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 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. For this reason different capillaries, in terms of size and material, have been investigated with different high voltage discharge circuits 11) 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. 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

The activity in 2019 was focused, from the theoretical point of view, on beam dynamics simulations and plasma studies to optimize the acceleration working point and remove the driver beam; the experimental activity concentrated on the setup and preliminary measurements of the single-shot

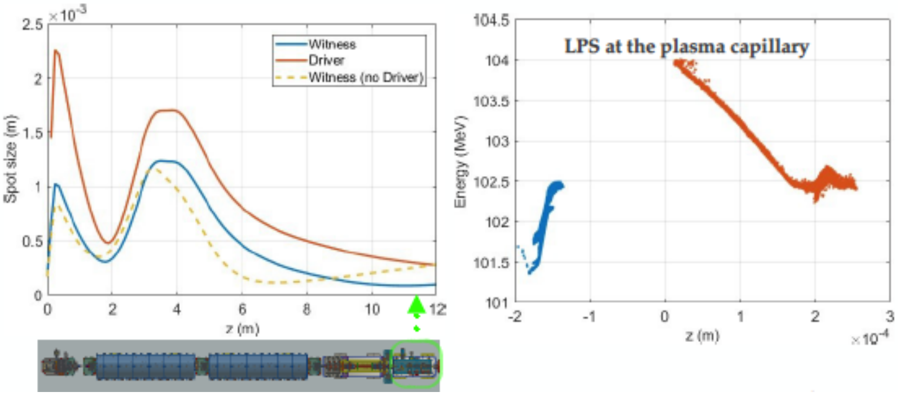

Figure 1: *GPT simulation from the cathode to the entrance of the plasma module. Left: Evolution of both driver and witness transverse spot size (green box and arrow indicate the plasma module). Right: Longitudinal phase space for both driver (red) and witness (blue).*

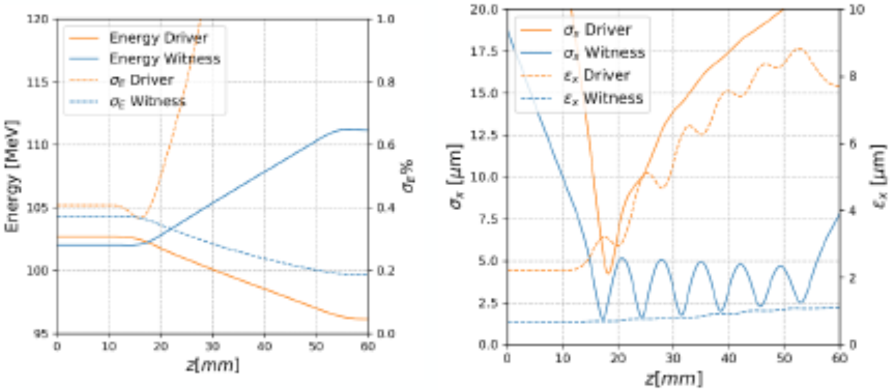

Figure 2: *Architect* [12] *simulation in the plasma module with input parameters from GPT. Left: Energy and energy spread evolution of both driver and witness bunches in the capillary. Right: Evolution of the transverse size and normalized emittance for both driver and witness bunches.*

longitudinal diagnostics for ultra-short electron bunches.

Start-to-end simulations with GPT and Architect from the cathode to the plasma exit have been performed: the comb beam parameters at the plasma entrance have been set in agreement with experimental measurements for driver (γ=200, Q=200 pC, $\varepsilon_{n_{x,y}}$=2.8 mm mrad, $\sigma_{x,y}$=6 μm, σ_z=52 μm) and witness (γ=198, Q=20 pC, $\varepsilon_{n_{x,y}}$=0.7 mm mrad, $\sigma_{x,y}$=5 μm, σ_z=6 μm) beams. The evolution of the transverse spot size and the longitudinal phase space of both driver and witness are shown in Fig. 1. Assuming a plasma density profile with 1 cm drift, 1 cm up ramp, 3 cm plateau with $2{\cdot}10^{15}$ cm^{-3}, 1 cm down ramp, the accelerating gradient is 300 MV/m with an energy gain in the 3 cm capillary of $\sim$9 MeV, with a witness beam emittance that remains below 1 mm mrad. Results are depicted in Fig. 2. Optimization of plasma density profile is still under investigation.

Studies on electron beam driver removal have been performed through simulations with GEANT4 and GPT codes. As starting point, we have considered a configuration using beam parameters out of the plasma capillary for the EuPRAXIA case, as listed in Table 1.

