EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EUPRAXIA: stato ed attività connesse (SPARC_LAB, EuAPS-PNRR)

R. Pompili (LNF-INFN)
On behalf of the EuPRAXIA@SPARC_LAB collaboration

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

A new 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 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.

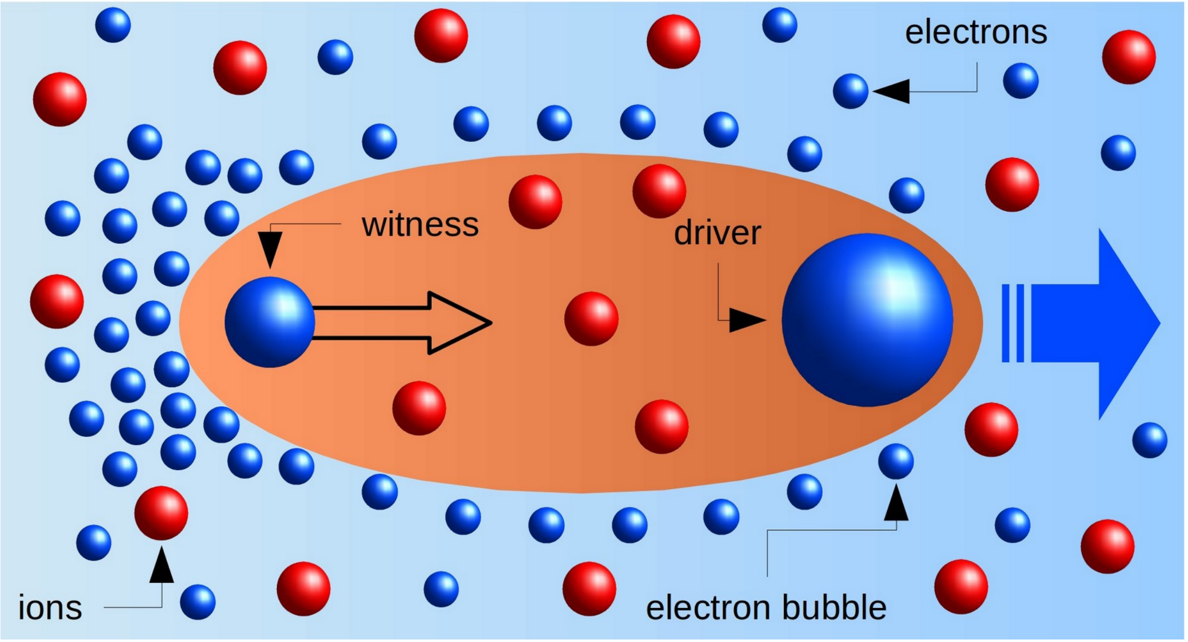
This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the 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.

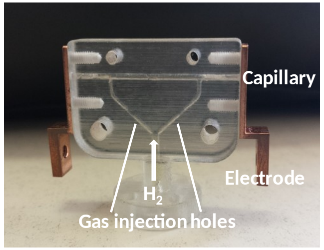
However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

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/

Plasma acceleration





$$E_0 = \frac{m_e c \omega_p}{e} \simeq 96\sqrt{n_0(cm^{-3})}$$

$$\rightarrow E_0 \approx 10\frac{GV}{m} @ n_0 = 10^{16}\, cm^{-3}$$

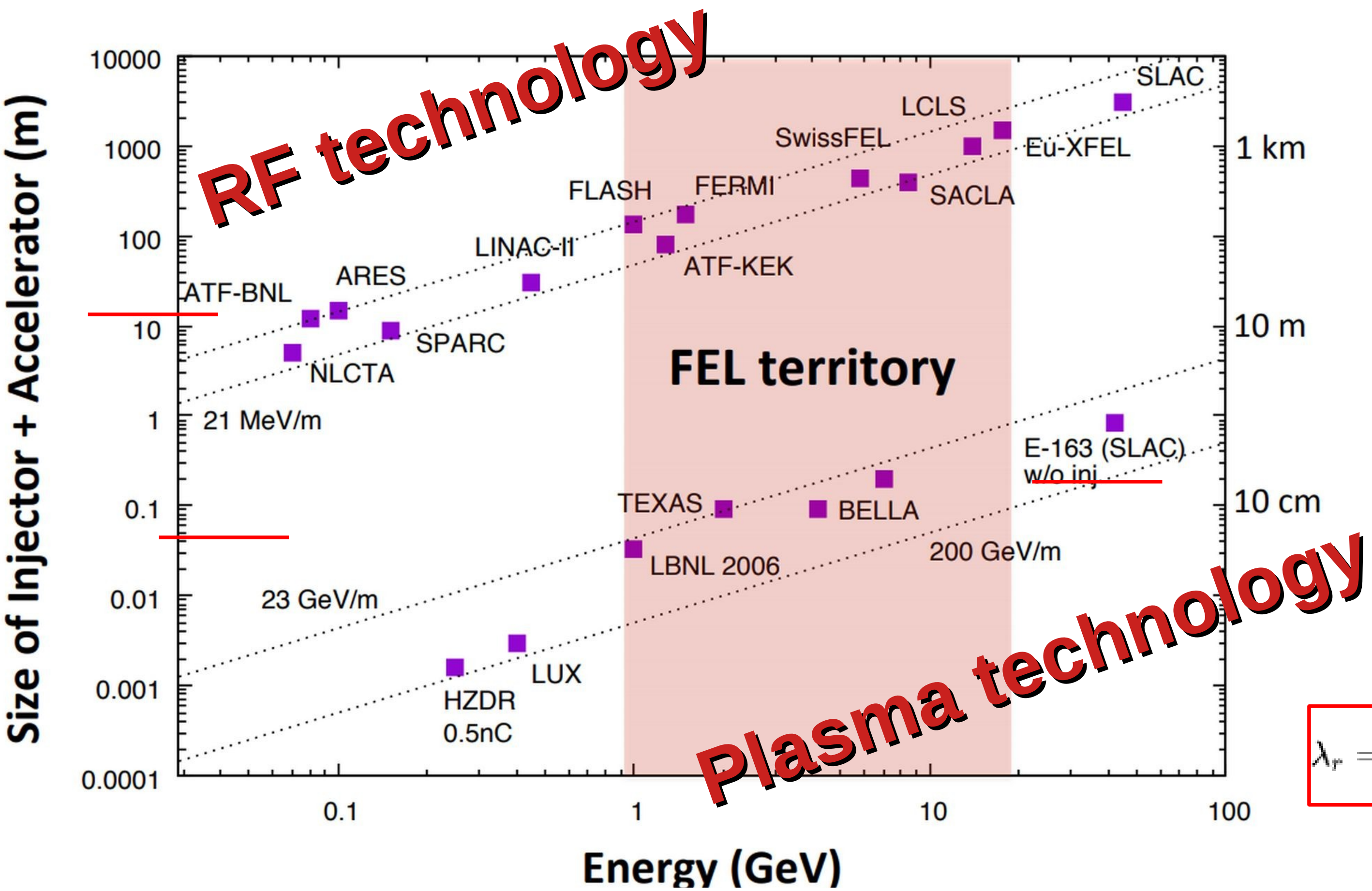
The **driver** creates the positive sphere (or ***bubble***). It can be a

