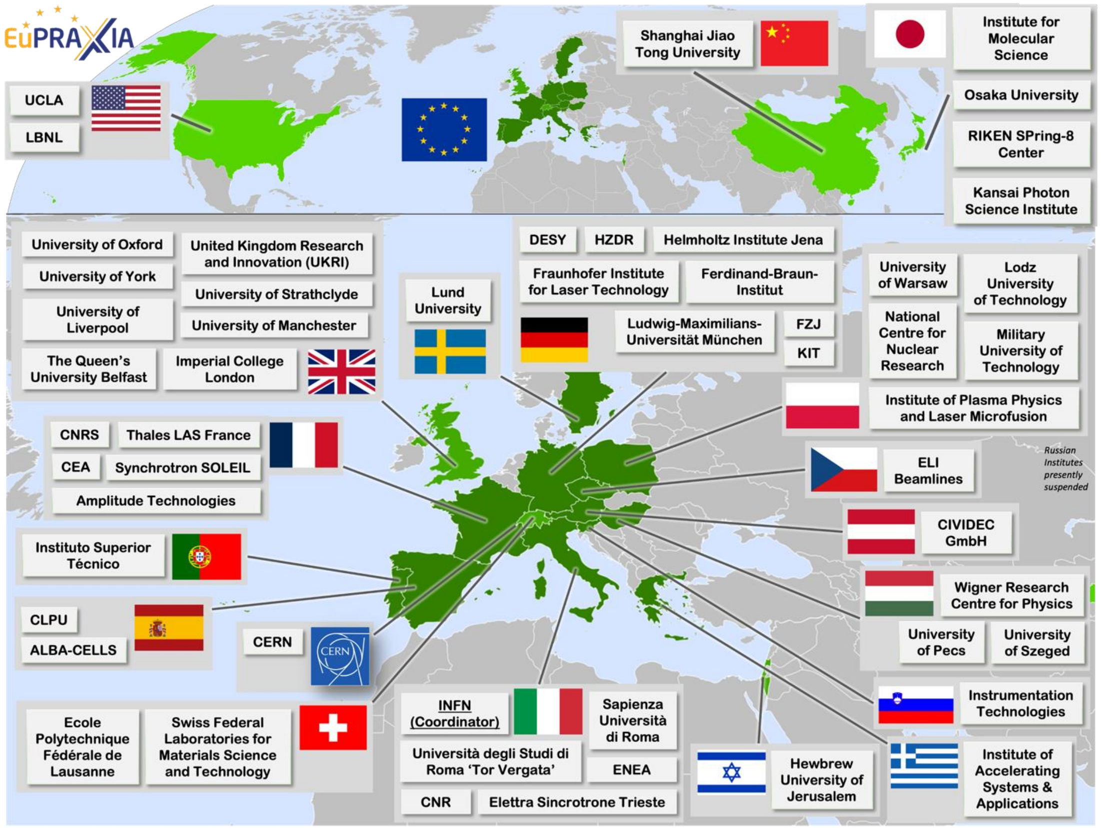
Seeded FEL radiation

- ✓ 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

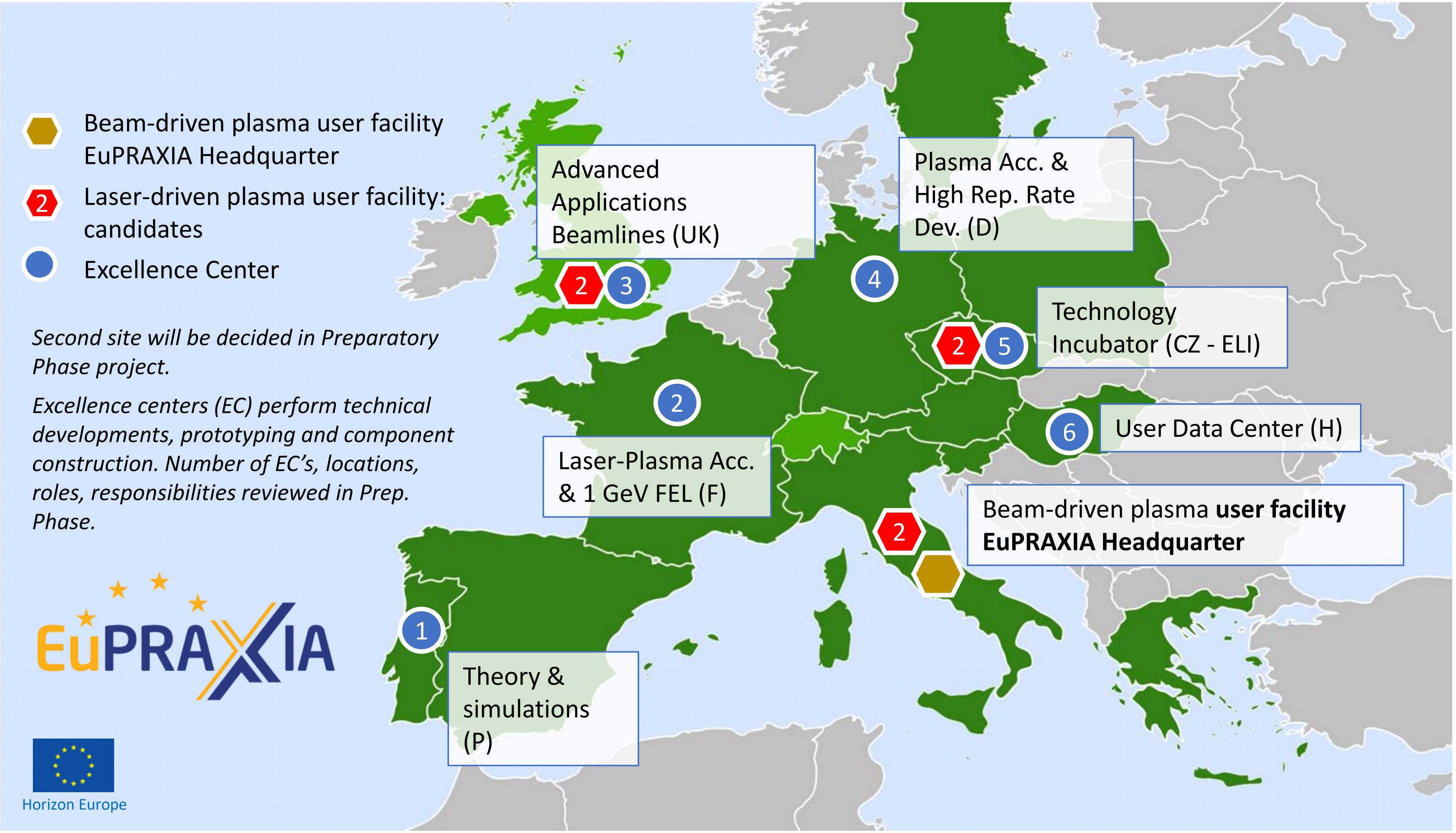
Wide International Collaboration

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)



Distributed Research Infrastructure



Second site will be decided in Preparatory Phase project.

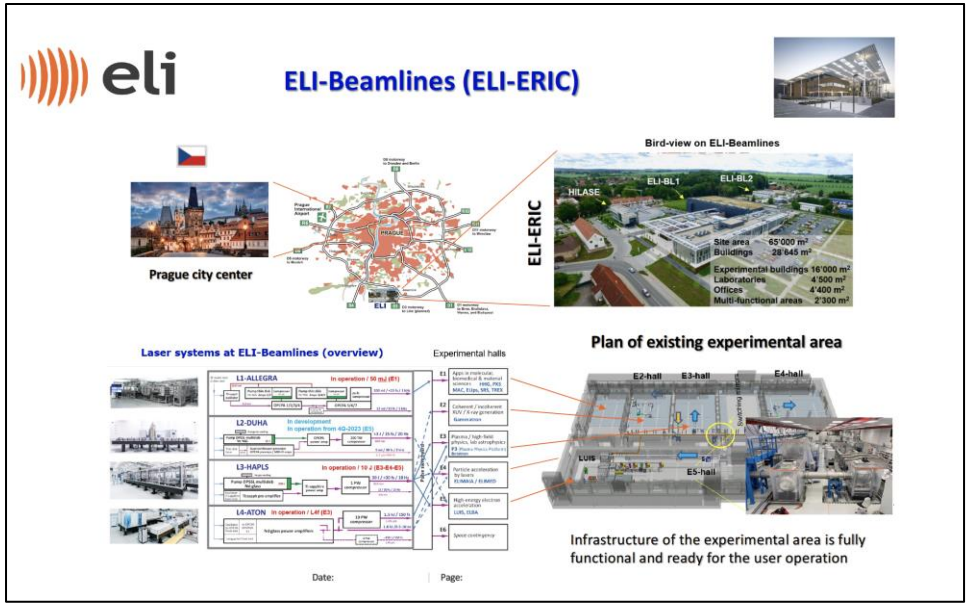
Excellence centers (EC) perform technical developments, prototyping and component construction. Number of EC's, locations, roles, responsibilities reviewed in Prep. Phase.

