ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPLXGD2

PROGRESS TOWARDS DEMONSTRATION OF A PLASMA-BASED FEL

E. Chiadroni*
Dept. of Basic and Applied Sciences for Engineering - Sapienza, University of Rome and INFN-LNF, Italy

Abstract

Plasma-based technology promises a revolution in the field of particle accelerators by pushing beams to gigaelectronvolt energies within centimeter distances. Several experiments are ongoing world-wide towards demonstration of a plasma based FEL enabling the realization of ultra-compact facilities for user applications like Free-Electron Lasers (FEL). The progress towards a plasma based FEL user facility is here reported, with particular focus on the recent results about the first experimental evidences of FEL lasing by both a particle beam-driven plasma accelerator at the SPARC_LAB test facility and a laser-driven plasma accelerator at SIOM. The status in the International scenario and prospects toward a plasma-based FEL are discussed.

MOTIVATION

Plasma-based accelerators, both laser and beam driven, have already demonstrated the ability to accelerate multi-GeV electrons in cm-scale plasma structures [1–4]. The current goal of the worldwide plasma, laser and photo-injector communities is to demonstrate the stable and repeatable acceleration of high brightness beams to drive a plasma-based user facility.

Owing to ultra-high accelerating gradients, combined with injection into micrometer-scale accelerating wakefield structure, plasma-based accelerators hold great potential to drive novel, smaller footprint light sources. Several advances, in particular focused on the optimization of the energy spread, have been done toward high quality plasma-accelerated beams paving the way to new generation of compact Free-Electron Lasers (FELs) based facilities. Two promising results on this topic are shown in Figs. 1 and 2, highlighting experiments performed at FLASHForward (DESY) [5] and at SPARC_LAB (LNF) [6].

Figure 1 demonstrates the preservation of the energy spread and the high efficiency acceleration, exploiting a strong beam loading when accelerating bunches with peculiar charge density profiles [7]; while Fig. 2 shows the reduction of the energy spread based on the assisted-beam loading technique: during the acceleration, the witness longitudinal phase space (LPS) is rotated and energy spread reduced by 40% with respect to the initial value. The energy chirp imprinted on the witness is thus used to both improve its beam loading and compensate the slope of the plasma wakefield, so that it can be considered an assisted beam-loading energy spread compensation [8].

To drive a plasma-based FEL facility the quality of the accelerated beam must not be degraded in the plasma, since

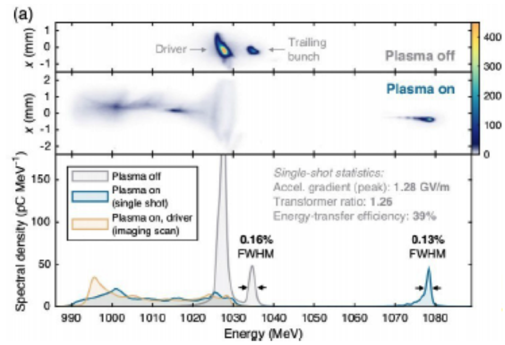

Figure 1: Preservation of the energy spread and the high efficiency acceleration based on strong beam loading induced by peculiar charge density profiles [7].

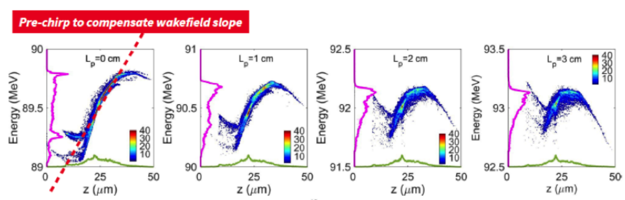

Figure 2: Witness beam longitudinal phase space: minimization of energy spread based on assisted beam loading technique [8].

the requirements on the 6D phase space to operate a FEL must be guaranteed. In particular, the following conditions on transverse normalized emittance, peak current and energy spread must be satisfied:

$$\varepsilon_n \ll \text{mm mrad}, \ \text{I} \approx \text{kA}, \ \frac{\Delta\gamma}{\gamma} \ll 1\%.$$

