SL_COMB2FEL

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1 Experiment Description

The experiment called SL_COMB2FEL aims at the acceleration, manipulation and transport of high brightness electron beams by resonant plasma wakefields [1]. At this regard, a train of high brightness bunches with THz repetition rate, so-called comb beam [2], is properly generated at the cathode, and manipulated through the velocity bunching technique [3, 4], in order to be injected in a H_2-filled plasma discharge capillary [5] with proper distance and length. A train of driver bunches separated by a plasma wavelength, λ_p, corresponding in our case to 1 ps, resonantly excites a plasma wake, which accelerates a trailing witness bunch injected at the accelerating phase. The development of compact accelerator facilities providing high-brightness beams is one of the most challenging tasks in the field of next-generation compact and cost affordable particle accelerators, to be used in many fields for industrial, medical, and research applications. In this regards, plasma wakefields can be also used to tune the longitudinal phase space of a high-brightness beam. Indeed, the electron beam passing through the plasma drives large wakefields that are used to manipulate the time-energy correlation of particles along the beam itself. We have experimentally demonstrated at SPARC_LAB [6] that such a solution is highly tunable by simply adjusting the density of the plasma and can be used to imprint or remove any correlation onto the beam [7]. This is a fundamental requirement when dealing with largely time-energy correlated beams coming from future plasma accelerators. Furthermore, going towards compact facilities, also plasma-based focusing devices deserve deep investigation. In this regard, in the framework of the previous experiment, named as SL_COMB, we have performed at SPARC_LAB theoretical and experimental studies on both active [8, 9] and passive [10] plasma lenses to understand their effect on the beam quality and pave the way to their integration in conventional transport beam lines [11]. For this reason different capillaries, in terms of size and material, have been investigated with different high voltage discharge circuits [12] to ionize the hydrogen gas filling the capillary. The discharge phenomenon deserves deep investigation in particular in case of plasma-filled capillaries for plasma lenses, setting the initial conditions and therefore the uniformity of the plasma density, which in turn manifests itself in the linearity of the magnetic field [13]. In addition, because of the nature of the gas-guiding structures used, detrimental effects on the beam stability due to wakefields might rise up requiring careful attention to minimize them.

2 Activity in 2022

SPARC_LAB [1] is a test-facility devoted to advanced radiation sources and innovative acceleration techniques. In 2022 the main activity has been focused on the generation and optimization of FEL radiation from a particle driven plasma accelerator. High-quality (small energy spreads and normalized emittances) electron beams [14)] have been accelerated in the plasma module, extracted and transported through the undulator resulting in the first proof of Free-Electron Laser (FEL) lasing from a plasma-accelerated electron beam both in the Self Amplified Spontaneous Emission [15)] (SASE) and in the seeded scheme [16)]. These experiments, together with the tests on large accelerating field, up to several GV/m, pave the way to the EuPRAXIA Preparatory Phase project [20)], for which the EuPRAXIA@SPARC_LAB test user facility that foresees the realization of the first ever plasma beam-driven facility at LNF [21)], represent one of the pillars.

The research activity on the plasma accelerator module focused on the enhancement of the shot-to-shot stability, taking into account the plasma source geometry, both to reach meter scale dimensions, and optimize the plasma electron density distribution. 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 [22)]. 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]. This stabilization technique allowed for the development of very long capillaries, as the one recently built at SPARC_LAB, *i.e.* 40 cm 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).

3 List of Conference Talks by LNF Authors in Year 2022

1. E. Chiadroni, Electron Beam Diagnostics, 767. WE-Heraeus-Seminar: Science and Applications of Plasma-Based Accelerators (May 2022), Bad Hoennef, Germany.

2. E. Chiadroni, Progress Towards Demonstration of a Plasma-based FEL, invited talk (plenary session) at the 13th International Particle Accelerator Conference (IPAC2022), Bangkok, Thailand (June 2022).

3. G. Costa, Development and characterization of Plasma Targets for LWFA experiments at SPARC_LAB, EuroNNAc Special Topics Workshop (September 2022), La Biodola, Isola d'Elba, Italy.

4. M. Ferrario, Status of the EuPRAXIA@SPARC_LAB project, EuroNNAc Special Topics Workshop (September 2022), La Biodola, Isola d'Elba, Italy.

5. A. Biagioni, Design of plasma sources for compact accelerators, EuroNNAc Special Topics Workshop (September 2022), La Biodola, Isola d'Elba, Italy.

4 List of Publications in Year 2022

1. R. Pompili et al., Free-electron lasing with compact beam-driven plasma wakefield accelerator, Nature **605**, 7911, 659–662 (2022).

2. M. Galletti, Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator, Physical Review Letters **129** (23), 234801(2022).

[1]https://sparclab.lnf.infn.it/

3. E. Chiadroni, Progress Towards Demonstration of a Plasma-based FEL, 13^{th} Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand, JACoW Publishing: ISBN: 978-3-95450-227-1 ISSN: 2673-5490; doi:10.18429/JACoW-IPAC2022-MOPLXGD2.

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4. A. Mostacci, et al., Advanced beam manipulation techniques at SPARC, in: Proceedings of 2011 International Particle Accelerator Conference, San Sebasti·n, Spain, 2011.
5. A. Biagioni et al., High-Voltage pulser to produce plasmas inside gas-filled discharge capillaries, SPARC-PL-19/001 (2019).
6. M. Ferrario et al., Nucl. Instrum. and Meth. in Phys. Res. B **309**, 183 - 188 (2013).
7. V. Shpakov et al., Phys. Rev. Lett. **122**, 114801 (2019).
8. R. Pompili et al., Appl. Phys. Lett. **110**(10), 104101 (2017).
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13. S. Arjmand et al., Characterization of plasma sources for plasma-based accelerators, Journal of Instrumentation **15**(9), C09055 (2020).
14. R. Pompili et al., Nature Physics **17** (4), 499–503 (2021).
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16. M. Galletti et al., Physical Review Letters **129** (23), 234801(2022).
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18. P. A. P. Nghiem et al., J. Phys.: Conf. Ser. **1350** 012068 (2019).
19. R. Pompili et al., Nature Physics (2020): 1- 5.
20. R. W. Assmann et al., The European Physical Journal Special Topics **229** (24), 3675–4284 (2020).
21. M. Ferrario et al., Nucl. Instr. and Meth. in Phys. Res. A **909**, 134–138 (2018).
22. E. Chiadroni, 13^{th} Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand, JACoW Publishing: ISBN: 978-3-95450-227-1 ISSN: 2673-5490; doi:10.18429/JACoW-IPAC2022-MOPLXGD2.