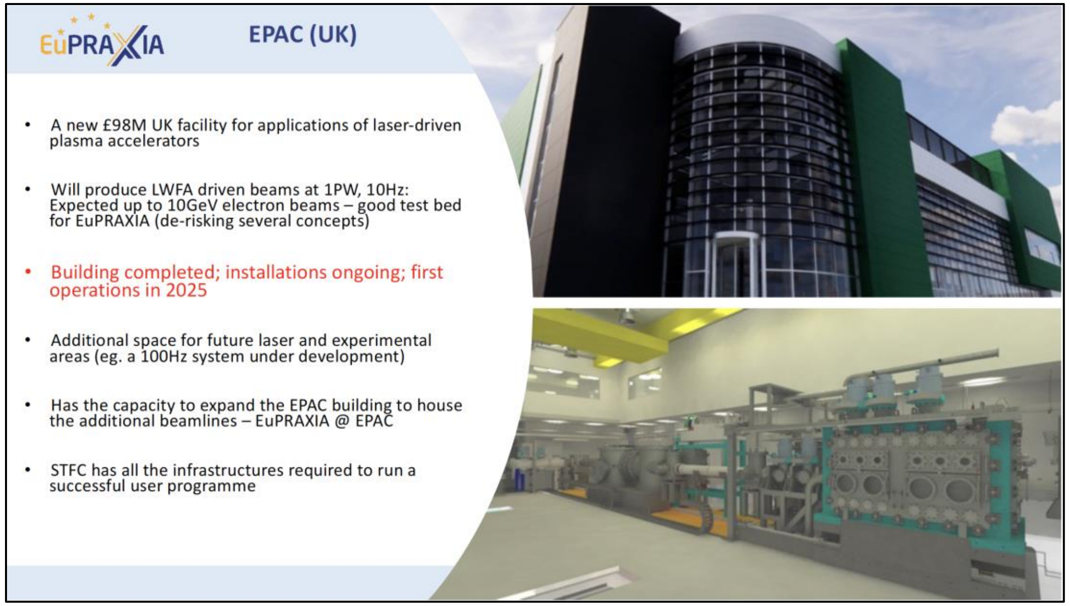
Today`s status

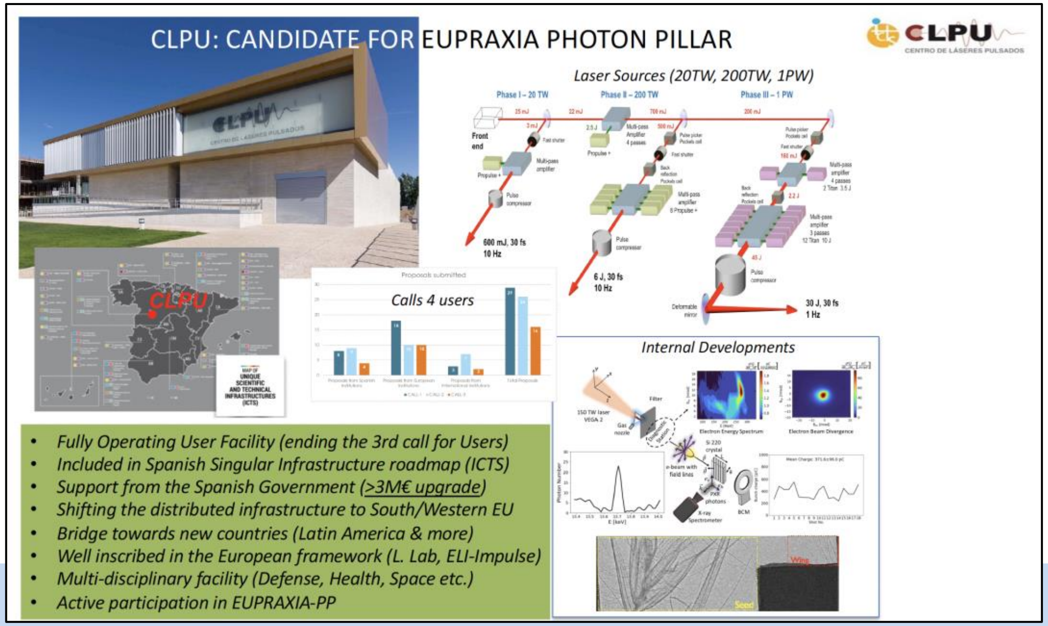
- Excellence centers: several (6 – 10) assumed to be realized
- First site: EuPRAXIA@SPARC_LAB
- Second site: one to be selected
- Connect with WP´s to Horizon Europe and national funding lines

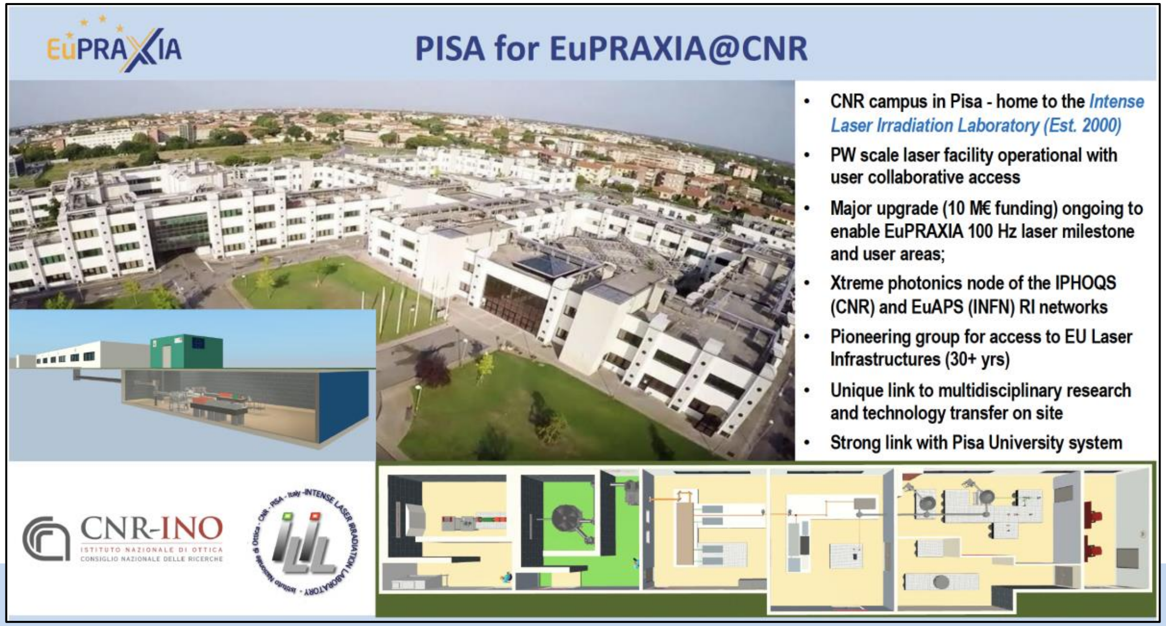
Funded by the European Union

Current Candidates for EuPRAXIA Laser Site









Headquarter and Site 1: EuPRAXIA@SPARC_LAB

Frascati`s future facility

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

Credit: INFN and Mythos – cosorzio stabile s.c.a.r.l.

~~Good~~ Excellent news first!

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MINISTERO DELLE INFRASTRUTTURE E DEI TRASPORTI

PROVVEDITORATO INTERREGIONALE PER LE OO.PP. PER IL LAZIO, L'ABRUZZO, LA SARDEGNA

* * * * *

VIA MONZAMBANO, 10 – ROMA

APPROVED

AVVISO

ai sensi dell'art. 29 del D.Lgs. 18 aprile 2016, n. 50

OGGETTO: C.d.S. n. [illegible]4 - Realizzazione di un nuovo complesso edilizio EuSPARC per ospitare la facility EuPRAXIA presso i Laboratori Nazionali di Frascati INFN.

Amministrazione Proponente: INFN Istituto Nazionale di Fisica Nucleare

Si comunica che ai sensi dell'art. 14-bis comma 5 della L. 241/90 e ss.mm. e ii., è da considerarsi acquisito l'assenso sul progetto in argomento da parte delle Amministrazioni invitate alla Conferenza. Si **DICHIARA**, pertanto, sulla scorta degli atti acquisiti, perfezionata l'intesa per la localizzazione e realizzazione dell'opera indicata in oggetto e, di conseguenza, **AUTORIZZATO** il relativo progetto definitivo.

