SL_COMB

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1 Experiment description

The experiment called SL_COMB aims at the acceleration 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], in order to be injected in a H_2-filled plasma discharge capillary [4] 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.

At SPARC_LAB [5] capillaries of different materials and size, 1-3-5 cm long sapphire or plastic (1 mm diameter), will be used and operated with a high voltage discharge circuit (20 kV, 200 A) to ionize the hydrogen gas filling the capillary. Assuming a plasma density $n_0 = 10^{16}$ cm^{-3}, the plasma wavelength is $\lambda_p = 330$ μm, corresponding to an oscillation period of 1 ps. The goal of the experiment is to provide an adequate accelerating gradient of the order of 1 GV/m, while preserving the brightness of the accelerated witness beam, *i.e.* low energy spread ($\Delta E/E < 1$ %) and transverse normalized emittance of the order of 1 mm mrad.

2 Activity

The activity in 2016 was focused on the commissioning of the COMB chamber, which has been installed on the SPARC main line at the end of the C-band accelerating structure. The chamber is fully equipped with permanent quadrupole magnets (PMQ) and both transverse (micrometer scale resolution based on Optical Transition Radiation imaging) and longitudinal diagnostics (based on both THz radiation and Electro-Optical Sampling).

A preliminary alignment of plasma capillary, PMQs and targets has been performed first with a laser through the linac, then with a beam-based alignment procedure, resulting in the full transport (100%) of the beam charge through the capillary.

The plasma discharge circuit has been tested online and operation at 1-5 Hz repetition rate with plasma successfully achieved, keeping vacuum level as low as 10^{-8} mbar.

The plasma diagnostics based on Stark effect to measure the plasma density has been fully setup and preliminary measurements performed, showing the possibility to control the plasma density evolution through the delay after the discharge.

The challenge of plasma-based accelerators is to accelerate high brightness electron beams, thus preserve their quality; an important issue is then the transverse matching of the electron beam at the plasma interface, resulting in a beam *rms* transverse size of few micrometers. At this regard, a device called active plasma lens [6] is under investigation at SPARC_LAB for the final focus transfer line.

An active plasma lens acts as a current-carrying conductor, realized by the discharge current produced between the two electrodes in a capillary, 1 mm in diameter and 3 cm in length. The

Figure 1: *Active plasma lens experimental layout. The beam passes through the discharge-capillary and is then imaged on the screen downstream.*

beam goes through the capillary filled with gas, while a current is flowing in it. Therefore, the bunch is focused by the azimuthal magnetic field generated by the discharge current, according to Ampére's law. Active plasma lenses have several advantages with respect to conventional, magnetic-based, transport lines: radial focusing, weak chromaticity (the focusing strength scales as γ^{-1}) and achievable focusing gradient of the order of kT/m, allowing for extremely compact transfer lines.

Figure 1 illustrates the experimental setup. The bunch is produced by the SPARC photo-injector, consisting in a 1.6 cell RF-gun followed by two accelerating sections embedded by solenoids coils. The results we report have been obtained with a 50 pC bunch at 126 MeV energy (50 keV energy spread), 1 mm mrad normalized emittance and 1.1 ps rms duration. For such parameters, the smallest bunch *rms* transverse size at the capillary entrance is about 90 μm. The capillary consists in a sapphire hollow tube of 1 mm diameter, 10 mm long, filled at 1 Hz rate by H_2 gas through one central inlet. The pulsed operation allows maintaining the vacuum level as low as 10^{-8} mbar in the RF linac while flowing H_2 . Two electrodes, placed on each end of the capillary, are connected to a 20 kV generator producing up to 100 A peak discharge current. The focusing field produced by the active plasma lens strongly depends on the discharge dynamics along the capillary. The arrival time of the electron beam is scanned with respect to the discharge pulse in order to change the active plasma lens focusing as shown in Fig. 2. With the discharge turned off at 0 ns, the unperturbed beam has a spot size of 75 μm. Its normalized transverse projected emittance is $\varepsilon_{nr} = 0.95\ mm\ mrad$, measured by quadrupole scan on the last screen. By turning the discharge on, the beam is focused down to 24 μm at -550 ns, but due to the nonlinear magnetic field in the capillary, its emittance becomes larger of a factor less than 2, as shown in Fig. 3. Indeed, Fig. 3 reports the emittance evolution as function of the delay from the beginning of the discharge: at -550 ns delay the measured emittance is 1.4 mm mrad in the horizontal plane and