Indeed many of these properties are described by the 1D model of the FEL interaction and are related to the so-called Pierce parameter

$$\rho = \frac{1}{2\gamma}\Big[\frac{I}{I_A}\Big(\frac{\lambda_u K[JJ]}{\sqrt{8}\pi\sigma_x}\Big)^2\Big]^{1/3}, \tag{1}$$

which determines the 1D gain length, $L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$, giving an estimation of the saturation power, $P_{sat} = P_{in}e^{z/L_g}$; γ is the Lorentz factor of the beam, I the peak current, $I_A = 17$ kA the Aĺfven λ_u the undulator period, K defines the maximum angle of the emitted radiation with respect to the axis, $[JJ]$ is the Bessel factor, defined as the difference between the J_0 and J_1 Bessel functions of an argument ξ that depends on K, and σ_x the rms beam transverse size.

In addition for driving plasma-based FEL, the long term and the shot-to-shot stability and reproducibility are issues to overcome and finally the high repetition rate would be

* enrica.chiadroni@uniroma1.it

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPLXGD2

preferable to increase the average power. Concerning this last issue, a new method has been conceived, based on the recovery time of the plasma wakefield, which places an upper limit on the maximum achievable repetition rate of plasma accelerators [9], paving the way to high repetition rate plasma-based accelerators.

METHODS

Plasma are used because the ionized plasma in any kind of plasma sources (e.g. gas-filled discharge capillary, a gas cell or a gas jet) can sustain accelerating gradients 2-3 orders of magnitude larger than in conventional RF-based accelerators. The maximum field a plasma structure can sustain before facing wave breaking is depending on the plasma density and, for typical values between 10^{16} – 10^{18} cm^{-3}, it is ≈ 10-100 GV/m. The plasma density defines also the characteristic scale length of the accelerating field, that is the plasma wave, which for density of the order of 10^{16} cm^{-3}, $\lambda_p \approx 300\,\mu$m. The accelerating method consists in the driver, which creates the bubble, being either a dense relativistic particle beam of sub-ps duration and kA current (particle-driven plasma wakefield, PWFA), or an ultra-intense laser pulse, ≈ 10^{18} W/cm^2, and pulse duration of few 10s of fs (laser-driven plasma wakefield, LWFA). The witness can be either self-injected or externally injected. The injected beam undergo then a rapid acceleration to ultra-relativistic energies in um scale structures, remaining short, dense and free of significant emittance degradation.

INTERNATIONAL SCENARIO

Several groups worldwide are pursuing these novel light sources, with methodology varying in the use of wakefield driver, plasma sources, phase space manipulation, beam line design.

LWFA Experiments

A list of experiments/facility aiming at the qualification of LWFA with the FEL process demonstration is reported in Table 1 [10].

The breakthrough experiment has been performed at the SIOM facility (Shangai), where the first proof-of-principle demonstration of LWFA-based FEL at around 27 nm was demonstrated [11]. A 200 TW Ti:Sa laser at 800 nm was focused onto a gas target to generate and accelerate electron up to 500 MeV. The electrons are then injected into 3 undulator modules. SASE FEL exponential growth has been observed for the first time in such a kind of plasma-driven accelerator, reaching a maximum radiation energy of a single pulse of 150 nJ, and the maximum obtained gain was approximately 100-fold in the third undulator, as measured by methods of orbit kick and spontaneous radiation calibration.

PWFA Experiments

A list of experiments/facility aiming at the qualification of PWFA with the FEL process demonstration is reported in Table 2 [10].

Both SLAC FACET II and Strathclyde have not yet begun experimental operation and for those target parameters are listed. In particular, FACET II aims to reach up to 10 GeV and multi-kA current electron bunches to explore a suite of advanced accelerator and coherent radiation experiments, toward the attosecond science user program.