Gli atti del procedimento sono in visione presso la Segreteria dell'Ufficio Conferenze di Servizi di questo Provveditorato

IL DIRIGENTE	IL RESPONSABILE DEL PROCEDIMENTO	IL PROVVEDITORE
Dott. Ing. Carlo Guglielmi	Dott. Arch. Alessia Costa	Dott. Ing. Vittorio Rapisarda Federico

Firmato digitalmente da
CARLO GUGLIELMI
O = MiMS
C = IT

Alessia Costa
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FEDERICO
Ministero delle
Infrastrutture
e dei Trasporti
23.05.2023
11:37:37
GMT+01:00

Roma, lì ____________________

PUBBLICATO ____________________

RITIRATO ____________________

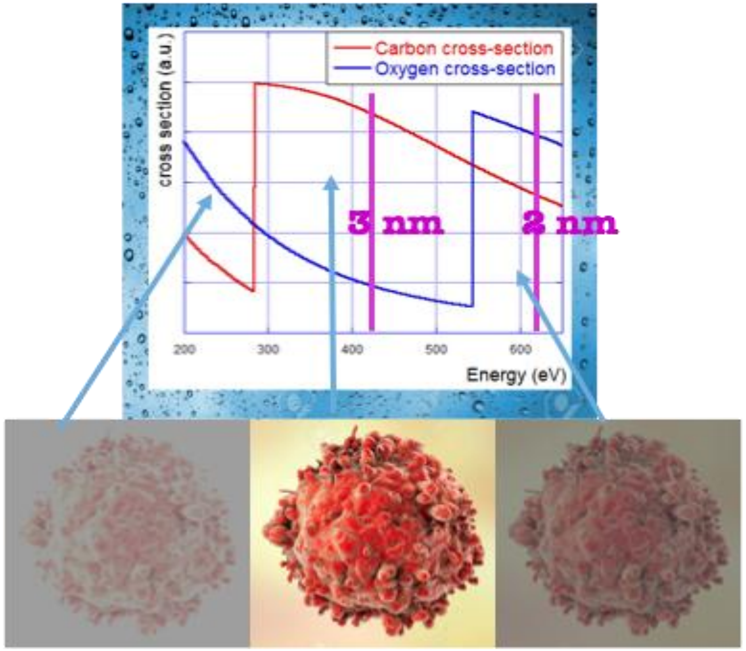
ISO 9001 BUREAU VERITAS Certification

Expected SASE FEL performances

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 Bandwith	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$mm^2 mrad\ bw(0.1\%)$	$\mathbf{1-2 \times 10^{28}}$	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	**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

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)

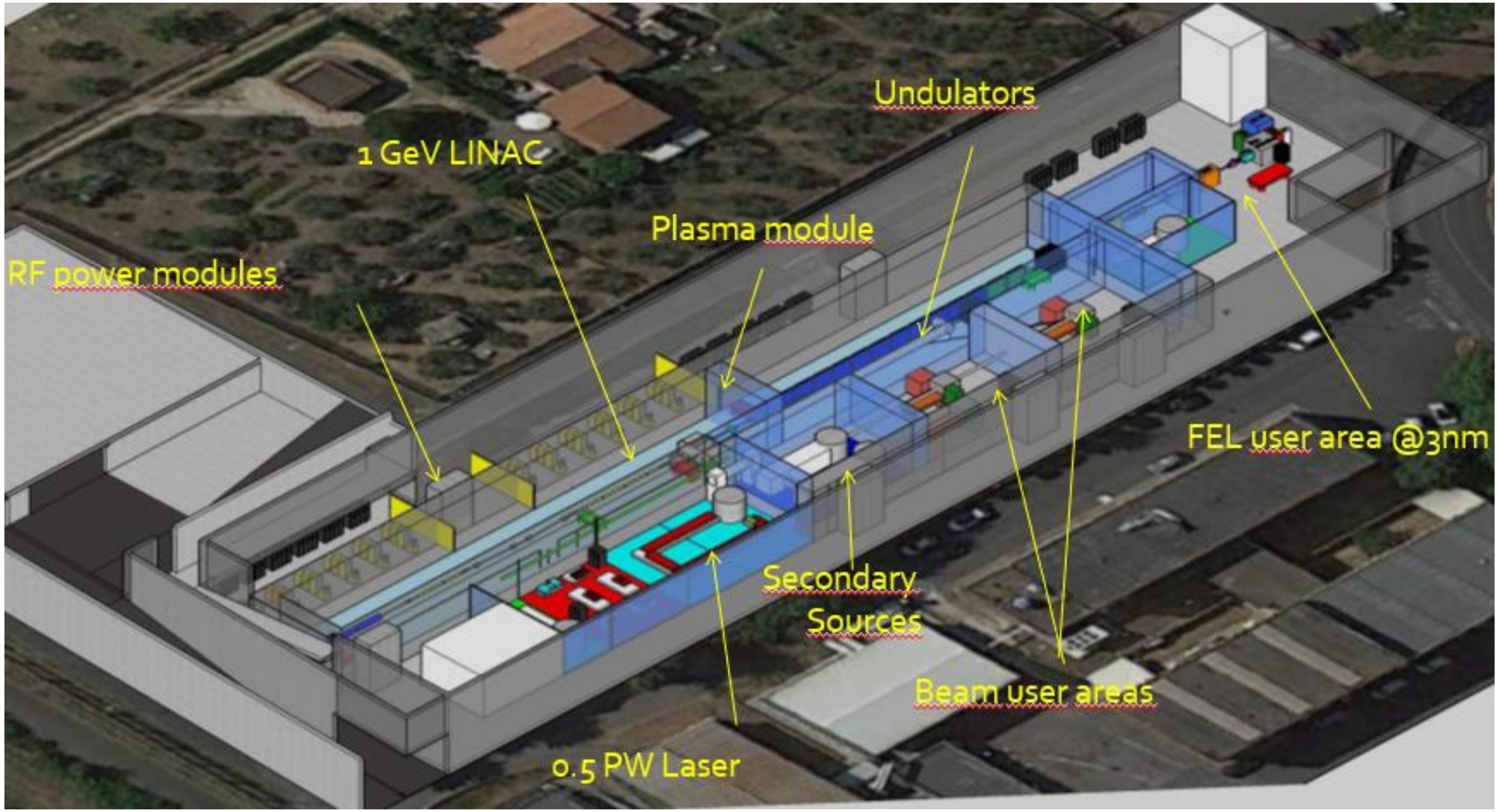


Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10 [11] photons/pulse needed

Intense R&D Program on critical components

Funded by the European Union

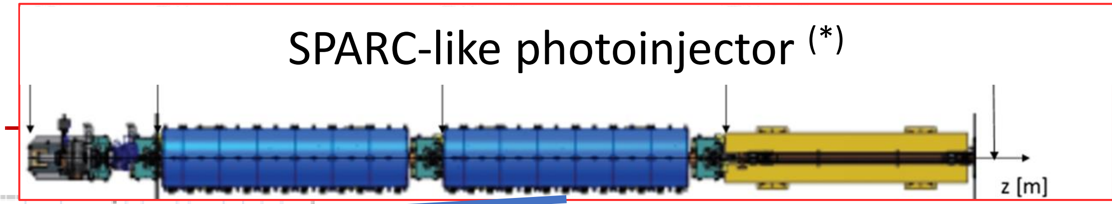
- **Electrons**
  (0.1-5 GeV, 30 pC)
- **Positrons**
  (0.5-10 MeV, 10^6)
- **Positrons** (GeV source)
- **Lasers**
  (100 J, 50 fs, 10-100 Hz)
- **X-band RF Linac**
  (60 MV/m , up to 400 Hz)
- **Plasma Targets**
- **Betatron X rays**
  (1-10 keV, 10^{10})
- **FEL light**
  (0.2-36 nm, 10^9-10^{13})

