

### Web Seminar at IJCLab Orsay - June 25th, 2021

## From SPARC\_LAB to EuPRAXIA@SPARC\_LAB: recent results and project status

Enrica Chiadroni (INFN - LNF)



## Outline



• Plasma-based R&D activities at SPARC\_LAB



• EuPRAXIA@SPARC\_LAB test user facility

Performances and time schedule



• EuPRAXIA concept distributed research infrastructure





## Motivation



Plasma-based acceleration has already proved the ability to reach ultra-high, ~GV/m, accelerating gradients

- \* J. Rosenzweig et al., Phys. Rev. Lett. 61, 98 (1988): First experimental demonstration of PWFA
- \* Mangles, Geddes, Faure et al., Nature **431**, (2004): *The dream beam*
- \* W. P. Leemans, Nature Physics vol. **2**, p.696-699 (2006): *GeV electron beams from a centimetre-scale accelerator*
- \* I. Blumenfeld et al., Nature **445**, p. 741 (2007): *Doubling energy in a plasma wake*
- \* P. Muggli et al, in Proc. of PAC 2011, TUOBN3: Driving wakefields with multiple bunches
- The next step is the acceleration, extraction and transport of stable and reliable high brightness electron beams to drive a plasma-based user facility (the EUPRAXIA Design Study has been funded from EU)
  - \* M. Litos et al., Nature **515**, 92 (2014): *High efficiency acceleration in the driver-trailing bunches*
  - \* S. Steinke et al., Nature 000 (2016) doi:10.1038/nature16525: Multi-stage coupling
  - ➡ Plasma-based user facility
    - \* <u>EuPRAXIA@SPARC\_LAB</u> Test User Facility



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- Conventional RF structures reached a practical limit: they cannot sustain accelerating gradients larger than ~100 MV/m (X-band structures) due to breakdown on the wall surfaces
- \* Ultra-high gradients require structures to sustain high fields
  - Plasma-filled structures
    - Maximum accelerating field a plasma can sustain: Wave breaking field

$$E_{Max}[V/m] = \frac{m_e c \omega_p}{e} \approx 100 \sqrt{n_0 [cm^{-3}]} \qquad n_0 = 10^{16} \div 10^{18} cm^{-3}$$
$$\lambda_p[\mu m] \approx \frac{3.3 \cdot 10^{10}}{\sqrt{n_0 [cm^{-3}]}} \quad \text{Scale length of the plasma wake}$$





## Two-bunch Train PWFA



- An intense, high-energy charged particle beam (driver) drives a high-gradient wakefield as it passes through the plasma
- \* The **space-charge** of the electron bunch **blows out plasma electrons**
- \* **Plasma electrons rush back in and overshoot** setting up a plasma density oscillation

$$\omega_p = \sqrt{\frac{n_0 e^2}{m_e \varepsilon_0}}$$

\* A second beam (**witness**), injected at the accelerating phase, is then accelerated by the wake





# PWFA at SPARC\_LAB

• **High quality**  $\varepsilon_n \ll 1mm \ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$ 

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External injection of high brightness electron beams



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ALaDyn sim., courtesy of A. Marocchino

 $\lambda_p \approx 330 \mu m @ n_p = 10^{16} cm^{-3}$ 

# Experimental Layout





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AR



# Two-beams configuration

- Two-bunches configuration produced directly at the cathode with laser-comb technique
  - 200 pC driver followed by witness bunch (20 pC)
- Ultra-short durations (200 fs + 30 fs)
- Separation approximately equal to half plasma wavelength (~1.2 ps)





3 cm long 3D-printed plastic capillary, I mm diameter aperture plasma is produced by ionizing hydrogen gas, injected through two inlets, by means of a high-voltage discharge (12 kV, 300 A) at I Hz repetition rate



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# Assisted beam-loading technique

Pre-chirp to compensate wakefield slope



# **Energy Spread Minimization**

- \* Energy spread reduction in the beam driven PWFA experiment
- \* 4 MeV acceleration in 3 cm plasma with 200 pC driver
  - ~133 MV/m accelerating gradient
  - ⋆ 2x10<sup>15</sup> cm<sup>-3</sup> plasma density

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Energy spread from 0.2% to 0.12%





Energy jitter of the witness energy is 0.5 MeV

R. Pompili et al., *Energy spread minimization in a beam-driven plasma wakefield accelerator* (2021), Nature Physics, **17** (4), pp. 499-503



