Consiglio di Laboratorio - Preventivi 2024
LNF - 06/07/2023

Betatron radiation source from beam-driven PWFA at SPARC_LAB: a test-bed for a plasma undulator device

Resp. Naz. LNF: *Enrica Chiadroni* (Sapienza Univ., Ass. LNF); Resp. Loc. **RM1**: *Andrea Mostacci*; Resp. Loc. **RM2**: *Alessandro Cianchi*; Resp. Loc. **Mi**: *Andrea Renato Rossi*

4-years experiment: 2024-2027

Dipartimento di Scienze di Base e Applicate per l' Ingegneria

Sapienza Università di Roma

International Scenario

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

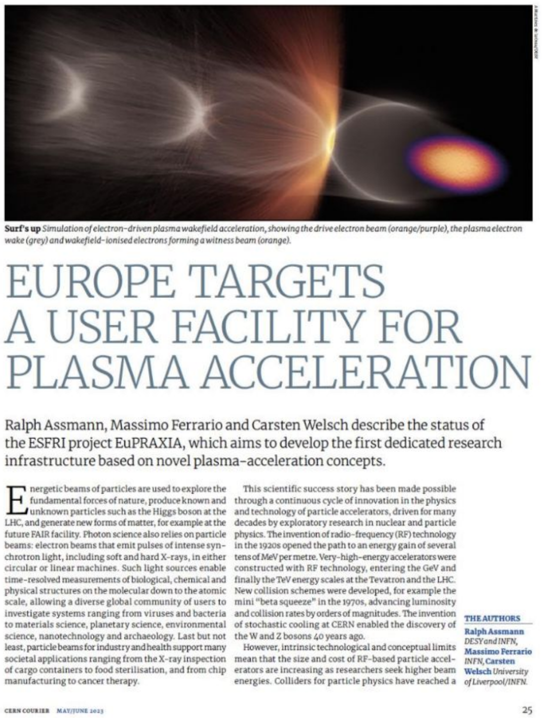
1 – 100 GV/m accelerating field

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

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



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.*

CERN COURIER MAY/JUNE 2023

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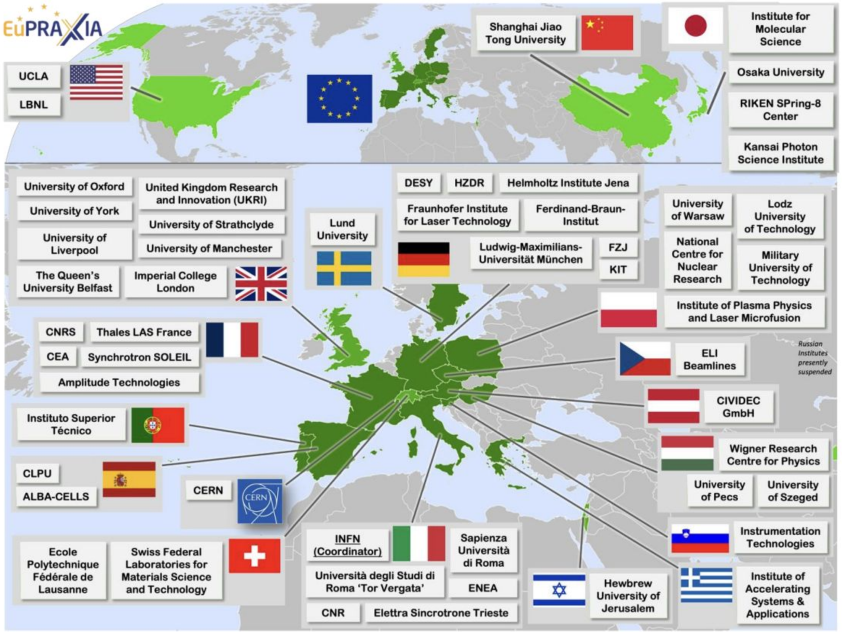
https://cerncourier.com/a/europe-targets-a-user-facility-for-plasma-acceleration/

