EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA@SPARC_LAB: Site 1

Alessio Del Dotto, INFN-LNF
On behalf of the EuPRAXIA@SPARC_LAB collaboration

6th European Advanced Accelerator Concepts workshop (EAAC2023)
Elba in Italy, September 17-23, 2023

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

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.*

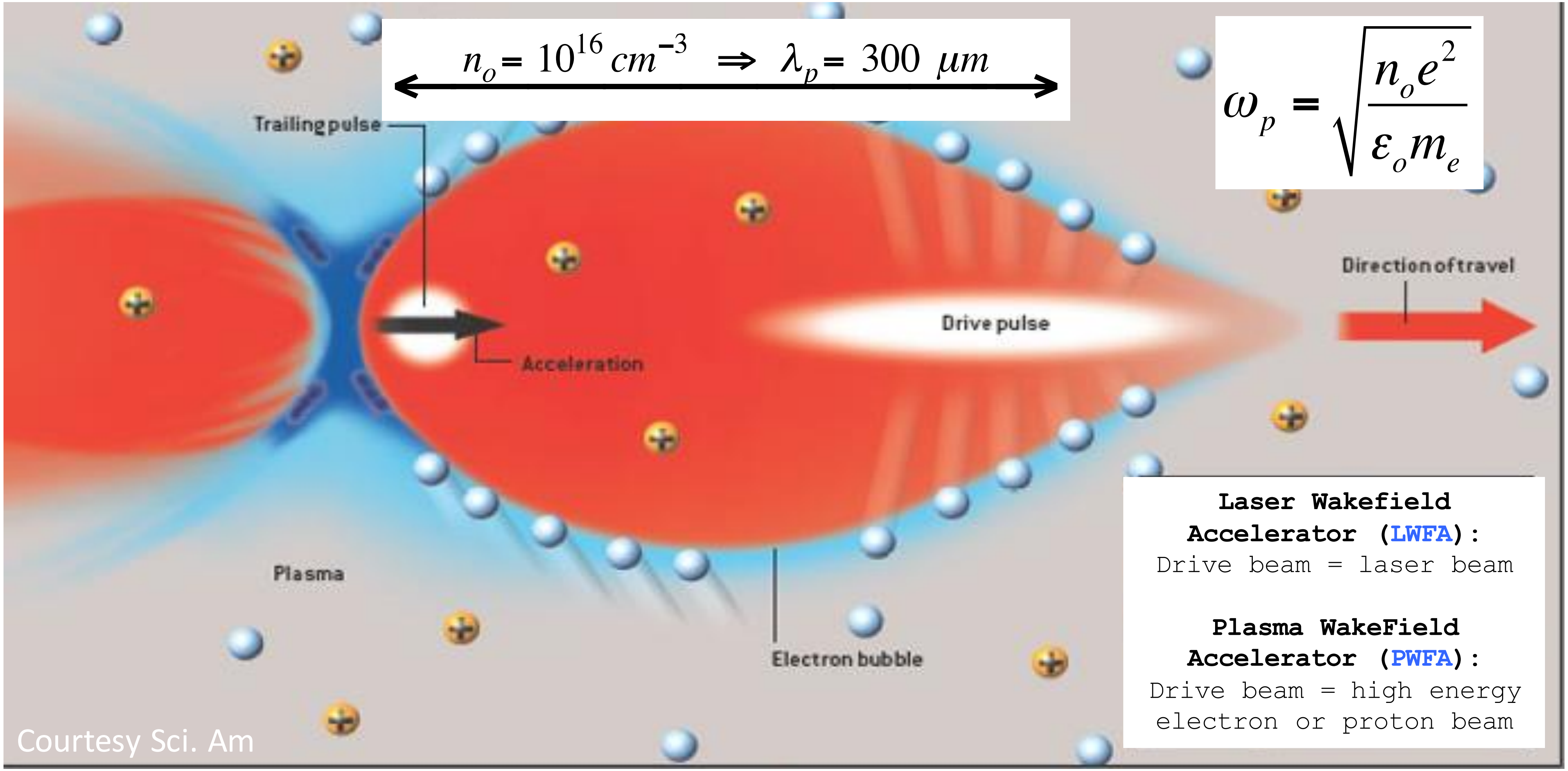
https://cerncourier.com/a/europe-targets-a-user-facility-for-plasma-acceleration/

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

Principle of plasma acceleration

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

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

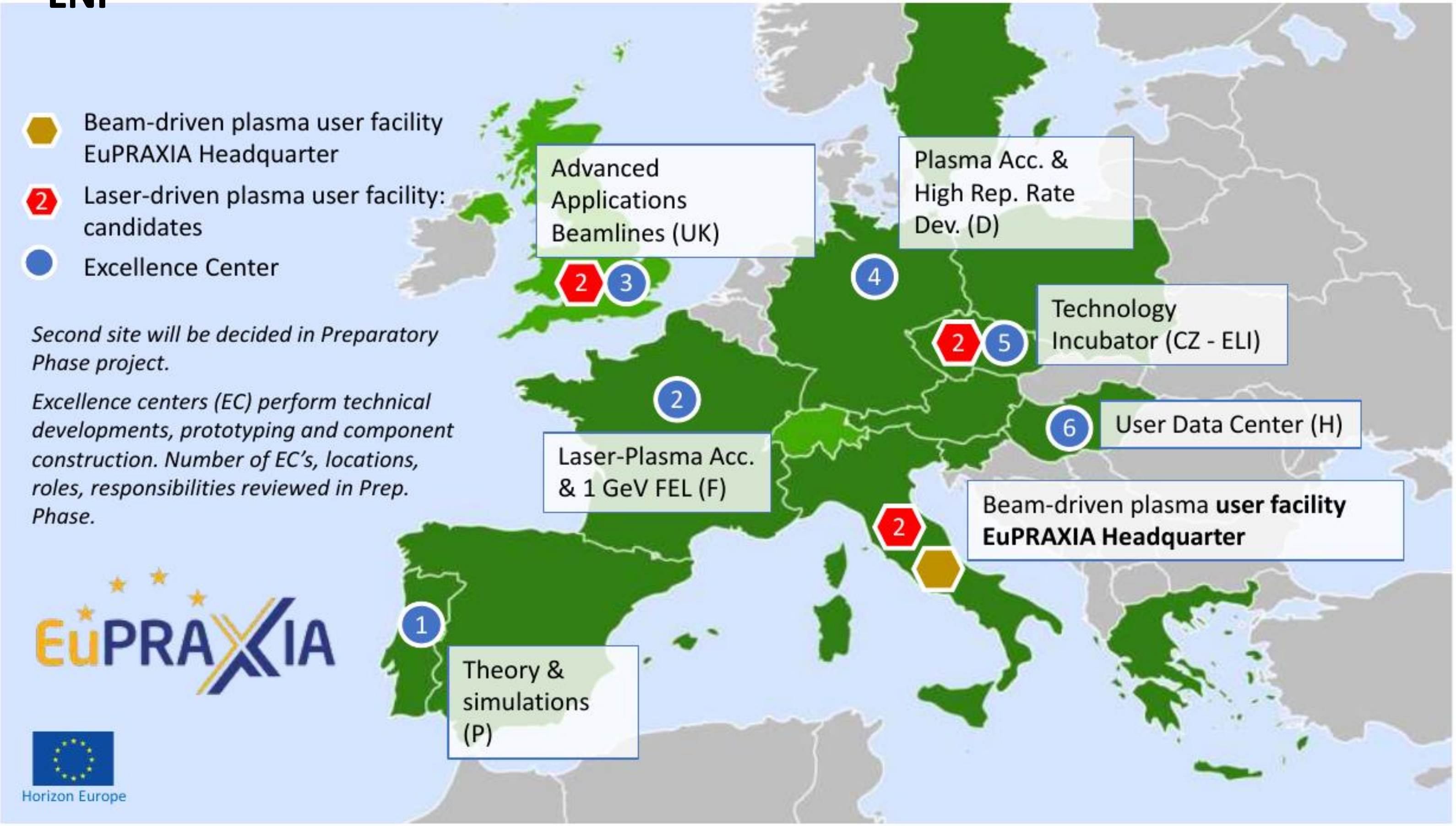


Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

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

First site: EuPRAXIA@SPARC_LAB

Beam – driven plasma user facility EuPRAXIA Headquarter at INFN LNF



https://sparclab.lnf.infn.it/sparc_lab-home/eupraxiasparc_lab/
https://euaps.infn.it/

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 driven by high gradient plasma accelerator (4 nm and 50-180 nm)

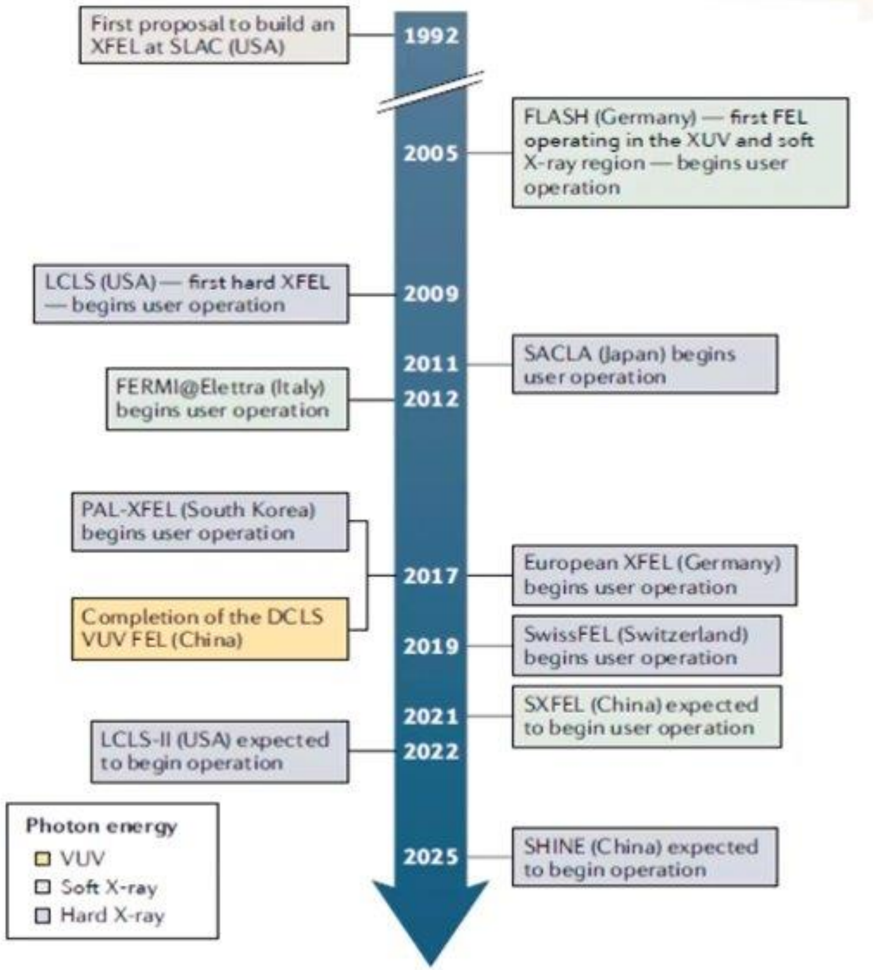
2. **EuAPS** (Advanced Photon Sources)
   - Fast X-ray source
   - Cheap and Compact photon sources
   - For users applications