## **Emittance Characterization**

#### First transverse normalized emittance characterization

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- Multi-shot quadrupole scan technique to measure the plasma-accelerated witness normalized emittance
  - \* emittance increase from 2.7 um to 3.7 um (rms) during acceleration



# **PWFA-driven FEL Studies**

## \* **First experimental observation of the gain growth** of a plasma-driven SASE FEL



- \* **Witness** is completely **characterized** (energy, spread, X/Y emittance) allowing to match it into the undulator beamline
- \* Jitter is online monitored with Electro-Optical Sampling (EOS) diagnostics
- \* Imaging spectrometer with iCCD used to detect FEL radiation



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## **PWFA-driven FEL Studies**

## \* **First experimental observation of the gain growth** of a plasma-driven SASE FEL

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# Experience with plasma at SPARC\_LAB

#### Activities with the high-brightness SPARC photo-injector

# Discharge OFF

#### Plasma characterization





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Biagioni, A., et al., Journal of Instrumentation 11.08 (2016): C08003.
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## Plasma-dechirper

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



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Focusing with active-plasma lenses

Pompili, R., et al., Physical review letters 121.17 (2018): 174801. Pompili, R., et al., Applied Physics Letters 110.10 (2017): 104101.



50



## The path towards EuPRAXIA@SPARC\_LAB



# Conceptual Design Report

 First ever international design of a plasma accelerator facility

SPARC

- Funded 2015-2019 by European Union (Horizon2020) with 3 Million Euro
- Coordinating lab: DESY (R. Assmann)
- Growing consortium: 32 → 41 labs, ELI, CERN, LBNL, Osaka, Shanghai, Russian labs
- Industry: Thales (France), Amplitude (France), Trumpf Scientific (Germany)

Conceptual Design Report submitted to EU on November 1<sup>st</sup>, 2019



## 653 page CDR, 240 scientists contributed

http://www.eupraxia-project.eu/

Assmann, R.W., Weikum, M.K., Akhter, T. et al. *EuPRAXIA Conceptual Design Report*. Eur. Phys. J. Spec. Top. **229**, 3675–4284 (2020)





## The Consortium Members for the Next Phase (from 16 to 40 Consortium Agreement signed\*)



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#### Courtesy R. Assmann

- 40 Member institutions in:
- Italy (INFN, CNR, Elettra, ENEA, Sapienza Università di Roma, Università degli Studi di Roma "Tor Vergata")
- France (CEA, SOLEIL, CNRS \*pending)
- Switzerland (EMPA, Ecole Polytechnique Fédérale de Lausanne)
- Germany (DESY, Ferdinand-Braun-Institut, Fraunhofer Institute for Laser Technology,

Forschungszentrum Jülich, HZDR, KIT, LMU München)

- United Kingdom (Imperial College London, Queen's University of Belfast, STFC, University of Liverpool, University of Manchester, University of Oxford, University of Strathclyde, University of York)
- Poland (Institute of Plasma Physics and Laser Microfusion, Lodz University of Technology, Military University of Technology, NCBJ, Warsaw University of Technology)
   Portugal (IST)
- Hungary (Wigner Research Centre for Physics)
- \* Sweden (Lund University)
- Israel (Hebrew University of Jerusalem)
- \* **Russia** (Institute of Applied Physics, Joint Institute for High Temperatures)
- United States (UCLA) \*pending
- \* CERN
- \* ELI Beamlines



## ESFRI Proposal: Financial and Political Support

(European Strategy Forum on Research Infrastructure)

Courtesy R. Assmann

A. Ministre dell'Unin

To become official European Research Infra-structure (RI) the EuPRAXIA project applied to **2021 update of the European Roadmap** for RI's. Process managed by **ESFRI**.

- \* Formal process with clear requirements.
- Lead Country: Italy (LNF/INFN)
   Political and financial support letter sent to ESFRI by Italian Ministry
- Political support letters (at least two needed from countries):
  - Hungary
  - Portugal
  - Czech Republic (ELI beamlines)
  - ∗ UK

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\* Note: All operational costs covered by host countries.







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\* Note: All operational costs covered by host countries.



We are glad to inform you that, following ESFRI internal procedures, **the proposal "European Plasma Research Accelerator with Excellence in Applications - EuPRAXIA" has been considered eligible** and can now be assessed for entering the ESFRI Roadmap 2021.

