EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

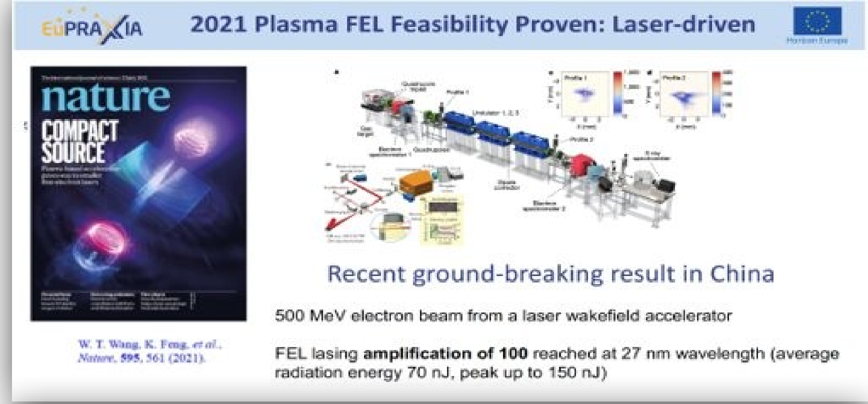
Status of the EuPRAXIA@SPARC_LAB Technical Design Report - WP15

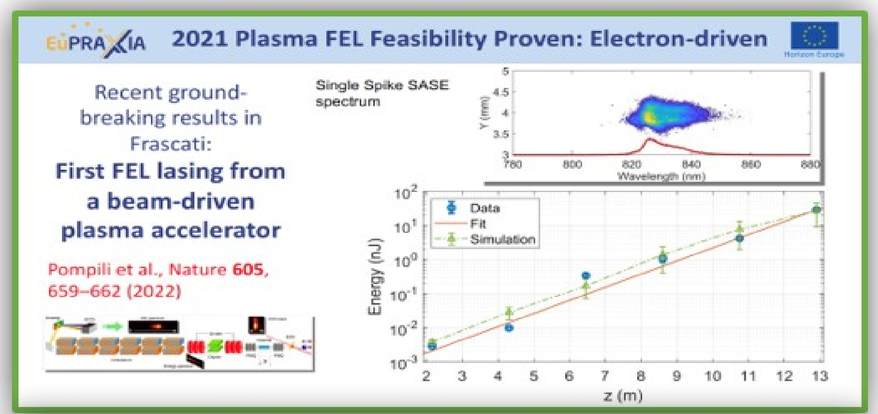
R. Pompili (LNF-INFN)
On behalf of the EuPRAXIA@SPARC_LAB collaboration

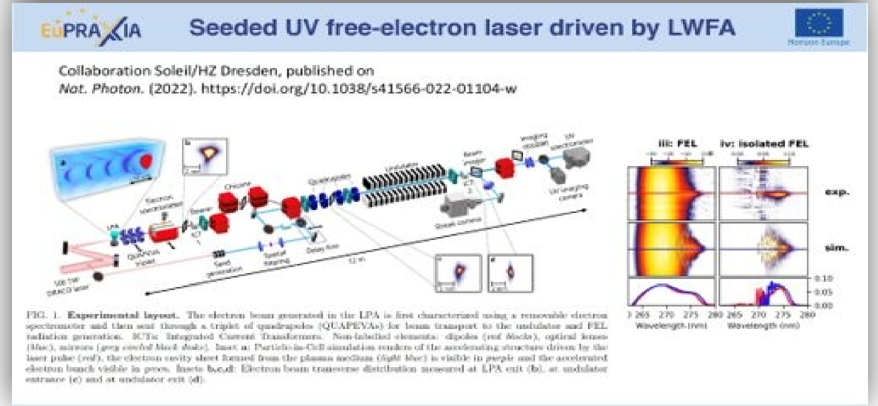
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement
No. 101079773

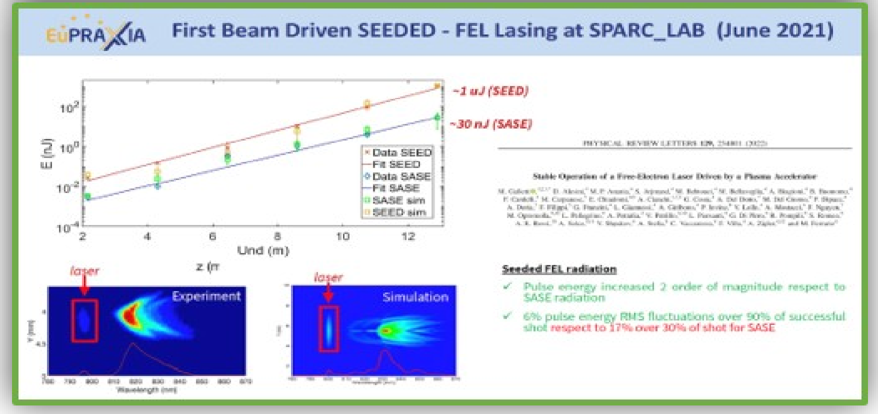
Pilot plasma-driven FELs experiments

Funded by the European Union





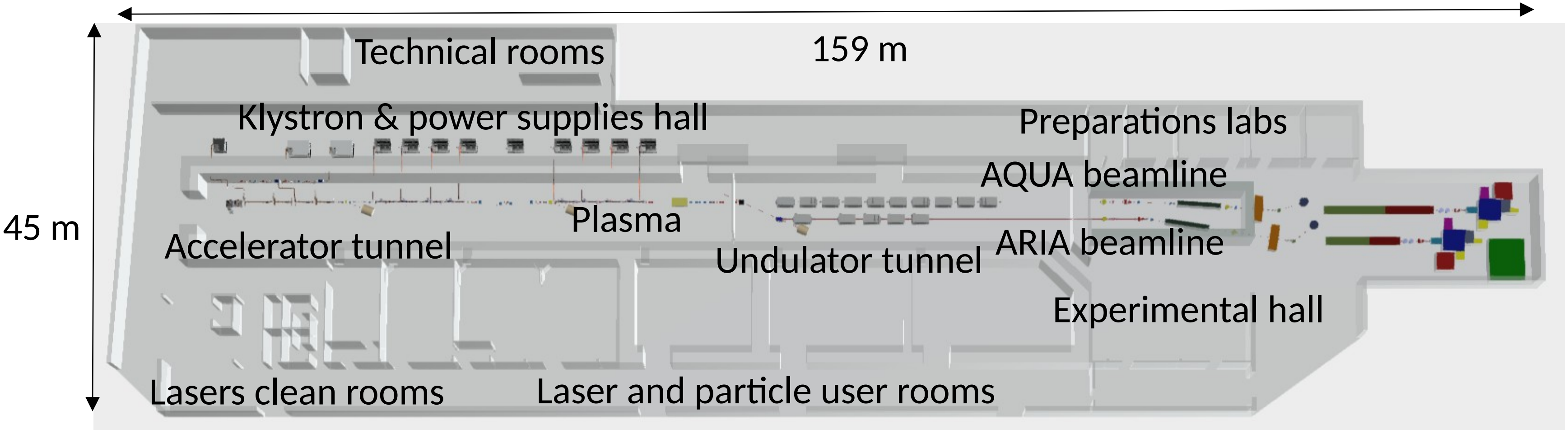




Review on plasma-driven FELs just published!

Galletti, M., et al. "Prospects for free-electron lasers powered by plasma-wakefield-accelerated beams." Nature Photonics (2024): 1-12.