- *particle bunch (PWFA)*
- *laser pulse (LWFA)*

The **witness** can be

- *Self-injected*
- *Externally injected*

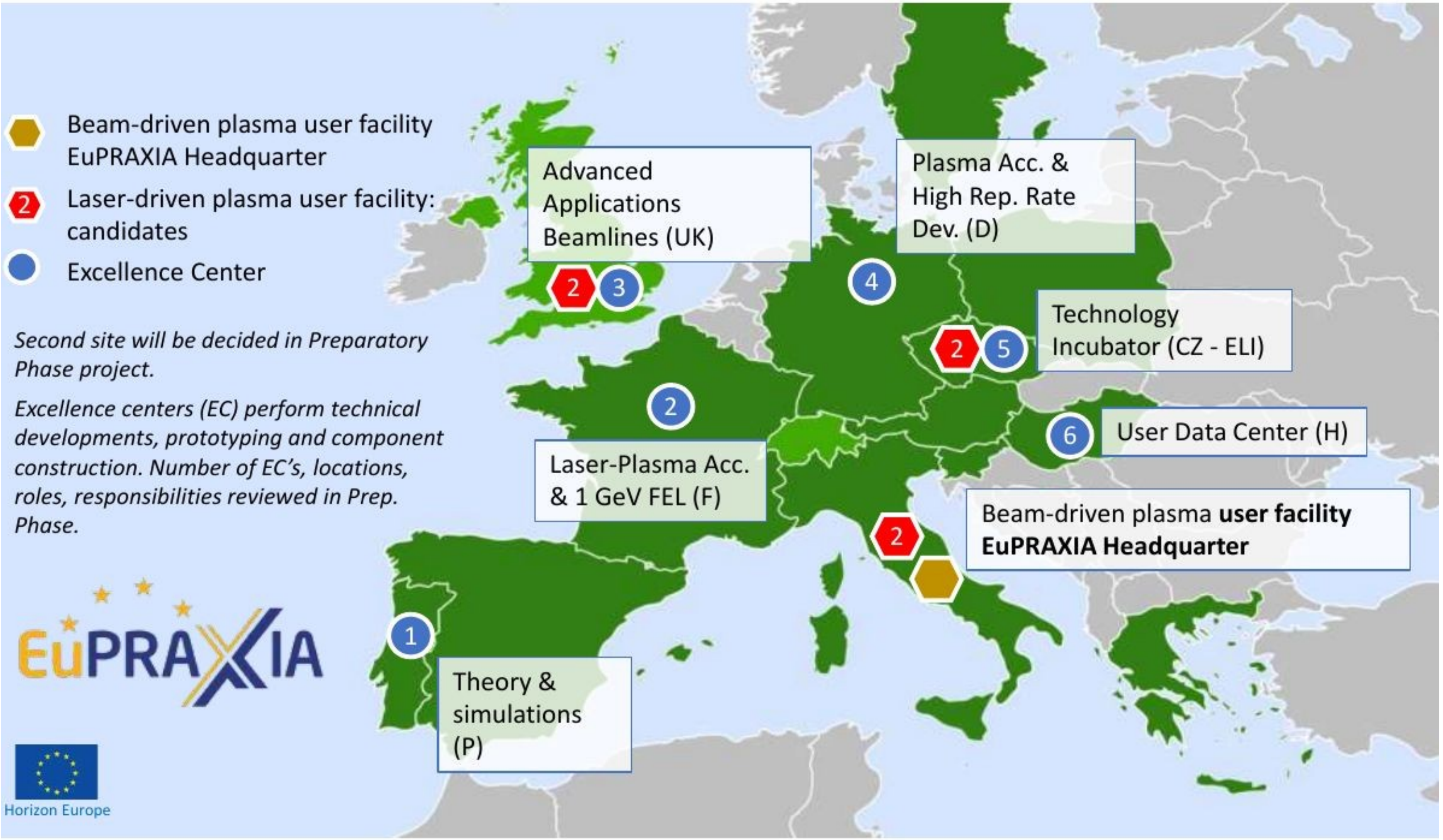
RF and Plasma technology



$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

R. Assmann

EuPRAXIA pillars

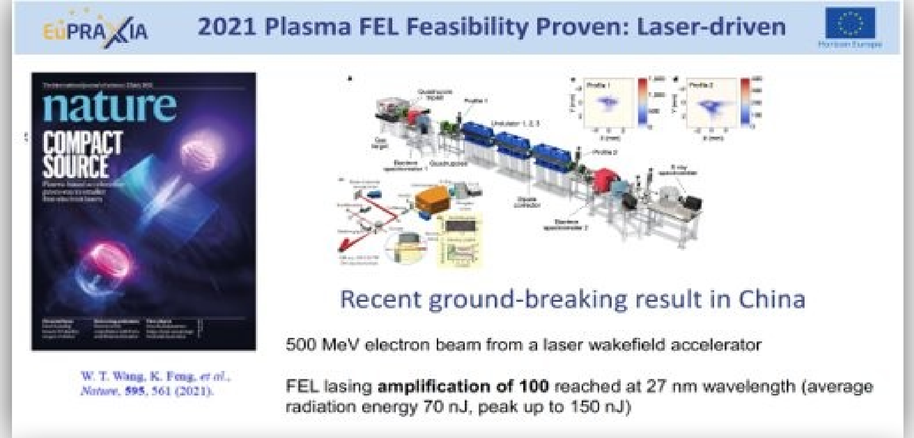


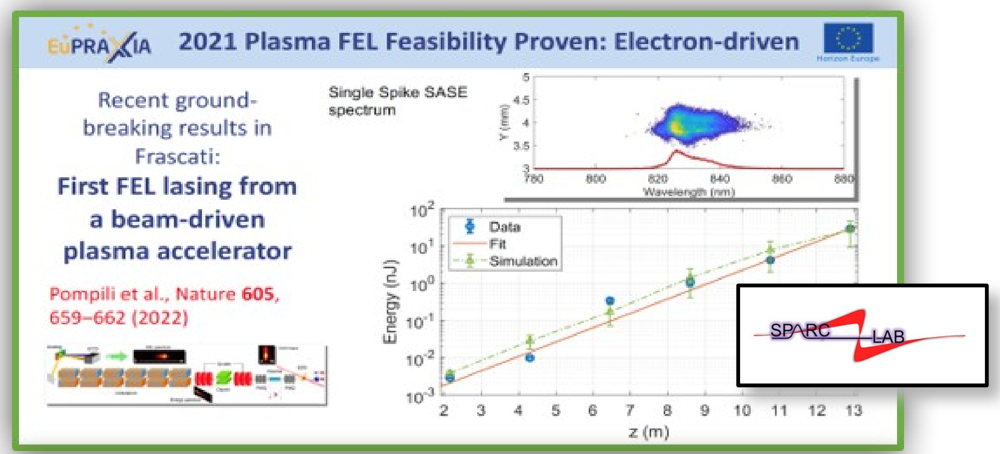
Two EuPRAXIA pillars at LNF:

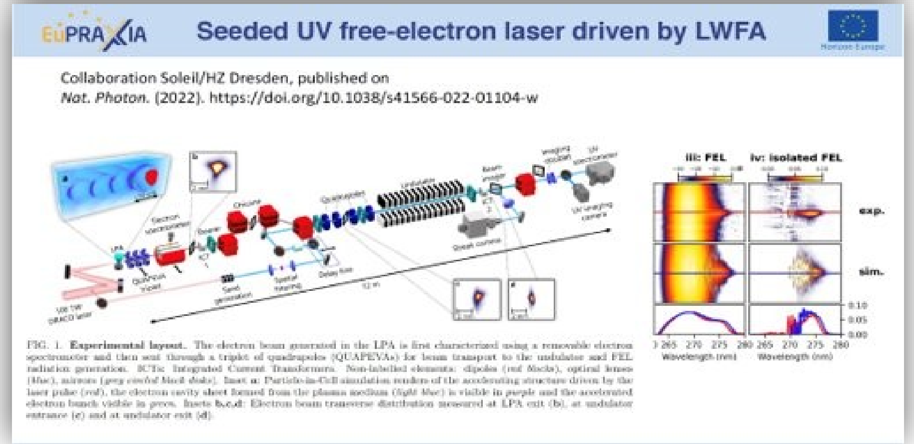
1. EuPRAXIA@SPARC_LAB
   a new infrastructure to hosting a facility with
   - *Plasma acceleration stage*
   - *1 GeV X-band linac*
   - *Two FEL lines driven by high gradient plasma accelerator (~4 nm and 50-180 nm)*
2. EuAPS (Advanced Photon Sources) a fast, cheap and compact X-ray source for users applications

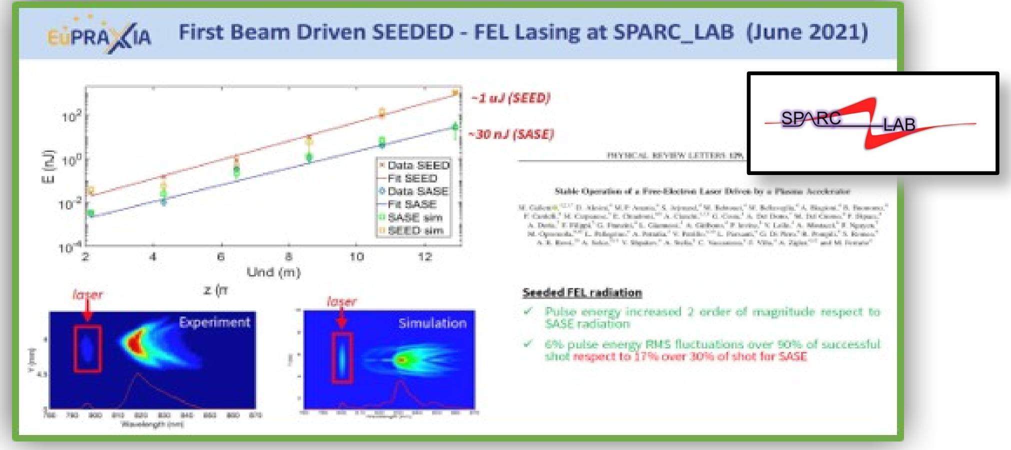
Pilot plasma-driven FELs experiments

Funded by the European Union

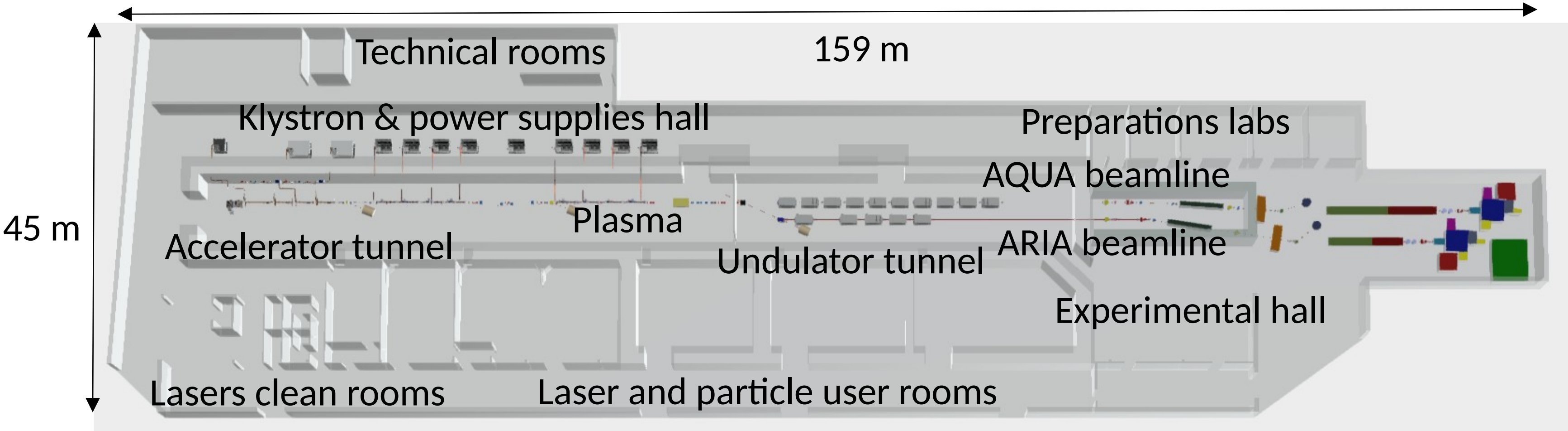


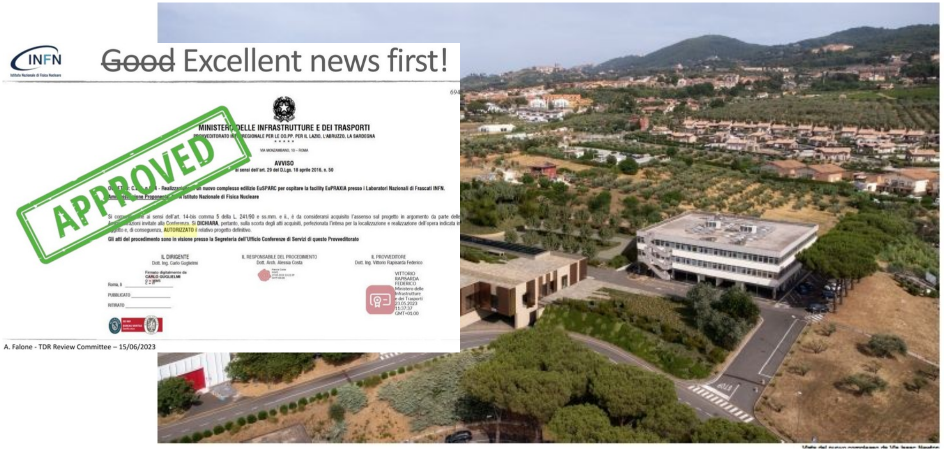






EuPRAXIA@SPARC_LAB layout





Headquarters and Site 1

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

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

FEL requirements

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

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

where

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

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

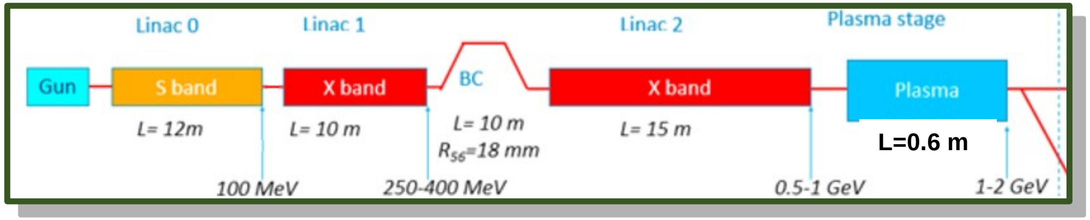
$$P_F \sim 1.6\,\rho_{fel} P_{beam}$$

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

M. Ferrario

Electron beam parameters

Parameter	Unit	PWFA	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	um	0.5	0.5