Funded by the European Union

FEL is a well-established technology

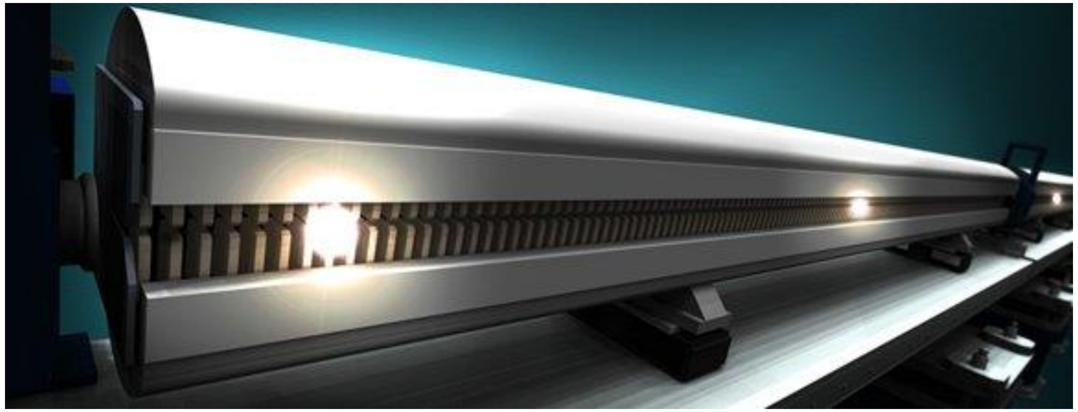
(But a widespread use of FEL is partially limited by its size and costs)

Funded by the European Union

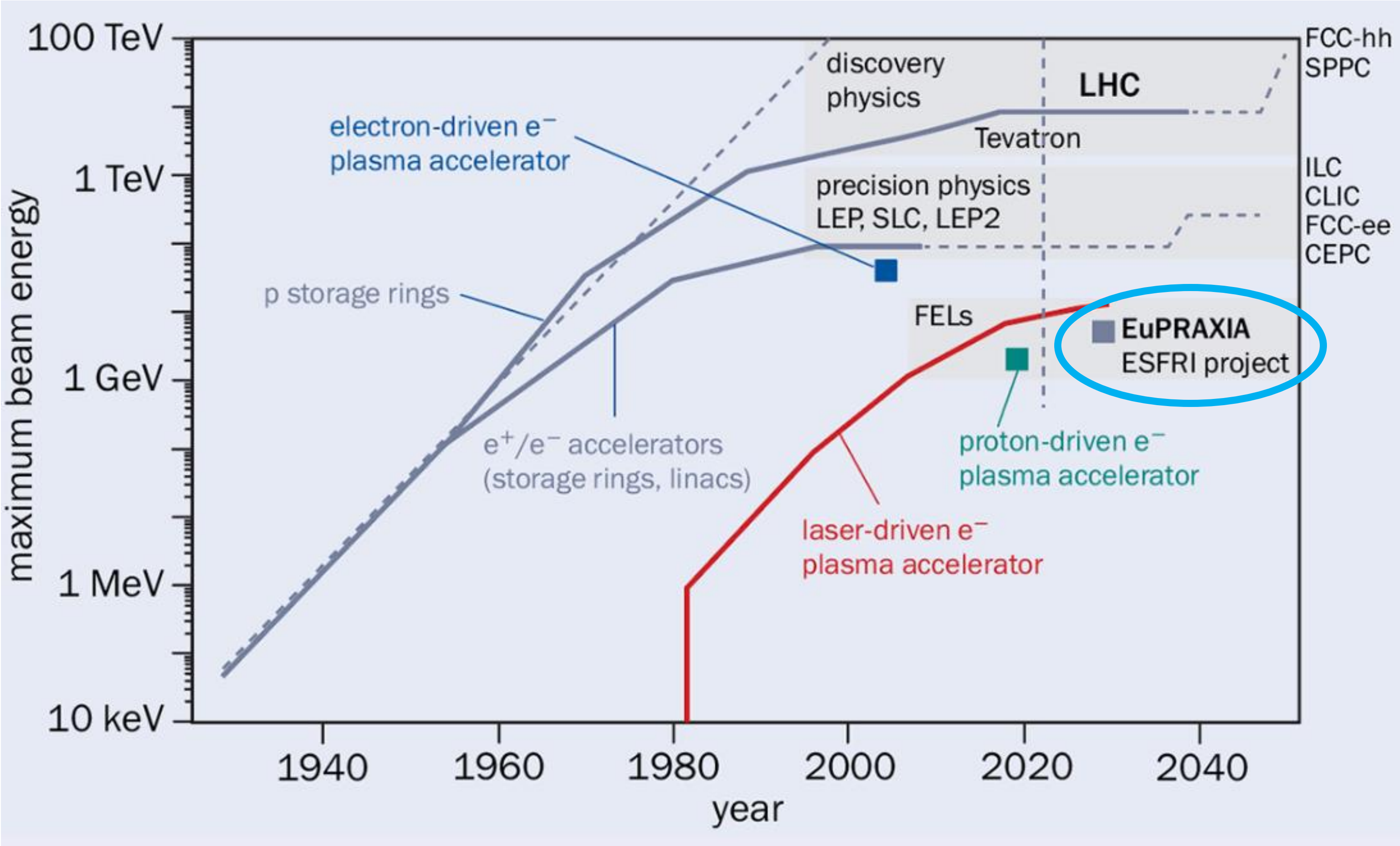


New facilities are expected to begin operation in the next 5 years in the USA and China, and the UK is considering the scientific case for an XFEL.

Iulia Georgescu



The Livingston 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

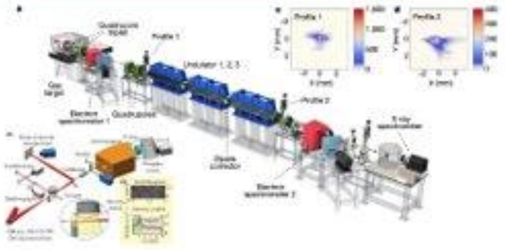
Courtesy of R. Assmann

Beam quality in pilot FEL experiments

Funded by the European Union

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

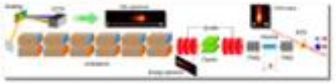
FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)

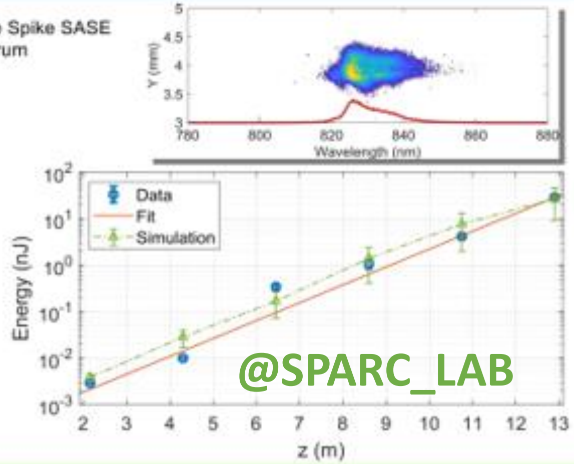
2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

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





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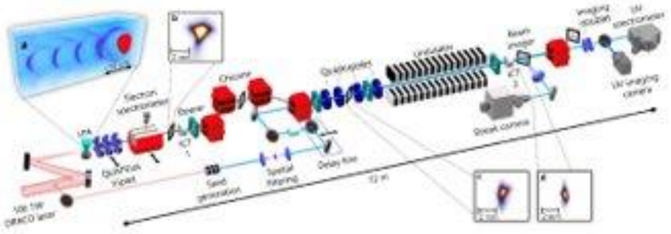
Seeded UV free-electron laser driven by LWFA

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



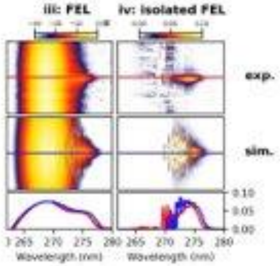
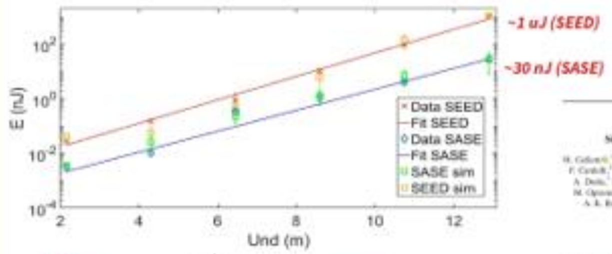
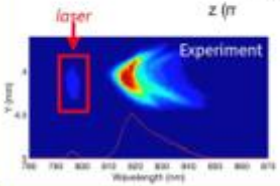
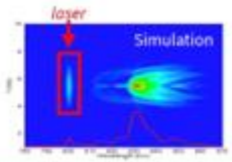


FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled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







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

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Headquarter and Site 1: EuPRAXIA@SPARC_LAB