Wide International Collaboration

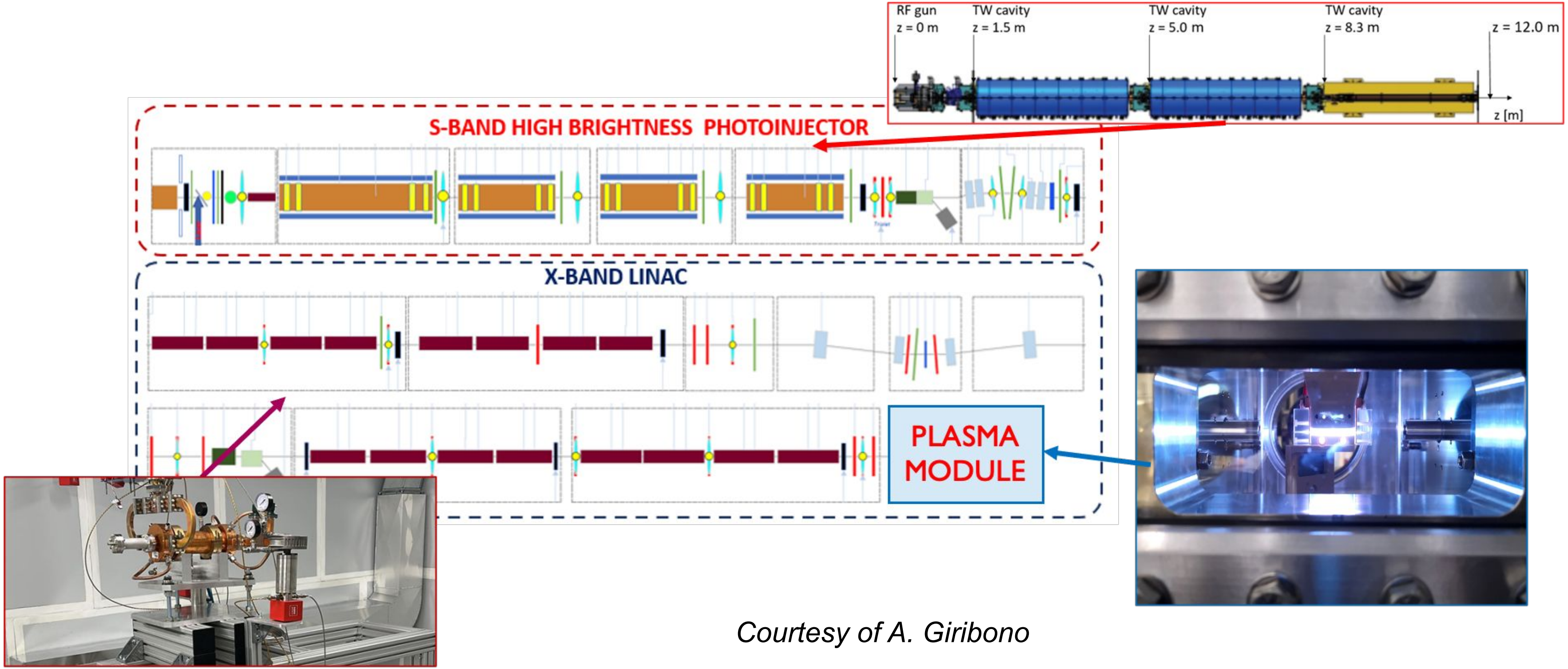
- ➔ The EuPRAXIA Consortium today: 54 institutes from 18 countries plus CERN
- ➔ Included in the ESFRI Road Map Wide International Collaboration
- ➔ Efficient fundraising:
  - ◆ Preparatory Phase consortium (funding EU, UK, Switzerland, in-kind)
  - ◆ Doctoral Network (funding EU, UK, inkind)
  - ◆ **EuPRAXIA@SPARC_LAB (Italy, in-kind)**
  - ◆ **PNRR - EuAPS Project (Next Generation EU)**



Courtesy of M. Ferrario

EuPRAXIA@SPARC_LAB: A High Brightness PWFA

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



Courtesy of A. Giribono

EuPRAXIA Advanced Photon Sources (EuAPS)

Laser-driven betatron radiation source at SPARC_LAB

- ➔ Supported by **PNRR funding**
- ➔ Collaboration among INFN, CNR, University of Tor Vergata
- ➔ **Operational facility at SPARC_LAB** by the end of 2025
- ➔ EuPRAXIA **precursor for a 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}

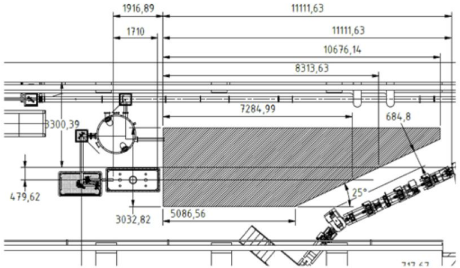
Finanziato dall'Unione europea
NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

EuPRAXIA
Advanced Photon Sources

Location of the source



Courtesy S. Lauciani

- EuAPS setup fits inside the SPARC Bunker
- Right now a space of about 10 meters for users' beamline is available
- We can consider also in the future to remove the dogleg and to gain about 20 meters.