EuPRAXIA@SPARC_LAB layout



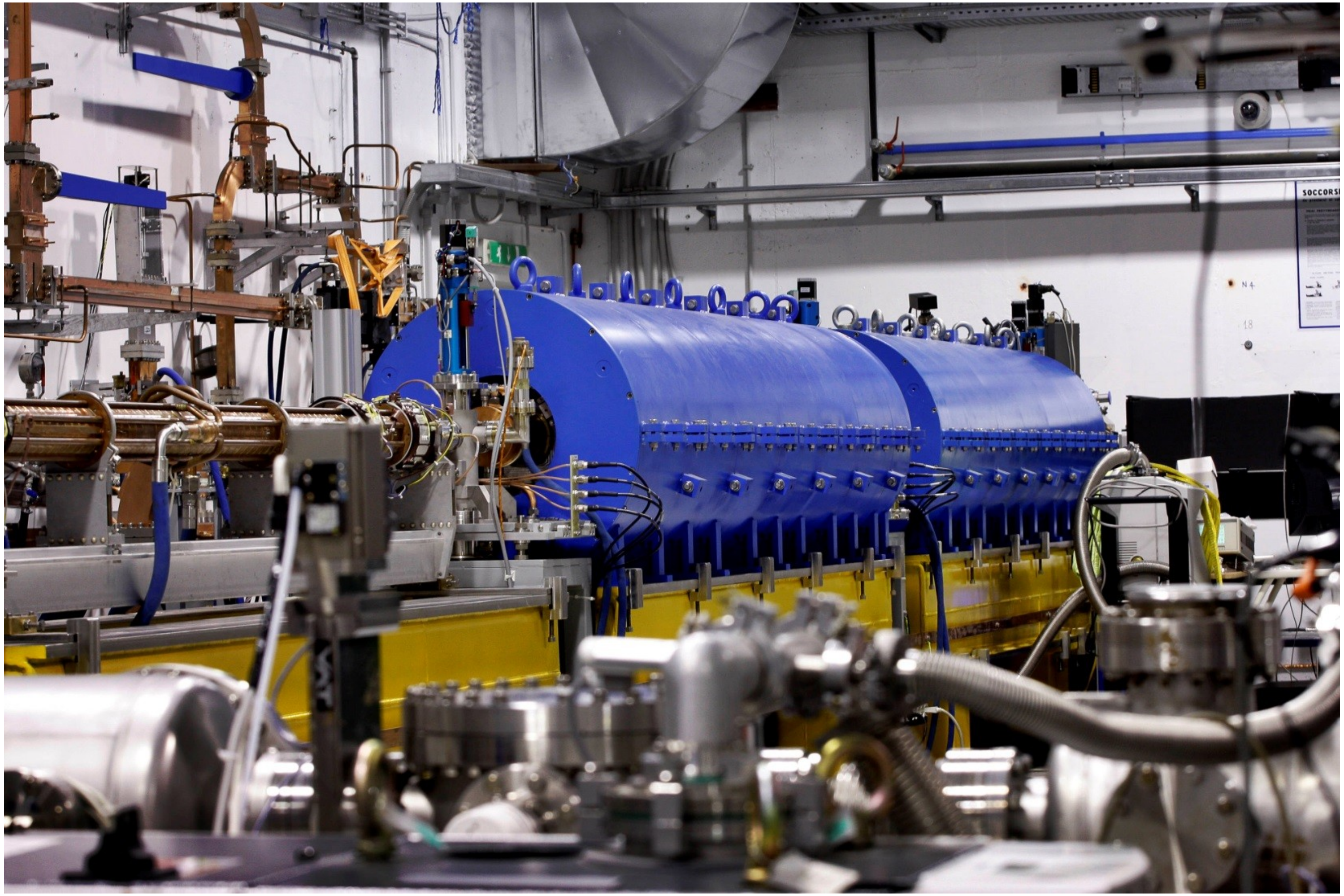
Electron beam parameters

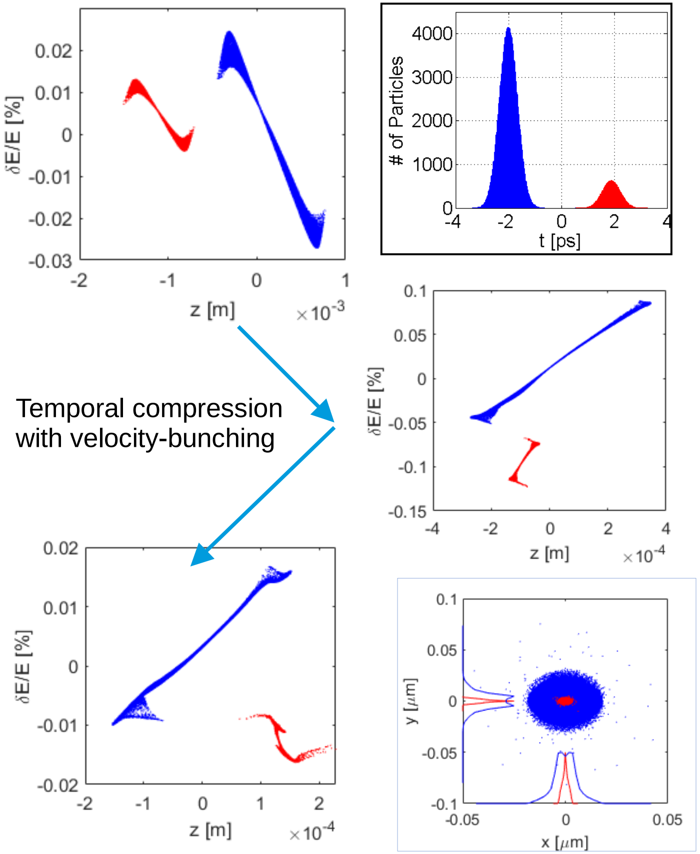
Parameter	Unit	PWFA	X-band
Electron Energy	GeV	1-1.2	1
Bunch Charge	pC	**30-50**	**200-500**
Peak Current	kA	1-2	1-2
RMS Energy Spread	%	0.1	0.1
RMS Bunch Length	μm	**6-3**	**24-20**
RMS norm Emittance	μm	1	1
Slice Energy Spread	%	≤0.05	≤0.05
Slice norm Emittance	um	0.5	0.5

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

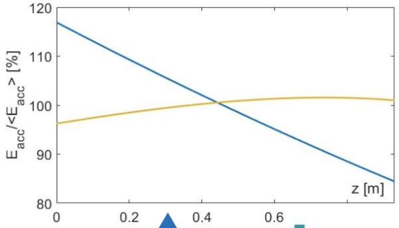


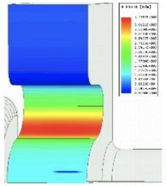


E. Chiadroni, A. Giribono, C. Vaccarezza

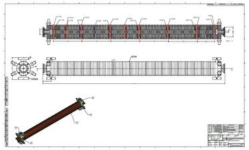
X-band LINAC, tests @ TEX

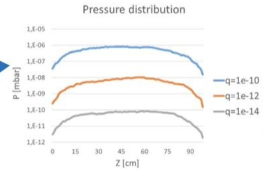
Funded by the European Union

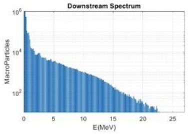




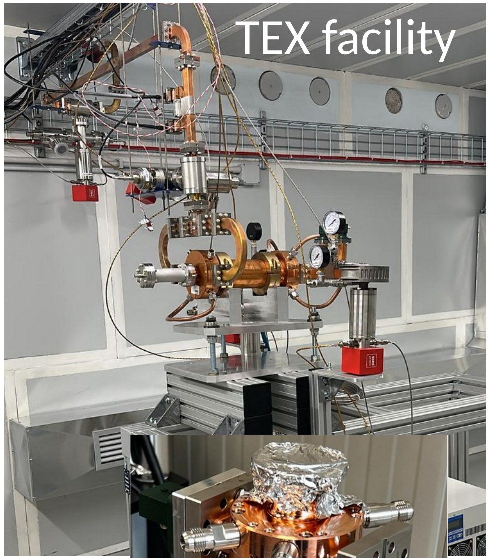
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*