FLASHForward and SPARC_LAB are both operating experiments putting efforts on the demonstration of high quality, high rep rate acceleration. In particular, SPARC_LAB (Frascati, Italy) based on these achieved parameters, succeeded to demonstrate the exponential gain growth in different FEL operation modes. This proof-of-principle experiment has demonstrated the high-quality of the plasma-accelerated beam able to drive a Free-Electron Laser [12]. To transport and match the beam at the undulator entrance, the witness has been completely characterized in terms of energy, energy spread, horizontal and vertical emittance (values are reported in Table 2. With the aim of stabilizing the emitted radiation, a second experiment has been performed at SPARC_LAB, demonstrating the operation of the first PWFA-driven seeded FEL. Results, validated with start-to-end simulations, show a significant increase in the pulse radiation energy, from 30 nJ up to 1 μJ and in stability of the emitted radiation, i.e. around 27% with SASE only up to 90% in the seeded regime (Fig. 3). Results have been submitted to Nature Photonics.

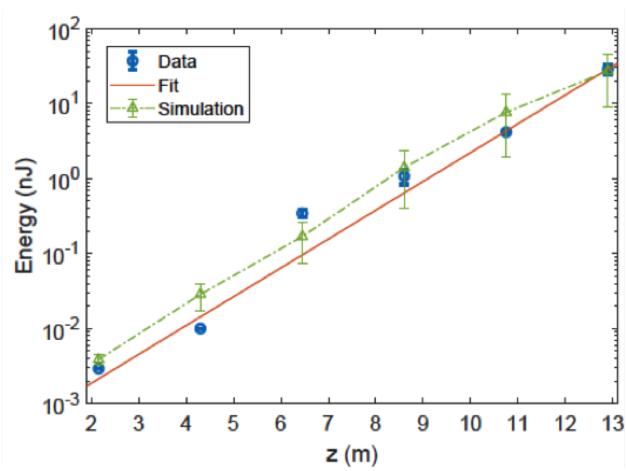

Figure 3: Exponential gain of SASE FEL radiation energy at SPARC_LAB. Data are taken with six (Si) photo-diodes downstream the undulators.

The stability and repeatability of the plasma formation is obtained by pre-ionizing the gas with a Nd:YAG laser focused at the capillary entrance (Fig. 4). This reduces the discharge timing-jitter from tens to few nanoseconds, because it is affected by the voltage and the gas pressure in the capillary and, in turn, the plasma density fluctuations from 12% to 6% [13, 14]. The stability shot-to-shot, measured in terms of relative standard deviation, has been presented in terms of the stability of the current pulse. This stabilization technique allowed for the development of very long capillaries, as the one recently built at SPARC_LAB, i.e 40 cm

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPLXGD2

Table 1: Summary of parameters for the facilities aiming at the demonstration of LWFA-driven FEL [10].

	COXINEL	DESY - LUX	SIOM	LBNL-BELLA
Charge density (pC/MeV)	0.5	4	1 - 5	2
Rep. Rate (Hz)	1 - 10	1	1 - 5	5
E_{mean} (GeV)	0.18 - 0.4	0.3	0.84	0.1 - 0.3
σ_E (%)	NA	0.5	0.24 - 0.4	0.2 - 1
Charge (pC)	NA	50	8 - 25	25
ε_n (mm mrad)	1	1.5 (H) - 0.3 (V)	0.4	0.3 - 1
FEL λ_r (nm)	UV-VUV	100	6 - 10	80
FEL operation modes	Decompression + seeding	Decompression + SASE	SASE Transverse Decompression	Decompression + seeding
Key challenge pursued	Demonstrate FEL gain	Demonstrate FEL gain	Demonstrate FEL gain	Demonstrate FEL gain

Table 2: Summary of parameters for the facilities aiming at the demonstration of PWFA-driven FEL [10].