Courtesy of A. Cianchi

Motivation

The EuPRAXIA@SPARC_LAB project focuses to realize a compact plasma-based user facility

- ➔ Plasma acceleration module
- ➔ Ancillary components
  - ◆ Compact diagnostic station
  - ◆ Active Plasma Lens based transfer line

Spin-off of SL_COMB2FEL

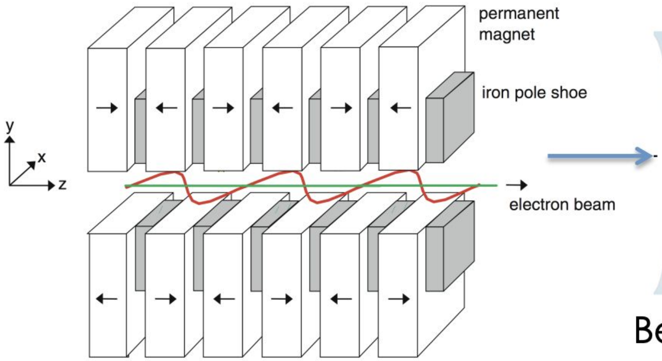
Conventional undulators are still too long => not compact and expensive

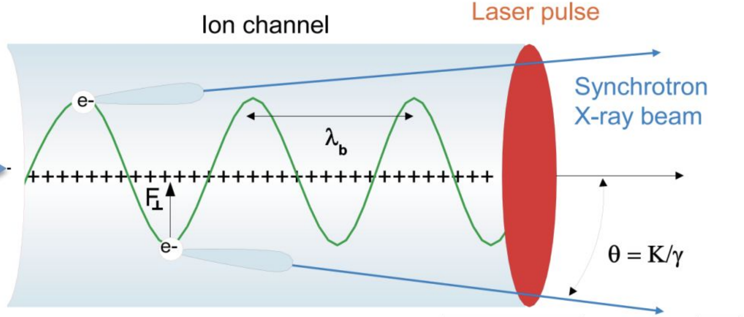
➔ *betatron* motion of electrons in an ion-channel to emulate an undulator

⇒ **very compact device**

- ➔ Betatron motion consists in oscillations normal to the propagation direction
- ➔ It is relevant only in a uniform focusing channel, like a plasma channel

Physical Principle





Betatron oscillation $k_\beta = \sqrt{2\pi r_e n_0 / \gamma} = k_p / \sqrt{2\gamma}$

A. Rousse *et al.,* Phys. Rev. Lett. **93**, 135005 (2004).

$$K = \frac{2\pi\gamma x_0}{\lambda_\beta} \simeq 1.33 \times 10^{-10}\, \gamma^{0.5}\, n_e^{0.5}[\mathrm{cm}^{-3}]\, x_0[\mu\mathrm{m}]$$

Amplitude dependent

K can reach ~100 (Requires large offset, $k_p x_0$ ~1)

$$E_c[\mathrm{eV}] = 5\times10^{-21}\, \gamma^2\, n_e[\mathrm{cm}^{-3}]\, x_0[\mu\mathrm{m}]$$

Photon energy up to

Can reach up to 100 MeV with dense plasma.

Plasma wigglers can give magnet field equivalent B_u>100 T with sub-cm wavelength