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**	



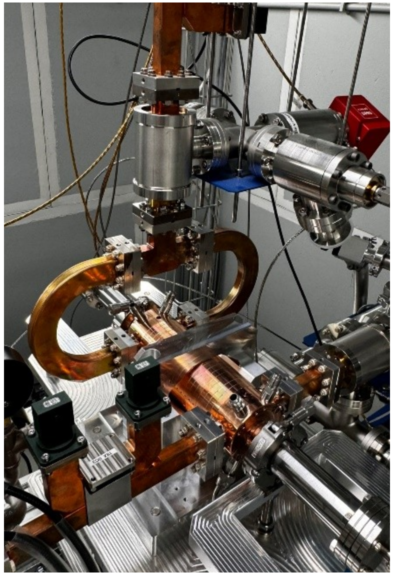
D. Alesini, F. Cardelli

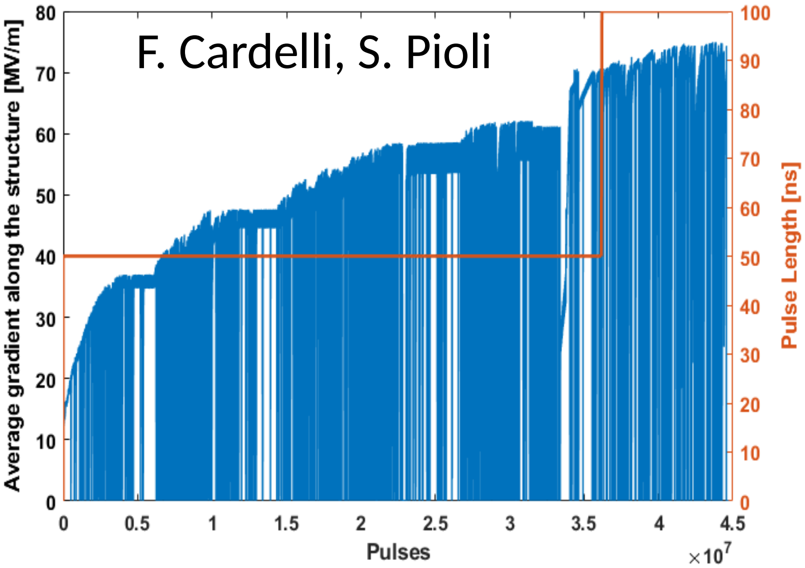
20 cells EuPRAXIA X-band tests

- 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



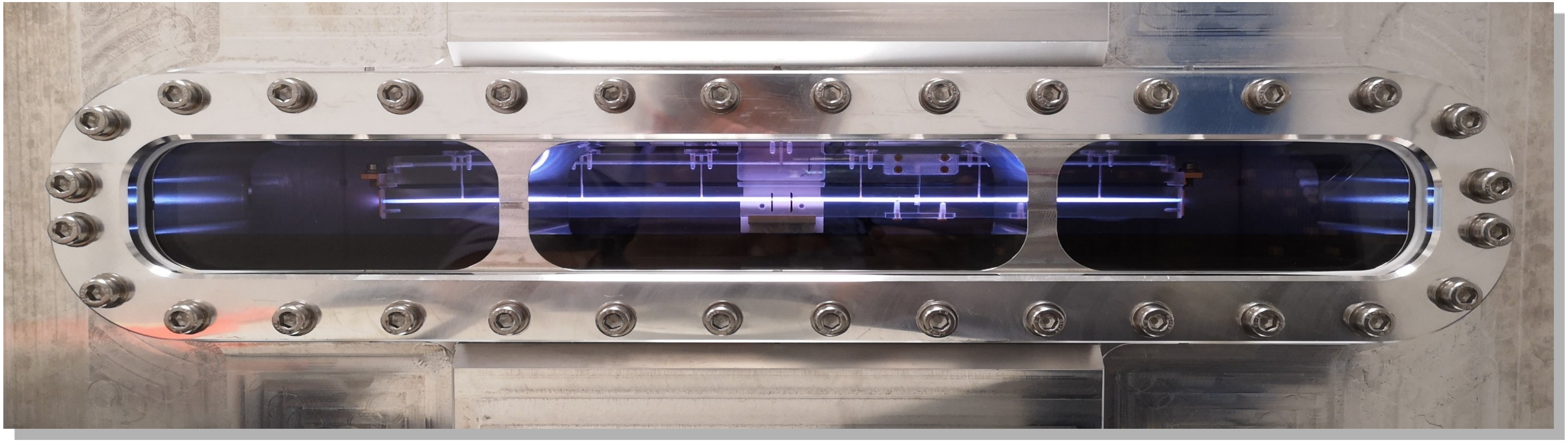


RF Source

VKX8311A Klystron

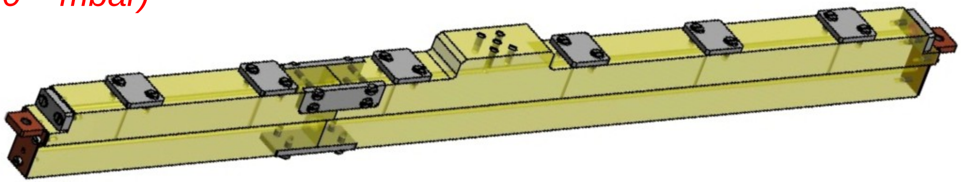
Plasma module

Funded by the European Union



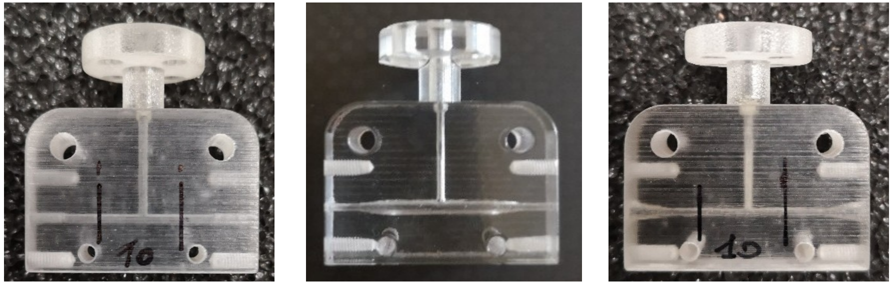
- 40 cm long capillary → 1st prototype for the EuPRAXIA facility
  - *Made with special junction to allow negligible gas leaks (<10^{-10} mbar)*
- Operating conditions
  - *1 Hz repetition rate (to be increased up to 100 Hz)*
  - *10 kV – 380 A minimum values for ionization*
  - *6 inlets for gas injection.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