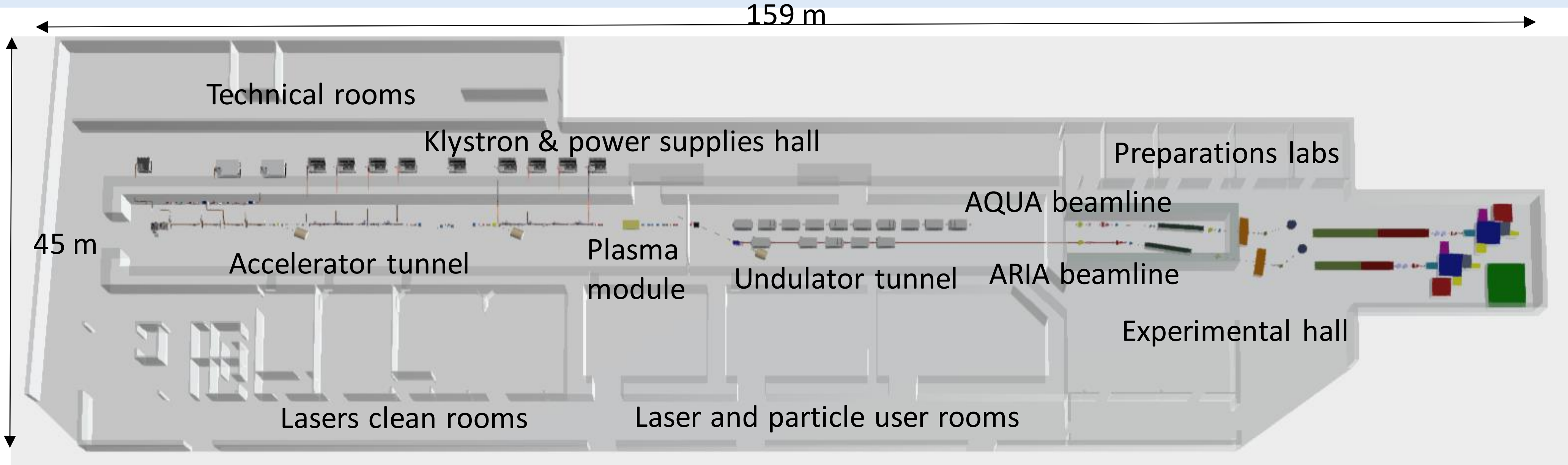
Funded by the European Union

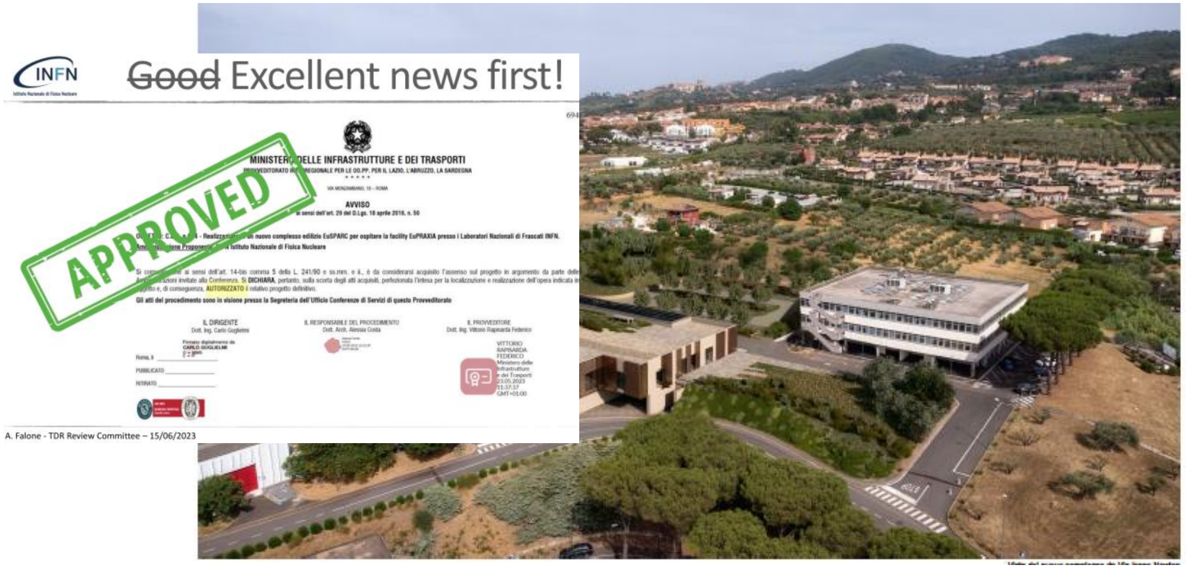
Frascati`s future facility

- > 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 – consorzio stabile s.c.a.r.l.

EuPRAXIA@SPARC_LAB layout





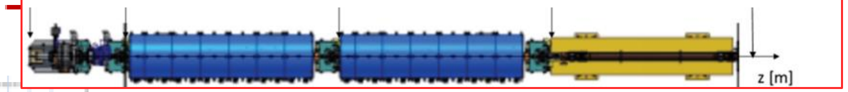
Courtesy F. Cioeta, E. Di Pasquale, A. Ghigo, A. Falone

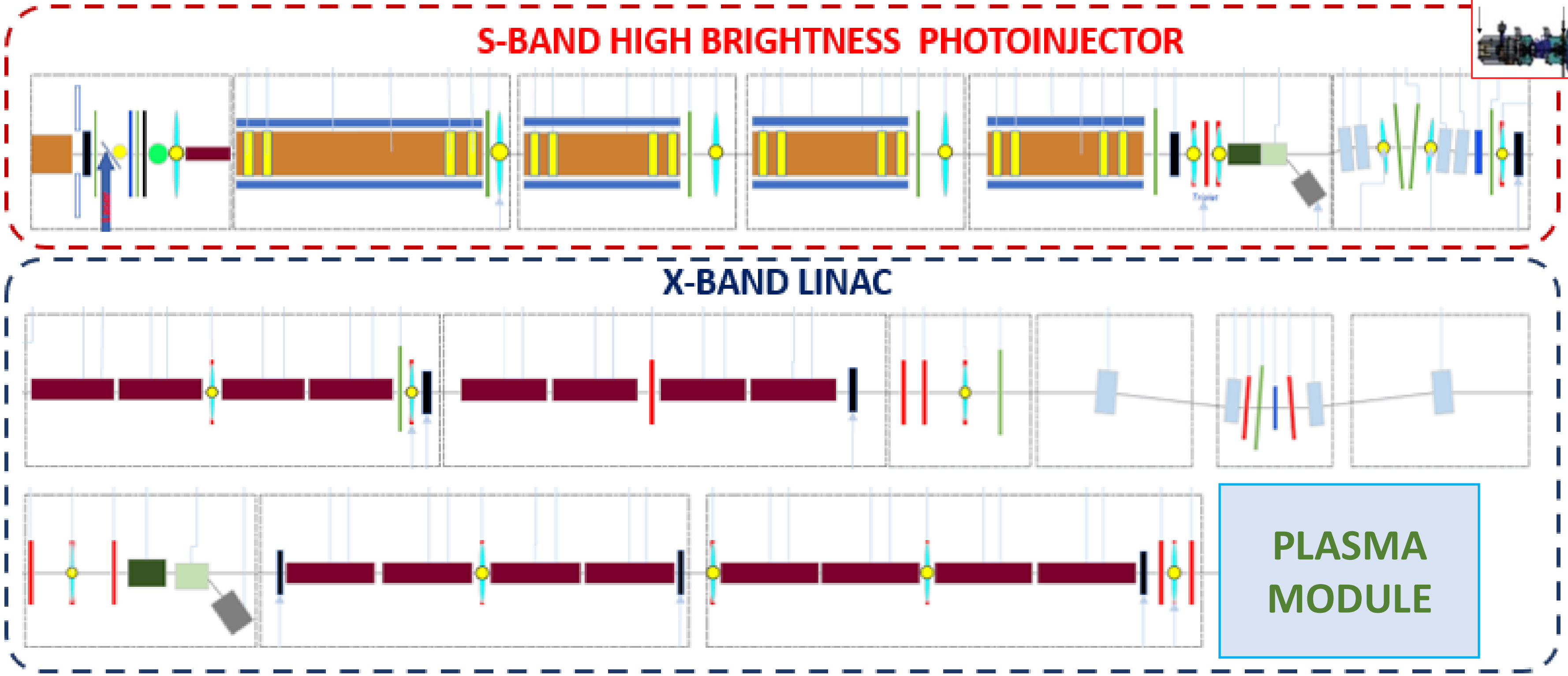
EuPRAXIA@SPARC_LAB: an high brightness PWFA

EuPRAXIA at SPARC_LAB

Funded by the European Union

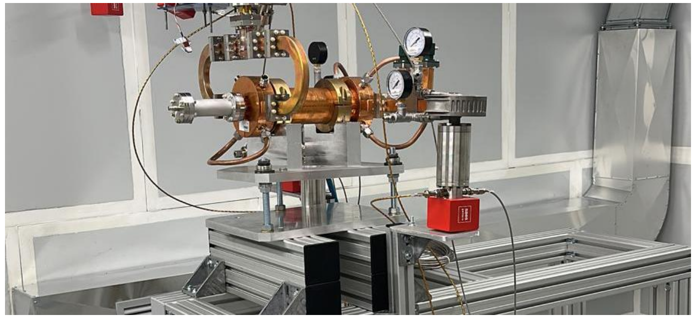
SPARC-like photoinjector (*)