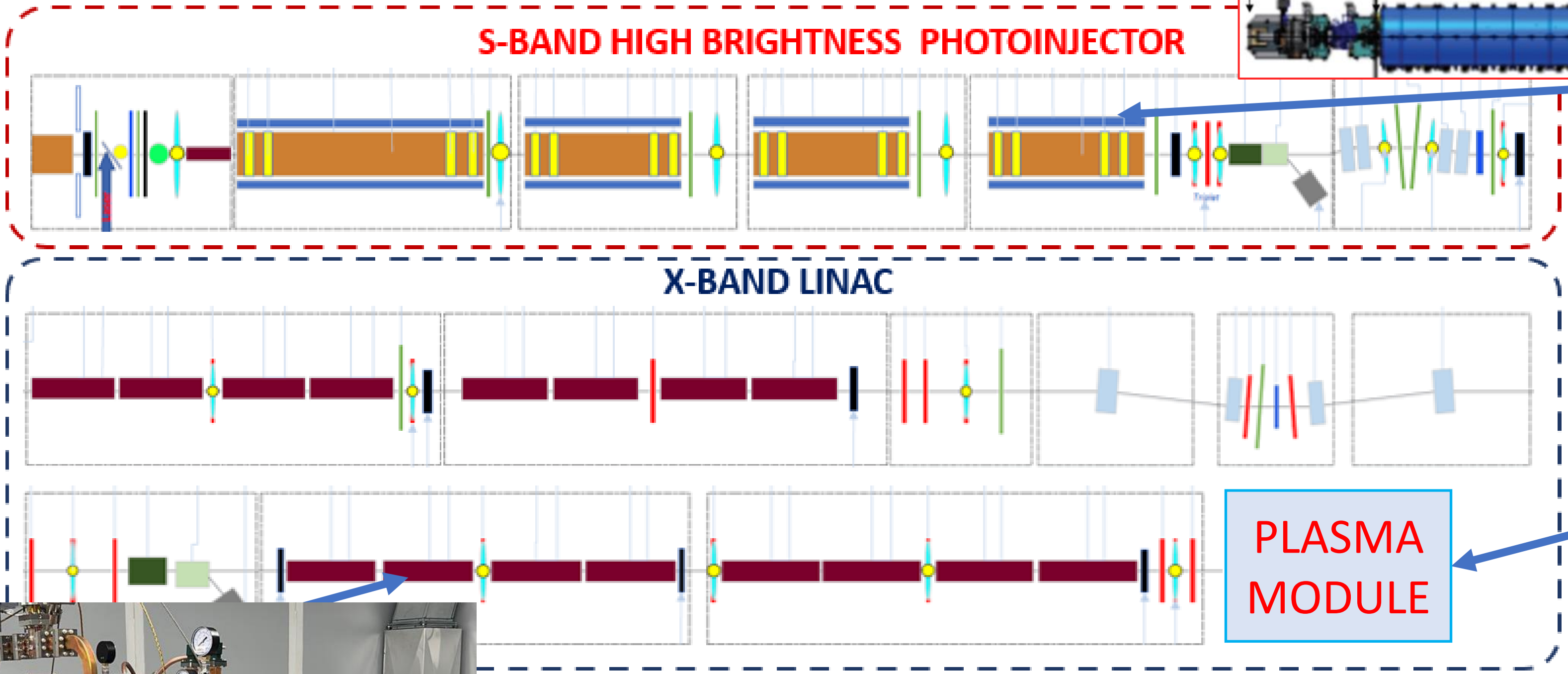


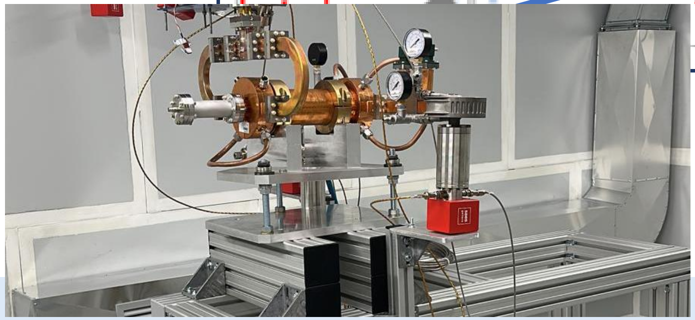
EuPRAXIA@SPARC_LAB: a high brightness PWFA

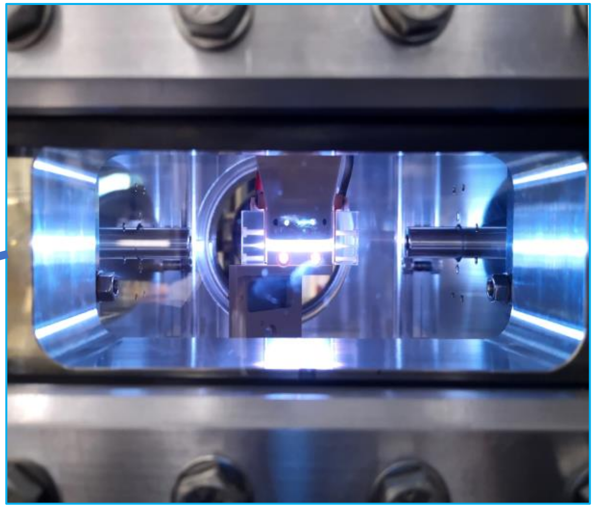
Funded by the European Union

The accelerator is based on the combination of a *high brightness RF injector* and a *plasma module*









EuPRAXIA at SPARC_LAB

Stable, reliable and reproducible electron beams

Funded by the European Union

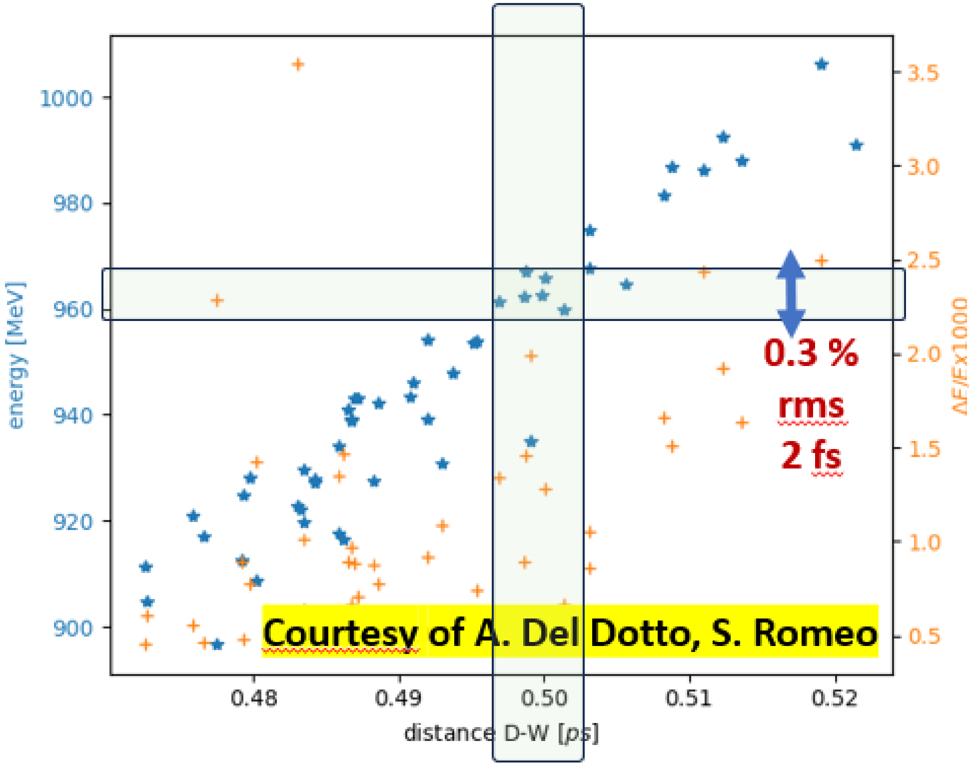
FEL requirement

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

D-W separation

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

$$2 \leq a \leq 4$$



Courtesy of A. Del Dotto, S. Romeo

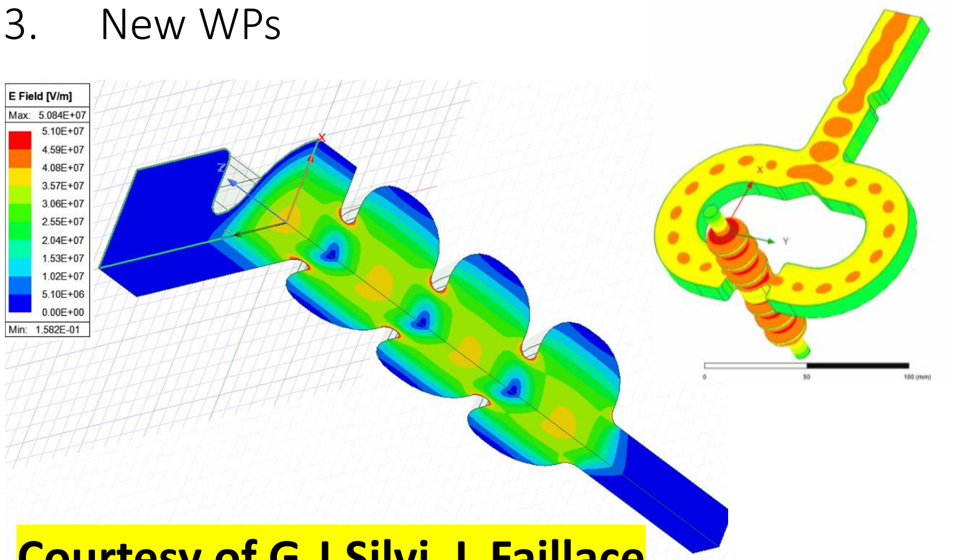
Results obtained by means of start to end simulations taking into accout state of the art jitters in conventional RF photoinjector

R&D Activities On The Photoinjector

1. Stabilization methods and technologies for the RF element power sources → promising results on the solid-state C-band technology with halved Δt (from 30 down to 15 fs)

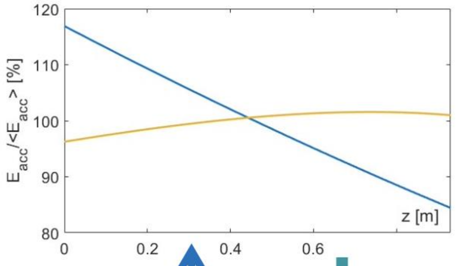
2. Inseriton of an higher harmonic accelerating cavity to stabilize the beam current profile