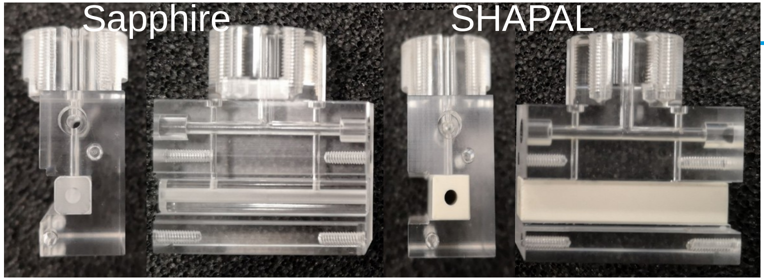
A. Biagioni, V. Lollo

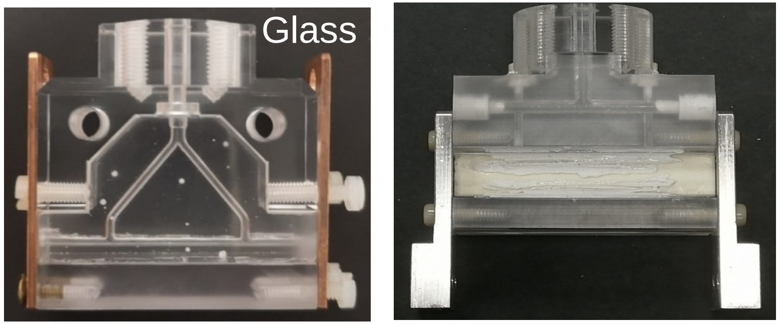


R&D on plasma acceleration

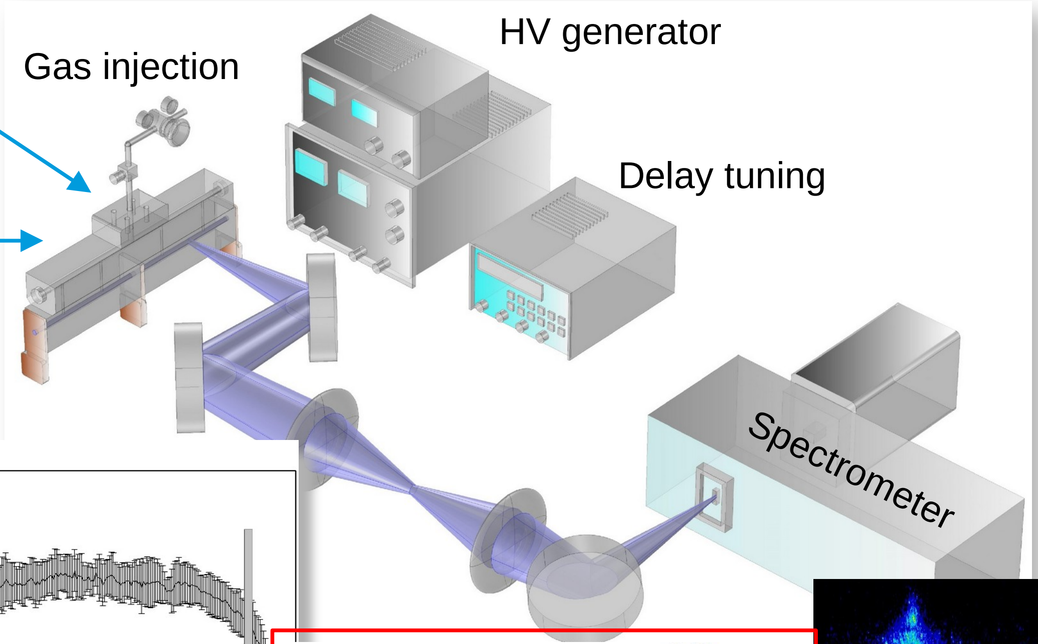
A. Biagioni, L. Crincoli, R. Demitra

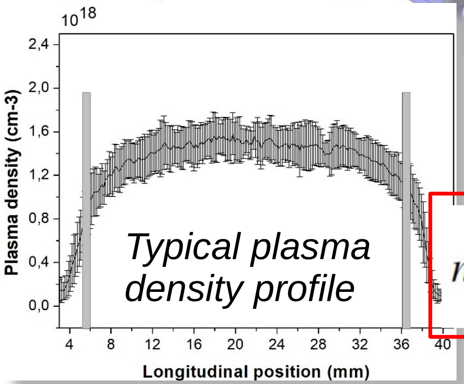




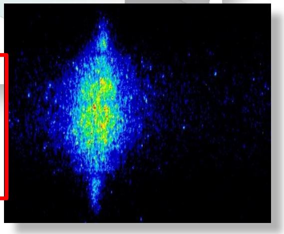


Capillary to be tested





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

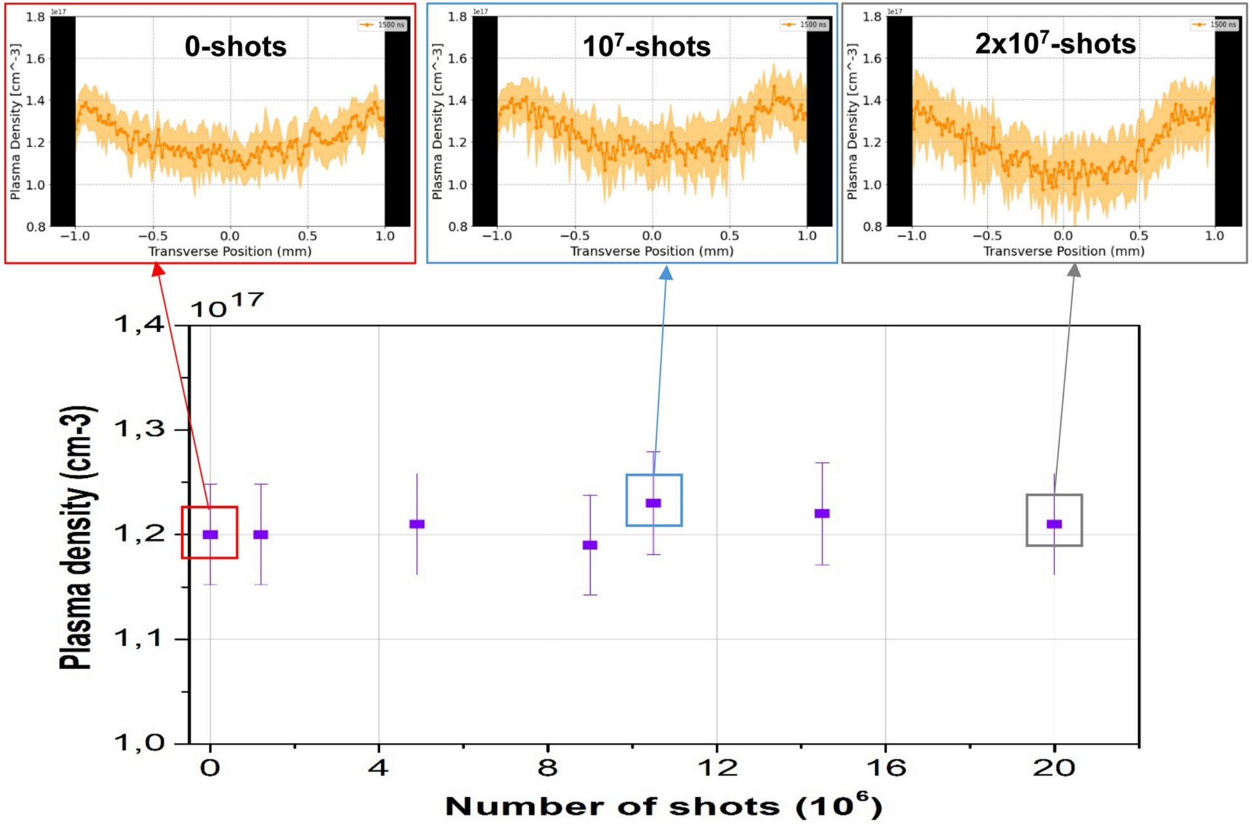


Stark broadening

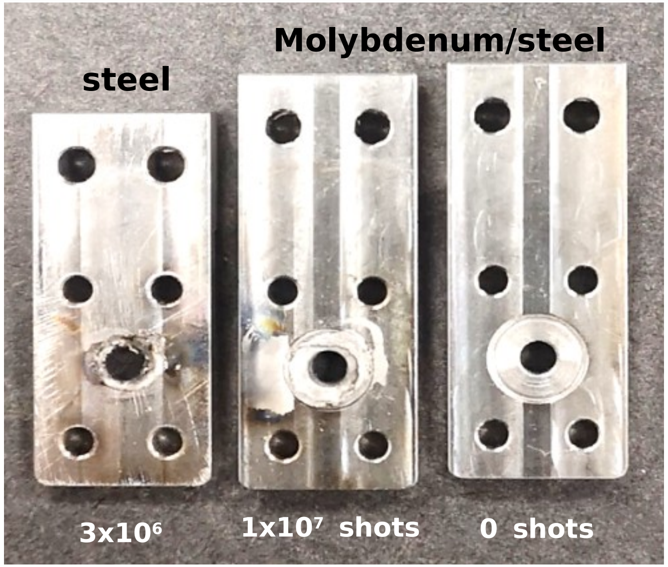
High rep rates and capillary longevity

Funded by the European Union

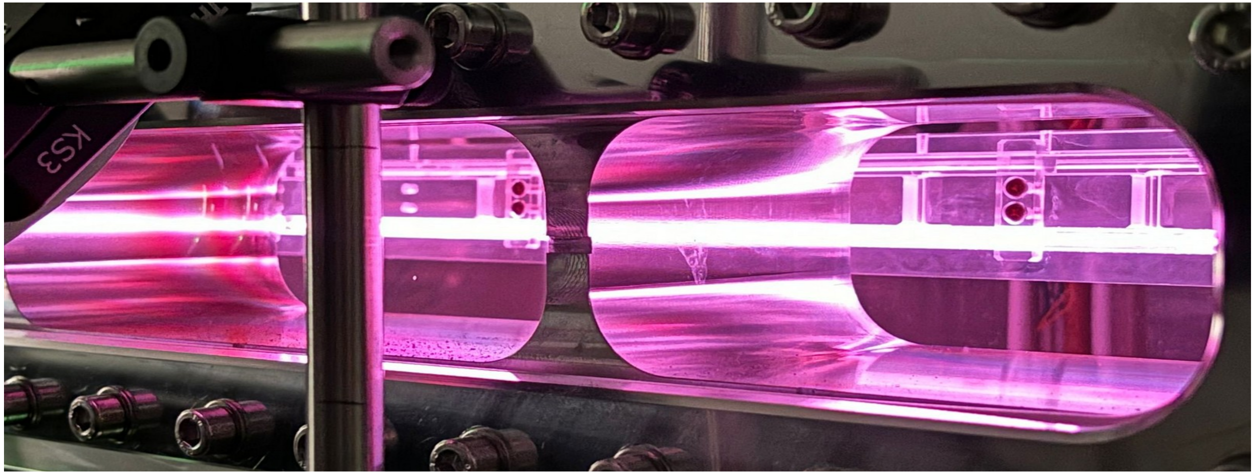
A. Biagioni, L. Crincoli, R. Demitra

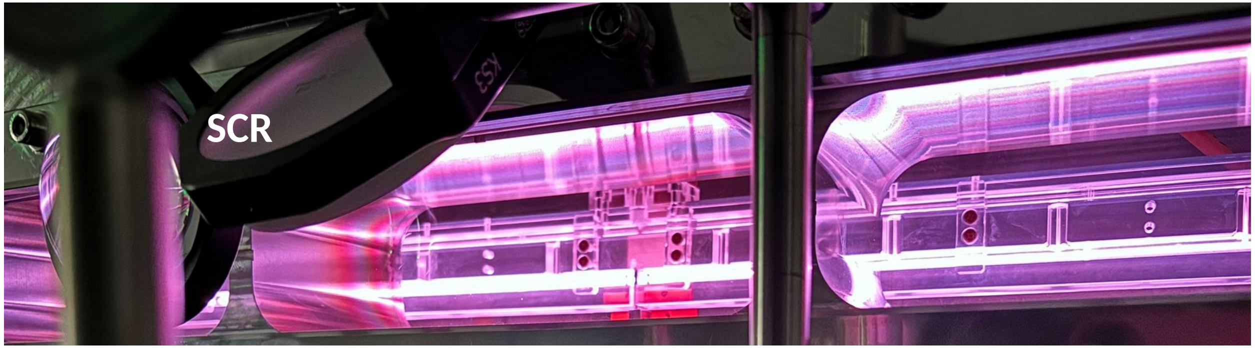


150 Hz repetition rate discharges

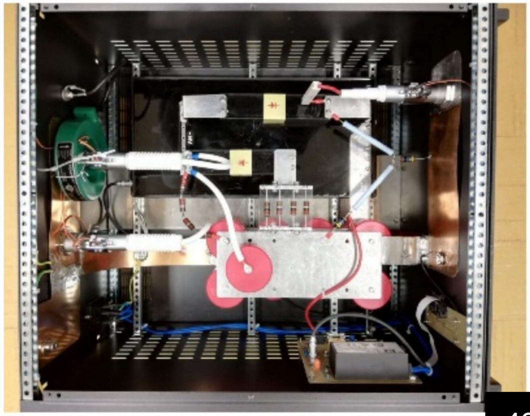


Temperature analysis