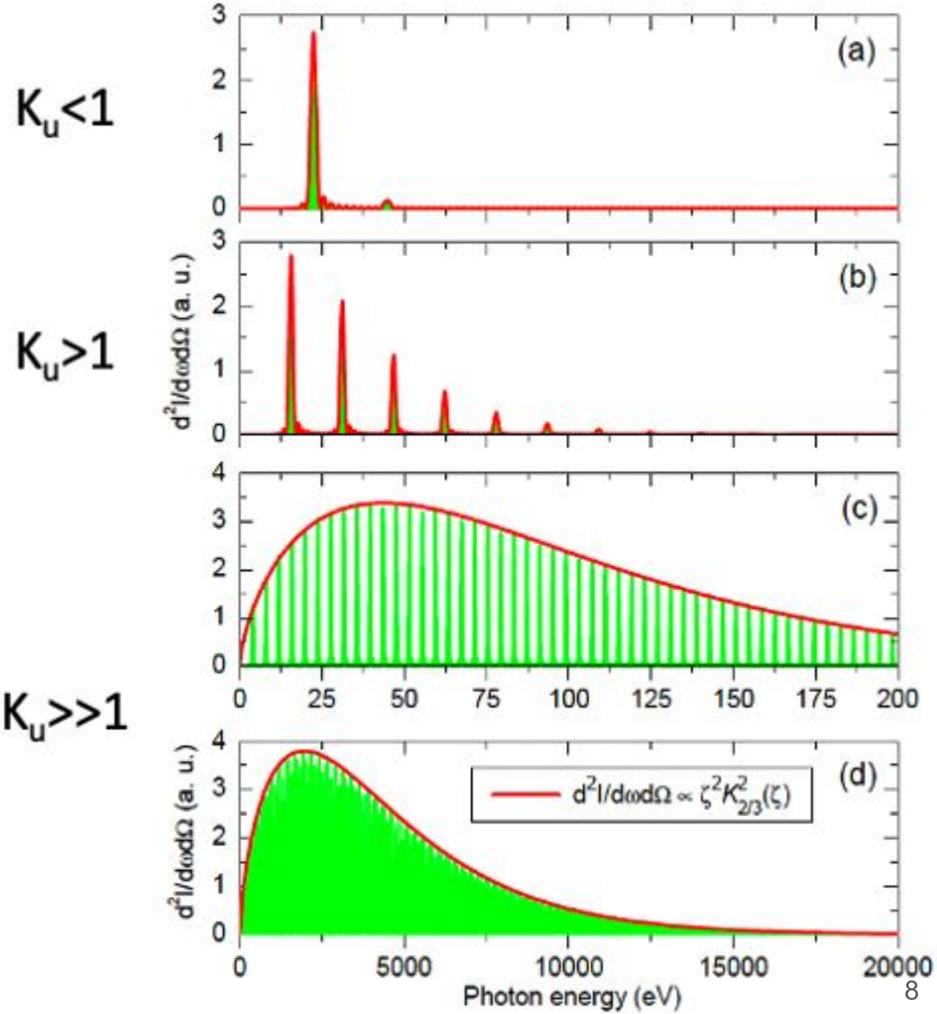
Courtesy of J. Rosenzweig

S. Kiselev et al., PRL **93**, 135004 (2004)

Radiation properties

➔ Betatron radiation is usually broadband

Relevant scalings:



Resonant frequency $\omega(t) \propto \gamma^{7/4}(t)$

Critical frequency $\omega_c \propto \gamma^3$

Peak power $P(t) \propto \gamma^{3/2}(t)$

Average power $P \propto \gamma^4$

Issues causing inhomogeneous broadening

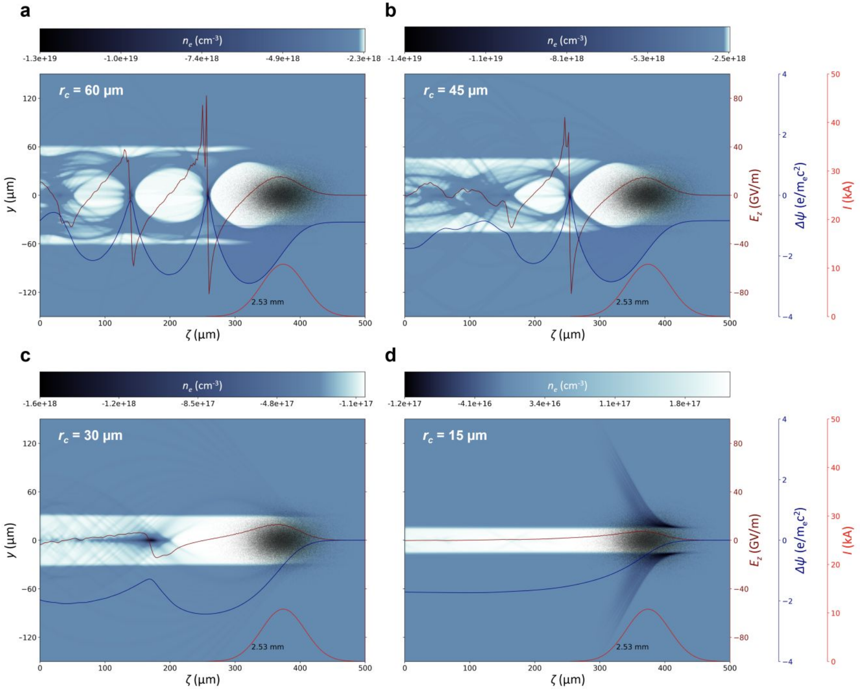
- ➔ Plasma bubbles act as accelerating but also focusing elements
- ➔ Focusing fields are quasi-electrostatic
- ➔ In **magnetic undulators** the strength parameter, *K*, depends only on physical constants and the magnetic field
- ➔ In a **plasma focusing bubble** the strength parameter is different for each electron and depends on the oscillation amplitude, leading to inhomogeneous broadening of the radiation spectrum