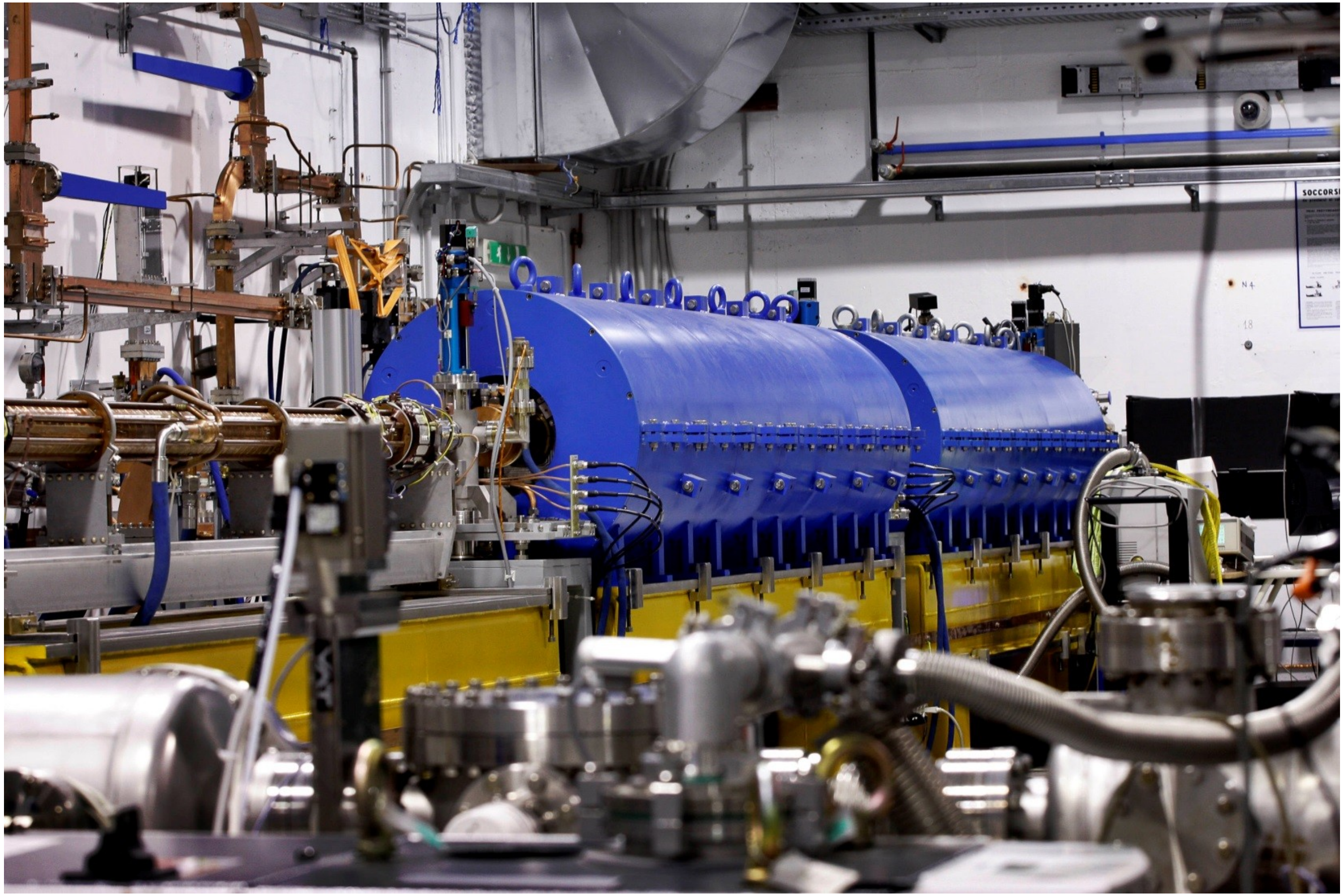


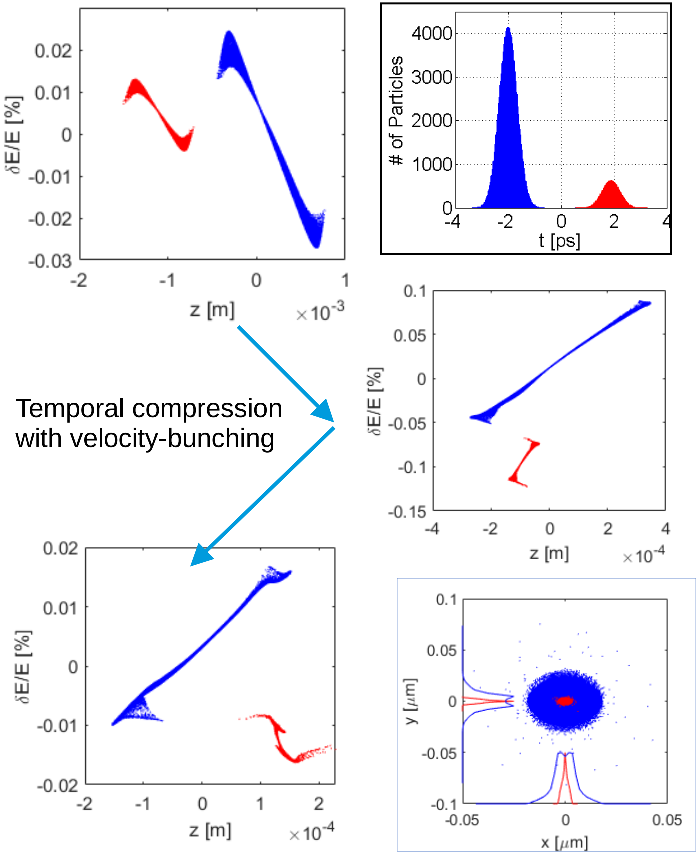
Two different configurations:

- 500 MeV beam from the X-band linac + 500 MeV from the compact plasma module
  - *Smaller accelerated charge*
  - *Shorter pulses*
  - *Final energy easily upgradable (up to 5 GeV) with similar building occupancy*
- 1 GeV beam from the X-band linac alone (requires additional RF power)
  - *Larger charge per bunch*
  - *Longer pulses*
  - *It exploits the largest RF field achievable with X-band technology*

S-band Photo-injector

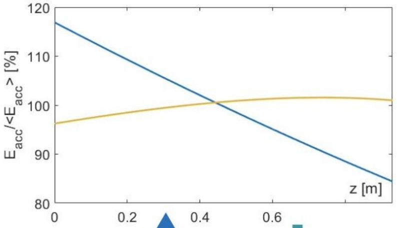
Funded by the European Union

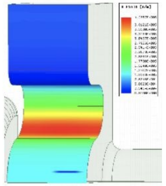




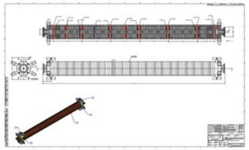
E. Chiadroni, A. Giribono, C. Vaccarezza

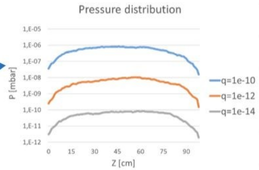
X-band LINAC, tests @ TEX

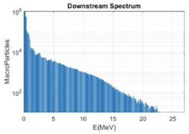




1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

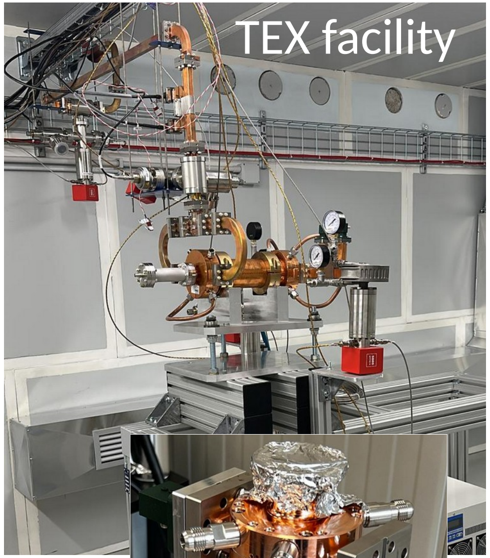


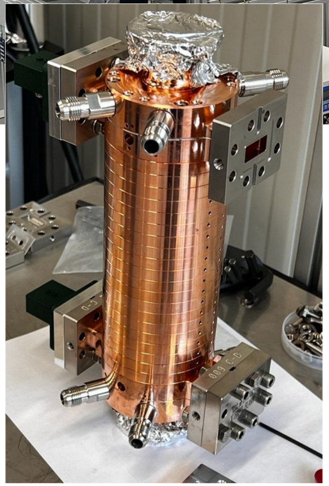




PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt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

TEX facility



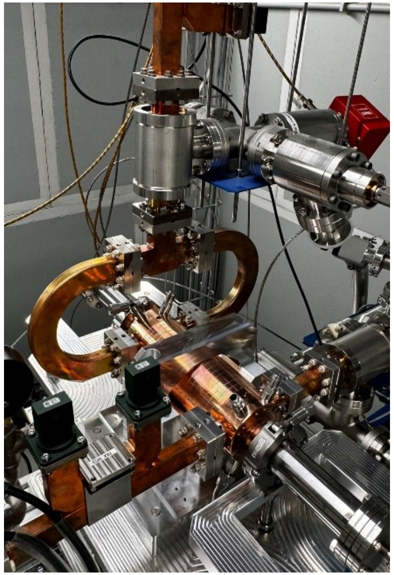


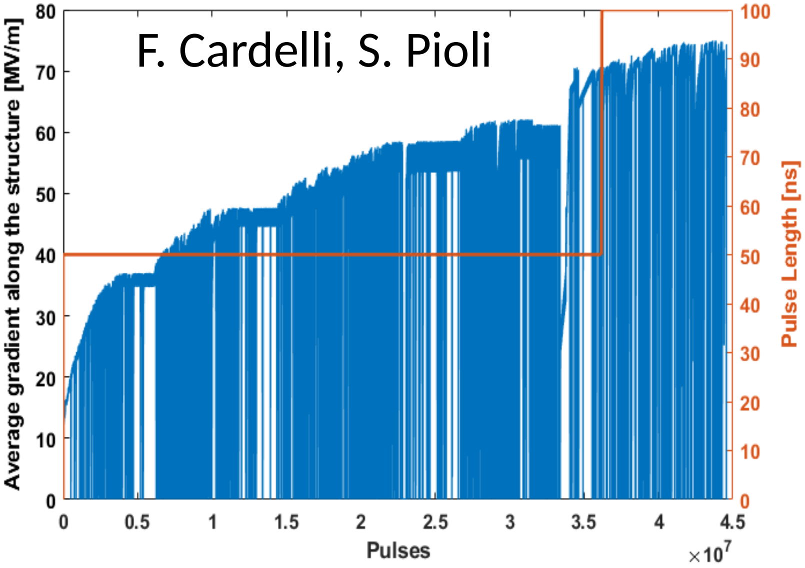
D. Alesini, F. Cardelli

20 cells EuPRAXIA X-band tests

Funded by the European Union

- From the 6th to the 17th of March we perform the high power test of the first EuPRAXIA@SPARC_LAB X-band structure prototype at **TEX**
- It is a 20 cells, constant impedance, RF prototype (the real structure will be 1 m long)
- In 10 days we reach an input pulse of 35 MW, 100 ns length at 50 Hz repetition rate, that correspond to an average gradient along the structure equal to 74 MV/m and a peak gradient at the structure input of 80 MV/m.