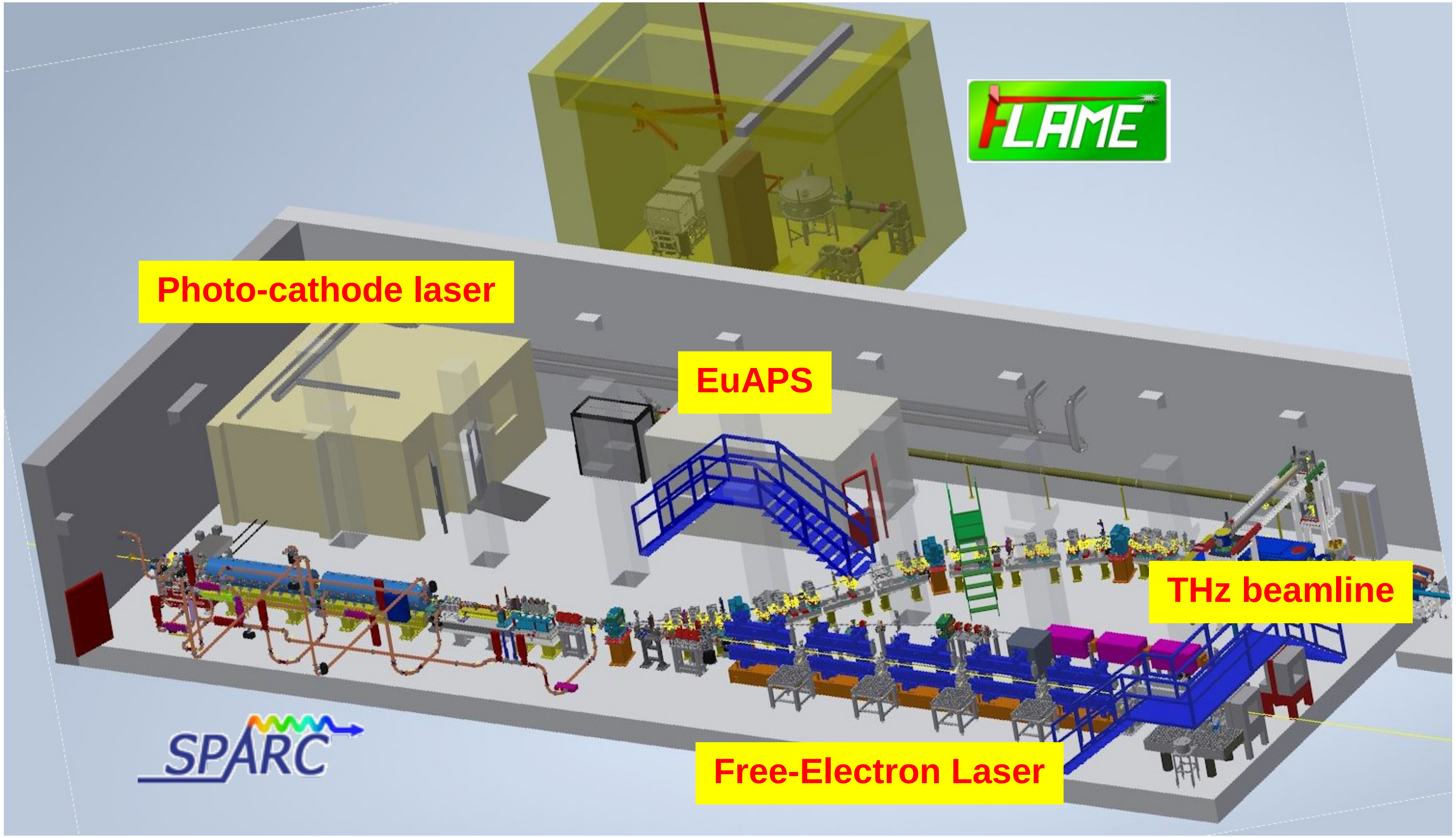
A. Biagioni, R. Demitra, L. Crincoli (→see talk on Thursday)



40@150 Hz

SPARC_LAB experience

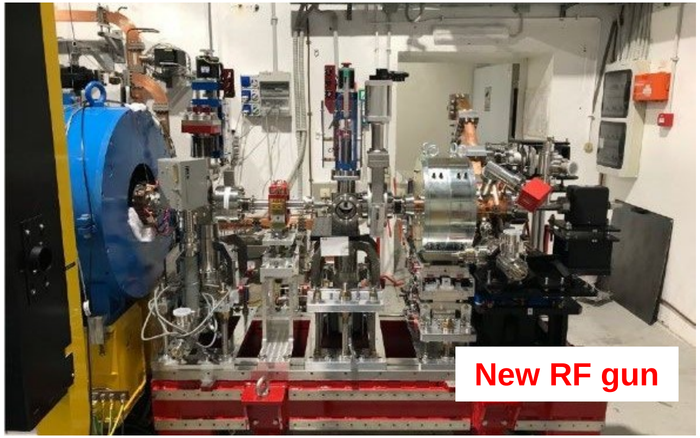
The SPARC_LAB facility

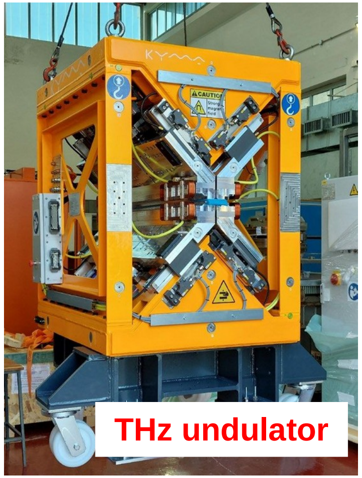


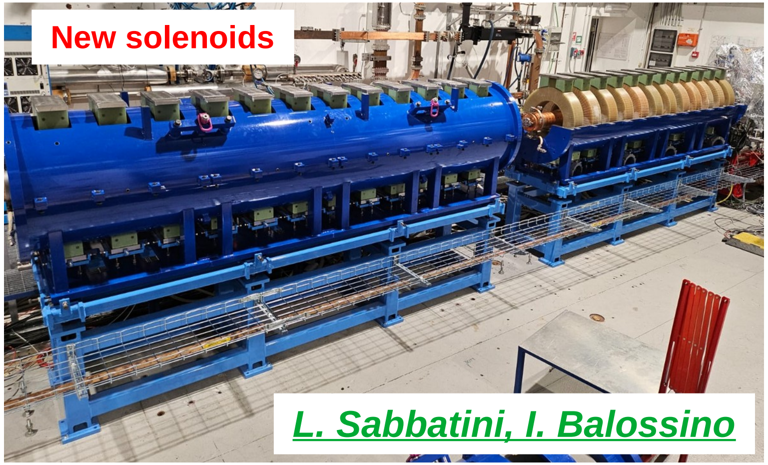
Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

SPARC upgrade with SABINA

Funded by the European Union





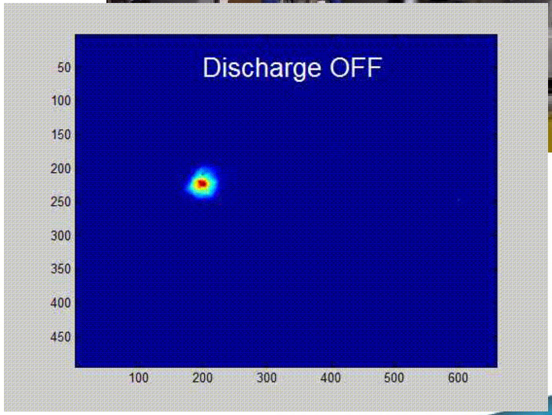


L. Sabbatini, I. Balossino

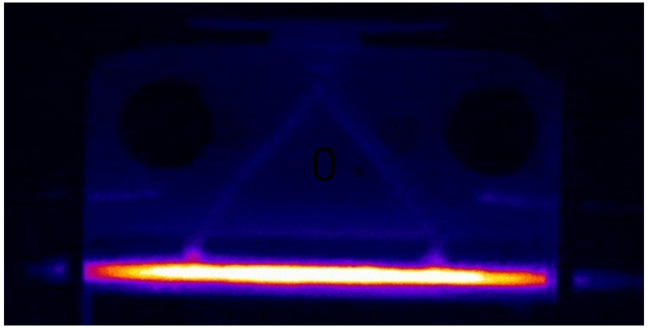
Milestones

Funded by the European Union

Activities with the high-brightness SPARC photo-injector

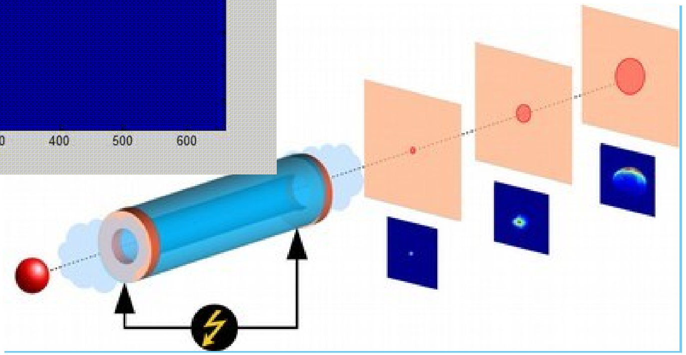


Plasma characterization



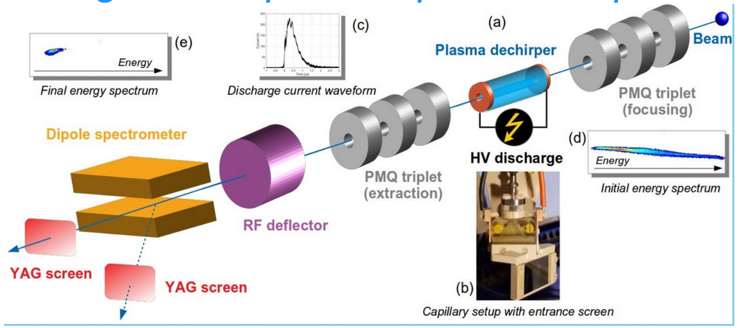
Biagioni, A., et al., Journal of Instrumentation 11.08 (2016)