⇒ Uniform ion column

Ion Column Formation

A.F. Habib et al.,
https://doi.org/10.48550/arXiv.2111.01502

- Neutral plasma creation through ionization laser
- Blowout of the plasma electrons through the driver beam
    - **plasma electrons are expelled from the plasma region toward the neutral gas region**
        - **negligible restoring force** outside column
        - **negligible accelerating force** inside column
        - **linear restoring force** inside column

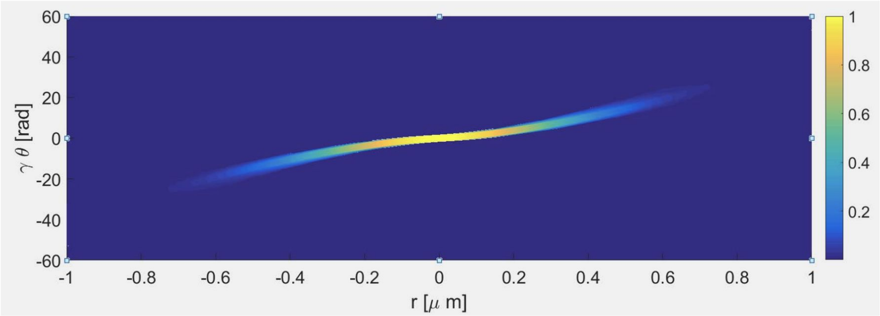


$$\lambda_{u,\beta}[\mu m] = 4.72 \cdot 10^{10}\sqrt{\gamma/n_0[cm^{-3}]}$$

$$K_{u,\beta} = 1.33 \cdot 10^{-10}\sqrt{\gamma/n_0[cm^{-3}]}r_\beta[\mu m]$$

Non-Intercepting Diagnostic

- ➔ Betatron radiation carries information about beam-plasma interaction
  - ◆ Both angular and spectral information yield information about the plasma accelerated beam
    - Single shot and non-intercepting electron beam diagnostic tool for plasma-accelerated witness
    - Possible to distinguish between driver and witness



$$\epsilon_{r_\beta N} = \gamma_0\sqrt{(\sigma_\gamma/\gamma_0)^2\sigma_r^2\sigma_\theta^2 + \epsilon_{r_\beta}^2}$$