Figure 2: *Transverse beam size evolution as function of the delay of the bunch with respect to the beginning of the discharge. At 0 ns the discharge is off, the waist corresponds to -550 ns delay.*

1.6 mm mrad in the vertical one. The estimated focusing gradient for this case is about 100 T/m. Plasma diagnostics has been commissioned to retrieve plasma density by measuring the widening of H_β Balmer line of Hydrogen through Stark effect. The light emitted from the capillary is imaged on the spectrometer slit and its spectrum measured by means of a gated Intensified CCD camera. The apparatus collects the light emitted within 100 ns along the entire capillary, allowing the reconstruction of the longitudinal density profile.

3 List of Conference Talks by LNF Authors in Year 2016

1. E. Chiadroni, Beam manipulation for resonant PWFA, Physics and Applications of High Brightness Beams, Havana, Cuba - March 28-April 1, 2016
2. R. Pompili, Beam-driven Plasma Wakefield Acceleration at SPARC_LAB, Advanced Accelerator Concepts 2016, National Harbor, MD (USA)
3. F. Villa, Generation, measure and FEL radiation of ultrashort electron beams at SPARC_LAB, Physics and Applications of High Brightness Beams, Havana, Cuba - March 28-April 1, 2016

4 Publications

1. R. Pompili et al., *Beam manipulation with velocity bunching for PWFA applications*, Nucl. Instrum. and Meth. in Phys. Res. A **829**, 17-23 (2016).
2. S. Romeo et al., *Beam dynamics in resonant plasma wakefield acceleration at SPARC_LAB*, Nucl. Instrum. and Meth. in Phys. Res. A **829**, 109-112 (2016).

Figure 3: *Emittance evolution as function of the delay of the bunch with respect to the beginning of the discharge. The waist corresponds to -550 ns delay.*

3. V. Shpakov et al., *Betatron radiation based diagnostics for plasma wakefield accelerated electron beams at the SPARC_LAB test facility*, Nucl. Instrum. and Meth. in Phys. Res. A **829**, 330-333 (2016).

4. F. Filippi et al., *Plasma density characterization at SPARC_LAB through Stark broadening of Hydrogen spectral lines*, Nucl. Instrum. and Meth. in Phys. Res. A **829**, 326-329 (2016).

5. F. Villa et al., *Laser pulse shaping for high gradient accelerators*, Nucl. Instrum. and Meth. in Phys. Res. A **829**, 446-451 (2016).

6. M. P. Anania et al., *Plasma production for electron acceleration by resonant plasma wave*, Nucl. Instrum. and Meth. in Phys. Res. A **829**, 254-259 (2016).

7. A. Marocchino et al., *Efficient modeling of plasma wakefield acceleration in quasi-non-linear-regimes with the hybrid code Architect*, Nucl. Instrum. and Meth. in Phys. Res. A **829**, 386-391 (2016).

8. A. Cianchi et al., *Observations and diagnostics in high brightness beams*, Nucl. Instrum. and Meth. in Phys. Res. A **829**, 343-347 (2016).

9. A. Cianchi et al., *Transverse emittance diagnostics for high brightness electron beams*, http://dx.doi.org/10.1016/j

10. F. Filippi et al., *Spectroscopic measurements of plasma emission light for plasma-based acceleration experiments*, Journal of Instrumentation **11**, C09015 (2016).

11. A. Biagioni et al., *Electron density measurement in gas discharge plasmas by optical and acoustic methods*, Journal of Instrumentation **11**, C08003 (2016).

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3. M. Ferrario et al., Phys. Rev. Lett. **104**, 054801 (2010).
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5. M. Ferrario et al., Nucl. Instrum. Methods Phys. Res. Sect. B **309**, 183 (2013).
6. W. K. H. Panofsky and W. R. Baker, Rev. Sci. Instrum. **21**, 445 (1950).