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. In this regard, a train of high brightness bunches with THz repetition rate, the so-called comb beam, is properly generated at the cathode, and manipulated through an RF longitudinal compression technique, named velocity bunching, to be injected into an H2-filled plasma discharge capillary with proper distance and length. A train of driver bunches separated by a plasma wavelength, corresponding in our case to 1ps, 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 regard, 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 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. 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 investigations. In this regard, in the framework of SL_COMB, we have performed at SPARC_LAB theoretical and experimental studies on both active and passive lenses to understand their effect on the beam quality and pave the way to their integration into conventional transport beamlines. For this reason, different capillaries, in terms of size and material, have been investigated with different high voltage discharge circuits to ionize the hydrogen gas filling the capillary. The discharge phenomenon deserves deep investigation in particular in the 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. 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 2023

The research activity in 2023 focused on the upgrade of some of the aged plants of the SPARC_LAB test facility, in the framework of the SABINA project. In particular, the photoinjector laser has been renewed, therefore installation and commissioning covered the first half of the year. The commissioning has revealed an improvement in energy stability (in the IR) of about a factor 2, an increased output energy (in the IR) by approximately 35%, and a broader bandwidth of the IR pulse, allowing for greater pulse temporal compression: we have measured IR pulses of about 40 fs (FWHM), compared to the previous 120 fs before the replacement.

In the second half of the year, several measurement campaigns have been conducted to reproduce the experimental results of 2022 (SASE FEL lasing) more stably. In this regard, the plasma injection and extraction line has been modified and optimized to meet the matching conditions at the entrance of the accelerating plasma module and to more efficiently extract the accelerated witness beam. In particular, an additional set of permanent magnet quadrupoles (12 sectors Halbach array) has been purchased (VAC company) and measured in laboratory (at LNF), showing dipole and multipole components at few ‰ level.

In addition, we have experimentally studied a compact device that integrates two active plasma lenses with ultra-short focal lengths to assist the plasma accelerator stage. A proof-of-principle experiment, where the three plasma stages have been merged in a compact device, has been performed, achieving, for the first time, the focusing, acceleration and extraction of a witness bunch in a plasma-based accelerator. The results demonstrate the feasibility of such an approach and allow for an energy gain of about 4.5 MeV over a distance of 3 cm. The integration of the two active plasma lenses enabled the realization of ultra-short focal lengths (about 5 cm), not achievable with conventional magnets, making the entire device very compact. The experiment represents a first attempt toward the accelerator system miniaturization, suggesting a simple and affordable solution in terms of sizes and costs towards the development of ultra-compact next-generation accelerators [1)].

Further measurement campaigns focused on the feasibility of measuring gradients of over 1 GV/m in plasma stages using relatively compact accelerators, within 15 meters as it is the case at SPARC_LAB, with initial beam energies below 100 MeV. This bears strategic relevance for the upcoming realization at LNF of the plasma-based user facility, EuPRAXIA@SPARC_LAB, which aims to achieve a final energy of 1.1 GeV from a 500 MeV electron beam injected into the plasma, utilizing a plasma section capable of ensuring an accelerating gradient of 1.5 GV/m. The most ambitious challenge was preparing the two beams upstream of the plasma and injecting them into the plasma itself, by using a triplet of quadrupoles with permanent magnets. The most interesting finding is certainly related to the measurement of the energy spectrum, showing an energy gain of approximately 35 MeV in 3 cm, corresponding to an accelerating gradient of 1.2 GV/m [2)].

An experimental research activity on electron beam diagnostics was focused on different scintillator materials to improve the quality of beam size measurement in terms of resolution, background reduction, etc. In particular, two screens, a YAP and GAGG:Ce, have been installed and successfully tested for transverse beam diagnostics.

The running time, consisting in preparation of the experimental setup, in setting up the working point and in data acquisition, has been approximately 60%. Following the experiment's conclusion, a lengthy installation phase has started at SPARC_LAB to continue the accelerator upgrade for the SABINA project. Meanwhile, the SPARC_LAB group's team will continue with the analysis of experimental data and numerical beam dynamics studies essential for future experiments, focusing on the multi-driver bunch operation for increasing the PWFA transformer ratio.

3 List of Conference Talks by LNF Authors in Year 2023

1. R. Pompili, Acceleration and focusing capabilities integrated in a new plasma-based device, 6th European Advanced Accelerator Concepts workshop (EAAC2023), La Biodola, Isola d'Elba, Italy.

2. L. Crincoli, Segmented plasma discharge capillary for staged particle acceleration, 6th European Advanced Accelerator Concepts workshop (EAAC2023), La Biodola, Isola d'Elba,

Italy.

3. M. Opromolla, Enhanced stability of a Free-Electron Laser driven by a plasma beam-driven accelerator and seeded by an external laser beam, 6th European Advanced Accelerator Concepts workshop (EAAC2023), La Biodola, Isola d'Elba, Italy.

4. A. Giribono, Beam dynamics studies for a stable, reliable and reproducible high brightness, high gradient plasma wakefield accelerator, Physics programs and initial data at Daphne, 6th European Advanced Accelerator Concepts workshop (EAAC2023), La Biodola, Isola d'Elba, Italy.

4 Publications

References

1. R. Pompili *et al*, Acceleration and focusing of relativistic electron beams in a compact plasma device, Physical Review Letters (Letter) - Status: With referee(s)

2. M. Carillo *et al*, Beam dynamics optimization for high gradient beam driven plasma wakefield acceleration at SPARC_LAB, in Proc. EAAC'23, La Biodola, Italy, September 2023.

3. M. Galletti *et al*, New J. Phys. **25**, 063014 (2023).

4. S. Romeo *et al*, Plasma Phys. Control. Fusion **65**, 115005 (2023).

5. S. Arjmand *et al*, JINST **18**, P08003 (2023).

6. S. Arjmand *et al*, JINST **18**, C05007 (2023).