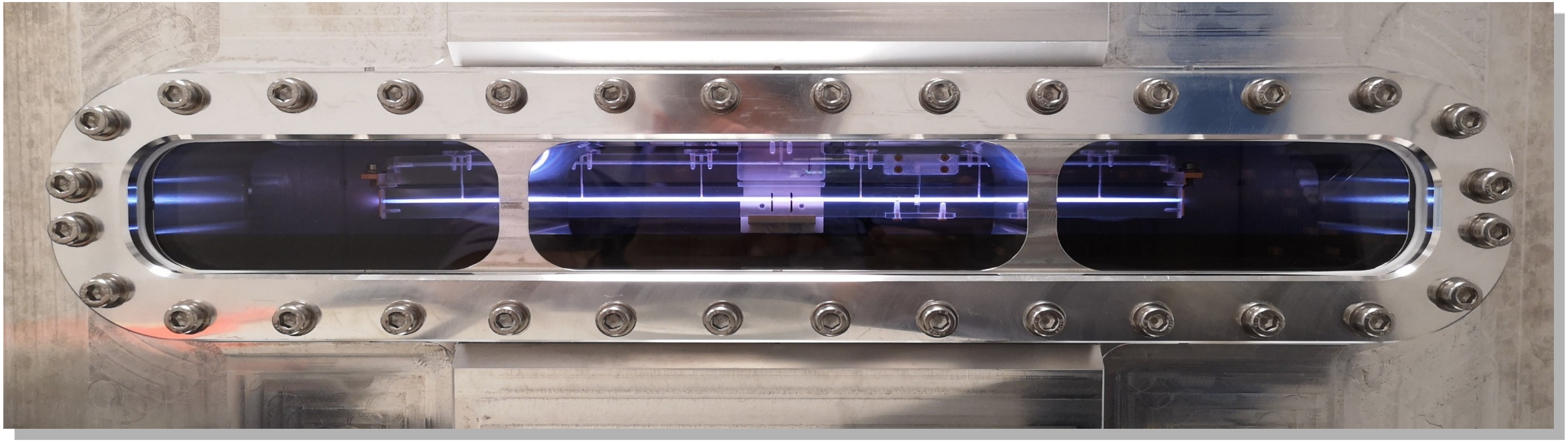
Control Room

LLRF system

RF Source

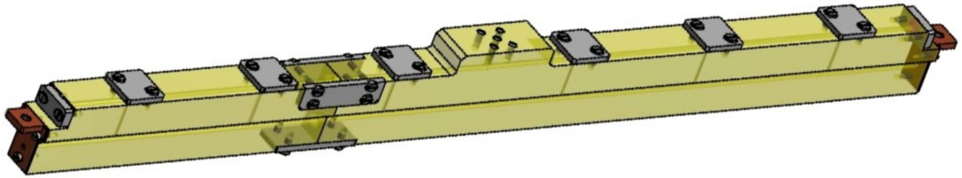
VKX8311A Klystron

Plasma module



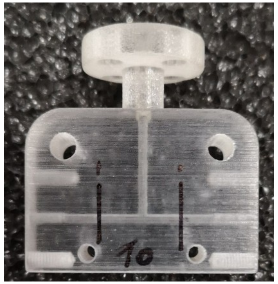
- 40 cm long capillary → 1st prototype for the EuPRAXIA facility
  - *Made with special junction to allow negligible gas leaks (<10^{-10} mbar)*
  - *Next step is to extend its length to 60 cm as required by last studies*
- Operating conditions
  - *1 Hz repetition rate (to be increased up to 100 Hz)*
  - *10 kV – 380 A minimum values for ionization*
  - *6 inlets for gas injection. Electro-valve aperture time 8-12 ms*

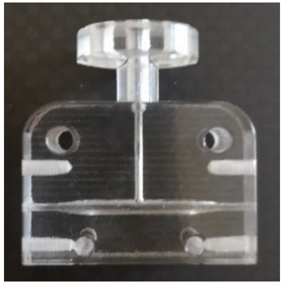
A. Biagioni, V. Lollo

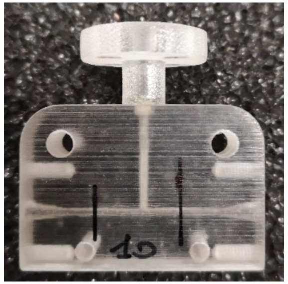


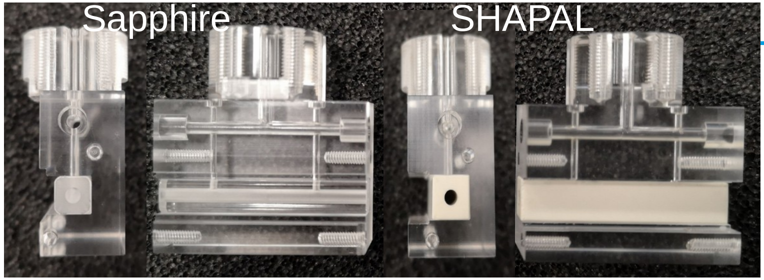
R&D on plasma acceleration

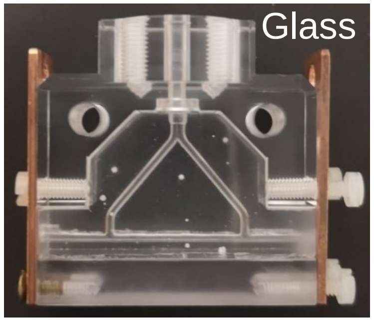
A. Biagioni, L. Crincoli

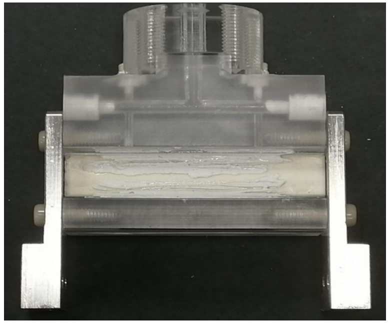




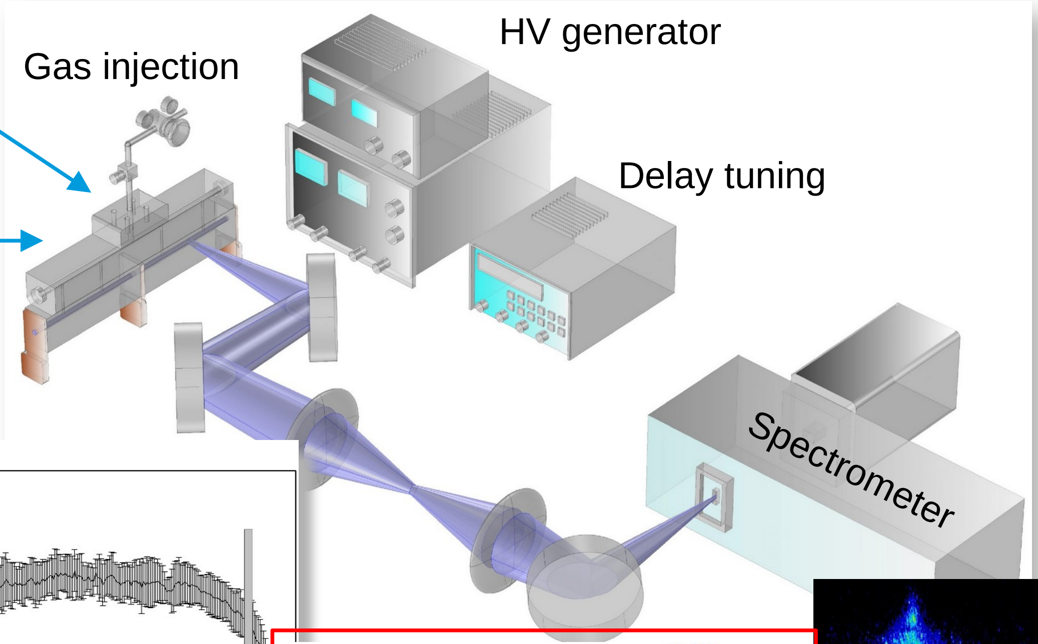


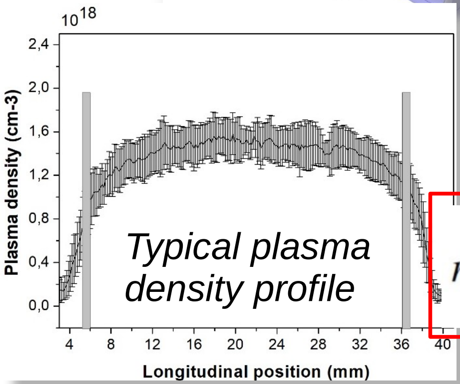




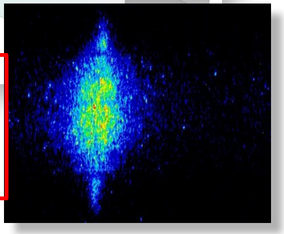


Capillary to be tested





$$n_e = 8.02 \times 10^{12} \left(\frac{\Delta\lambda}{\alpha}\right)^{3/2} cm^{-3}$$



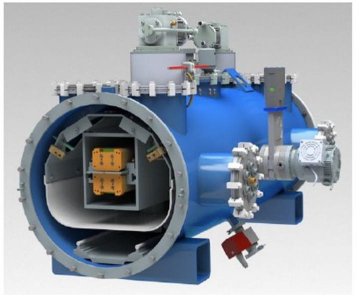
Stark broadening

FEL beamlines

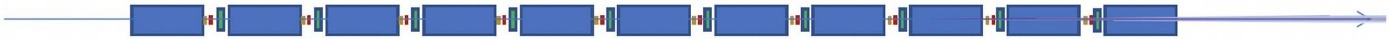
Funded by the European Union

Two FEL lines:

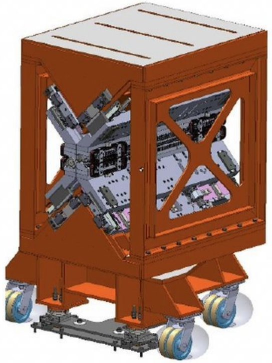
L. Giannessi



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

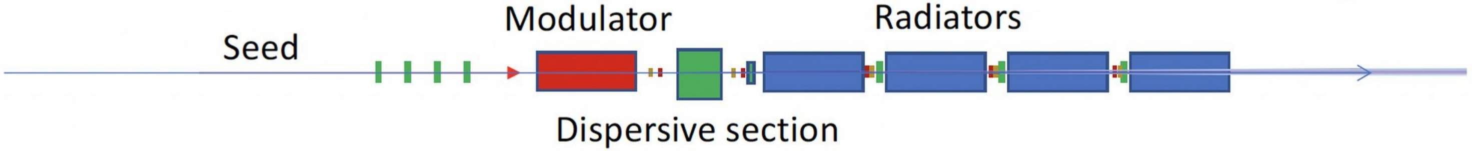


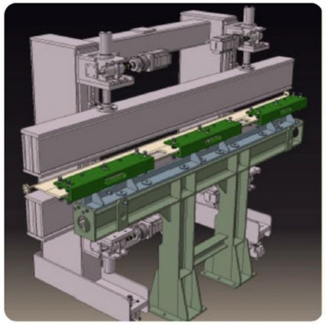
SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress



FERMI FEL-1 Radiator

2) *ARIA*: VUV seeded HGHG FEL beamline for gas phase



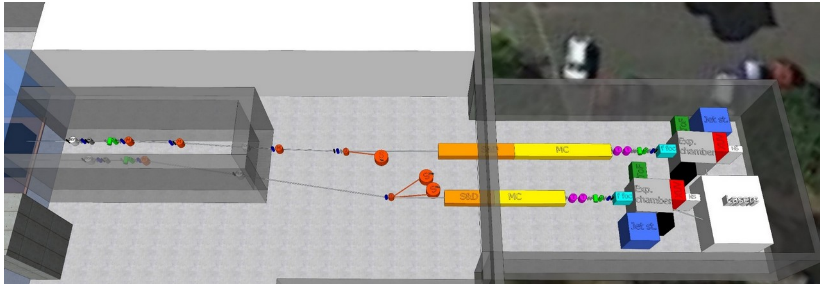


SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 290 – 430 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC_LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.

