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

Despite of the Covid-19 Pandemic, the activity in 2020 was focused on the optimization of the plasma accelerated beam, in terms of energy spread minimization and emittance preservation, for FEL radiation production. In particular, the 20 pC witness beam has been accelerated of 4 MeV in

3 cm plasma with 200 pC driver beam and the energy spread compensation has been demonstrated during the acceleration thanks to assisted beam loading effects 16). The results from more than 300 consecutive shots are shown in Fig. 1. The results highlight a resulting mean energy $E_w \pm \Delta E_w =$ 93.1±0.5 MeV and an average accelerating gradient $E_z = 133{\pm}16$ MV/m. The energy stability is 1 - $\Delta E_w/E_w \approx 99.5\%$. The most interesting result, however, is related to the energy spread $\sigma_E =$ 0.12±0.03 MeV (corresponding to a relative spread $\sigma_E/E_w \approx 0.1\%$), which is ∼40% lower than that with the plasma turned off. This result is attributed to the rotation of the witness LPS during the acceleration so that its correlated energy chirp is removed and the spread minimized. In addition, the normalized transverse emittance of the witness beam has been measured after the acceleration in the plasma module. Thanks to the achieved low energy spread after the acceleration, we were able, using a conventional transport line and multi-shot quadrupole scan technique, to measure the transverse emittance of the beam. The final normalized emittance of the beam was measured at the level of 3.8 μm, with initial emittance of 2.8 μm. Simulation studies indicate that such a growth was mainly caused by non-optimal transverse matching conditions. The experimental beam parameters measured in the experiment have been used as input for a preliminary evaluation of FEL performances, demonstrating a measurable growth of the FEL gain.

3 List of Conference Talks by LNF Authors in Year 2020

1. E. Chiadroni, Status of the EuPRAXIA@SPARC_LAB Project, Italy @ EuXFEL Workshop, 10 and 11 December 2020, via ZOOM.

4 List of Publications in Year 2020

1. R. W. Assmann et al., EuPRAXIA Conceptual Design Report, European Physical Journal: Special Topics **229**(24), pp. 3675?4284 (2020).
2. A. Del Dotto et al., Compact and tunable active-plasma lens system for witness extraction and driver removal, Journal of Physics: Conference Series **1596**(1), 012050 (2020).
3. S. Arjmand et al., Characterization of plasma sources for plasma-based accelerators, Journal of Instrumentation **15**(9), C09055 (2020).
4. P. A. P. Nghiem et al., Toward a plasma-based accelerator at high beam energy with high beam charge and high beam quality, Physical Review Accelerators and Beams **23**(3), 031301 (2020).

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4. A. Mostacci, et al., Advanced beam manipulation techniques at SPARC, in: Proceedings of 2011 International Particle Accelerator Conference, San Sebastin, 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. A. Marocchino et al., Nucl. Instrum. and Meth. in Phys. Res. A **829**, 386 - 391 (2016).
15. P. A. P. Nghiem et al., J. Phys.: Conf. Ser. **1350** 012068 (2019).
16. R. Pompili et al., Nature Physics (2020): 1- 5.

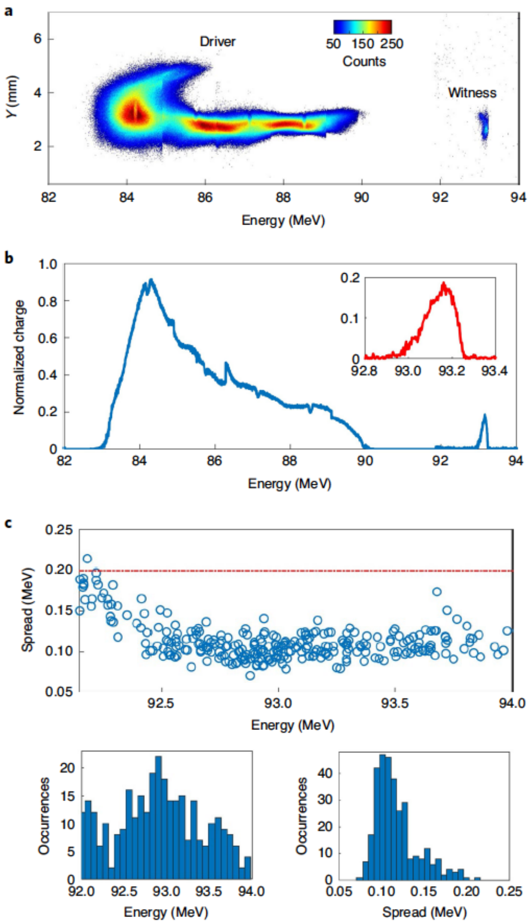

Figure 1: *Acceleration with the 200 pC driver. a, Spectrometer image. b, Energy projection for the driver. The inset shows the projection for the witness spectrum. c, Analysis of 320 consecutive shots. The top plot shows the correlation between the central energy and energy spread of the witness bunch. The red dashed line is the witness energy spread with the plasma turned off. The histograms below report the energy (left) and spread (right) distributions.*