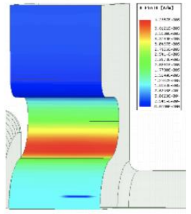
3. New WPs



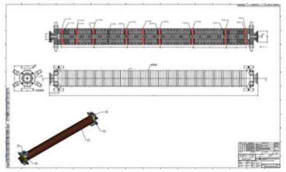
Courtesy of G.J.Silvi, L.Faillace

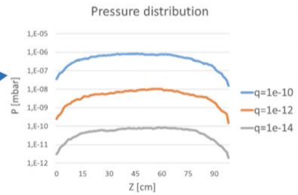
World`s Most Compact RF Linac: X Band

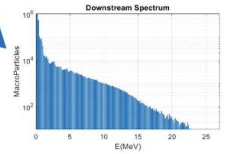




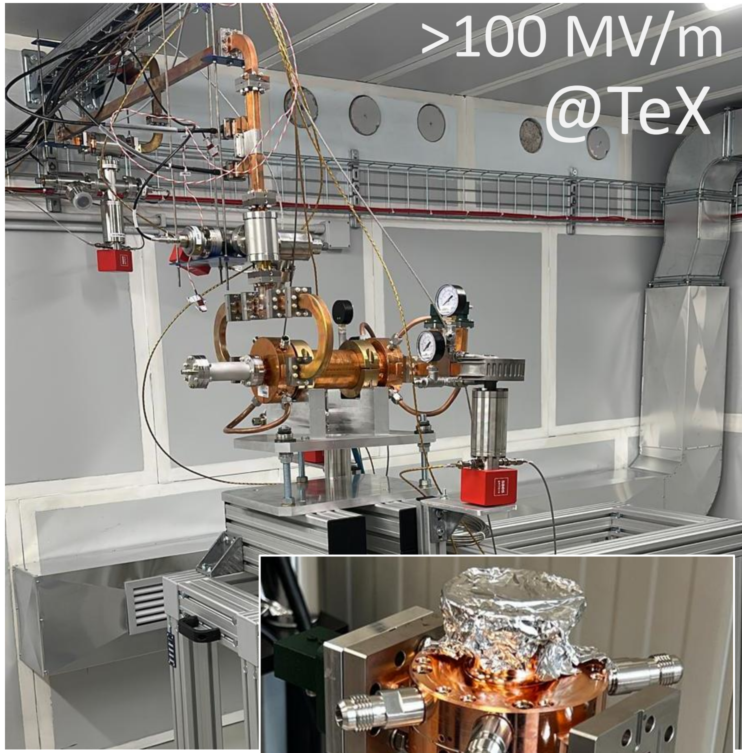
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

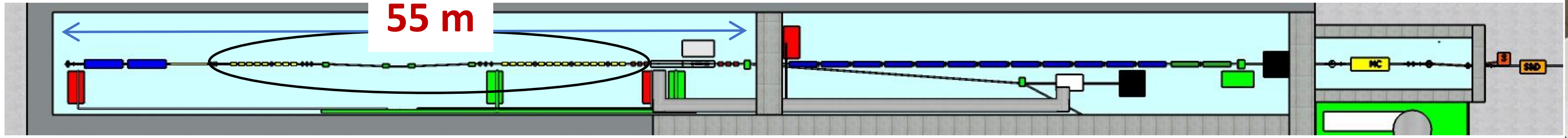






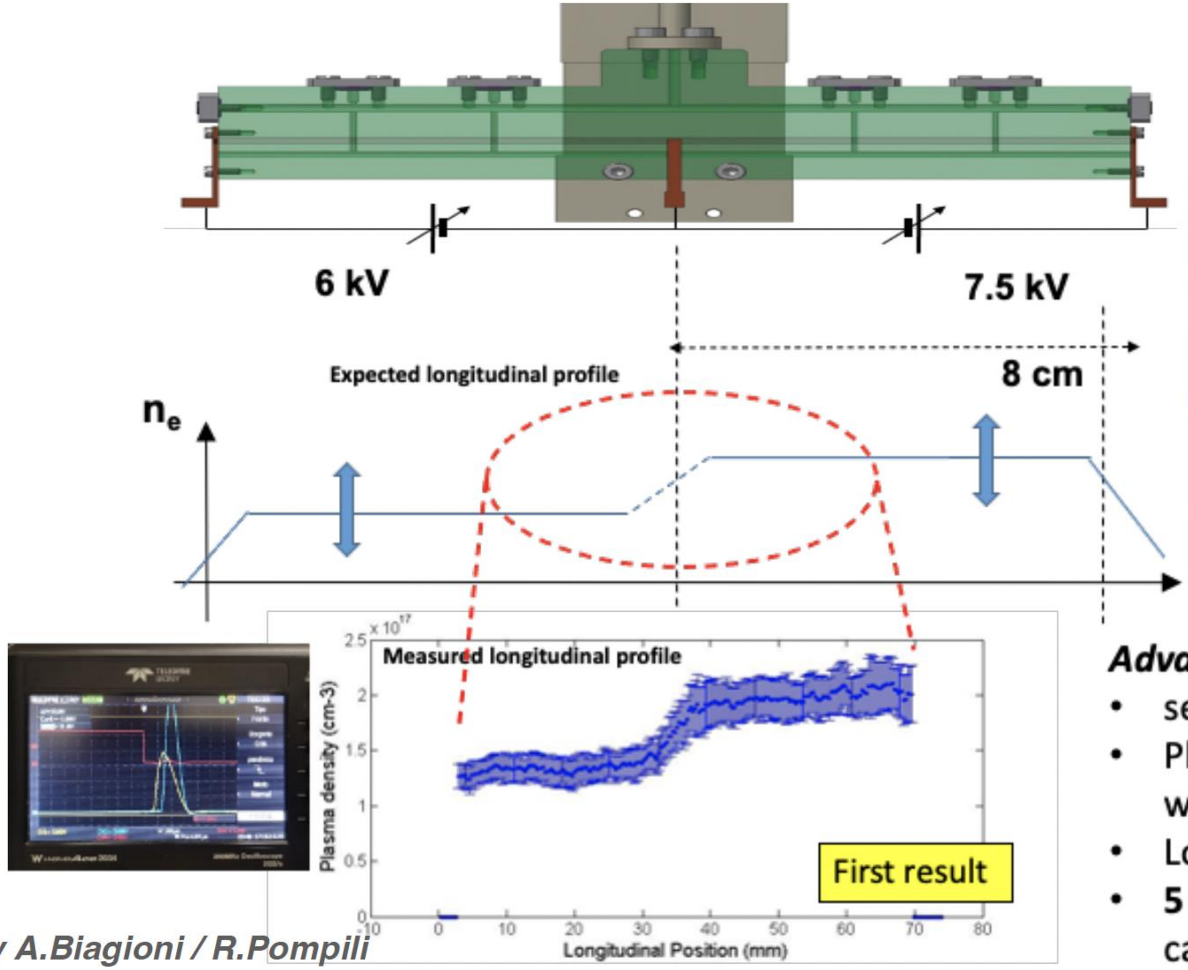
PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt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

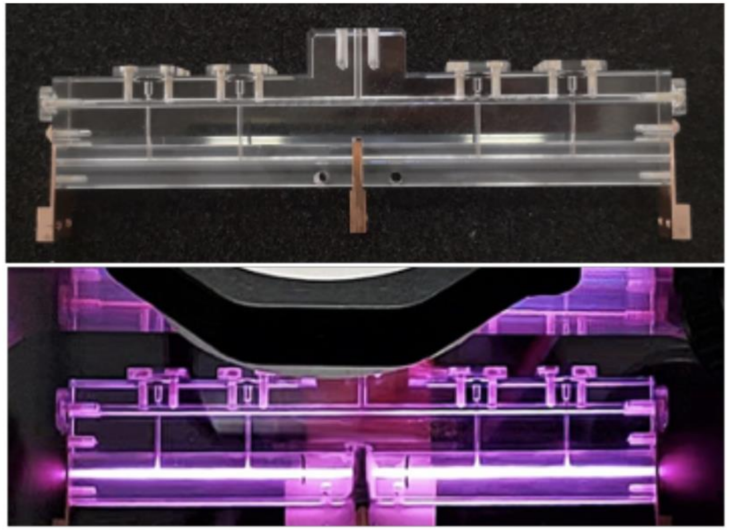




Courtesy D. Alesini, F. Cardelli

Plasma Module



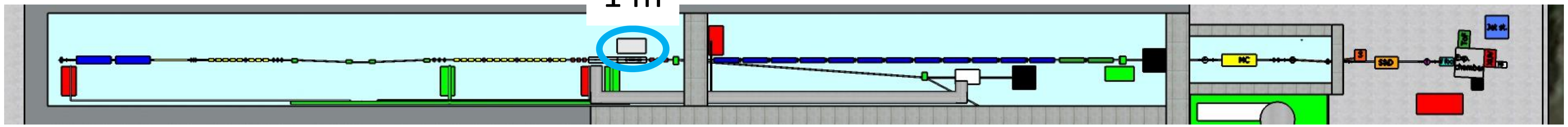


Courtesy A.Biagioni / R.Pompili

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)

1 m

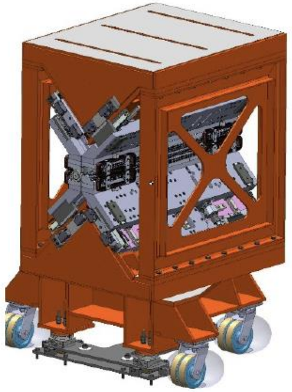


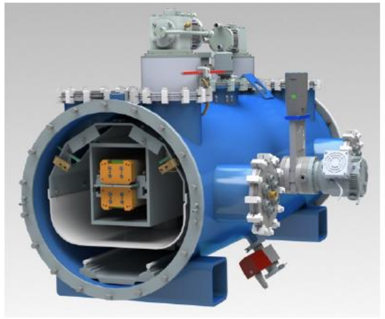
Courtesy A. Biagioni, R. Pompili

Radiation Generation: FEL

Two FEL lines:

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

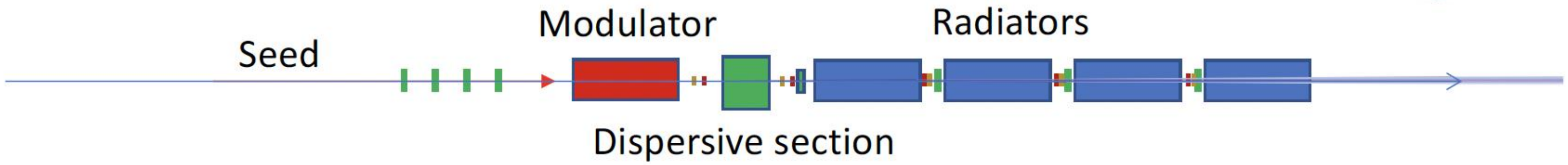




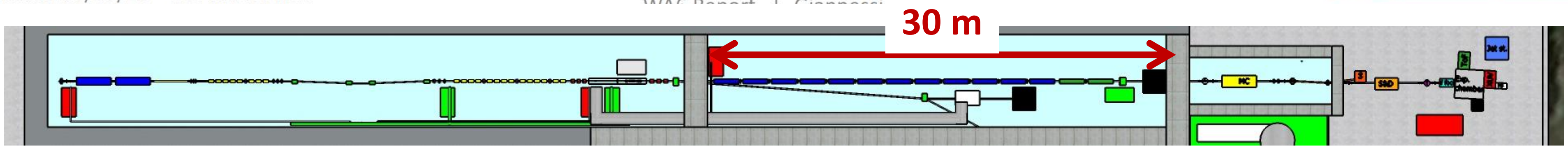
First *SABINA* undulator in FRASCATI March 29, 2023

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 (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.



Courtesy L. Giannessi

EuPRAXIA Advanced Photon Sources (EuAPS)

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

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

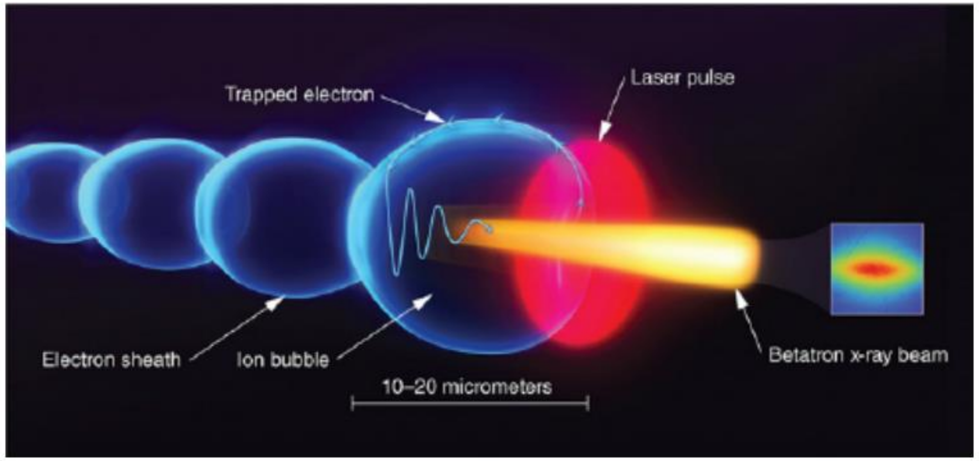


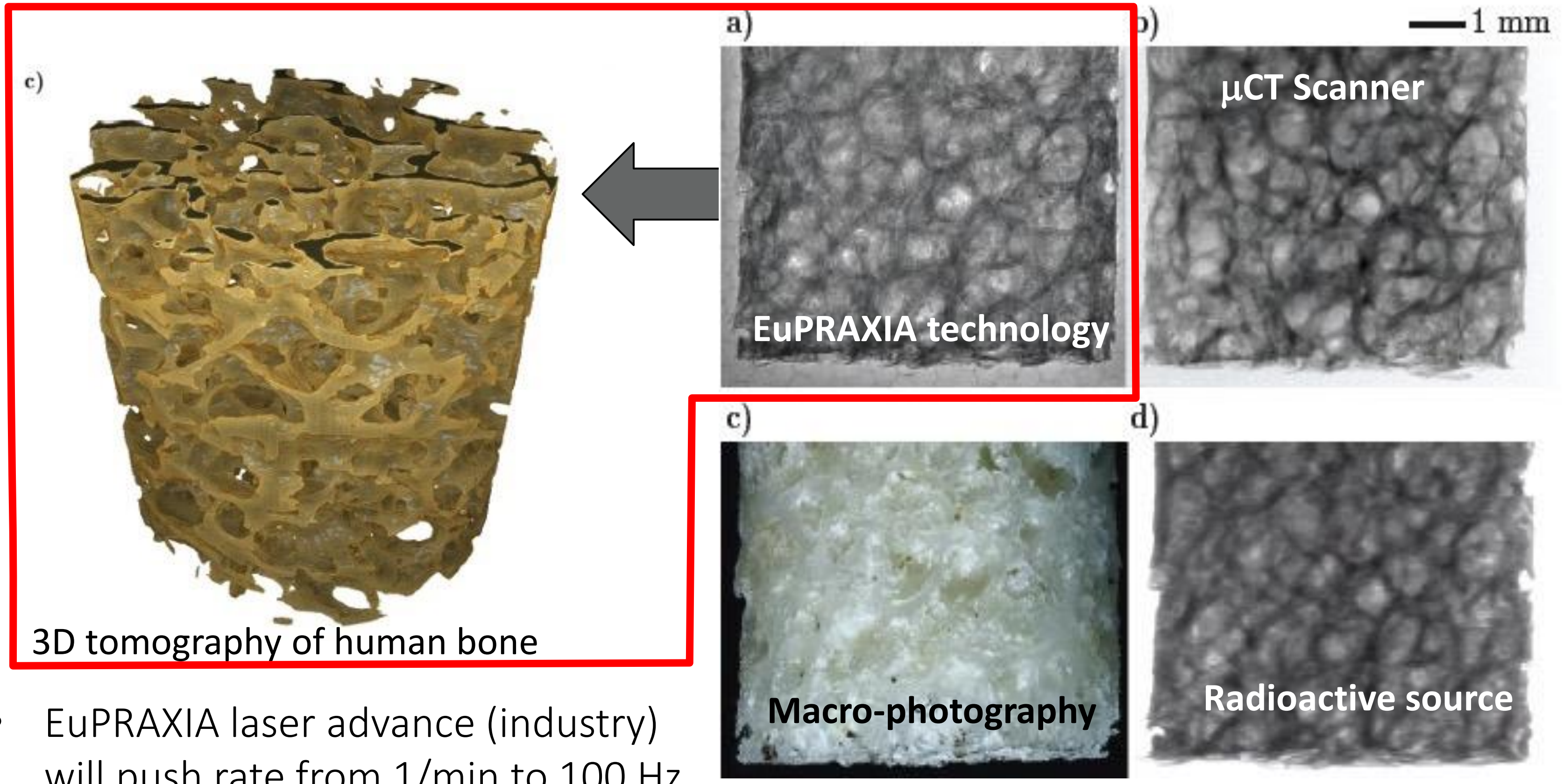
Figure 3: Principle of betatron X-ray emission from a LWFA. Electrons trapped at the back of the wakefield are subject to transverse and longitudinal electrical forces; subsequentlythey are accelerated and wiggled to produce broadband, synchrotron-like radiation in keV energy range [6].

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).

Next Step: 'plasma-based compact undulators'

Betatron X-Rays: Compact Medical Imaging

J.M. Cole et al, "Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone". Nature Scientific Reports 5, 13244 (2015)



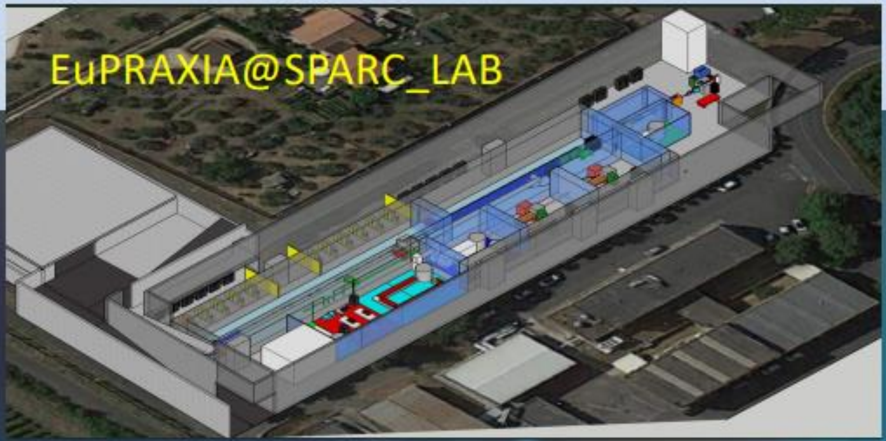
- EuPRAXIA laser advance (industry) will push rate from 1/min to 100 Hz.
- Ultra-compact source of hard X rays → exposing from various directions simultaneously is possible in upgrades

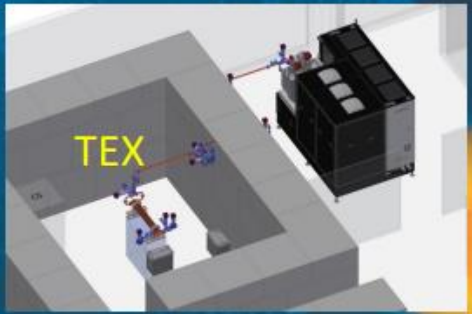
<u>Physics & Technology Background:</u>

- **Quasi-pointlike** emission of X rays.
- High spatial coherence and resolution
- **Sharper image from base optical principle.**
- Quality demonstrated and published, but takes a few hours for one image.
- Advancing flux rate with EuPRAXIA laser by factor > 1,000!