Normalized rms emittance (correlated): 0.6 mm mrad

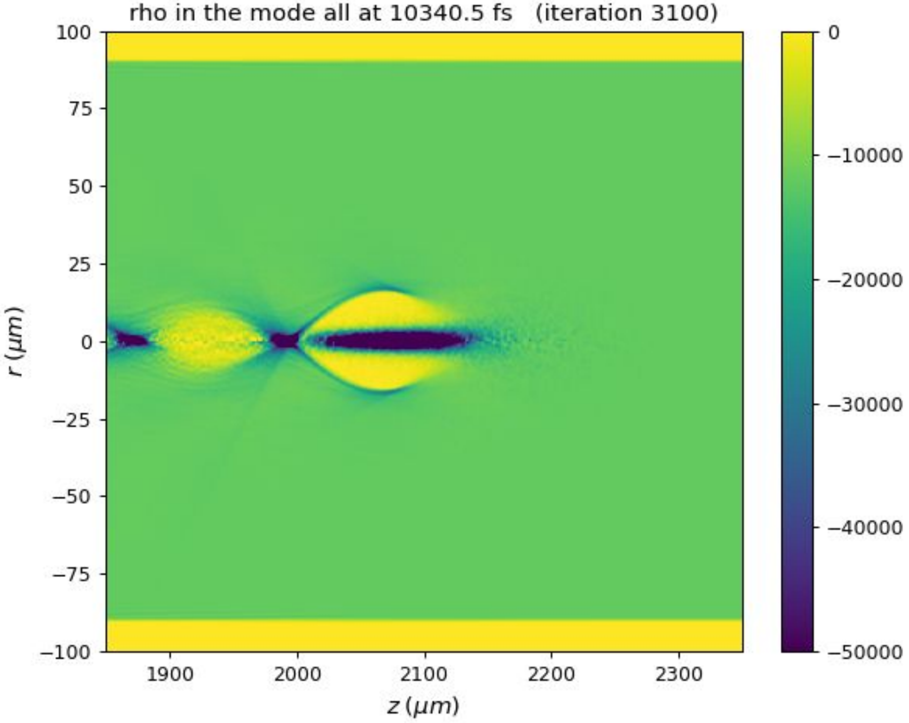
A. Curcio et al., PR AB **20**, 012801 (2017)

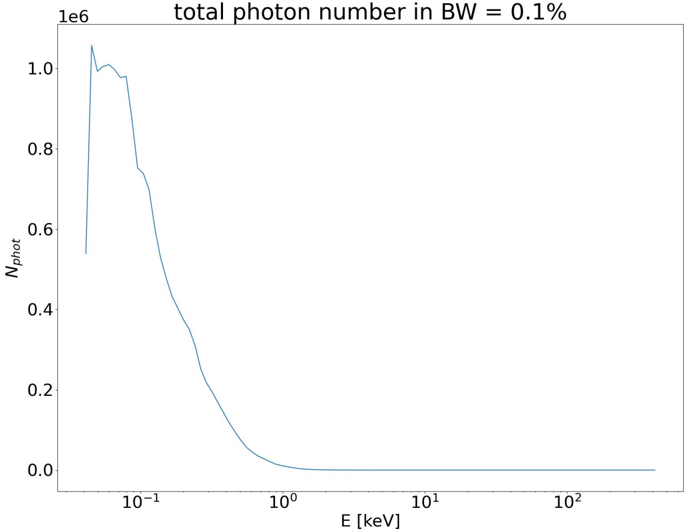
Deliverables and Milestones

- D1. Demonstration of high gradient and high brightness PWFA beam
  - M1.1 Simulations
- D2. Generation of plasma waves with sufficient numbers of wiggle periods
  - M2.1 Simulations of beam dynamics and beam/plasma interaction to
    - optimize the betatron radiation emission => Single, driver-like, bunch: 500 pC …
  - M2.2 Project of instrumentation and photon diagnostics
  - M2.3 Project of plasma diagnostics
  - M2.4 Experimental studies
- D3. Betatron-based emittance diagnostics
  - M3.1 Simulations of beam dynamics and beam/plasma interaction to
    - act as non-destructive, single shot, electron beam diagnostic => driver + witness configuration
    - Procurement of beam instrumentation
- D4. Study of the radiation emitted by an injected electron bunch in a ion column
  - M4.1 Plasma source design and project
    - Ion Channel Laser-driven
    - Ion Channel Particle-driven
  - M4.2 Implementation of plasma source, including diagnostics
  - M4.3 Experimental studies