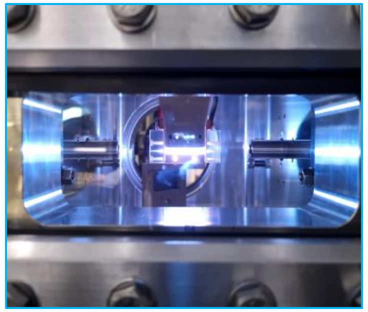




A combination of **cutting edge technology:**

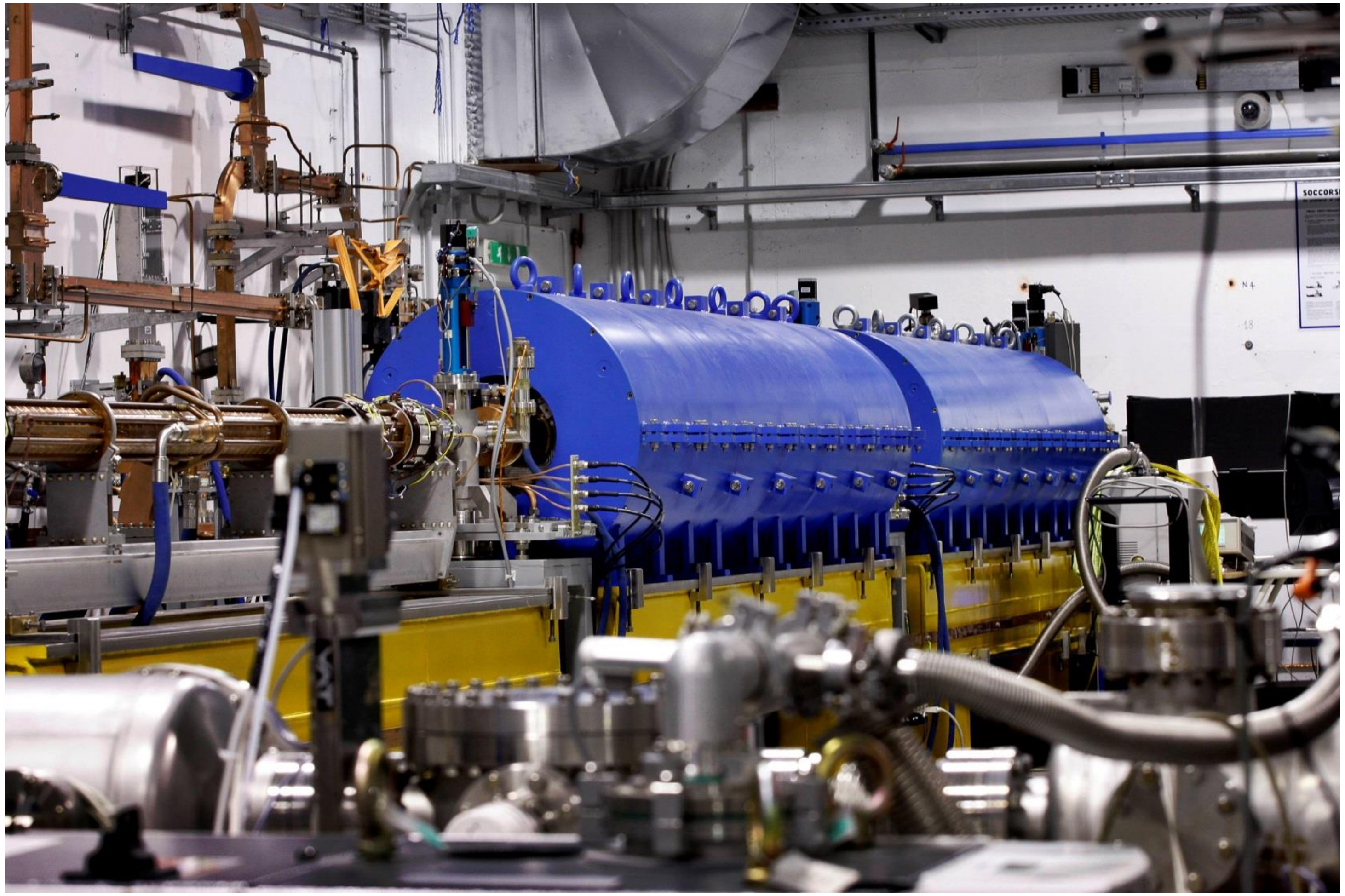
- *high brightness RF injector*
- *X-band linac*
- *Plasma module for PWFA*





Intense R&D Program on critical components

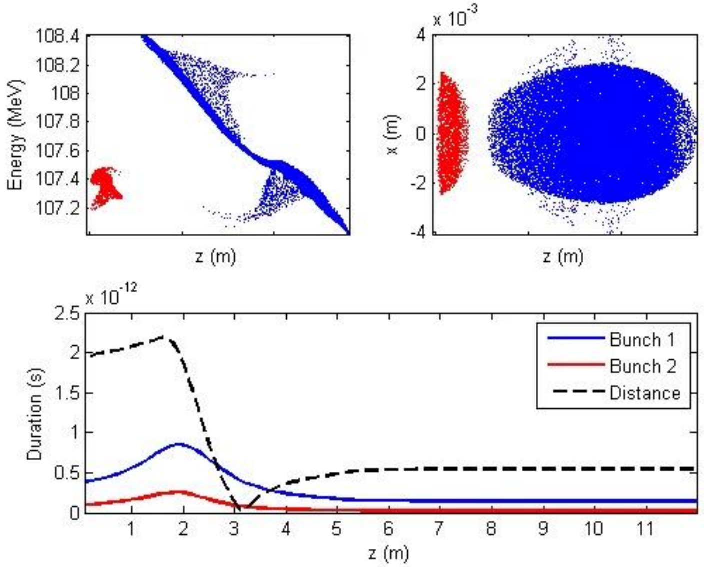
High quality electron beam

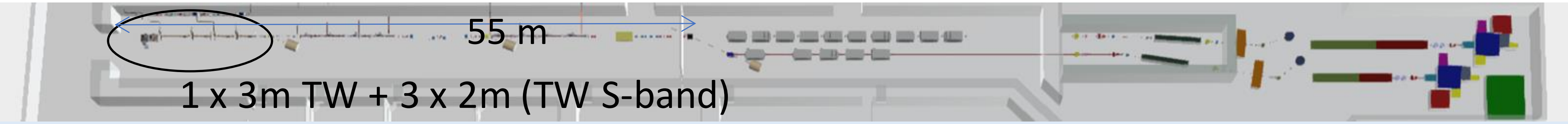


courtesy of E. Chiadroni

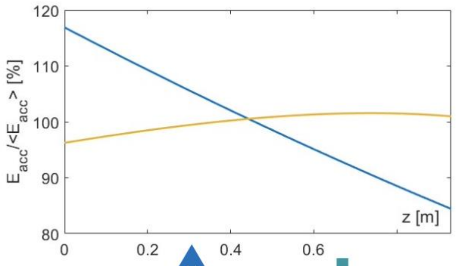
Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

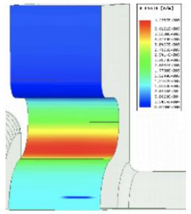
Table 7.2: Driver and witness beam parameters at the end of photo-injector.

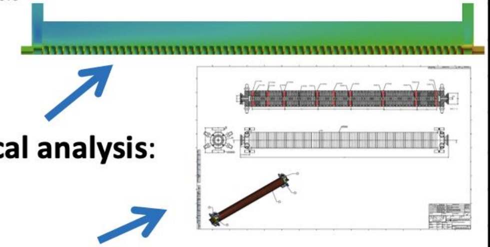




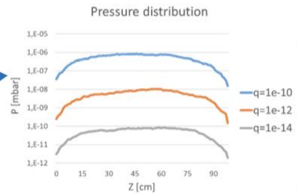
World`s Most Compact RF Linac: X Band

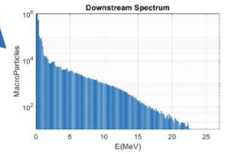




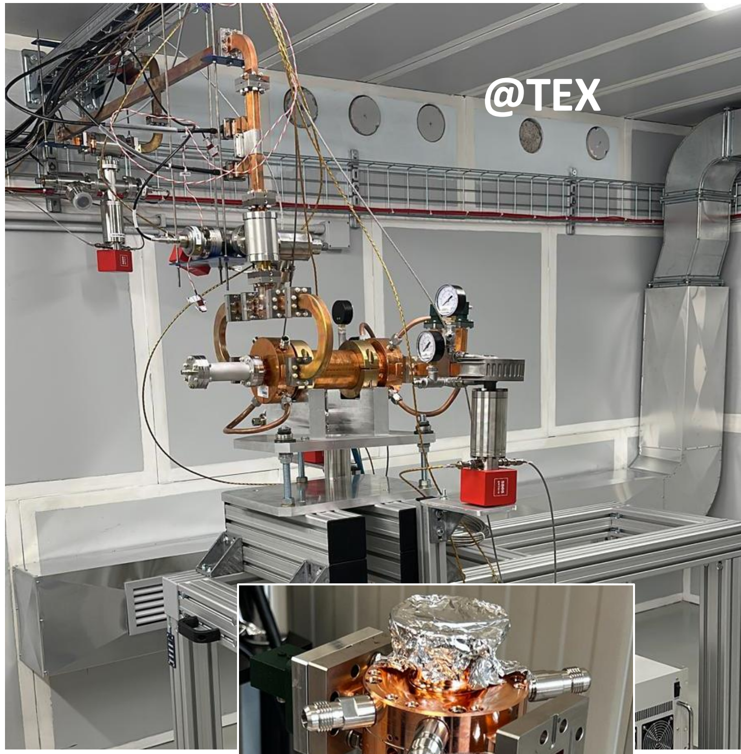


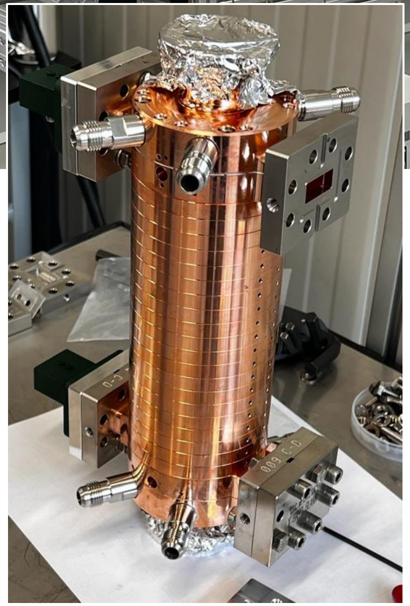
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*



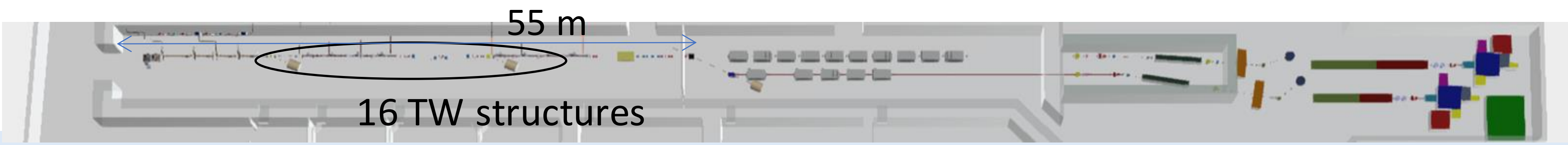


PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt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