	SLAC FACET II	DESY - FLASHForward	Strathclyde	SPARC_LAB
I_p (kA)	10 - 500	1	1 - 100	2.6
Rep. Rate (Hz)	1	10 (up to 10^4 after future upgrade)	Variable	1
E_{mean} (GeV)	5 - 10	1	1 - 5	0.094
σ_E (%)	0.1 - 1	0.15	0.01 - 2	0.3
Charge (pC)	10 - 100	100	0.1 - 500	20
ε_n (mm mrad)	1 - 10	1 - 20	0.01 - 1	~ 2
FEL λ_r (nm)	10 - 50	Soft X-Rays	Hard X-rays	800
FEL operation modes	Compression + prebunching	SASE	Multiple	SASE and Seeded
Key challenge pursued	Attosecond FEL pulses	High average power FEL	Hard X-rays FEL gain	Demonstration of SASE

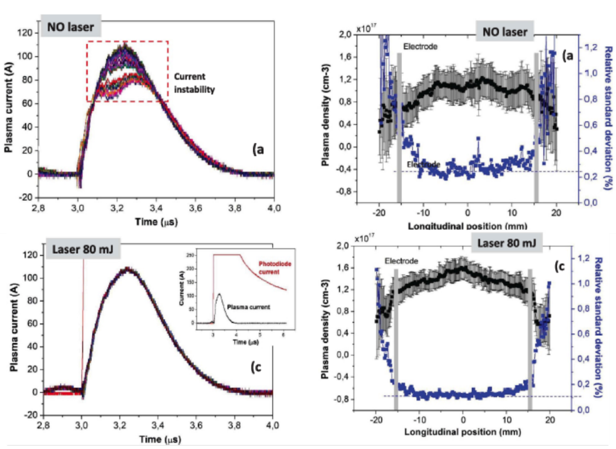

Figure 4: Current profiles (left) and plasma density (right) measured without (top) and with (bottom) pre-ionization laser.

long, 2 mm diameter, operating at 10 Hz, representing the first EuPRAXIA plasma source enabling the 1.1 GeV energy gain (corresponding to 1.5 GV/m accelerating gradient).

TOWARD A PLASMA-BASED FEL FACILITY

The Horizon2020 Design Study EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications), has submitted in October 2019 a Conceptual Design Report to propose the first European Research Infrastructure, dedicated to demonstrate usability of plasma accelerators delivering high brightness beams up to 1-5 GeV for users [15]. The EuPRAXIA project represents the first world-wide conceptual design report of a plasma accelerator facility, funded by EU Horizon2020 program, and completed by 16+25 institutes. In addition, it is the first plasma accelerator project selected and placed on the European ESFRI roadmap with the preparatory phase (PP) project on a plasma accelerator facility recently funded by EU. The EuPRAXIA organization architecture is based on a distributed research infrastructure concept, composed by four pillars, with ex-

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPLXGD2

perience in particle-driven plasma and laser-driven plasma acceleration, plasma simulations and theory, laser technology. The headquarter and the site dedicated to particle-driven plasma wakefield acceleration (PWFA) have been chosen to be at the Frascati National Laboratories (LNF) of the INFN, where the EuPRAXIA@SPARC_LAB future facility has been funded with more than 108 Meuro [16]. The EuPRAXIA@SPARC_LAB facility will equip LNF with a unique combination of a high brightness GeV-range electron beam generated in a state-of-the-art (RF-based) advanced compact linear accelerator, a 0.5 PW-class laser system and the first 5th generation light source. The EuPRAXIA@SPARC_LAB facility will represents the Europe's most compact and most southern FEL and the world's most compact RF accelerator (X band in collaboration with CERN).

CONCLUSIONS

Impressive progress has been done toward the operation of a FEL user facility, as highlighted by the recent demonstration of SASE FEL driven by both PWFA (SPARC_LAB, INFN Frascati) and LWFA (SIOM, Shangai). These successes have been driven by the ability of the community to overcome several key challenges facing plasma-based FEL operation, in particular the stabilization and control of the acceleration process, which turns into energy spread mitigation, normalized emittance preservation and overall stability gain. However, improvements are still needed: in terms of electron beam quality, the energy spread should be improved from sub-percent to sub-per-mille, and the normalized emittance must be kept to below 1 mm mrad. In addition, the routine operation of a user facility demands a high level of shot-to-shot stability, which is still an issue to be fixed. Concerning the repetition rate, both novel ideas and laser technology, are demonstrating the possibility to reach the kHz level. An entire community is working hard to achieve this result and the selection of EuPRAXIA, as first ever plasma accelerator project, in the ESFRI Roadmap is the validation of the quality and readiness of the work done and the technology. Therefore the realization of a plasma-based user facility seems more and more a reality.