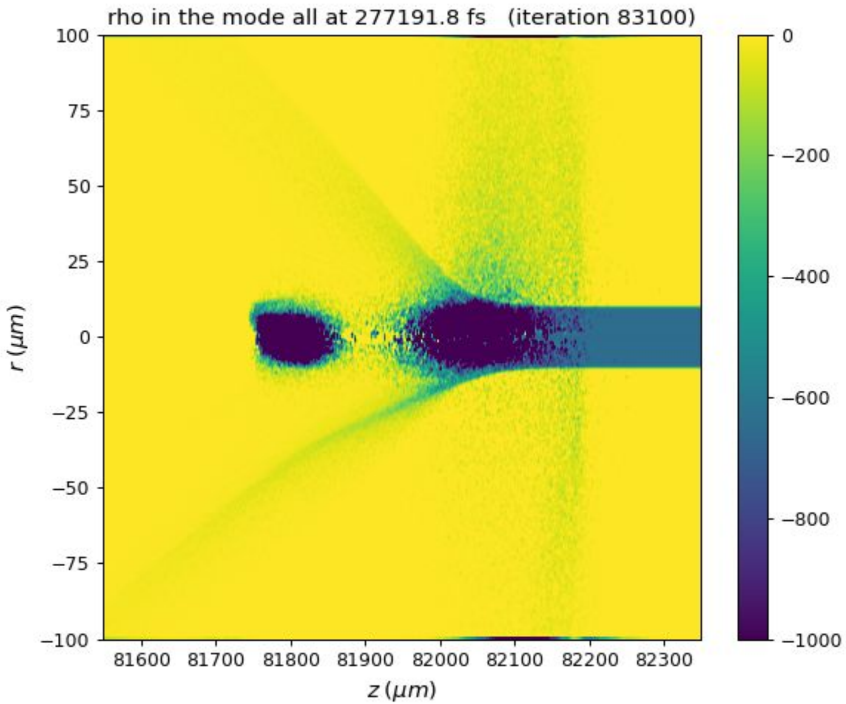
Very preliminary simulations

Single, driver-like, bunch: 800 pC, 3 cm capillary, $n_0 \sim 10^{17}$ cm^{-3}





Very preliminary simulations



Comb-like, driver and witness, **beam**:
500 pC + 50 pC, 3 cm acceleration + 10 cm undulator, $n_0 \sim 4\ 10^{15}$ cm^{-3}

Total Financial Request

I year ⇒ Consumables: Capillaries, electrovalves, electrodes ⇒ 20 keuro

Missioni ~ 10 keuro

II year ⇒ Hardware: detectors’ and plasma diagnostics: test and prototypes ⇒ 30 keuro

Missioni ~ 10 keuro

III year ⇒ Hardware: Vacuum chamber including attuators ⇒ 40 keuro

Missioni ~ 10 keuro

IV year ⇒ Sub-judice: Laser beamline to the COMB chamber ⇒ 40 keuro

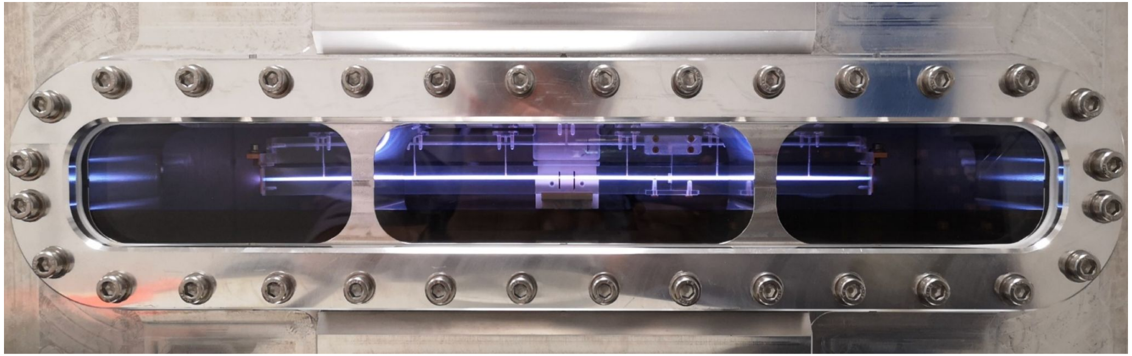
Missioni ~ 10 keuro

Human Resources at LNF (so far)

Name	FTE (%)	Name	FTE (%)
E. Chiadroni (Ass. LNF)	50	…	
M. Bellaveglia	20		
D. Alesini	10		
L. Piersanti	10		
A. Del Dotto	50		
A. Curcio	50		
G. Costa	20		
M. Ferrario	10		
M.P. Anania	30		

Conclusions

- ➔ First EuPRAXIA plasma source enabling **1.1 GeV** (1.5 GV/m) in **40 cm** length capillary ($n = 10^{16}$ cm^{-3})
- ➔ Active Plasma Lenses (APL) based final focus and extraction line
- ➔ APL-based driver removal, transfer and matching line
- ➔ Plasma-based undulator



- Length: 40 cm
- Diameter: 2 mm
- 10 kV – 380 A (10^{17} cm^{-3})
- 6 inlets of 1 mm in diameter

Courtesy of A. Biagioni

⇒ Toward a whole plasma-based facility