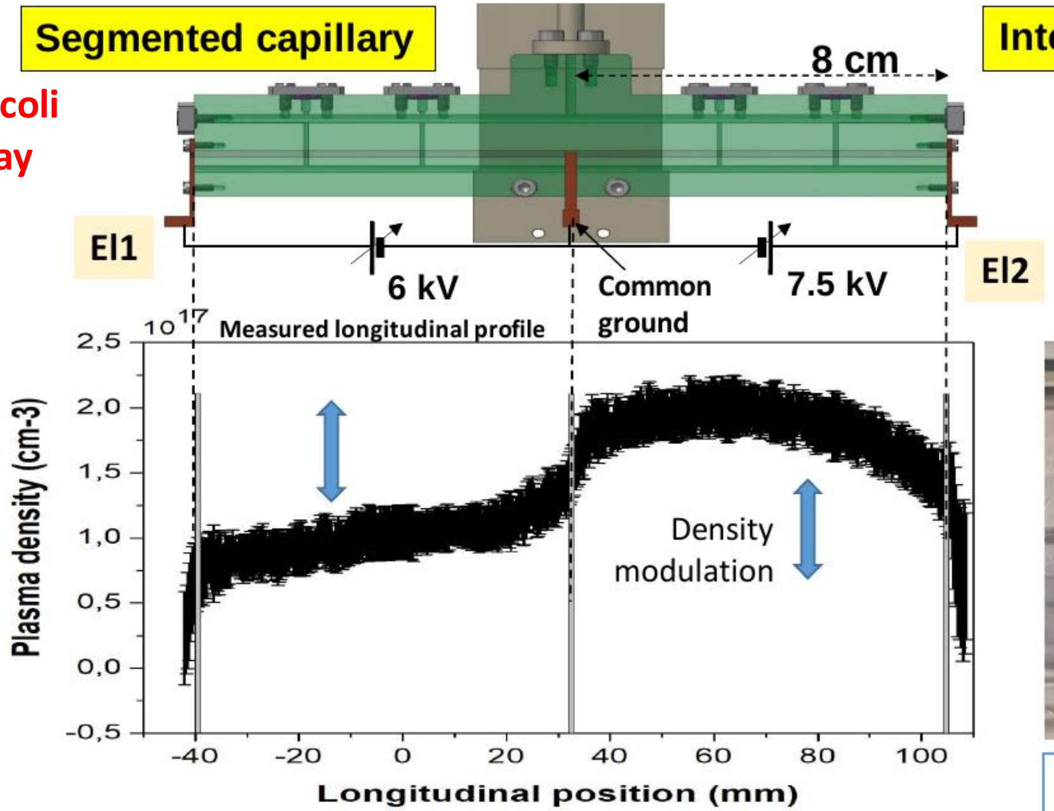


Courtesy of D. Alesini, F. Cardelli

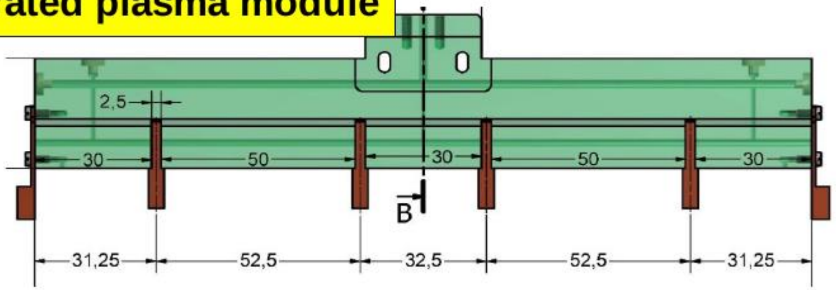


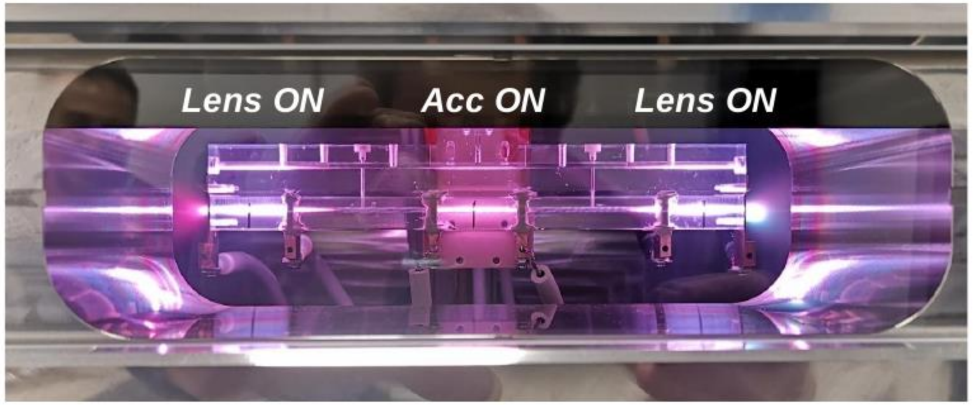
Plasma modeles R&D

Talk of L.Crincoli on Wednesday (WG8)



Talk of R. Pompili on Thursday (WG1)

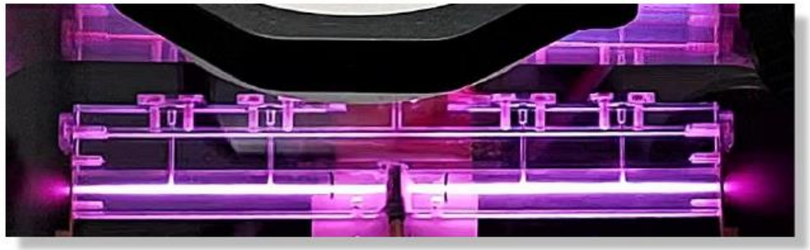




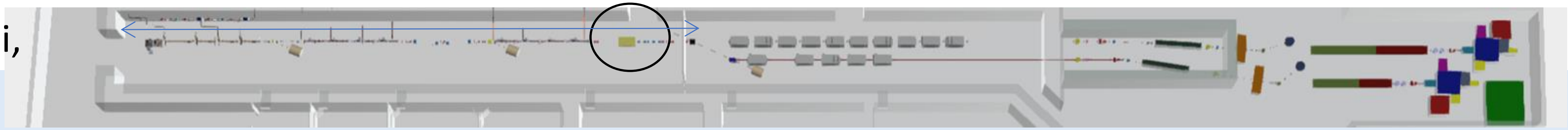
- **Plasma sources larger than 40 cm** (m-scale) with HV pulses less than 10 kV
- Longitudinal **density modulation**
- **5 GeV** case for EuPRAXIA (1.5 GV/m m-scale capillary - density 10^{16} cm-3)
- Implementation of cutting edge **integrated plasma-based structures**

Talk of S. Romeo on Monday (WG1)

R&D on plasma ramps



Courtesy of A. Biagioni, R. Pompili



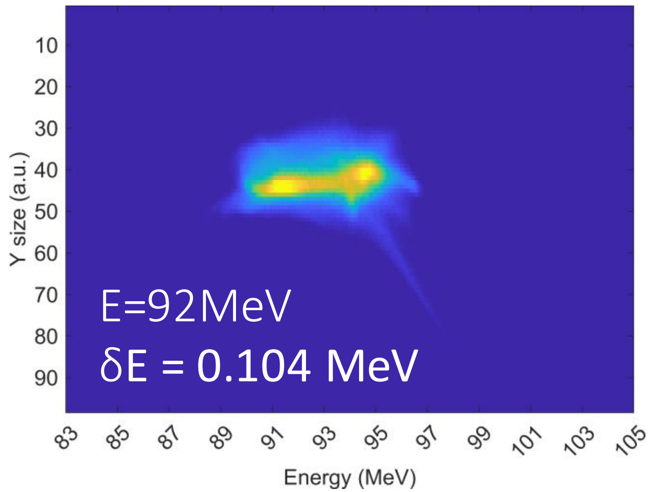
The SPARC_LAB experience

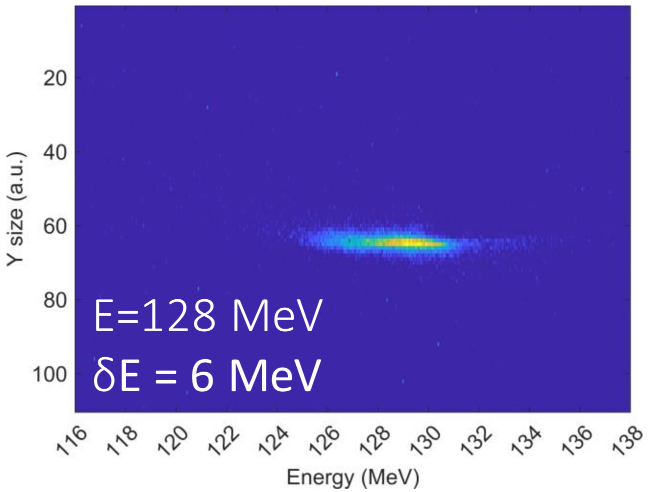
Funded by the European Union

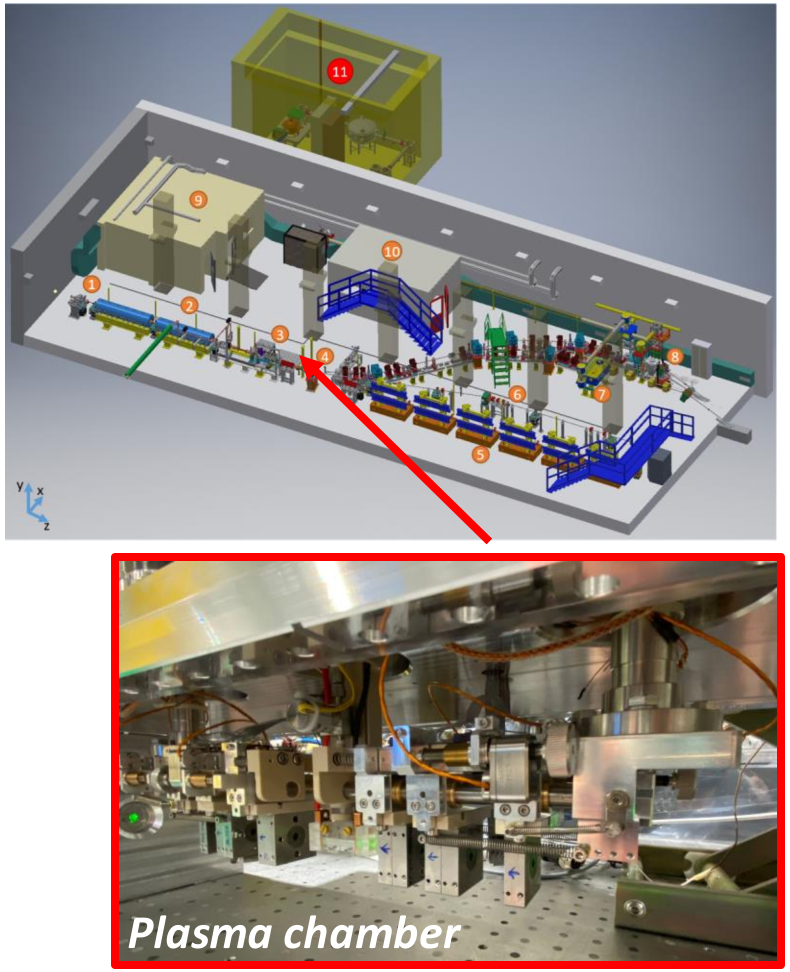
SPARC_LAB test facility at LNF, in the last years devoted to R&D activity and experiments on plasma accelerators and FEL
(consisting in a conventional high brightness RF photo-injector, SPARC, and a multi-hundred terawatt laser (FLAME))

Achieved (last November) 1.2 GV/m accelerating gradient (30 MeV in 3 cm)!