REFERENCES

[1] J. Rosenzweig *et al.*, "Experimental observation of plasma wake-field acceleration", *Phys. Rev. Lett.*, vol. 61, p. 98, 1988. doi:10.1103/PhysRevLett.61.98

[2] S. P. D. Mangles *et al.*, "Monoenergetic beams of relativistic electrons from intense laser–plasma interactions", *Nature*, vol. 431, pp. 535–538, 2004. doi:10.1038/nature02939

[3] W. P. Leemans, "GeV electron beams from a centimetre-scale accelerator", *Nat. Phys.*, vol. 2, pp. 696-699, 2006. doi:10.1038/nphys418

[4] I. Blumenfeld *et al.*, "Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator", *Nature*, vol. 445, pp. 741–744, 2007. doi:10.1038/nature05538

[5] R. D Arcy *et al.*, "FLASHForward: plasma wakefield accelerator science for high-average-power applications", *Philos. Trans. R. Soc. London A*, vol. 377, p. 20180392, 2019. doi:10.1098/rsta.2018.0392

[6] M. Ferrario *et al.*, "SPARC_LAB present and future", *Nucl. Instrum. Methods Phys. Res. Sec. B*, vol. 309, pp. 183-188, 2013. doi:10.1016/j.nimb.2013.03.049

[7] C. A. Lindstroem *et al.*, "Energy-spread preservation and high efficiency in a plasma-wakefield accelerator", *Phys. Rev. Lett.*, vol. 126, p. 014801, 2021. doi:10.1103/PhysRevLett.126.014801

[8] R. Pompili *et al.*, "Energy spread minimization in a beam-driven plasma wakefield accelerator", *Nat. Physics*, vol. 17, no. 4, pp. 499-503, 2021. doi:10.1038/s41567-020-01116-9

[9] R. D Arcy *et al.*, "Recovery time of a plasma-wakefield accelerator", *Nature*, vol. 603, pp. 58–62, 2022. doi:10.1038/s41586-021-04348-8

[10] C. Emma *et al.*, "Free electron lasers driven by plasma accelerators: Status and near-term prospects", *High Power Laser Sci. and Eng.*, vol. 9, p. e57 (15 pages), 2021. doi:10.1017/hpl.2021.39

[11] W. Wang *et al.*, "Free-electron lasing at 27 nanometres based on a laser wakefield accelerator", *Nature*, vol. 595, pp. 516–520, 2021. doi:10.1038/s41586-021-03678-x

[12] R. Pompili *et al.*, "Free-electron lasing with compact beam-driven plasma wakefield accelerator", *Nature*, vol. 605, pp. 659–662, 2022. doi:10.1038/s41586-022-04589-1

[13] M. Galletti *et al.*, "Advanced Stabilization Methods of Plasma Devices for Plasma-Based Accelerations", *Symmetry*, vol. 14, no. 3, p. 450, 2022. doi:10.3390/sym14030450

[14] A. Biagioni *et al.*, "Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse", *Plasma Phys. Control. Fusion*, vol. 63, p. 115013, 2021. doi:10.1088/1361-6587/ac1f68

[15] R. W. Assmann *et al.*, "EuPRAXIA conceptual design report", *Eur. Phys. J. Spec. Top.*, vol. 229, pp. 3675–4284, 2020. doi:10.1140/epjst/e2020-000127-8

[16] D. Alesini *et al.*, "EuPRAXIA@SPARC_LAB conceptual design report", Instituto Nazionale di Fisica Nucleare, Italy, Rep. INFN-18-03, May 2018.