Focusing with active-plasma lenses



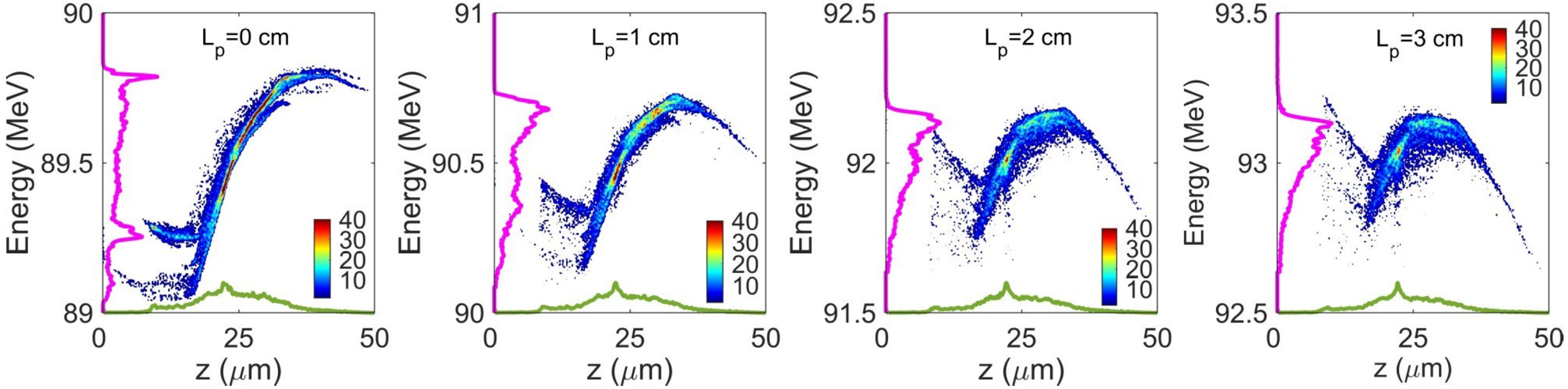
Pompili, R., et al., Physical review letters 121.17 (2018): 174801.

Longitudinal phase-space manipulation



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

Control of the energy spread



nature physics

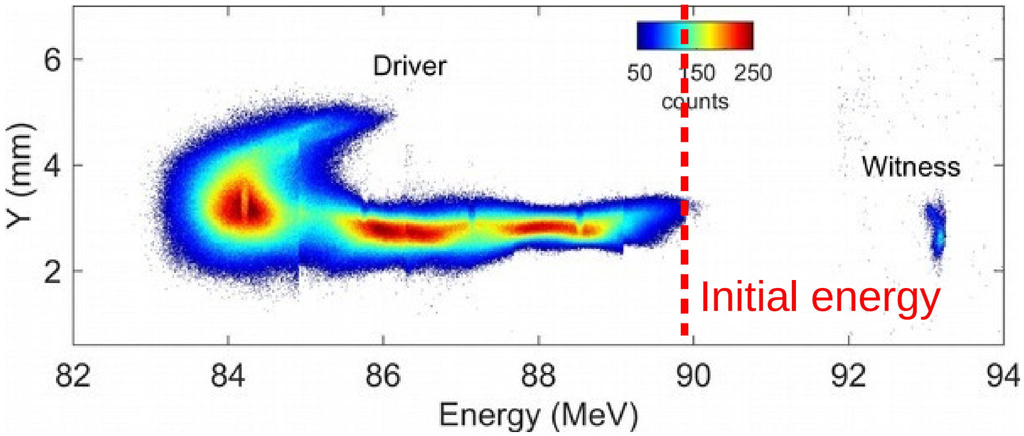
LETTERS

https://doi.org/10.1038/s41567-020-01116-9

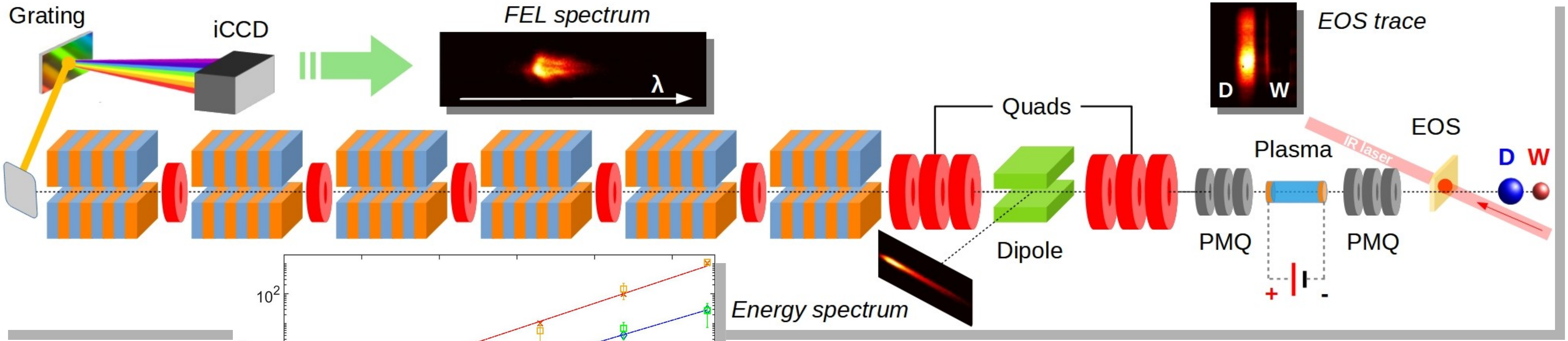
Check for updates

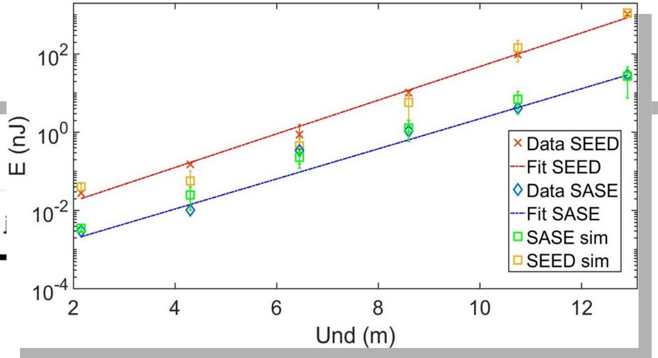
Energy spread minimization in a beam-driven plasma wakefield accelerator

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]



Demonstration of FEL lasing





nature

Explore content ⌄ About the j

nature › articles › article

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

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About

Access by INFN

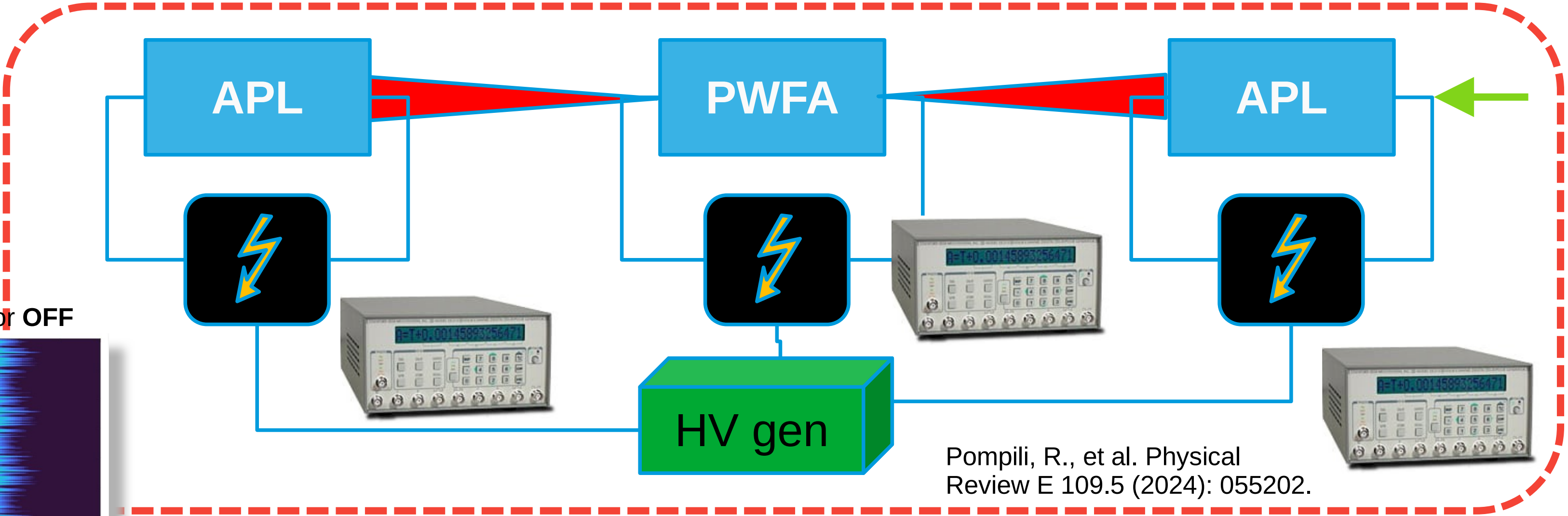
Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti *et al.*