The evaluation exercise has just started and below you can find the next steps with an indicative timeframe:

invitation for the hearing with list of critical questions: February - March 2021

Hearing: April - May 2021



# Organization



#### Courtesy R. Assmann





# Concept Distributed Research Infrastructure



![](_page_20_Picture_2.jpeg)

Courtesy R. Assmann

# EuPRAXIA@SPARC\_LAB Test User Facility

![](_page_21_Figure_1.jpeg)

EuPRAXIA@SPARC\_LAB will combine **compact X band RF technology** from CLIC and the plasma accelerator **at its Frascati construction site**.

## Multiple users from different fields (A. Balerna et al., Condens. Matter 2019, 4(1), 30):

- studying and understanding bacteria, viruses, materials, ...
- using intense bursts of photons, electrons, positrons resolving time-dependent processes in ultra-fast science
- co-developing novel technologies for accelerators, users, ...

![](_page_21_Picture_7.jpeg)

EuPRAXIA@SPARC\_LAB Conceptual Design Report is publicly available and can be downloaded from http://www.lnf.infn.it/sis/preprint/ pdf/getfile.php?filename=INFN-18-03-LNF.pdf

![](_page_21_Picture_9.jpeg)

# EuPRAXIA@SPARC\_LAB Test User Facility

![](_page_22_Figure_1.jpeg)

#### Executive design of the building officially started: delivery of the design expected by the end of 2021.

![](_page_22_Picture_3.jpeg)

EůPRA

![](_page_22_Picture_4.jpeg)

![](_page_22_Picture_5.jpeg)

# Preliminary Layout

INFN

![](_page_23_Picture_1.jpeg)

![](_page_23_Picture_2.jpeg)

SPARC

LAB

## **Expected SASE FEL Performances** SPARC

4	Chapter 2. Free Electron Laser design princi			
	Units	Full RF case	Plasma case	
Electron Energy	GeV	1	1	
Bunch Charge	pC	200	30	
Peak Current	kA	2	3	
RMS Energy Spread	%	0.1	1	
RMS Bunch Length	fs	40	4	
RMS matched Bunch Spot	μm	34	34	
RMS norm. Emittance	μm	1	1	
Slice length	μm	0.5	0.45	
Slice Energy Spread	%	0.01	0.1	
Slice norm. Emittance	μm	0.5	0.5	
Undulator Period	mm	15	15	
Undulator Strength K		1.03	1.03	
Undulator Length	m	12	14	
Gain Length	m	0.46	0.5	
Pierce Parameterp	x 10 <sup>-3</sup>	1.5	1.4	
Radiation Wavelength	nm	3	3	
Undulator matching $\beta_u$	m	4.5	4.5	
Saturation Active Length	m	10	11	
Saturation Power	GW	4	5.89	
Energy per pulse	μJ	83.8	11.7	
Photons per pulse	x 10 <sup>11</sup>	11	1.5	

Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV)

Water is almost transparent to radiation in this range while nitrogen and carbon are absorbing (and scattering)

![](_page_24_Figure_5.jpeg)

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

Courtesy F. Stellato, UniToV

![](_page_24_Picture_8.jpeg)

Table 2.1: Beam parameters for the EuPRAXIA@SPARC\_LAB FEL driven by X-band linac or Plasma acceleration

![](_page_24_Picture_10.jpeg)

![](_page_25_Picture_0.jpeg)

![](_page_25_Figure_1.jpeg)

![](_page_25_Figure_2.jpeg)

![](_page_25_Picture_3.jpeg)

![](_page_25_Picture_5.jpeg)

## Conclusions

- R&D activities on PWFA at SPARC\_LAB show promising results concerning stability and beam quality needed to pilot a FEL
  - \* First observation of SASE FEL gain growth
- \* The EuPRAXIA project is ongoing
  - ESFRI roadmap submitted

The Italian EuPRAXIA, i.e.
 EuPRAXIA@SPARC\_LAB, has received
 binding commitments for more than 100 M€

![](_page_26_Picture_6.jpeg)

![](_page_26_Picture_7.jpeg)

![](_page_26_Figure_8.jpeg)

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![](_page_26_Picture_10.jpeg)

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## THANK YOU FOR THE KIND ATTENTION

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