

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



<u>enrica.chiadroni@lnf.infn.it</u>





- 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



enrica.chiadroni@lnf.infn.it



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
 - ⋆ 2x10¹⁵ cm⁻³ 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)



enrica.chiadroni@lnf.infn.it



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.



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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 1st, 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





Courtesy R. Assmann

EuPRAXIA@SPARC_LAB Test User Facility



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, ...



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



EuPRAXIA@SPARC_LAB Test User Facility



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



EůPRA





Preliminary Layout

INFN





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 ⁻³	1.5	1.4	
Radiation Wavelength	nm	3	3	
Undulator matching β_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 ¹¹	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)



Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state **Possibility to study dynamics** ~10¹¹ photons/pulse needed

Courtesy F. Stellato, UniToV



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













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€















THANK YOU FOR THE KIND ATTENTION