Table 1: *Driver and witness beams parameters out of the plasma accelerating module for the EuPRAXIA case.*

	Driver	Witness
Charge (pC)	200	30
Energy (GeV)	0.460	1
Energy spread (%)	16	0.73
Normalized emittance (mm mrad)	5	0.6
RMS Spot size (μm)	7	1.2
RMS Duration (fs)	160	11.5
Peak current (kA)	1.2	2.6

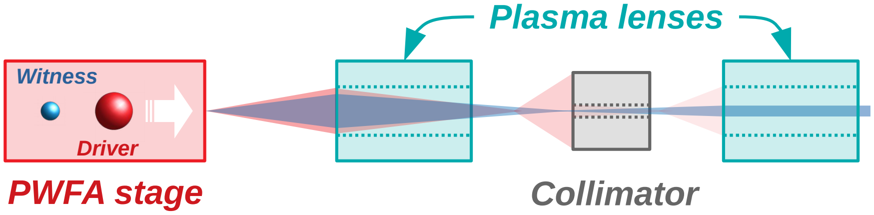

Figure 3: *Layout of driver removal system and transverse distribution.*

We have assumed a layout made of lens-collimator-lens module, as depicted in Fig. 3. Each element length and inter-distance has been optimized to preserve the witness in charge and quality and almost remove the driver as shown in Fig. 4 $^{13)}$. The position of the lens with respect to the plasma module has been carefully chosen to preserve as much as possible the witness normalized emittance. The majority of the driver charge (≈98%) is removed by the collimator, with only 4 pC that have remained after it. The optimized plasma lenses and collimator parameters are listed in Table 2.

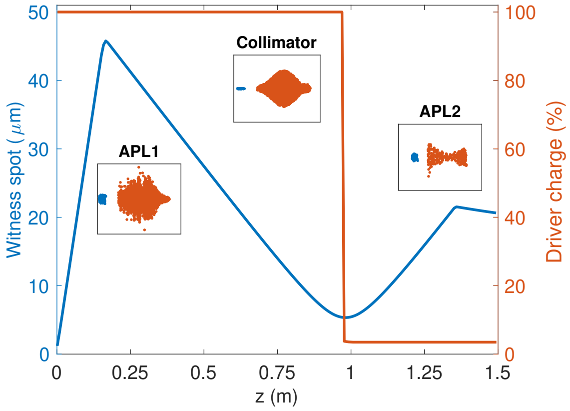

Figure 4: *Evolution of the witness envelope (blue line) and driver charge (red line) along the beam line. The insets show the x-z plane of the bunches at the entrance of the first plasma lens, the collimator, and the second plasma lens.*

Table 2: *Plasma lens and collimator parameters.*

	Length (cm)	Distance† (cm)	Discharge current (kA)	Capillary radius (μm)
Plasma lens 1	2	15	1	500
Collimator	3	97.3	-	200
Plasma lens 2	1	135	0.583	500

† The distance is from the exit of the plasma module.

From the experimental point of view, the single-shot diagnostics for ultra-short electron bunches has been set up and preliminary measurements performed. The experiment has been carried on in collaboration with ELI-beamlines colleagues in the framework of EuPRAXIA Design Study 14). The experiment consists in the generation of Coherent Transition Radiation (CTR) through less than 20 fs (rms) electron bunches and the direct measurement of CTR spectrum, which lies in the THz/MIR region, through a dispersive prism. The spectrum has been recorded by a detector array which allows single shot operation. First of all, beam dynamics simulations have been performed with the GPT code to properly set up the SPARC photo-injector in order to produce ¡20 fs electron bunches. The electron bunch has been compressed by applying the velocity bunching 3) in both S-band sections. Figure 5 shows the longitudinal phase space (LPS) and the longitudinal profile (right and left, respectively) for a 20 pC, 100 MeV, 6 μm (rms) beam.

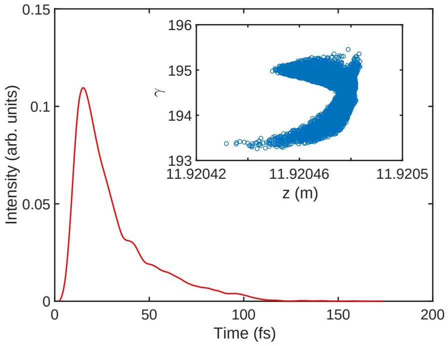

Figure 5: *Beam longitudinal profile and its longitudinal phase space (inset).*

THz/MIR band-pass filters have been used to sample the CTR spectrum up to tens of THz. In particular, the signal measured at 31.5 THz (magenta curve in Fig. 6) demonstrates that ultra-short electron bunches have been produced. A more systematic campaign of measurements is foreseen in Autumn 2020.

3 List of Conference Talks by LNF Authors in Year 2019

List of conference talks by LNF authors:

1. V. Shpakov, Plasma devices: plasma dechirper and plasma lens, 4th European Advanced Accelerator Concepts Workshop (EAAC 2019), La Biodola, Isola D'Elba, Italy.