Frascati 06/05/23 – EUPRAXIA TDR

Expected FEL performances

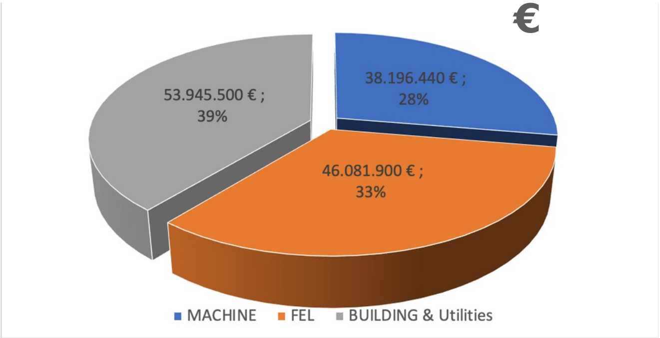
Parameter	Unit	AQUA PWFA	AQUA X-band	ARIA PWFA	ARIA X-band
Radiation Wavelength	*nm*	3-10	4-10	50-180	50-180
Photons per Pulse	$\times 10^{12}$	0.25-1	0.25-1	10-60	12-150
Photon Bandwith	*%*	0.3	0.3	3	0.05
Configuration		SASE		HGHG seeding	

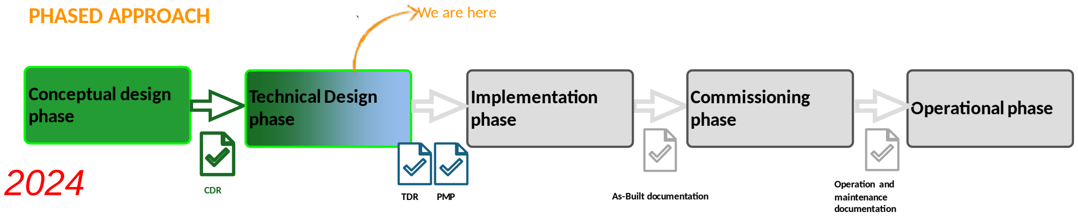


Funded by the European Union

- EuPRAXIA has been included in the ESFRI 2021 Roadmap
  - *ESFRI Roadmap lasts 10 years, i.e. in order to become a ESFRI Landmark project we have to enter the full operational phase (user activities) by 2031.*
- The implementation of the Phase I of the EuPRAXIA@SPARC_LAB Beam Driven Pillar has been funded by Italian Government in 2019 with 108 M€ (commitment for the ESFRI Application).
  - *Italian Government funding is until 2030.*
- 4 M€ are being used for the TDR phase
- Latest news
  - *First draft of the **TDR** to be completed within June 2024*
  - *Executive layout is ongoing (to be completed within 2024)*
  - *3. Autorizzazione dalla sovrintendenza - OK*
  - *4. Autorizzazione dai VVFF - OK.*
  - *5. Gara per la verifica del progetto - terminata e in fase di aggiudicazione.*
  - *Tender for the building should be assigned within 2025*

TOT=138.223.840 €

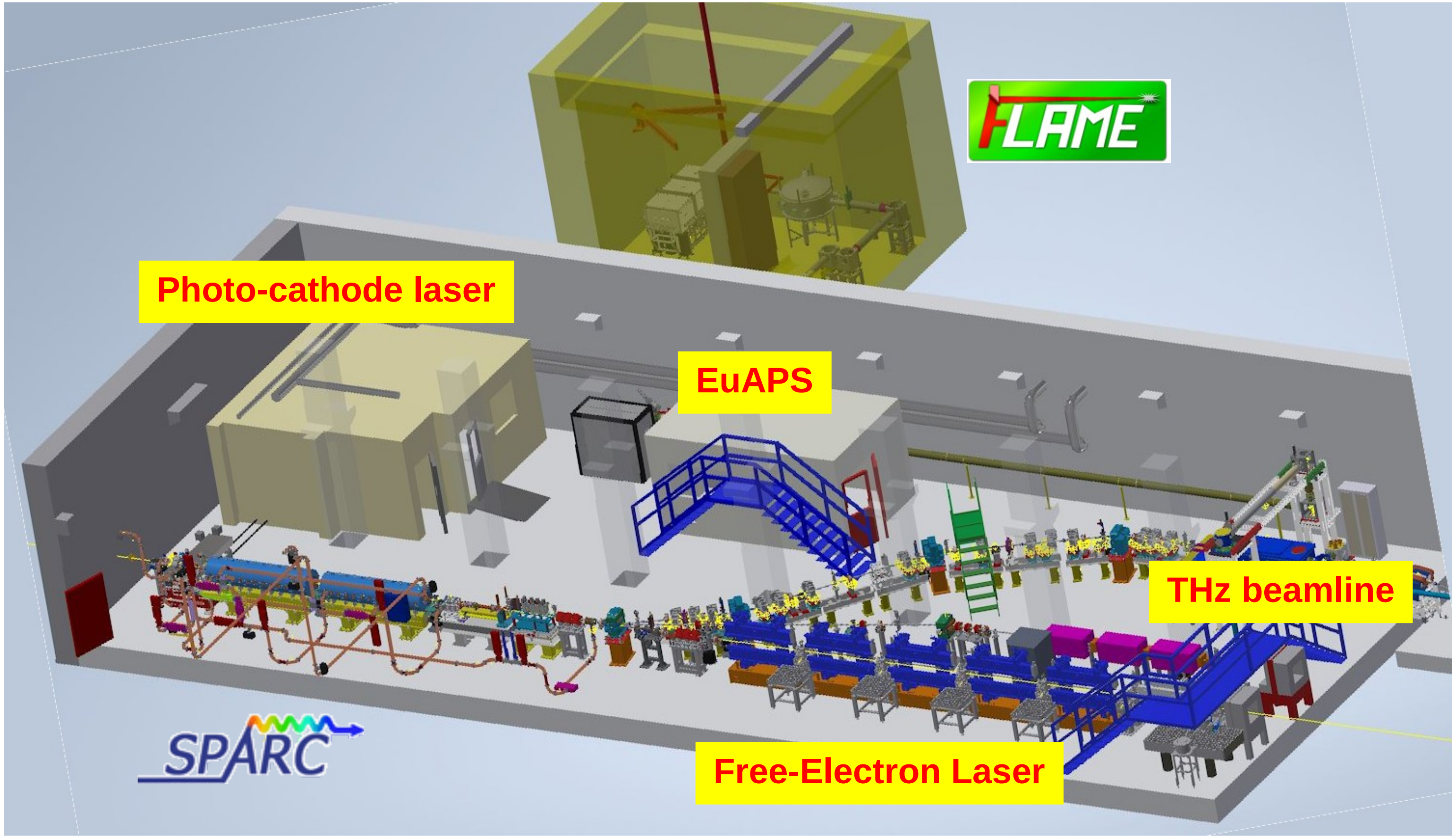




A. Falone

SPARC_LAB experience

The SPARC_LAB facility

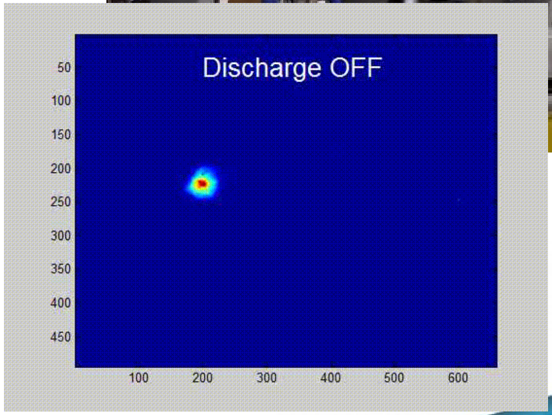


Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

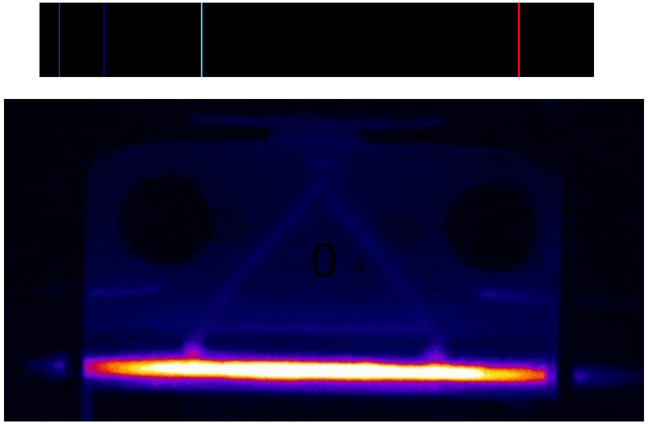
Milestones

Funded by the European Union

Activities with the high-brightness SPARC photo-injector

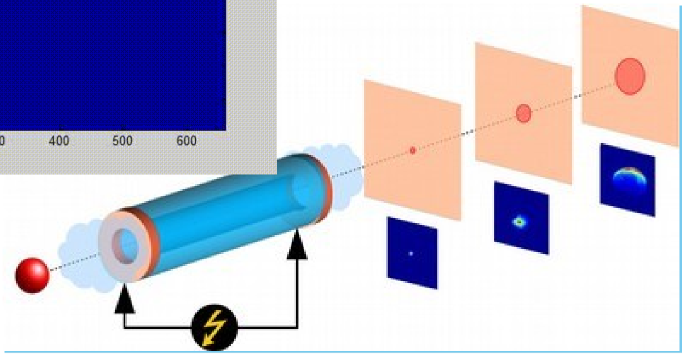


Plasma characterization



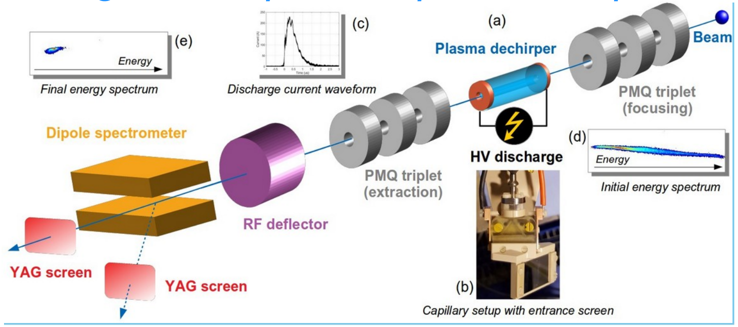
Biagioni, A., et al., Journal of Instrumentation 11.08 (2016)

Focusing with active-plasma lenses



Pompili, R., et al., Physical review letters 121.17 (2018): 174801.

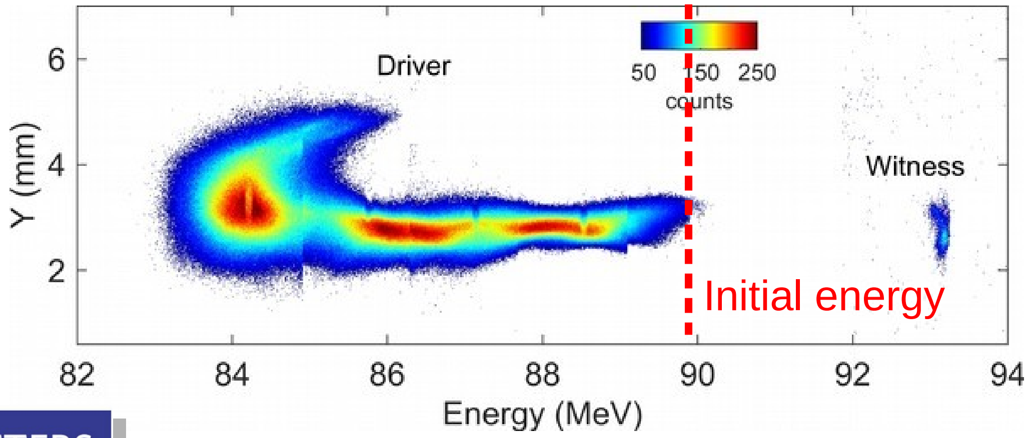
Longitudinal phase-space manipulation



V. Shpakov et al. Phys. Rev. Lett. 122, 114801 (2019)

Control of the energy spread

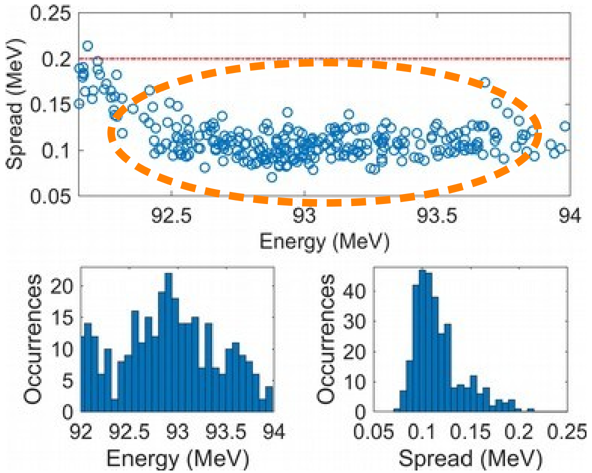
4 MeV acceleration in 3 cm plasma with 200 pC driver
~133 MV/m accelerating gradient
2×10^{15} cm^{-3} plasma density
<u>Demonstration of projected energy spread compensation</u>
Spread from 0.2% to 0.12%