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

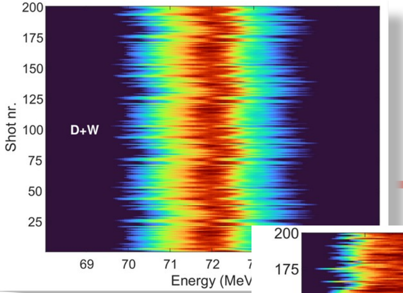
“All-in-one” capillary

Funded by the European Union

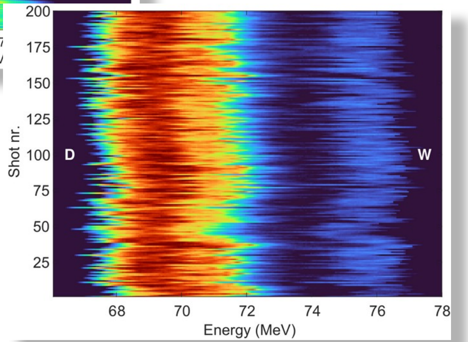


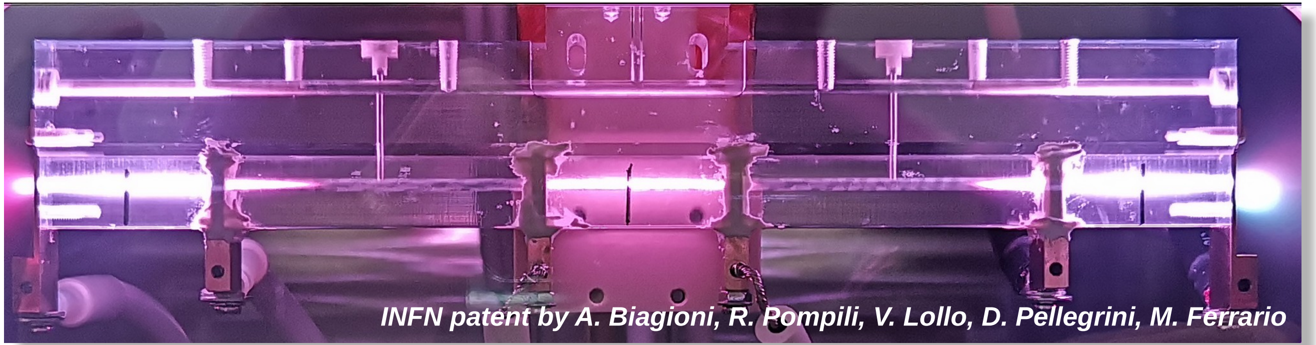
Pompili, R., et al. Physical Review E 109.5 (2024): 055202.

Lenses ON, Accelerator **OFF**



Lenses ON, Accelerator **ON**



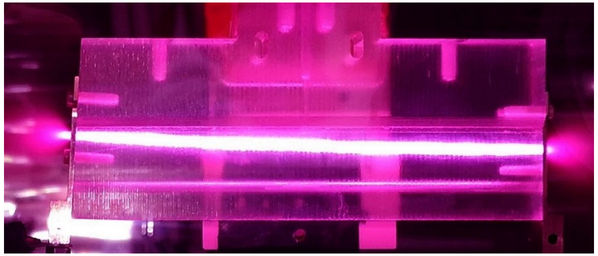


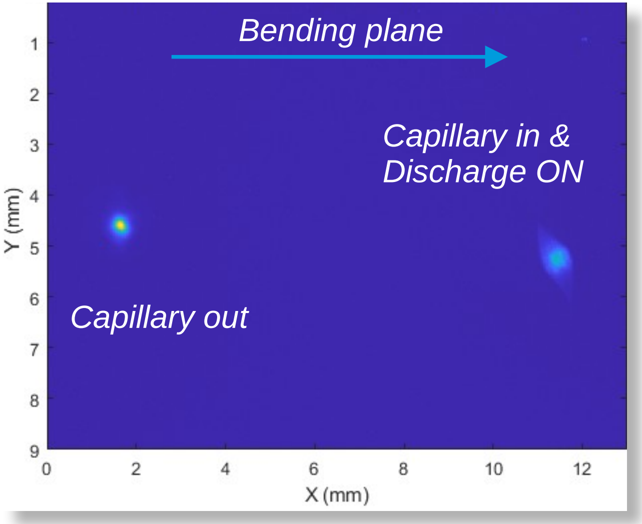
INFN patent by A. Biagioni, R. Pompili, V. Lollo, D. Pellegrini, M. Ferrario

Particle bending with plasma

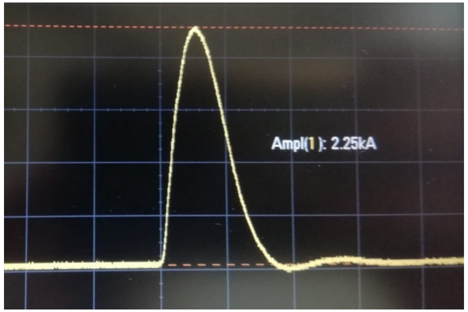
- Yet another use of plasma
- The large magnetic fields produced in the plasma can be used to bend particles
  - *Compactness. Large deflection angles*
  - *Tunability. The bending is tuned by adjusting the discharge-current*
  - *Low-cost solution*
  - *Tunable dispersion*

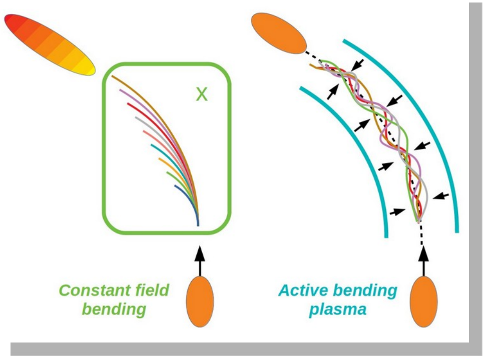
PRL Cover, May 2024





Pompili, R., et al. Physical Review Letters 132.21 (2024): 215001.





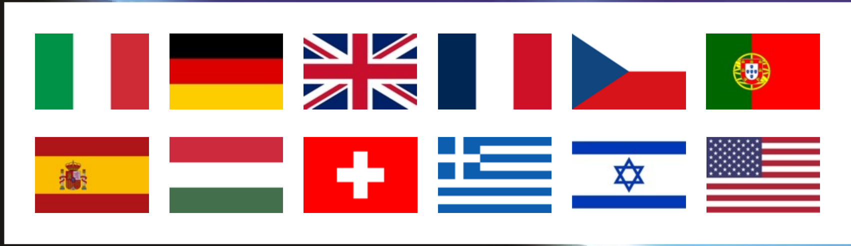
Frazzitta, A., et al. Physical Review Accelerators and Beams 27.9 (2024): 091301.