Added value

- Sharper images with outstanding **contrast**
- **Identify smaller features** (e.g. early detection of cancer at micron-scale – calcification)
- Laser advance in EuPRAXIA → **fast imaging** (e.g. following moving organs during surgery)





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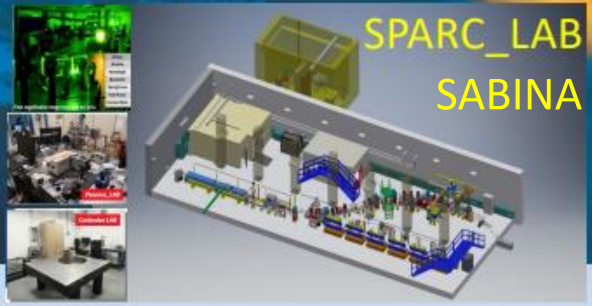
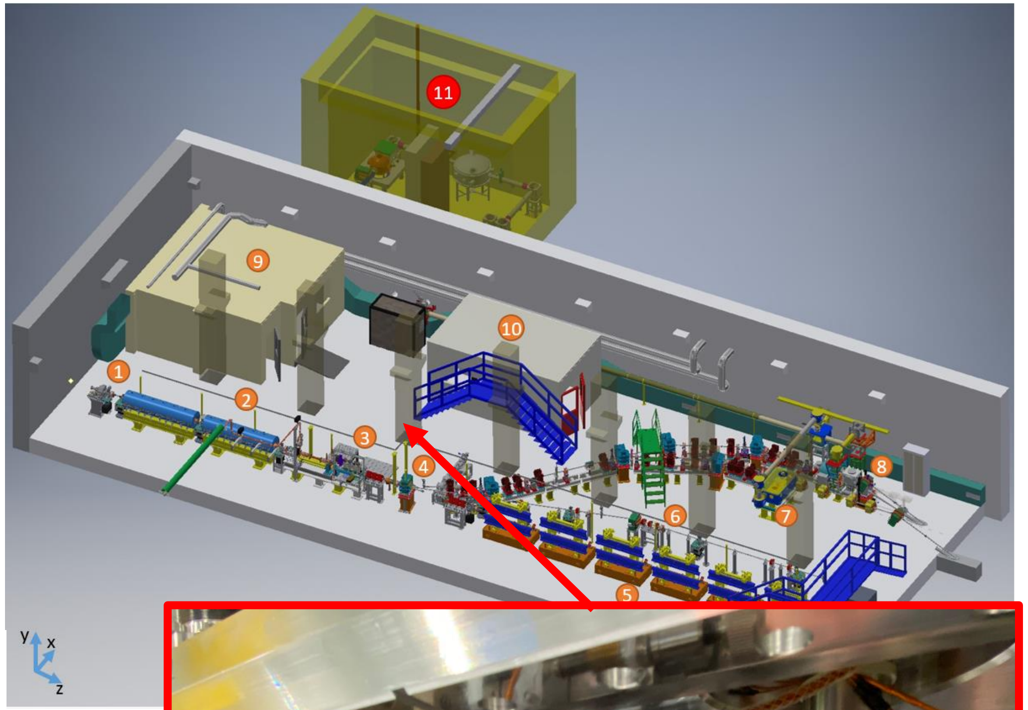
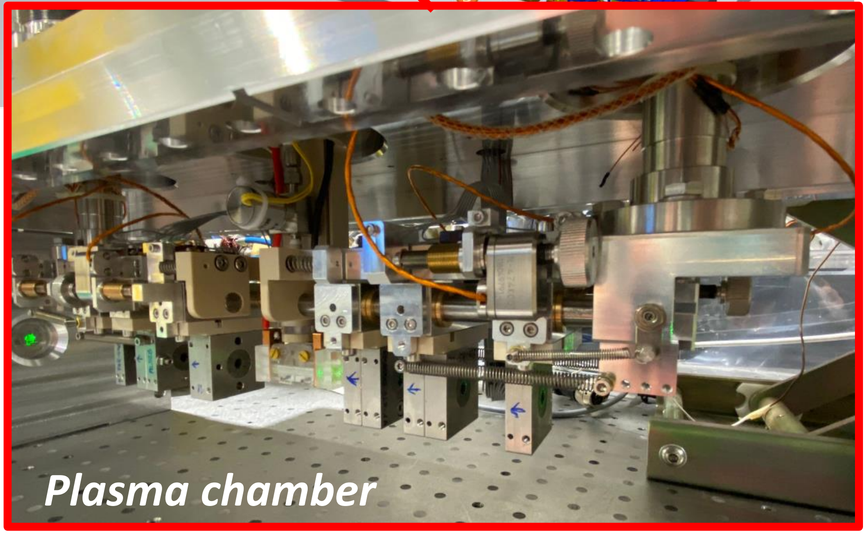


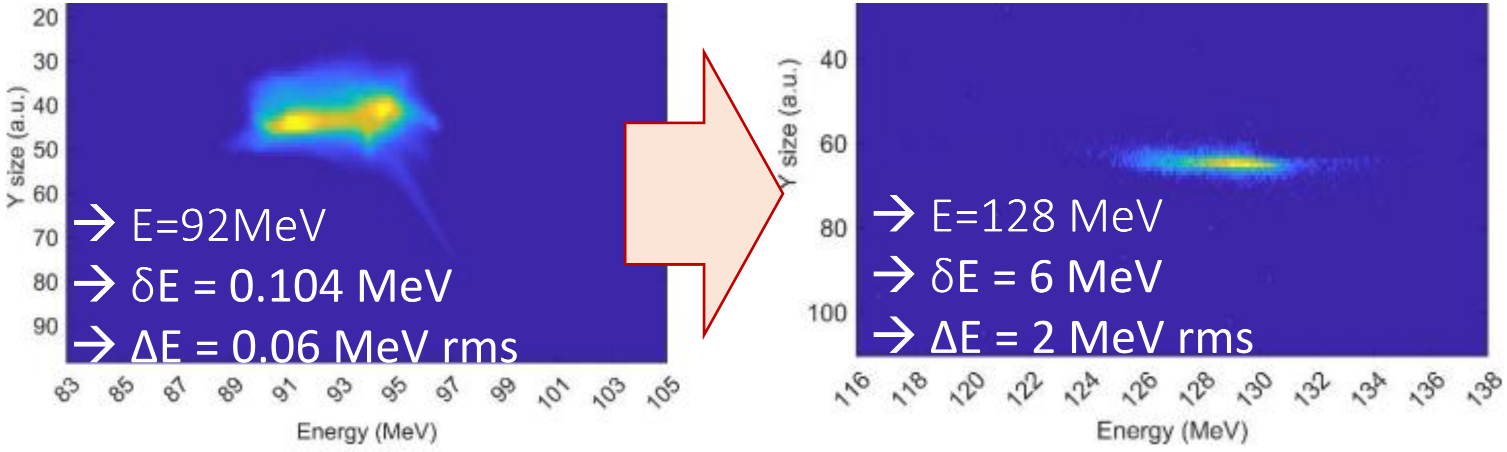
The SPARC_LAB Experience

- SPARC_LAB is a test facility (INFN-LNF) mainly devoted to the R&D activity on ultra-brilliant electron beam photo injector and FEL physics.
- In the last few years, research activity has been focused to investigate the PWFA technique → *Maximum accelerating gradient of the order of 1.0 GV/m has been measured last November.*
- *Crucial activity for the forthcoming EuPRAXIA@SPARC_LAB* project aiming to be the first ever plasma beam-driven facility at LNF