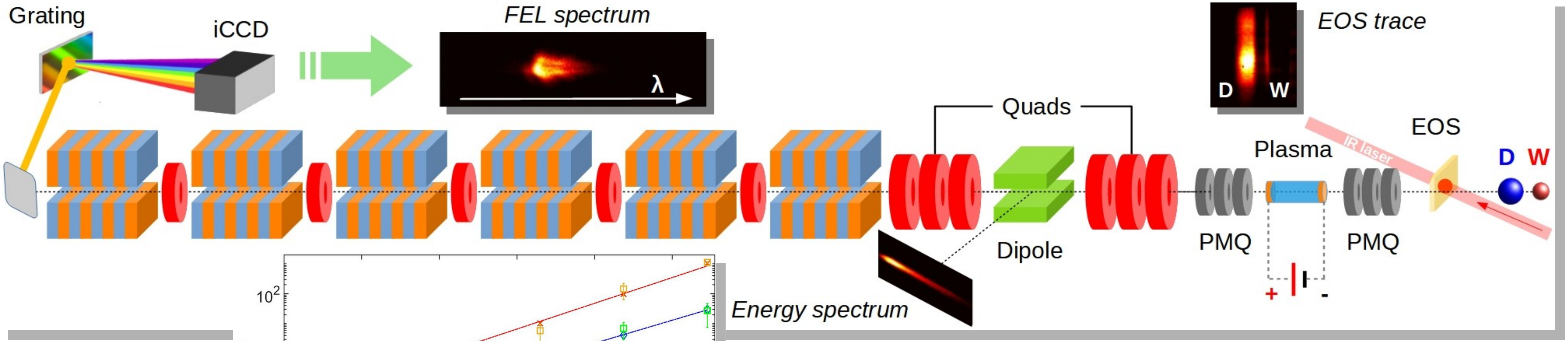
nature physics
LETTERS
https://doi.org/10.1038/s41567-020-01116-9
Check for updates

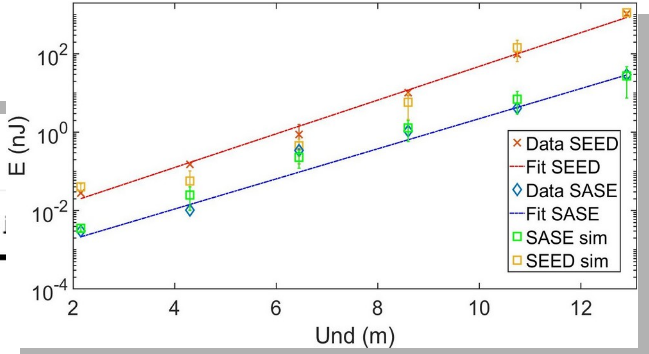
Energy spread minimization in a beam-driven plasma wakefield accelerator

R. Pompili[1✉], D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], L. Magnisi[1], M. Marongiu[1], A. Mostacci[2], L. Piersanti[1], G. Di Pirro[1], S. Romeo[1], A. R. Rossi[4], J. Scifo[1], V. Shpakov[1], C. Vaccarezza[1], F. Villa[1] and A. Zigler[1,5]



First demonstration of FEL lasing





nature

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Article | Published: 25 May 2022

Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, … M. Ferrario + Show authors

Nature **605**, 659–662 (2022) | Cite this article

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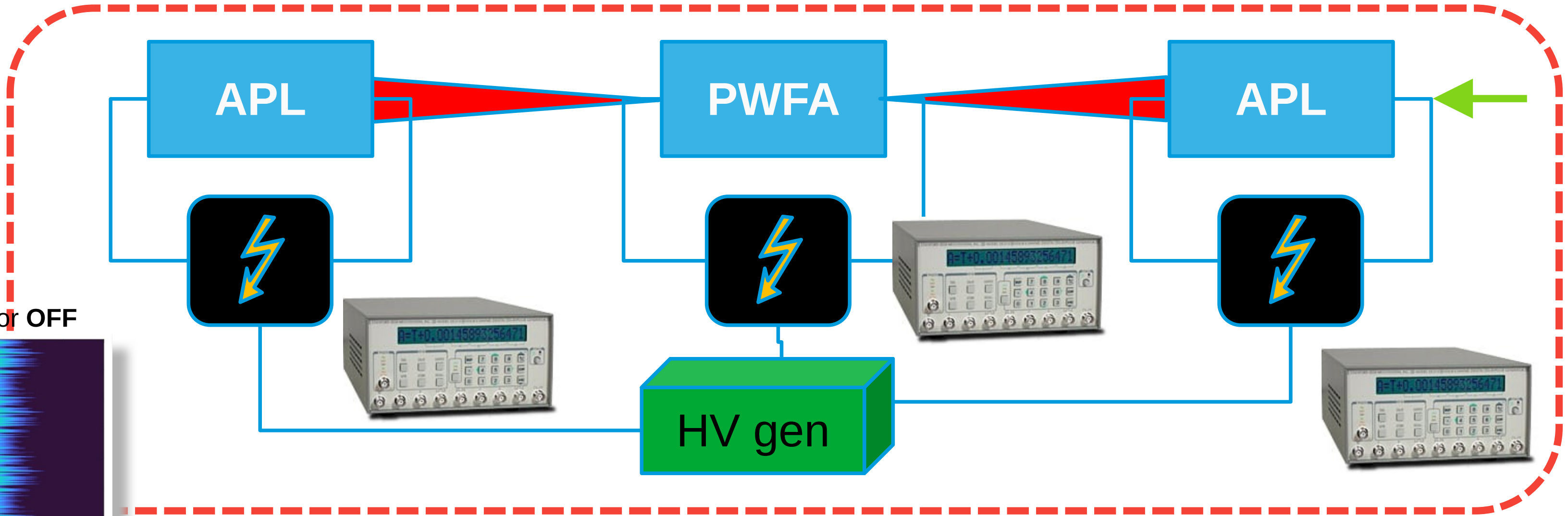
Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti *et al.*

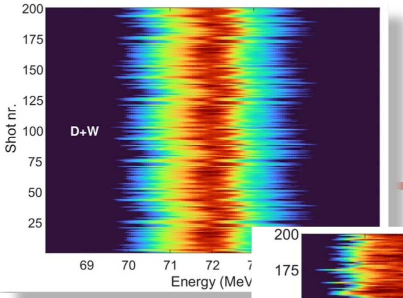
Phys. Rev. Lett. **129**, 234801 – Published 29 November 2022

"All-in-one" capillary

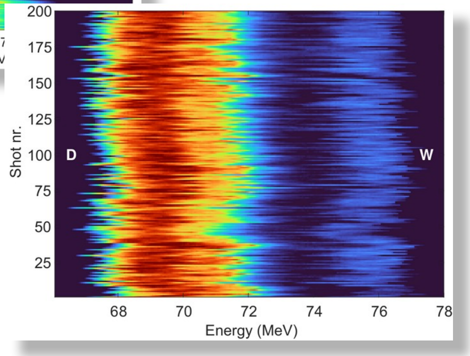
Funded by the European Union

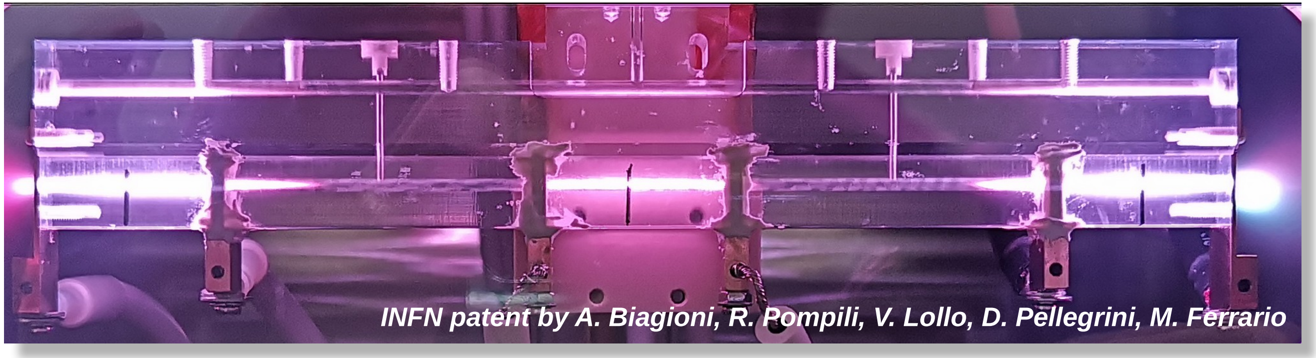


Lenses ON, Accelerator **OFF**



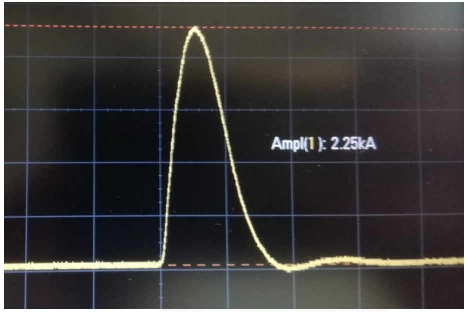
Lenses ON, Accelerator **ON**



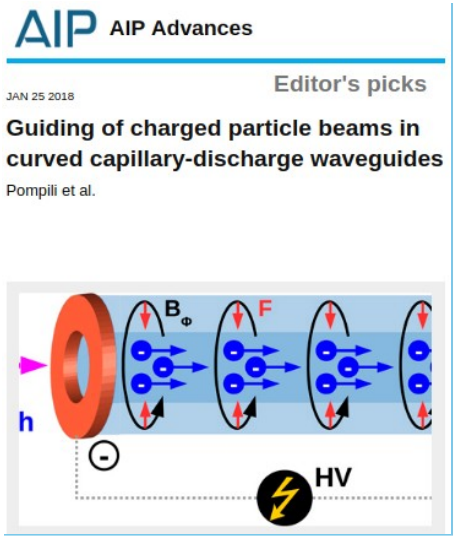


Particle bending with plasma

- Yet another use of plasma
- The large magnetic fields produced in the plasma can be used to bend particles
  - *Compactness. Large deflection angles*
  - *Tunability. The bending is tuned by adjusting the discharge-current*
  - *Cheap solution*
  - *Tunable dispersion (dispersion-free also possible) by changing the discharge current*