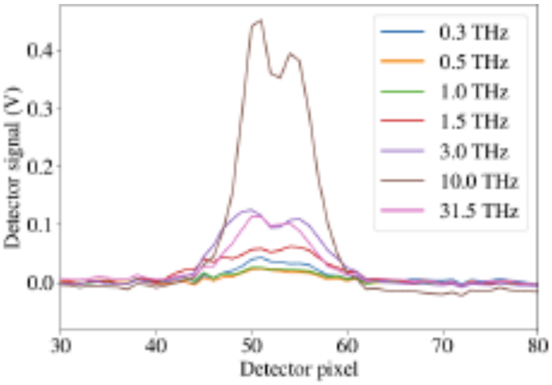

Figure 6: *CTR measured at different frequencies, up to 31.5 THz, as sampled by THz band-pass filters.*

2. J. Scifo, Spatial autocorrelation study for laser beam quality estimation, 4^{th} European Advanced Accelerator Concepts Workshop (EAAC 2019), La Biodola, Isola D'Elba, Italy.
3. M. Croia, High gradient ultra-high brightness C-band photoinjector, 4^{th} European Advanced Accelerator Concepts Workshop (EAAC 2019), La Biodola, Isola D'Elba, Italy.
4. D. Alesini, Ultra-fast C-band RF gun for high gradient/high repetition rate photoinjectors, Physics and Applications of High Brightness Beams (HBB 2019), Rethimno, Crete.
5. V. Shpakov, Recent experimental results of active plasma lens and plasma de-chirper studies at SPARC_LAB, Physics and Applications of High Brightness Beams (HBB 2019), Rethimno, Crete.
6. R. Pompili, From SPARC_LAB to EuPRAXIA@SPARC_LAB, Physics and Applications of High Brightness Beams (HBB 2019), Rethimno, Crete.
7. R. Pompili, From SPARC_LAB to EuPRAXIA@SPARC_LAB, Annual Meeting of the Italian Synchrotron Radiation Society (SILS 2019), Camerino, Italy.
8. J. Scifo, The characterization measurements of yttrium photocathode performed at the Cavity Test Facility at Elettra, European Workshop on photocathodes for Particle Accelerator Applications (EWPAA 2019), Villigen, Swiss.
9. M. Ferrario, From Dream to Reality: Prospects for Applying Advanced Accelerator Technologies to Next Generation Scientific User Facilities, 10^{th} International Particle Accelerator Conference (IPAC 2019), Melbourne, Australia.
10. R. Pompili, Plasma-based experiments at SPARC_LAB, Conference on High Intensity Laser and attosecond science in Israel (CHILI2019), Tel Aviv, Israel.

4 Publications

5 List of Publications in Year 2019

1. V. Shpakov et al.

   Longitudinal Phase-Space Manipulation with Beam-Driven Plasma Wakefields

Phys. Rev. Lett. **122**, 114801 (2019).

2. M. K. Weikum et al.,
   Status of the Horizon 2020 EuPRAXIA conceptual design study
   J. Phys.: Conf. Ser. **1350** 012059 (2019).
3. P. A. P. Nghiem et al.,
   Eupraxia, A Step Toward A Plasma-Wakefield Based Accelerator With High Beam Quality
   J. Phys.: Conf. Ser. **1350** 012068 (2019).
4. A. Balerna et al.,
   The Potential of EuPRAXIA@SPARC_LAB for Radiation Based Techniques
   Condens. Matter **4**(1), 30 (2019).
5. A. Biagioni et al.
   Temperature analysis in the shock waves regime for gas-filled plasma capillaries in plasma-based accelerators
   JINST **14** C03002 (2019).
6. M. K. Weikum et al.,
   EuPRAXIA - a compact, cost-efficient particle and radiation source
   AIP Conference Proceedings **2160**, 040012 (2019).
7. A. Curcio et al.,
   Towards the detection of nanometric emittances in plasma accelerators
   JINST **14** C02004 (2019).
8. R. Pompili et al.,
   From SPARC_LAB to EuPRAXIA@SPARC_LAB
   Instruments **3**(3), 45 (2019).
9. R. Pompili et al.,
   Plasma lens-based beam extraction and removal system for plasma wakefield acceleration experiments
   Phys. Rev. Accel. Beams **22**, 121302 (2019).
10. A. Curcio et al.,
    Modeling and diagnostics for plasma discharge capillaries
    Phys. Rev. E, **100**-5, 053202 (2019).

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1. E. Chiadroni et al., Nuclear Instruments and Methods A **865**, 139 (2017).
2. M. Ferrario et al., Nuclear Instruments and Methods in Physics Research A **637**, 43 (2011).
3. M. Ferrario et al., Phys. Rev. Lett. **104**, 054801 (2010).
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).
9. R. Pompili et al., Phys. Rev. Lett. **121**, 174801 (2018).
10. A. Marocchino et al., Appl. Phys. Lett. **111**(18), 184101 (2017).
11. M. Anania et al., Nucl. Instrum. and Meth. in Phys. Res. A **829** (2016).
12. A. Marocchino et al., Nucl. Instrum. and Meth. in Phys. Res. A **829**, 386 - 391 (2016).
13. R. Pompili et al., Phys. Rev. Accel. Beams **22**, 121302 (2019).
14. P. A. P. Nghiem et al., J. Phys.: Conf. Ser. **1350** 012068 (2019).