- 500 pC driver followed by a 50 pC witness
- plasma density ~2x10^{15} cm^{-3}







Witness energy measurement before and after the plasma

- Pompili, R., et al. "Free-electron lasing with compact beam-driven plasma wakefield accelerator." *Nature* 605.7911 (2022): 659-662.
- Galletti, M., et al. "Stable operation of a free-electron laser driven by a plasma accelerator." *Physical Review Letters* 129.23 (2022): 234801.

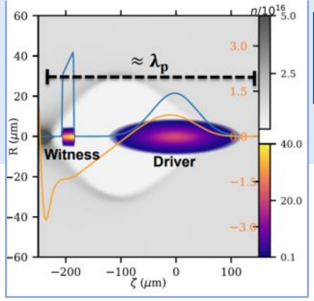
Talk of M. Opromolla on Monday (WG1)

Crucial activity for the forthcoming EuPRAXIA@SPARC_LAB project!

Beam Dynamics Advanced Concepts

EuPRAXIA at SPARC_LAB

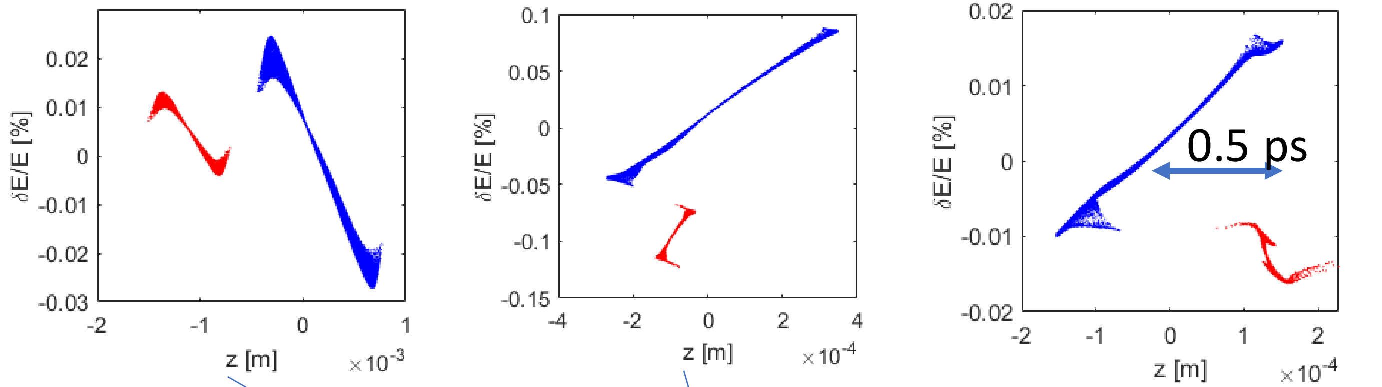
Talk of A. Giribono on Wednesday, WG1



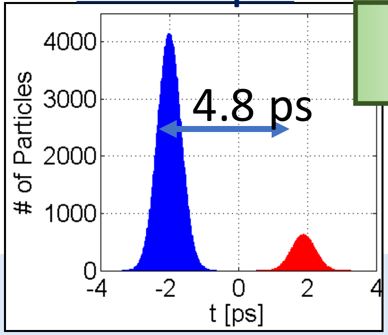
- Beside the FEL specifications, the <u>reference working point</u> has been determined by the plasma module
  - **At least 500 MeV energy gain (in less than 1 m)**
  - Weakly non-linear regime

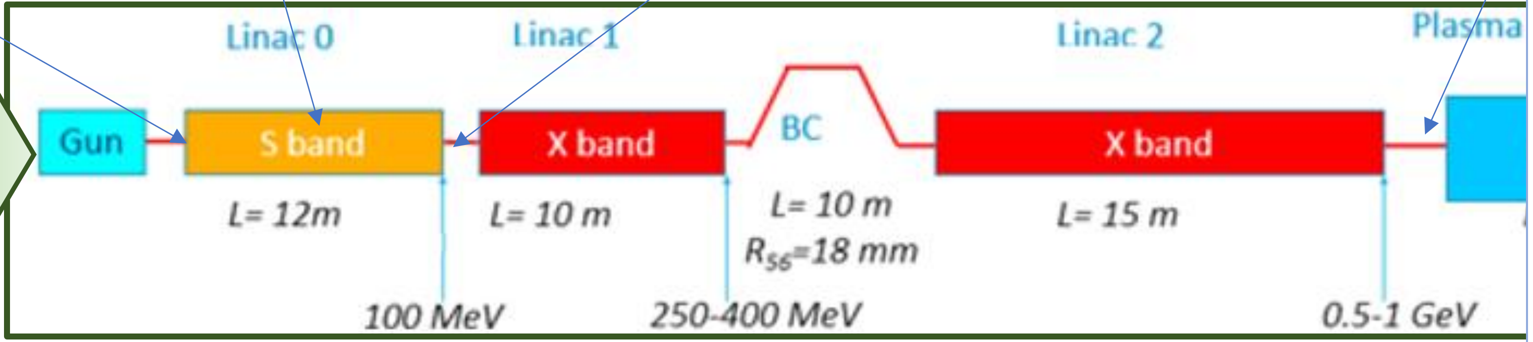
1. 200-500 pC driver + 30-50 pC witness
2. plasma density order $\mathbf{10^{16} cm^{-3}}$ ($\lambda_p = 334\ \mu m$)
3. Driver-witness separation around **0.5 ps** (i.e. $\lambda_p/2$)
4. Driver and witness bunches of 200 fs and 10 fs rms
5. Driver and witness spot size of 4 and 1 μm with α=1