D. Pellegrini, T. De Nardis, G. Grilli

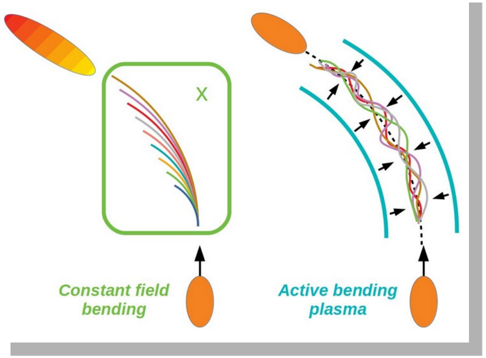

AIP AIP Advances

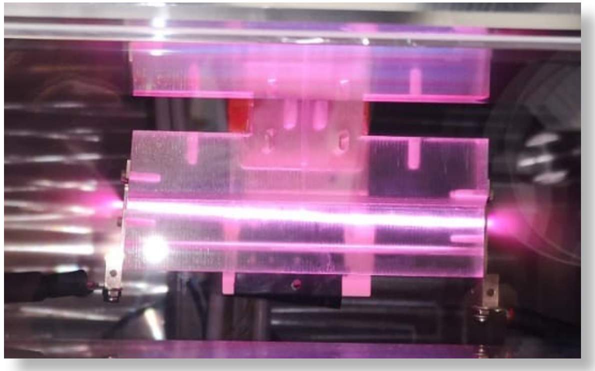
Editor's picks

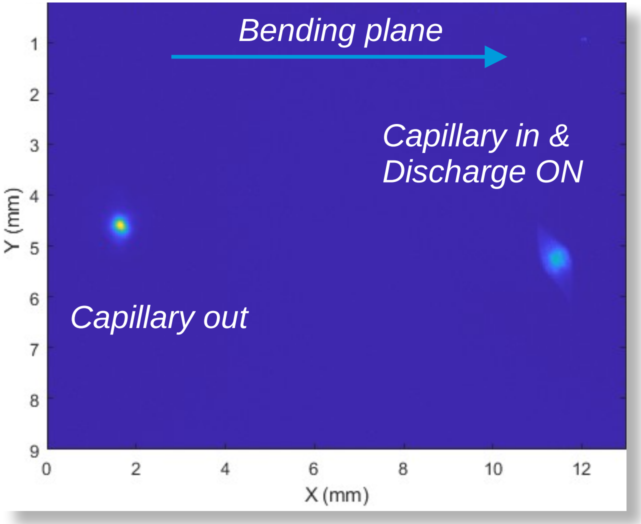
JAN 25 2018

Guiding of charged particle beams in curved capillary-discharge waveguides

Pompili et al.

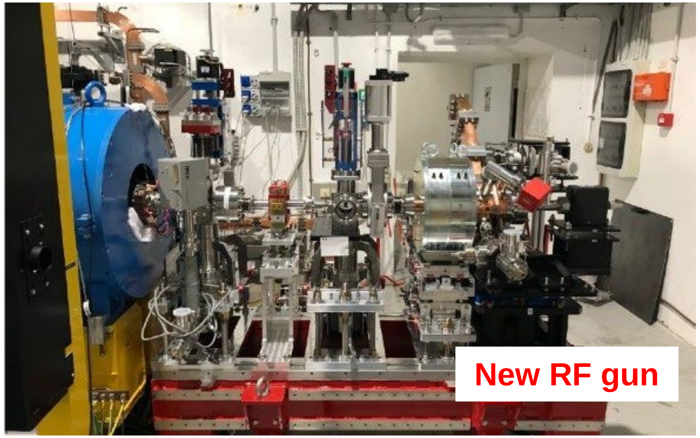


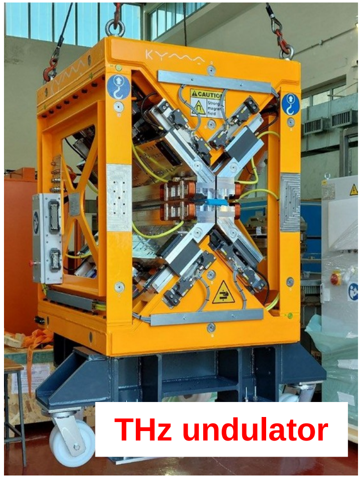


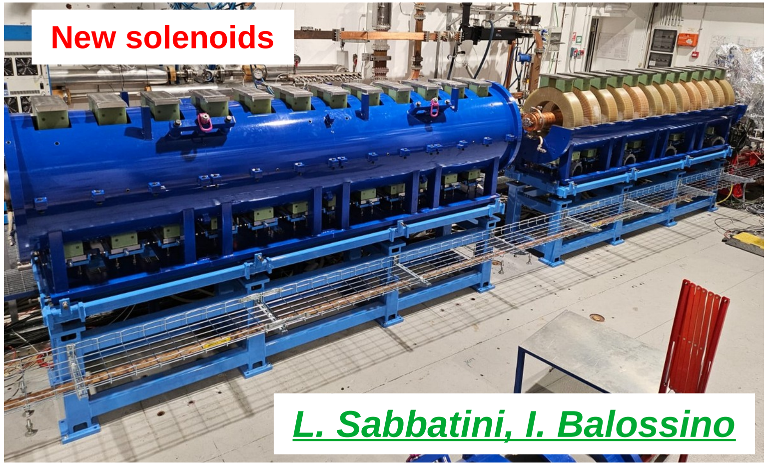


SABINA installations

Funded by the European Union







L. Sabbatini, I. Balossino

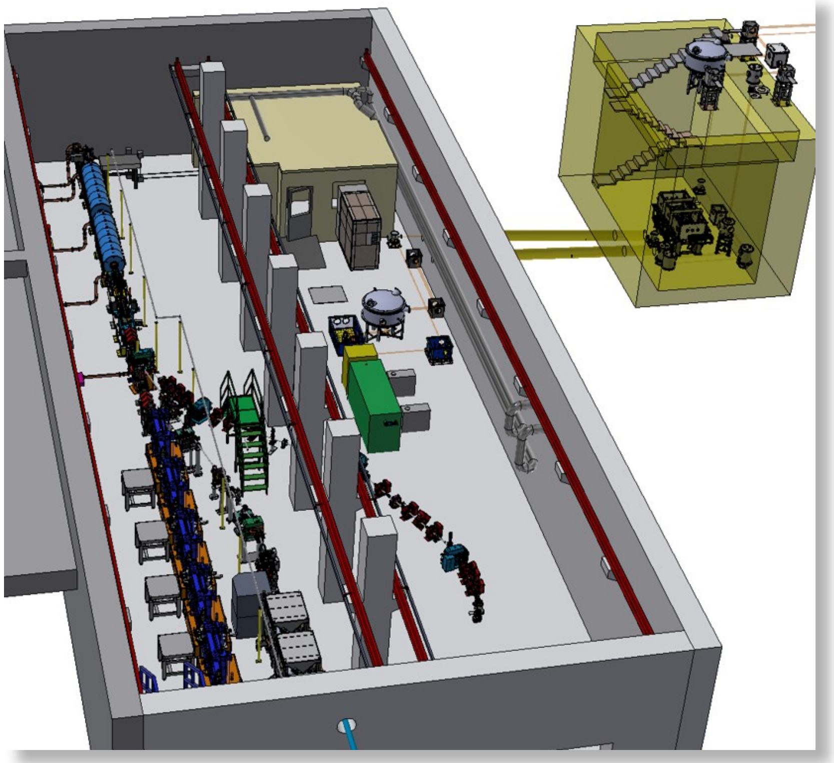
Status of EuAPS (PNRR)

EuAPS goals

Funded by the European Union

- WP2- “Betatron radiation Source” will deliver a new Plasma based Laser driven X-rays source at INFN-LNF.
- The implementation of this WP includes
  - *numerical simulations*
  - *optimization of the plasma target*
  - *design and realization of the plasma source*
  - *commissioning of the timing and synchronization system*
  - *photon diagnostics design and implementation*
  - *user end station design and test*
- The expected outcome is a bright, compact and stable X rays source based on betatron radiation

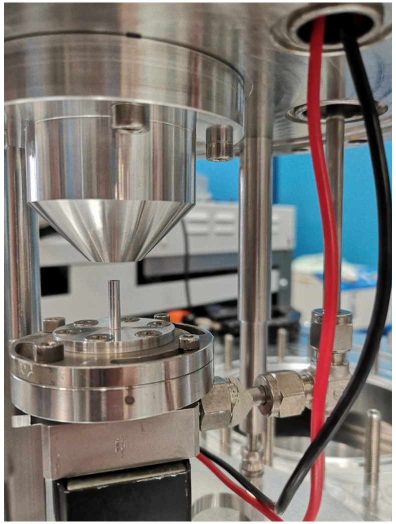
Parameter	Value	unit
Electron beam Energy	100-500	MeV
Plasma Density	10^{18}-10^{19}	cm^{-3}
Photon Critical Energy	1 -10	keV
Number of Photons/pulse	10^{6}-10^{9}	
Repetition rate	1	Hz
Beam divergence	3-20	mrad

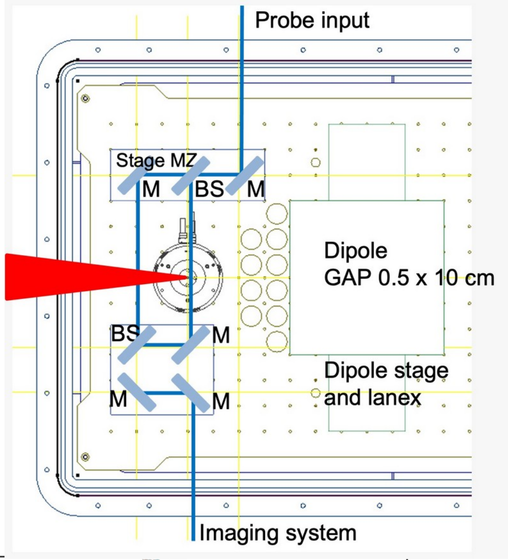


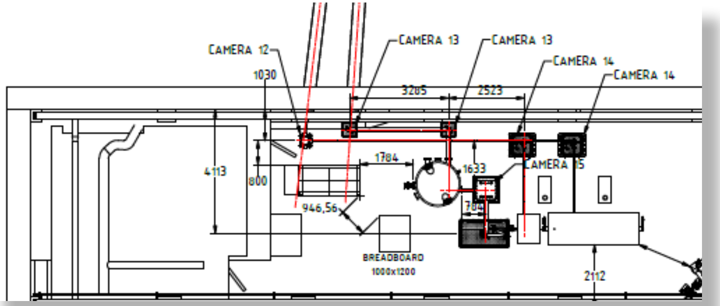
A. Cianchi

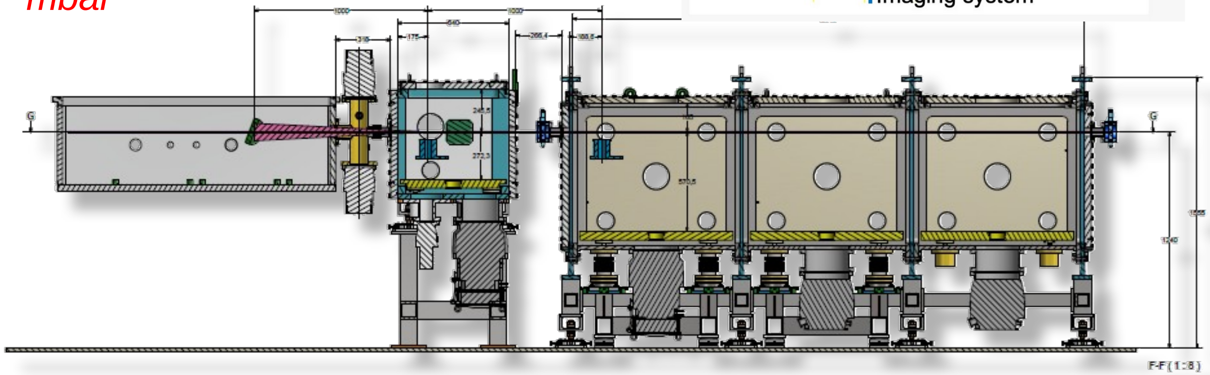
Current status

- Layout in the SPARC bunker and connection with FLAME building
- Drawings completed
- All purchasing procedures completed
- Prototype system developed and tested
- Several challenges
  - *Main issue is the pumping of 20-30 bar with repetition rate at least 1 Hz*
  - *The focusing parabola has to be in a 10^{-4} mbar environment*





