RECENT EXPERIMENTAL RESULTS ON THE PARTICLE DRIVEN ACCELERATION AT THE SPARC_LAB TEST FACILITY

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Abstract

Plasma accelerators are emerging as formidable and innovative technology for the creation of table-top devices thanks to the possibility to sustain several GV/m accelerating gradients at normal conducting temperature. Among others, the particle-driven configuration has been successfully tested at the SPARC_LAB test facility also demonstrating the emission of plasma-based FEL radiation in SASE and seeding operation. Recently we have performed further experiments devoted to heightening the accelerating gradient in the plasma. The so-called comb beam has been set up with a 500 pC driver followed by a 50 pC trailing bunch. The maximum measured energy gain in the plasma has been of almost 30 MeV turning in an accelerating gradient of the order of 1.2 GV/m. The result represents a fundamental achievement also looking at the forthcoming EuPRAXIA@SPARC_LAB plasma-based user facility. Further experimental runs are planned for the next year on the measurements of transverse quality of the electron beam and its eventual preservation. The paper reports on the obtained experimental results and on the numerical studies for the next future experiment at the SPARC_LAB test-facility.

INTRODUCTION

SPARC_LAB [1], Sources for Plasma Accelerators and Radiation Compton with Lasers and Beams, is a test facility located at the INFN National Laboratories in Frascati, merging the potentialities of the SPARC_LAB high power high intensity laser system, named FLAME [2], and the former SPARC project [3], mainly devoted to the R&D activity on ultra-brilliant electron beam photo injector and on FEL physics.

The test facility hosts a 180 MeV high brightness photo injector which feeds a 12 m long undulator; the versatile machine layout allowed the investigation of several beam manipulation techniques and linac matching schemes useful for a wide range of linac-based radiation sources and new advanced acceleration concepts, whose combination led in the past few years to the generation of an FEL radiation source with a plasma beam-driven accelerator module [4].

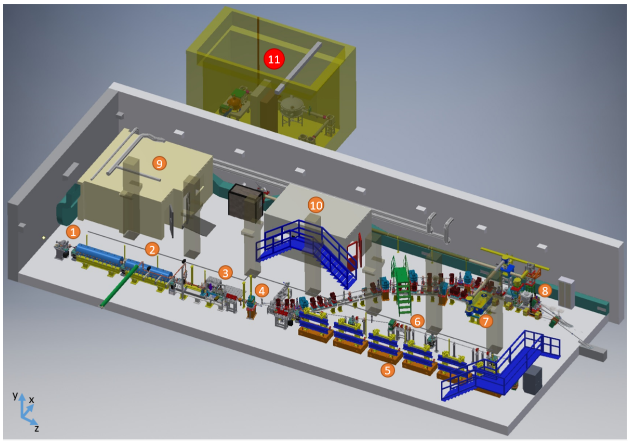

Figure 1: SPARC_LAB layout: the RF gun (1) is followed by an hybrid linac consisting of two S-band and a C-band TW structures (2), a THz source station and a vacuum chamber devoted to plasma-based experiments (3); the downstream 14 degree dipole (4) delivers the electron beam towards two beamlines devoted to FEL physics (5, 6) and beam diagnostics (6). A third beamline is devoted to temporary experiment.

The scheme layout of the test facility is reported in Fig. 1: SPARC_LAB layout: the RF gun (1) is followed by an hybrid linac consisting of two S-band and a C-band TW structures (2), a THz source station and a vacuum chamber devoted to plasma-based experiments (3); the downstream 14 degree dipole (4) delivers the electron beam towards two beamlines devoted to FEL physics (5, 6) and beam diagnostics (6). A third beamline is devoted to temporary experiment. The vacuum chamber placed downstream the linac, hosting the plasma-based experiments, is embedded with two triplet of permanent magnets devoted to the injection and extraction matching of the electron beam in the capillary region where the resonant PWFA, the so called COMB experiment, is taking place by now. In details, is under study the realization of plasma-based acceleration experiments with the aim

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to provide large accelerating field, up to several GV/m, for high-quality (small energy spreads and normalized emittances) electron beams [5]. This activity is crucial for the forthcoming EuPRAXIA@SPARC_LAB project that aims to be the first ever plasma beam-driven facility at LNF [6]. The paper reports on the recent experimental campaign devoted to heightening the accelerating gradient in the plasma of a factor four with respect to [5]. Beside a considerable effort to upgrade the SPARC facility with the installation of a new RF gun system in the framework of the SABINA project, a new working point has been set up with a comb beam consisting of higher beam charges, i.e. a 500 pC driver followed by a 50 pC trailing bunch. In this configuration the maximum measured energy gain in the plasma has been of almost 30 MeV, turning in an accelerating gradient of the order of 1.2 GV/m.