<u>Velocity bunching technique</u>

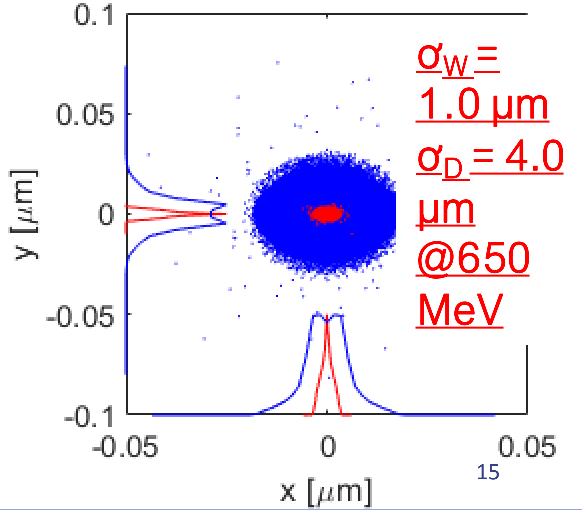


<u>Laser comb technique</u>





<u>Strong focusing system</u>



Courtesy of C. Vaccarezza, A. Giribono

Stability and reproducibility PWFA study

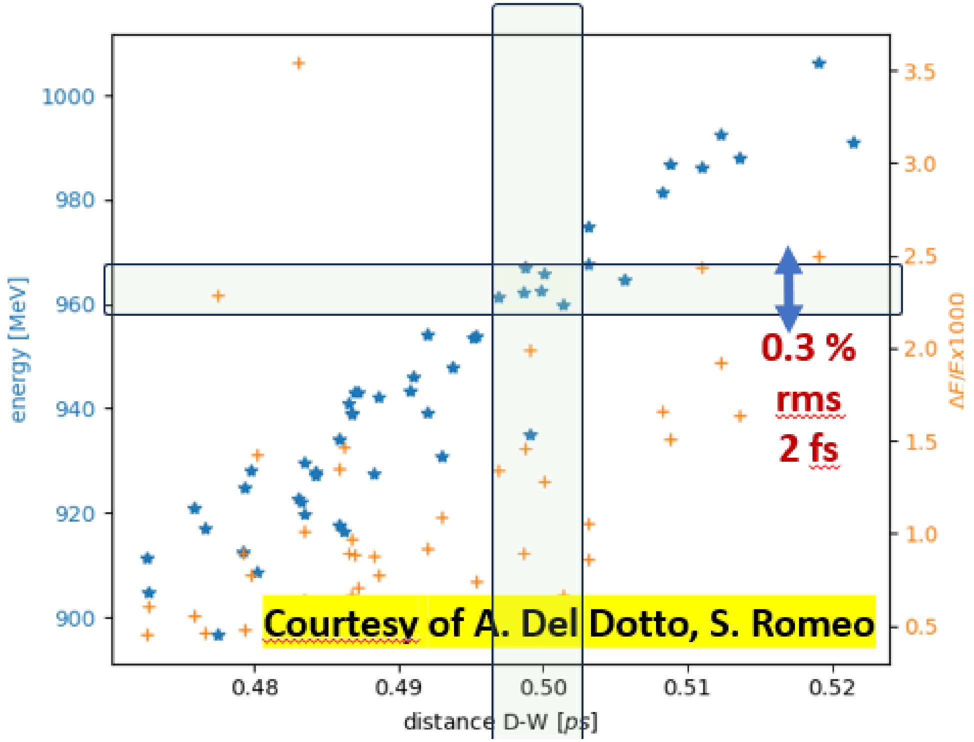
FEL requirement

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

D-W separation

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

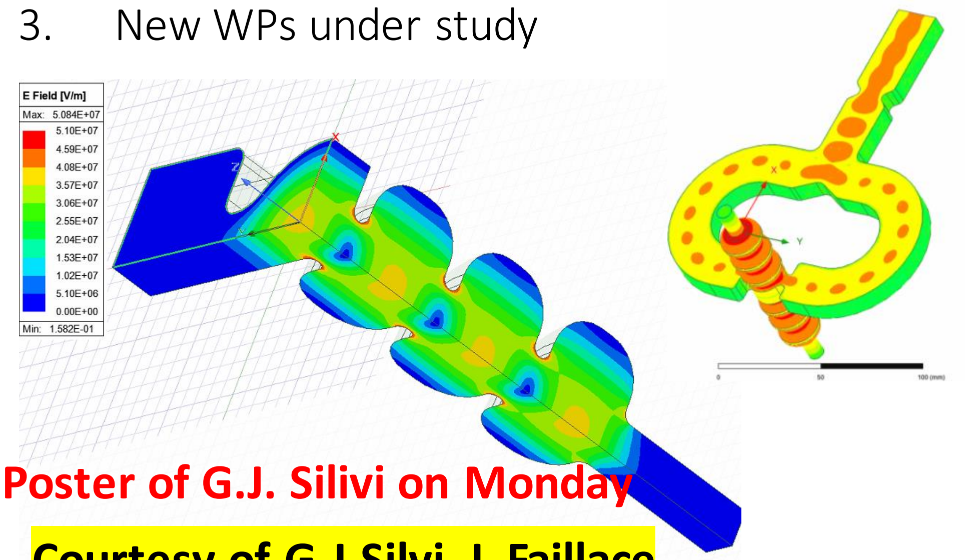
$$2 \le a \le 4$$



Results obtained by means of **start to end simulations** taking into account **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 are under study: solid state modulators (C-band), **Δt (from 30 down to 15 fs)**
2. Inseriton of an higher harmonic accelerating cavity to stabilize the beam current profile
3. New WPs under study



Poster of G.J. Silivi on Monday

Courtesy of G.J.Silvi, L.Faillace

Expected electrons parameters

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

Courtesy of C. Vaccarezza

- Two different configurations:
  - $\sim$500 MeV beam from the X-band linac + 50 cm capillary **PWFA** acceleration up to **1.2 GeV**
    - Smaller accelerated charge
    - Shorter pulses
    - Final energy easily upgradable in future with similar building occupancy ($\sim m$)
  - $\sim$**1 GeV** beam from the **X-band** linac alone (with additional RF power)
    - Larger charge per bunch
    - Longer pulses
    - At the upper limit of RF technology (not easily upgradable without extending the occupancy)

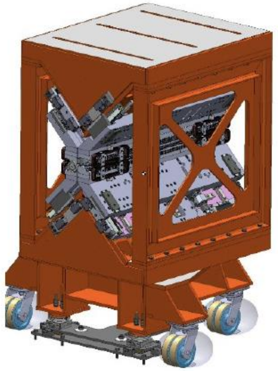
Radiation generation: FEL

Funded by the European Union

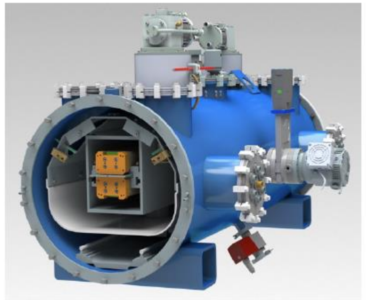
Two FEL lines:

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



Designed by Kyma

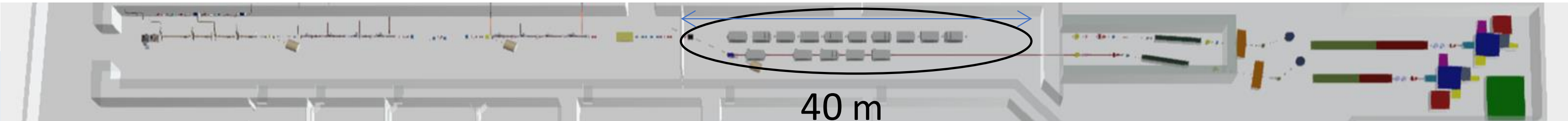


First *SABINA* undulator in FRASCATI March 29, 2023

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.

Frascati 06/05/23 – EUPRAXIA TDR



Courtesy of L. Giannessi

Radiation generation: FEL

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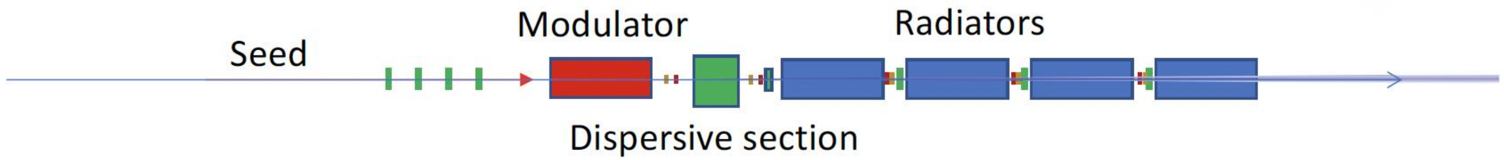
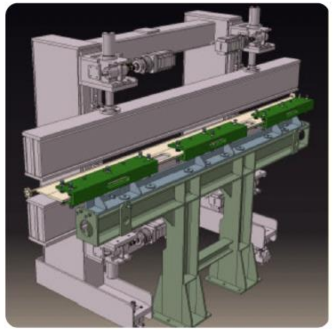


FERMI FEL-1 Radiator



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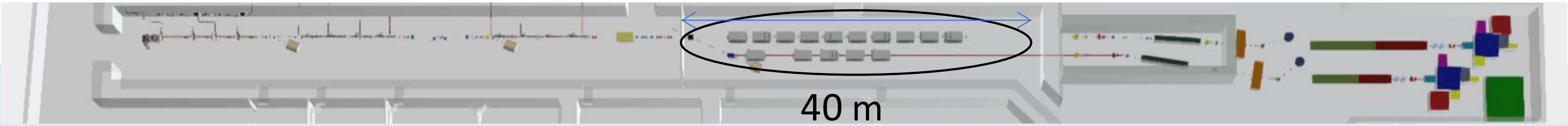
Frascati 06/05/23 – EUPRAXIA TDR



Courtesy of L. Giannessi

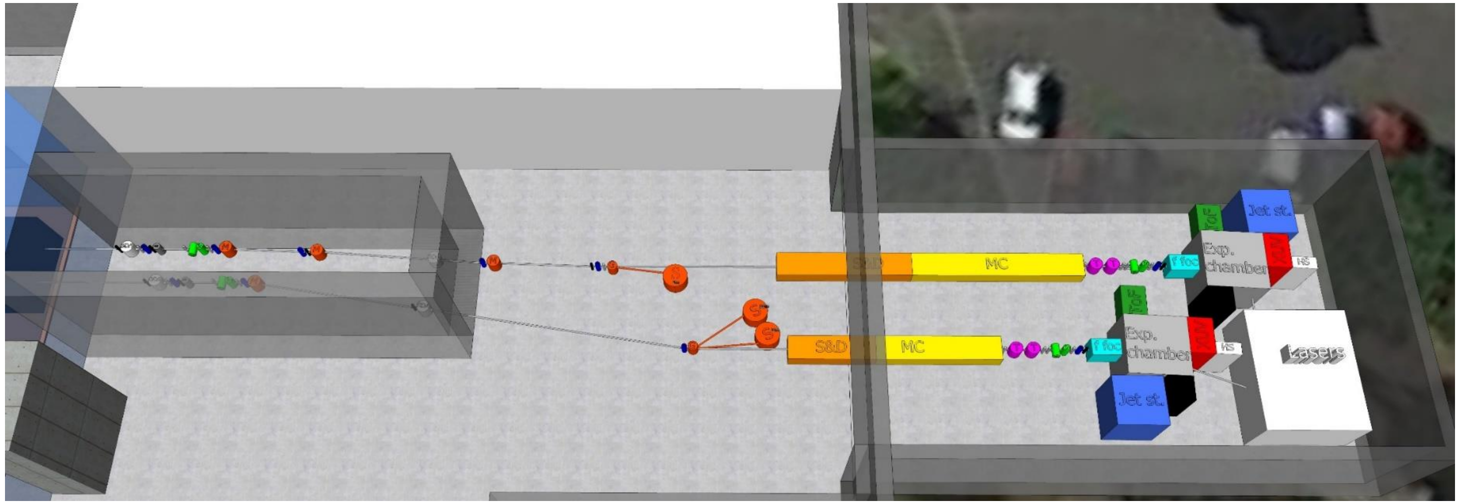
Expected FEL performances

Funded by the European Union

Parameter	Unit	AQUA PWFA	AQUA X-band	ARIA PWFA	ARIA X-band
Radiation Wavelength	*nm*	3-10	4-10	50-150	50-180
Photons per Pulse	$\times 10^{12} \times 10^{12}$	0.25-1	0.25-1	10-60	12-150
Photon Bandwith	*%*	0.3	0.3	3	0.05
Configuration		SASE		HGHG seeding	