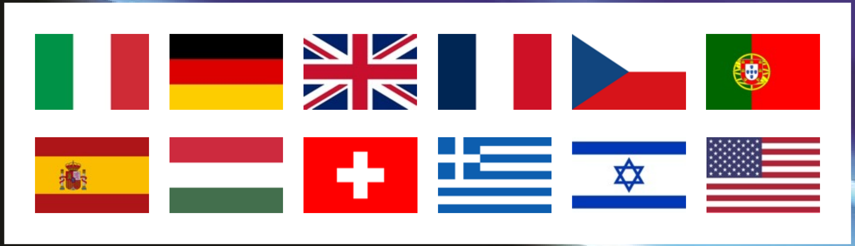




EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

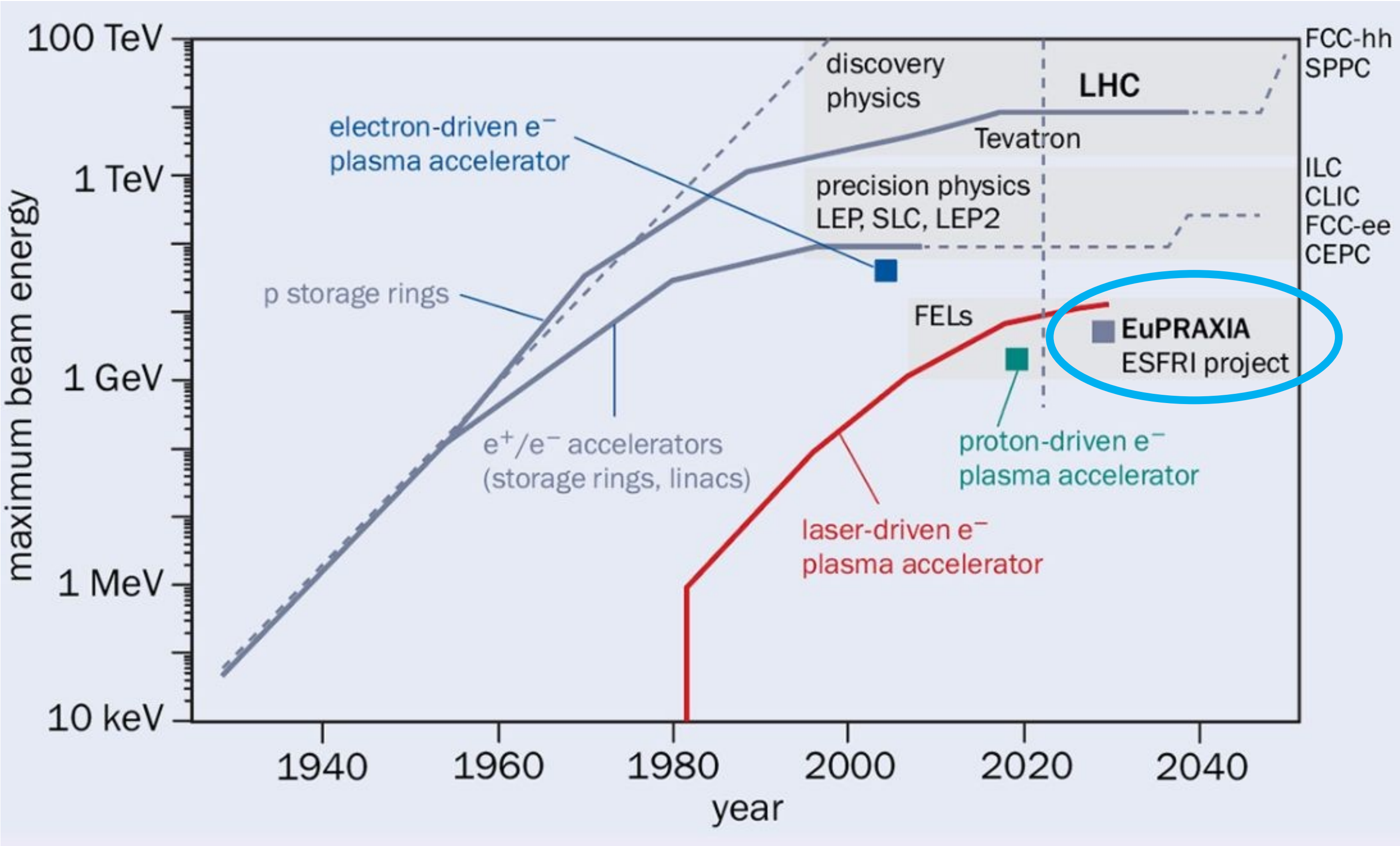
Thanks!

R. Pompili (LNF-INFN)
On behalf of the EuPRAXIA@SPARC_LAB collaboration



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

The Livingston plot



Plasma Accelerator Achievements

- Gradients up to 100 GV/m
- Acceleration >10 GeV of electron beams
- High-quality beams to deive FELs

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

AQUA beamline

- AQUA will explore the spectrum in the “water window” range
  - *i.e., between C (4.4 nm) and O (2.33 nm) K-absorption edges*
- Biological samples are mainly composed of light atoms (mostly carbon) and find their native environment in aqueous solutions → the absorption contrast between the C atoms (from sample) and the O (from water) is the highest in such window.
  - *This makes possible measurements of unstained cells and viruses in their hydrated native state*

Undulator parameters	AQUA
Period (mm)	18
Max strength (k)	1.47
Min gap (mm)	6
Active length (m)	19.8

Radiation parameters	PWFA	X-band
Energy per pulse (μJ)	10	10
Wavelength tunability (nm)	4-10	4-10
Bandwidth (%)	0.3	0.3
Pulse length (fs)	15	60

Villa, et al. "EuPRAXIA@ SPARC_LAB status update." X-Ray Free-Electron Lasers: Advances in Source Development and Instrumentation VI. Vol. 12581. SPIE, 2023.

ARIA beamline

Funded by the European Union

- ARIA will operate at a longer wavelengths in the VUV range
  - 50-180 nm
- It will operate in the seeded mode exploiting the High-Gain Harmonic Generation (HGHG) configuration
  - OPG-OPA Ti:Sapphire laser with fundamental wavelength 600-800 nm and 320-400 nm for the SHG
  - ~20 µJ pulse energy, ~200 fs duration
- It can support a wide range of experiments in atomic, molecular, and cluster physics, as well as solid, liquid, and gas phase materials, probe new electronic transitions well within the 7-20 eV range for classes of cluster materials such as nano-carbons and potential gap dielectrics such as metal oxides using the ultra-fast pump-probe configuration

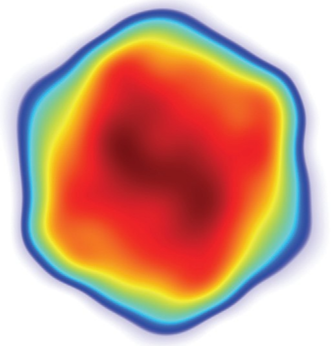
Undulator parameters	ARIA	
	modulator	radiator
Period (mm)	100	55
Active length (m)	3.0	8.4
Seeding wavelengths (nm)	320-400 + 600-800	
Seeding energy per pulse (μJ)	> 20	
Seeding length (fs)	200	
Radiation parameters	PWFA	X-band
Energy per pulse (μJ)	200	200
Wavelength tunability (nm)	50-180	50-180
Bandwidth (%)	3	0.05
Pulse length (fs)	15	100

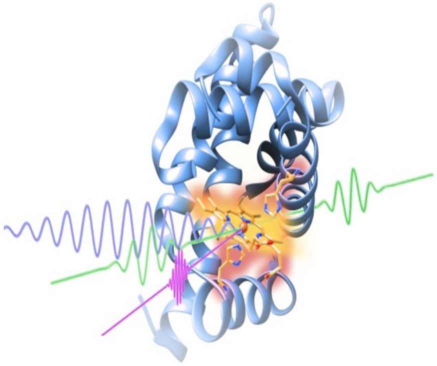
Villa, et al. "EuPRAXIA@ SPARC_LAB status update." X-Ray Free-Electron Lasers: Advances in Source Development and Instrumentation VI. Vol. 12581. SPIE, 2023.

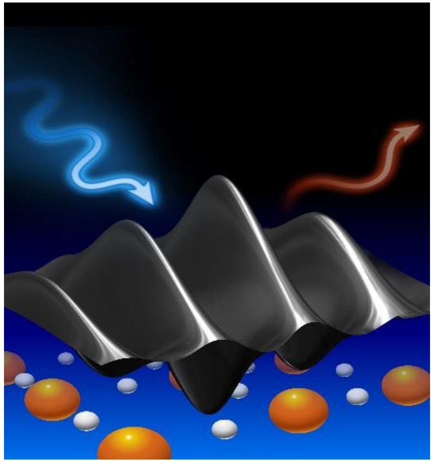
Funded by the European Union

AQUA - Techniques & Samples in the water window

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





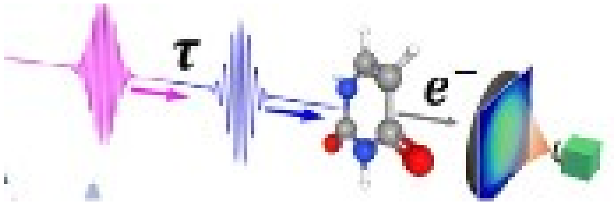


Proteins
Viruses
Bacteria
Cells
Metals
Semiconductors
Superconductors
Magnetic materials
Organic molecules
Organometallic compounds

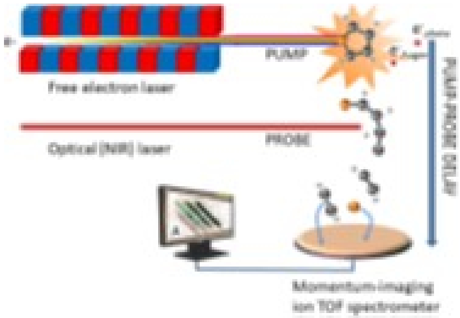
Balerna *et al.* Cond. Mat. 2022

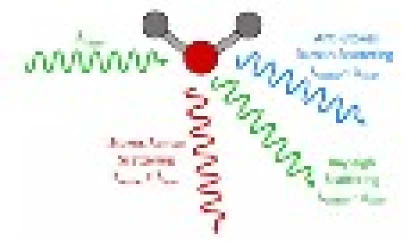
AQUA beamline scientific case

ARIA - Techniques & Samples @ 50-180 nm



- 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)

Villa et al. Cond. Mat. 2022

TEX Facility Now

The **TEst-stand for X-band (TEX)** is conceived for R&D and test on high gradient X-band accelerating structures, RF components, LLRF systems, Beam Diagnostics, Vacuum system and Control System

It has been co-funded by Lazio region in the framework of the **LATINO project** (Laboratory in Advanced Technologies for INnOvation). The setup has been done in **collaboration with CERN** and it will be also used to test **CLIC structures**

The installation and commissioning of the whole system (Source and RF network, LLRF, vacuum and control system) have been completed by the end of 2022 [3].

Period	Device tested at high power
Jan. - Feb. 2023	3D printed Spiral RF loads and wg
May - Oct. 2023	X-band T24 CLIC structure
Nov. - Dec. 2023	X-band Mode converter/circular wg
Jan. - Feb. 2024	X-band RF waterload from PSI
March 2024	20 cells EuPRAXIA prototype

F. Cardelli, S. Pioli

Control Room

LLRF system

RF Source

VKX8311A Klystron