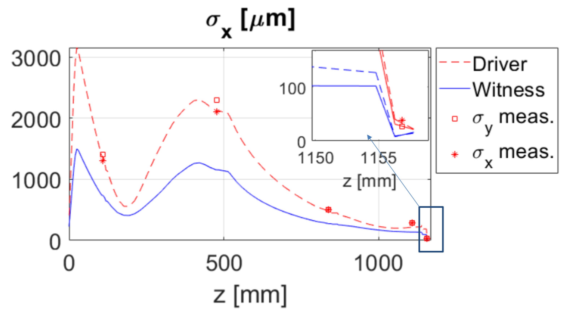

Figure 2: Witness (blue) and driver (dashed red line) beam spot size evolution along the photo-injector; the measured spot size are also reported (cross horizontal and square vertical ones) showing a good agreement between simulations and measurements.

BEAM DYNAMICS STUDIES

Beam dynamics in the accelerator has been studied by means of start to end simulations from the cathode up to the undulator entrance aiming to guide and then reproduce the experimental results obtained at SPARC_LAB. The comb-beam features have been mainly determined by the plasma module especially regarding the delay between the beams and the beam spot size at the plasma injection. In details, the driver-witness delay must be in the range 0.9 - 1.8 ps, which corresponds to half of the plasma wavelength ($\lambda_p/2$), i.e. almost 750 μm for a plasma background density of the order of almost $2x10^{15}$ cm^{-3} and the driver and witness bunch length must be of the order of 100 fs and 300 fs (FWHM), respectively. A fine tuning of witness emittance and of the Twiss parameters at the permanent magnet focusing channel and of the beam delay is then essential for an efficient acceleration while preserving the beam quality.

The Photo-Injector

The photo-injector consists of an S-band RF gun, equipped with a photo-cathode laser and an emittance compensation solenoid, followed by two S-band traveling wave accelerating structures and a C-band TW accelerating structures. The S-band sections are surrounded by solenoids to enable the emittance compensation in case of RF longitudinal compression [7].

The beam dynamics has been studied by means of simulations performed with the TStep code [8], that takes into account the space charge effects relevant at very low energies and the intrinsic emittance at the cathode. The witness and driver bunches have been simulated with 10 k and 100 k macro-particles respectively, corresponding to 50 pC and 500 pC. The photo-cathode laser has been shaped in order to provide at the cathode the witness pulse preceding the driver of 3.0 - 6.3 ps. The witness and driver have gaussian longitudinal distributions with 100 fs rms length and uniform transverse distribution of radius between 150 and 650 μm rms size. The driver spot size on the cathode has been chosen looking at the witness quality that strongly depends on the density of the beams at the overlapping point, as illustrated in [9].

The gun operates with a peak field at the cathode of 114 MV/m; a slightly de-phasing between the field and the beam allows to maximise the energy gain in this part. The S-band structures operate at almost 18 MV/m, the first one in the velocity bunching regime so to compress the beam length down to the required hundreds of femtosecond scale, and the C-band one at 21.5 MV/m on average. The magnetic field of the solenoids are set to optimise the witness emittance and to match the Twiss beam parameters at the final focusing channel entrance, i.e $\beta_{x,y} < 10$ m and $\alpha_{x,y}$ around zero. This scheme has been designed to provide at the capillary entrance a driver and witness beams with 20 and 5 μm rms spot size respectively.

From measurements the reference working point relied on a witness exiting the photo-injector 1.0 ps later than the driver and with an emittance of 1.0 mm-mrad, an rms duration of 40 μm, and a spot size of 8 μm rms, and a driver presenting an asymmetrical spot size of 28x38 μm. In this case 0.9 MeV/m energy gain in the plasma has been measured. The Fig. 2 shows the Witness (blue) and driver (dashed red line) beam spot size evolution along the photo-injector; the measured spot size are also reported showing a good agreement between simulations and measurements. The Table 1 reports the measured and simulated parameters for the driver and witness beams. More details are reported in [10].

It has to be noticed that the best experimental result in terms of energy gain in the plasma, i.e. 1.2 GV/m accelerating gradient, has been obtained with beam delay at the plasma of 1.5 ps, i.e. beam spacing at the cathode of 6.3 ps. Even if a measurement of the beam spot size at the plasma for this configuration is missing, the simulations have shown an rms beam spot size of 6 and 30 μm, i.e the desired values to heighten the plasma efficiency.