Repetition rate 100 Hz

* Options to run @ 400 Hz are being explored

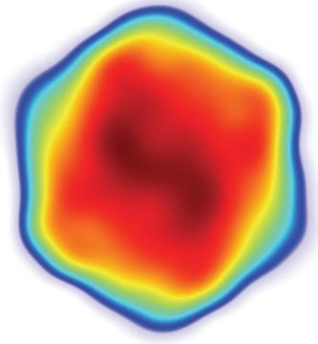


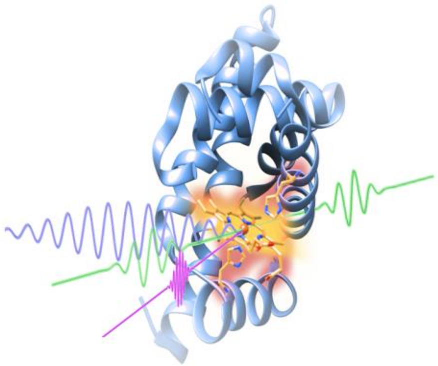
Courtesy of L. Giannessi, F. Stellato

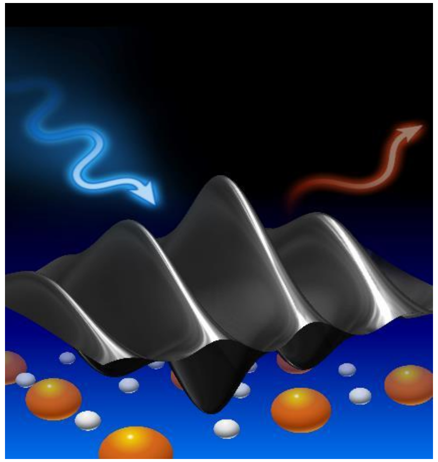
AQUA - Techniques & Samples in the water window

Experimental techniques and typology of samples

- Coherent imaging (advanced methods)
- X-ray spectroscopy
- Raman spectroscopy
- X-ray scattering

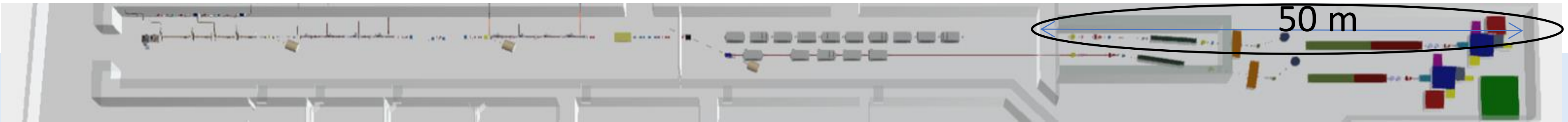






Proteins
Viruses
Bacteria
Cells
Metals
Semiconductors
Superconductors
Magnetic materials
Organic molecules
Organometallic compounds

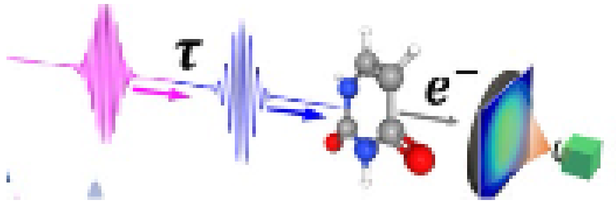
Balerna *et al.* Cond. Mat. 2022



Courtesy of F. Stellato

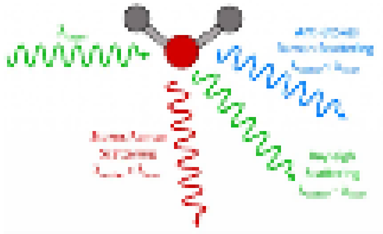
ARIA - Techniques & Samples @ 50-180 nm

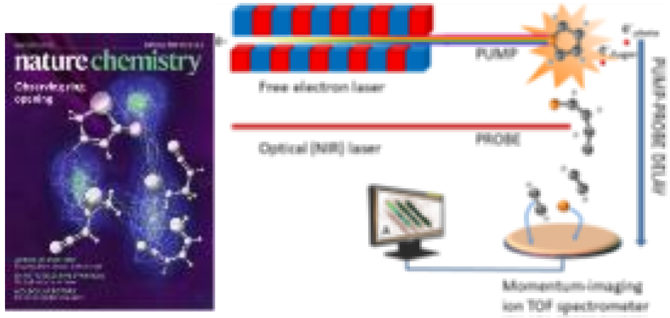
Experimental techniques and typology of samples (and applications)



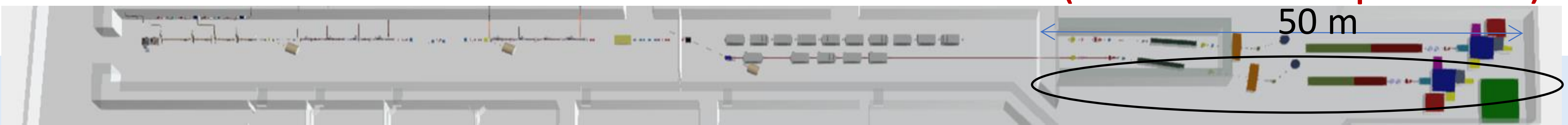
Villa *et al.* Cond. Mat. 2022

- Photoemission Spectroscopy
- 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 e deposition)



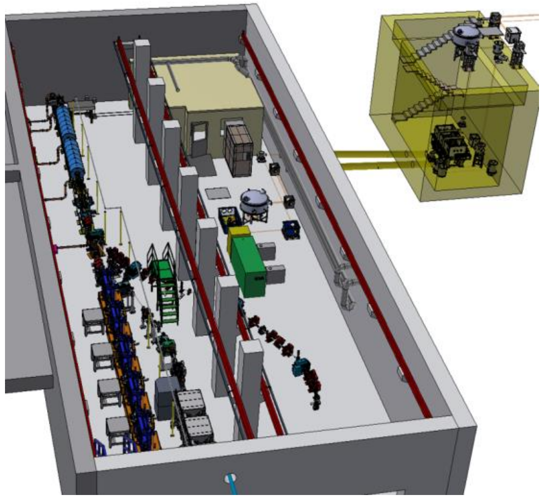
Courtesy of F. Stellato

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

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).

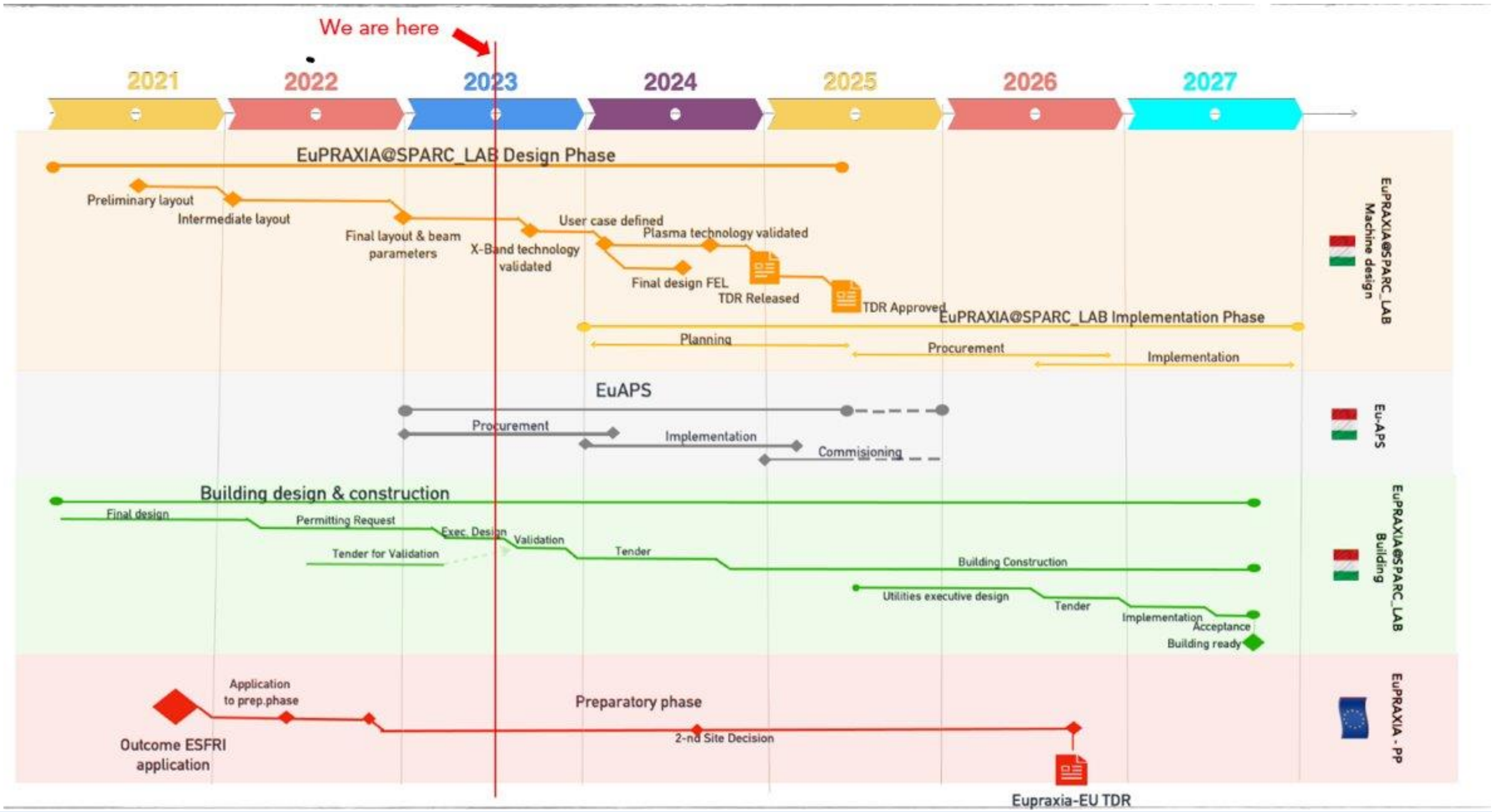
Parameter	Value	unit
Electron beam Energy	100-500	MeV
Plasma Density	10^{18}-10^{19}	cm^{-3}
Photon Critical Energy	1 -10	keV
Number of Photons/pulse	10^{7}-10^{9}	
Repetition rate	1-5	Hz
Beam divergence	3-20	mrad



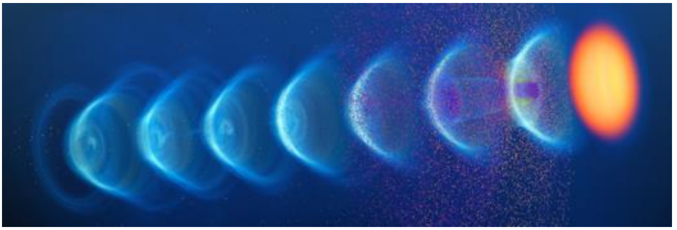
Courtesy of A. Cianchi
Talk on Monday (WG5)

EuPRAXIA Project Timeline

Funded by the European Union



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:** THE ENTIRE EUPRAXIA@SPARC_LAB TEAM

Funded by the European Union

Thank for your attention