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

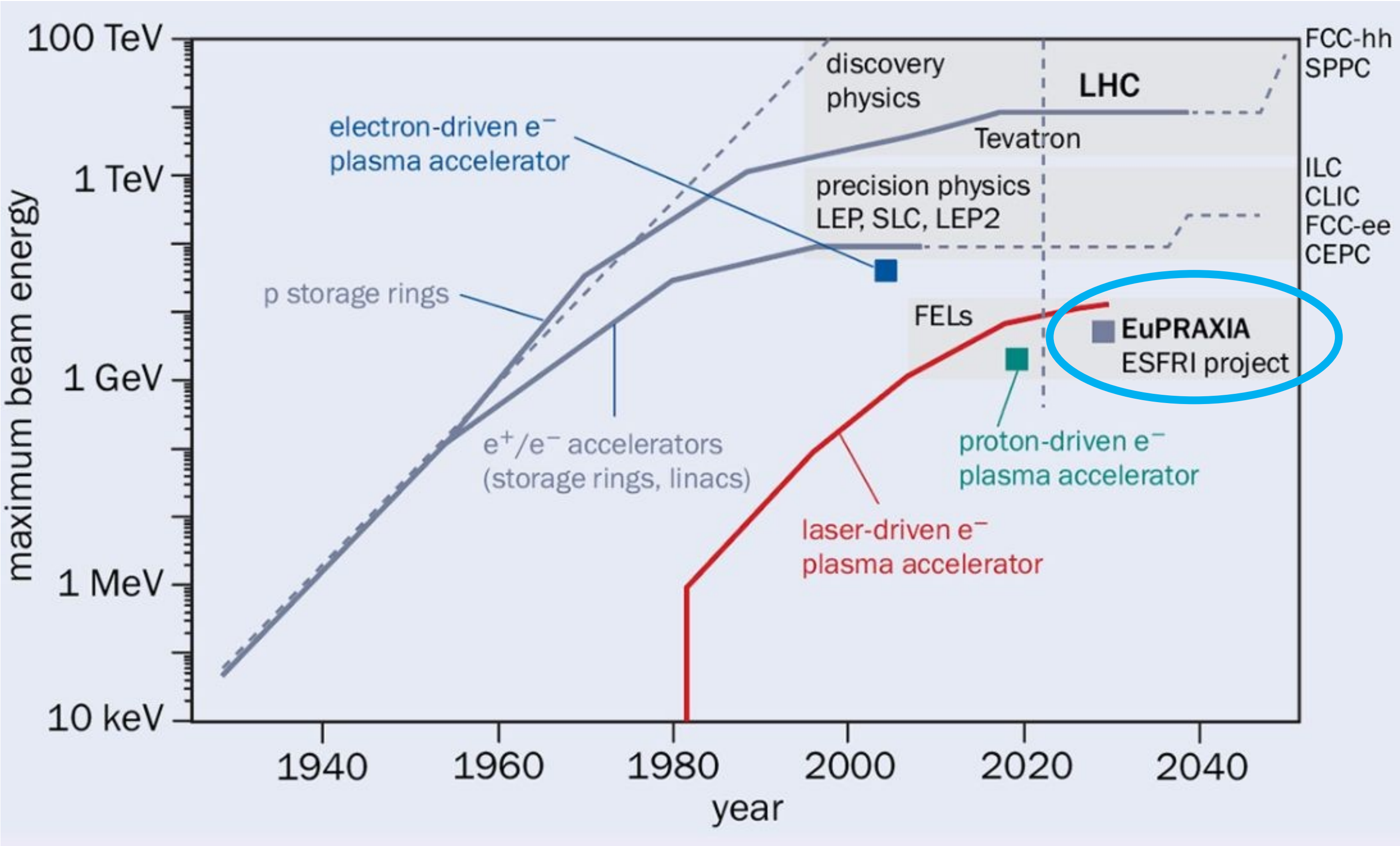
Thanks!

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

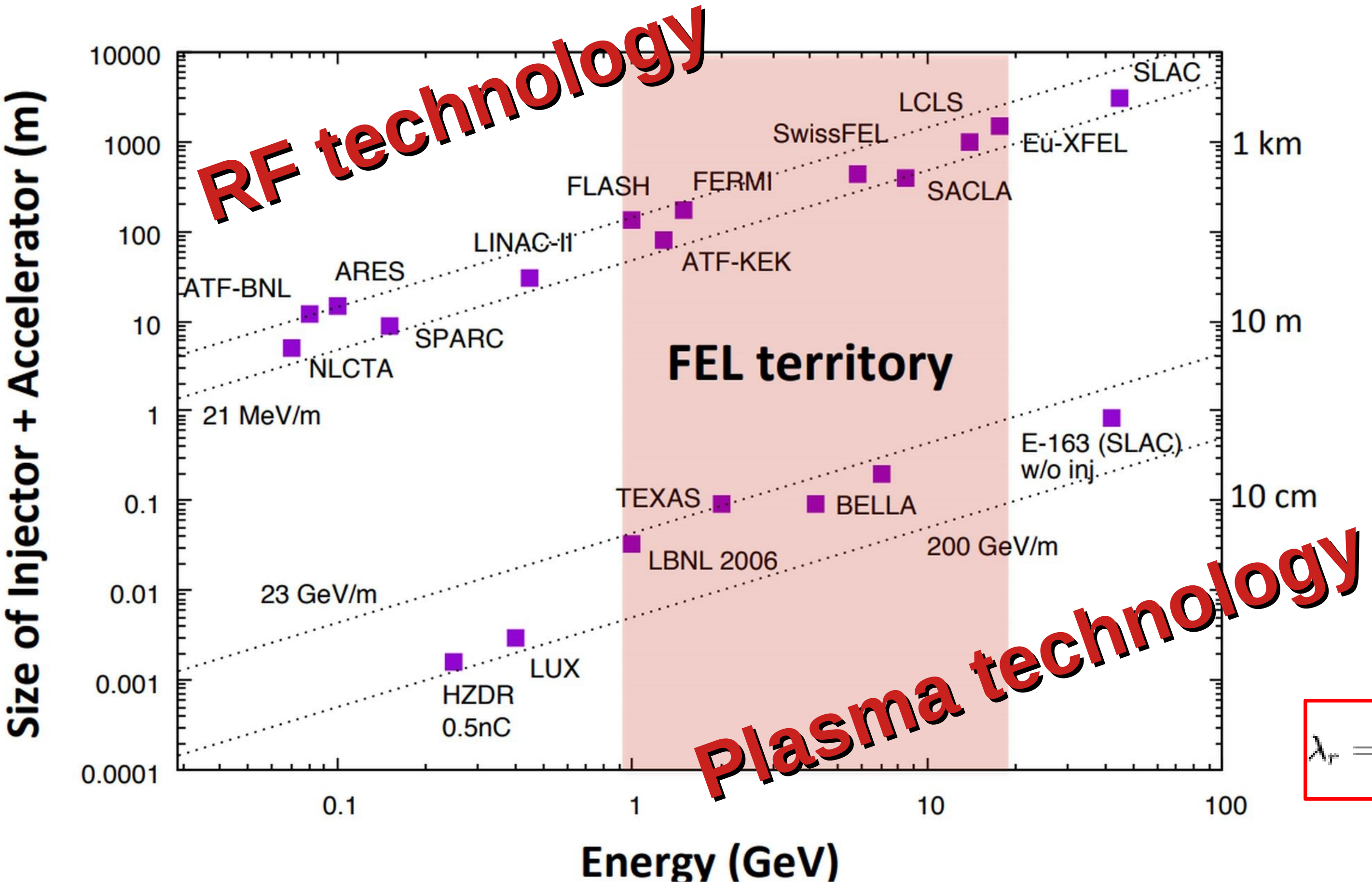


Plasma Accelerator Achievements

- 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!

RF and Plasma technology



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

R. Assmann

FEL requirements

Funded by the European Union

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

AQUA beamline

Funded by the European Union

- 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

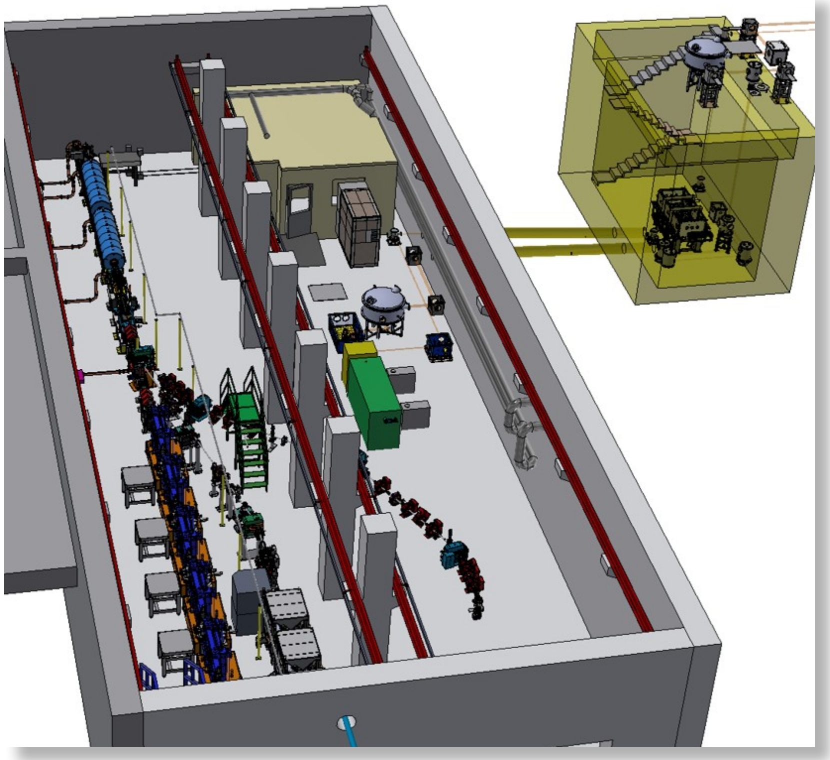
Villa, et al. "EuPRAXIA@ SPARC_LAB status update." X-Ray Free-Electron Lasers: Advances in Source Development and Instrumentation VI. Vol. 12581. SPIE, 2023.

Status of EuAPS (PNRR)

EuAPS goals

- 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

Work in progress

- 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*