The Plasma Module

An extensive simulation campaign has been devoted to define the optimum working point to demonstrate the 1 GV/m

Table 1: Measured (Meas) and simulated (Sim) parameters for the driver and witness beams. All quantities are intended as RMS, unless the energy and the distance (mean values). The asterisk indicates noisy measurements due to systematic errors on the diagnostic system.

	Witness		**Driver**	
	Sim	**Meas**	**Sim**	**Meas**
Emittance [μm·rad]	1.25	-	6.05	6.8
Spot Size [μm]	8x9	-	27x36	25x38
Energy [MeV]	92.4	93.5	94.0	93.85
Energy Spread [keV]	140	104*	580	507
Length σ_z [fs]	75	60*	230	220
Distance Δt [ps]	1.0	1.1	0	0

accelerating gradient in the plasma facing with the technological issues related to the SPARC facility. The main one comes from the minimum delay between the two beams that can be obtained in the SPARC_LAB photoinjector, i.e. almost 1 ps, while keeping the beam length itself smaller than 350 fs and set the plasma wavelength order of magnitude, that is in turn linked to the accelerating gradient in the plasma. Also stability issues, as for example the the tens of femtosecond scale beam jitter, final focusing system acceptance limited to few percent of 90 MeV energy and residual misalignment of the solenoids surrounding the s-band cavities do not allow for operating the plasma with densities higher than 10^{15} order of magnitude.

The beam dynamics has been studied with the Architect fast tracking code [11]. Architect is a non quasi-static hybrid 2D fluid-3D kinetic code for beam driven PWFA only. Several bunches, that can be ideally generated in-code or imported by previous simulation stage, can be initialized in vacuum before the plasma channel, handling the transition from vacuum to plasma with or without ramp indifferently. The plasma profile can be defined in-code or imported by a measured or simulated plasma profile.

The Fig. 3 reports the evolution of the energy in the plasma stage for the witness for different witness-driver delay at a plasma density of 2^{15} as obtained by Architect simulations. The Fig. 3 shows a maximum energy gain of about 0.8 GeV/m with as input beam the one from the simulation previously described and illustrated in Fig. 2. The Fig. 4 reports instead the witness energy measurement is case of maximum energy gain.

CONCLUSIONS

The electron beam dynamics has been described in the SPARC_LAB test facility with regards to the recent plasma-based beam driven experiment. In details, simulations and measurements have been described showing a good agreement between them. A maximum accelerating gradient of 1.2 GV/m has been also demonstrated, and further numerical campaign are ongoing to find a match with the experimental results in the plasma channel. In the next future the analysis of experimental data and the numerical studies will be enlarged in order to optimise and consolidate the described results. Further experiments are foreseen in order to fully characterize the accelerated witness beam quality. Also multi driver scheme and new plasma sources will be studied in order to stabilize the energy gain mechanism.

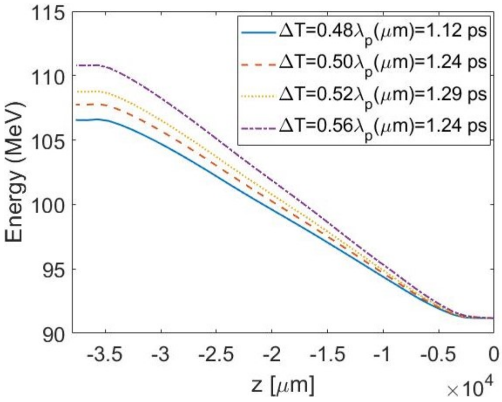

Figure 3: Evolution of the beam parameters in the plasma stage for the witness for different witness-driver delay at a plasma density of 2^{15} as obtained by Architect simulations. The maximum energy gain is of about 0.8 GeV/m with as input beam the one from the previously described simulations and illustrated in 2.

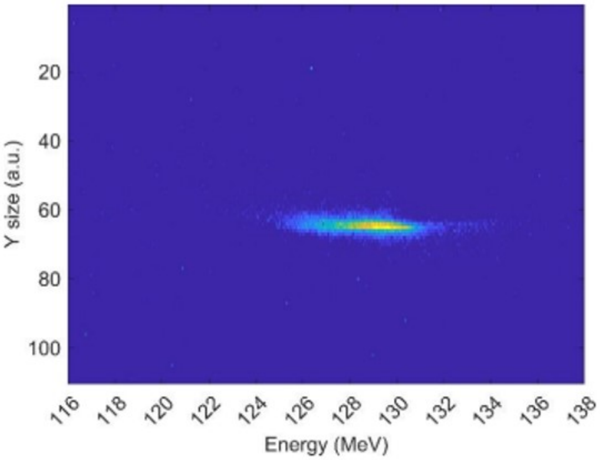

Figure 4: Witness energy measurement is case of maximum energy gain.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No 777431 and No. 653782.

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