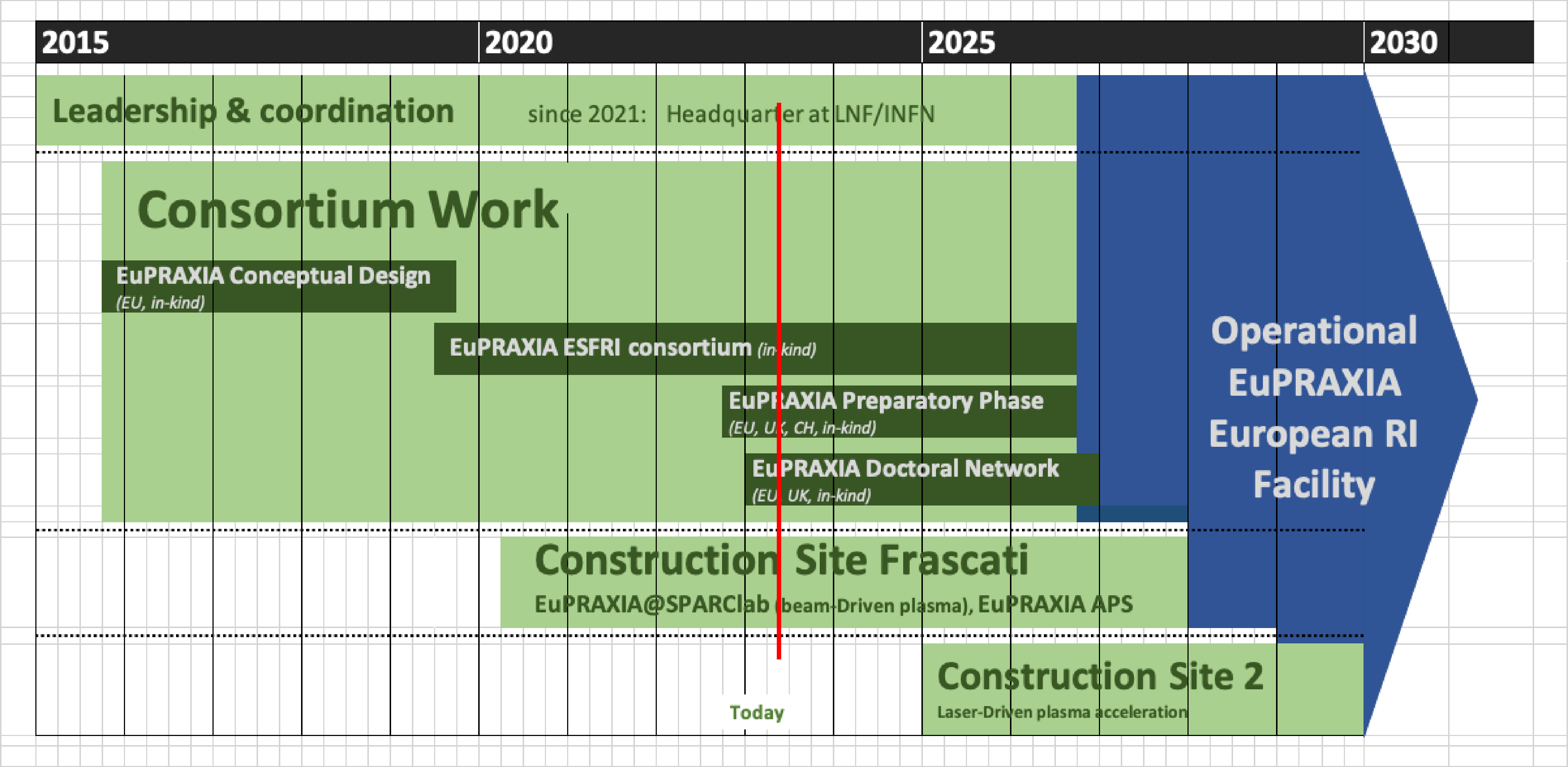


30 MeV in 3 cm !



Witness energy measurement before and after the plasma

EuPRAXIA Project Timeline



Courtesy A. Falone

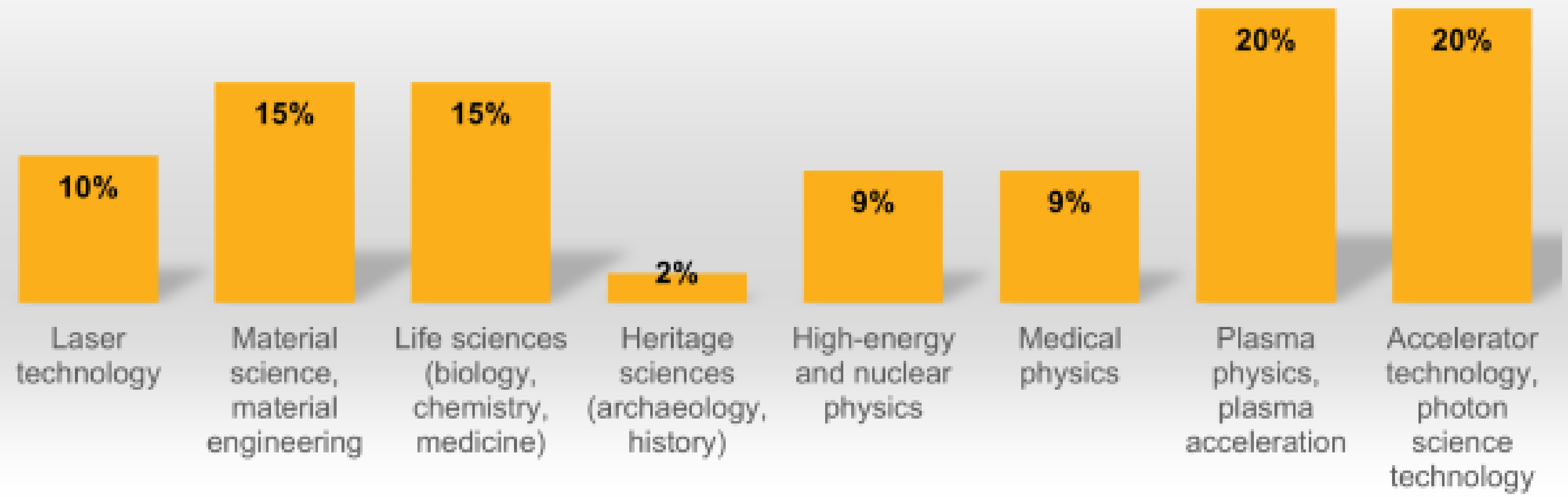
Compact EuPRAXIA Facility Will Deliver to Users

Ultra-short pulses with 10-100 Hz of*

- 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)
- Betatron X rays (1-110 keV, 10^{10})
- FEL light (0.2-36 nm, 10^{9}-10^{13})

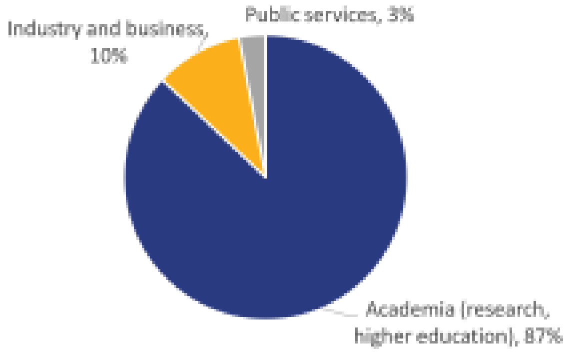
** Parameter ranges are application- / user-driven and still have flexibility in the current design*

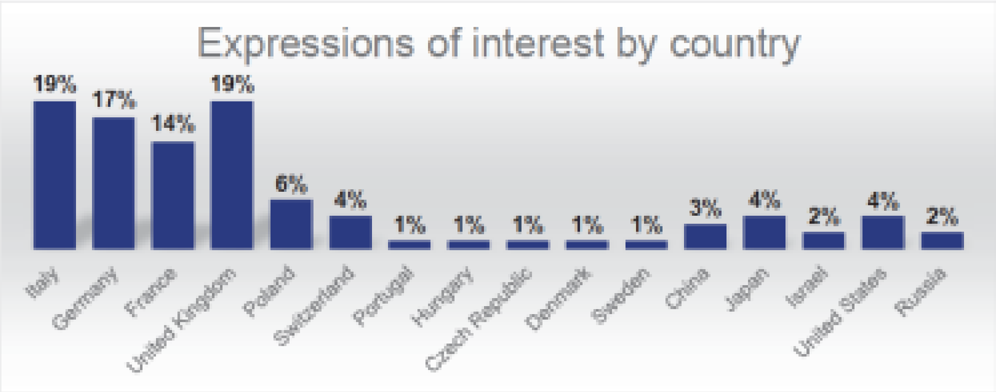
Targeted user community by scientific field



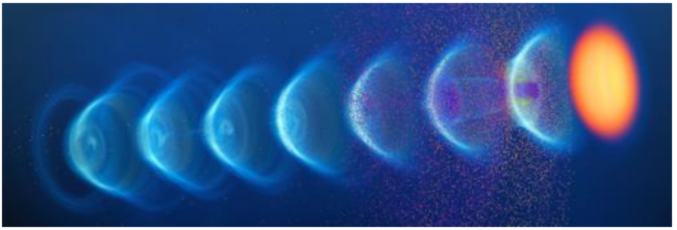
Expressions of interest from **95 research groups** received, representing several thousand scientists in total.

Form basis of **user demand analysis**.





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.
- EuAPS will be a pre-cursor of the next EuPRAXIA user-facility
- 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: Massimo Ferrario, Ralph Assmann, Antonio Falone,** Enrica Chiadroni, Cristina Vaccarezza, Andrea Ghigo, David Alesini, Riccardo Pompili, 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