PLASMA ACCELERATION EXPERIMENT AT SPARC_LAB WITH EXTERNAL INJECTION

A.R. Rossi*, M. Belleveglia, M. Castellano, E. Chiadroni, G. Di Pirro, A. Gallo, M. Ferrario,
G. Gatti, C. Vaccarezza, INFN/LNF, Frascati, Italy
A. Bacci, L. Serafini, INFN/MI, Milan, Italy
A. Cianchi, Università di Tor Vergata, Rome, Italy
C. Maroli, V. Petrillo, P. Tomassini, Università di Milano, Milan, Italy
A. Mostacci, Univarsità di Roma "La Sapienza", Rome, Italy

Abstract

At the SPARC_LAB facility of INFN-LNF we are installing two transport lines for ultra-short electron bunches and an ultra-intense laser pulses, generated by the SPARC photo-injector and by the FLAME laser in a synchronized fashion at the tens of fs level, to co-propagate inside a hydrogen filled glass capillary, in order to perform acceleration of the electron bunch by a plasma wave driven by the laser pulse. The main aim of this experiment is to demonstrate that a high brightness electron beam can be accelerated by a plasma wave without any significant degradation of its quality. A 10 pC electron bunch, 10 fs long is produced by SPARC and transported to injection into the capillary, which is 100 micron wide, at a gas density around $10^{17} cm^{-3}$. The laser pulse, 25 fs long, focused down to 65 microns into the capillary is injected ahead of the bunch, drives a weakly non-linear plasma wave with wavelength of about 130 microns. A proper phasing of the two pulses allows acceleration of electrons from the injection energy of 150 MeV up to about 570 MeV for a 8 cm long capillary. Installation of the beam lines is foreseen by the end of 2012 and first tests starting in mid 2013.

INTRODUCTION

The external injection experiment at SPARC_LAB aims at combining the high accelerating gradient characteristic of plasma-based accelerators with the production of high quality, stable and reproducible beams, typical of conventional RF linear accelerators. In terms of electron beam parameters, the target beam, after acceleration, possesses a low normalized emittance (a few mm mrad), short time duration (a few tens of fs) and an energy spread of less than 1%. Such high quality electron bunches can actually enable a variety of applications of plasma accelerators, such as front-end injectors for conventional accelerators and drivers for compact, short-pulse radiation sources.

Plasma accelerators are based on the excitation of large amplitude waves (or wakes) in a plasma; they can be driven by laser pulses [1] (Laser WakeField Acceleration , LWFA) or by particle bunches [2] (Plasma WakeField Acceleration, PWFA). The driver first displaces plasma electrons while propagating in the plasma; the subsequent oscillation of the plasma creates a plasma wave (a wake) following the driver. The accelerating field of the wake depends on the unperturbed plasma density and can reach a value of several GV/m, up to 1 TV/m in some regimes.

THE SPARC_LAB FACILITY

The SPARC_LAB facility at LNF consists in a conventional high brightness RF photo-injector, SPARC, and a multi-hundred terawatt laser, FLAME.

SPARC is able to produce and accelerate high brightness electron beams up to 150 MeV. Its layout is peculiar, since the first two accelerating sections are equipped with additional focusing solenoids in order to provide magnetic focusing at low energies; varying the current feeding the solenoid coils, one can tailor the focusing field along the beam path. Such solenoids are routinely used to control transverse dynamics for managing challenging SPARC working points, such as low energy RF bunch compression (velocity bunching [3]). Profiting of such particular layout, electron beams with record brightness has been produced [4], carrying up to 1 kA peak current with rms normalized emittance of about 1.5 mm mrad, to serve mainly the SASE and Seeding FEL experiments, which successfully generated FEL radiation up to saturation in the 530 nm and harmonics down to 67 nm spectral range [5]. Recently, SPARC demonstrated a novel active technique for beam generation and manipulation of ps-spaced, high brightness electron bunch trains, the so called comb-beam [6].

FLAME, whose completion has been already funded by INFN, has been successfully put into operation with the achievement of its nominal specifications. A laser pulse carrying 6 J of energy, compressed down to the nominal 25 fs pulse length, has been transported into the experiment bunker. By focusing into a supersonic gas jet in the interaction chamber, LNF recently produced self-injected bunches of electrons (INFN Self Injection Test Experiment). Such technique is already known in literature, but the results confirm that all the different part of the facility, from control to diagnostics, have been commissioned properly.

At the moment SPARC and FLAME are working as independent systems. The timing and synchronization of the photons and electron is a critical issue. The task is not simple since both electrons and photons are as long as tens of fs; jitters typical of conventional RF synchronization may prevent the correct operation. For this reason a synchronization system based on optical distribution of the reference signal will be installed shortly. Preliminary results

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* andrea.rossi@lnf.infn.it

show that the jitters between the master oscillators can be as low as 10 fs peak to peak.

A very versatile dogleg (Figure 1) is under commissioning for delivering SPARC bunches to the external injection interaction chamber; this dogleg will also serve the Thomson back-scattering X-ray source planned to operate at SPARC_LAB.

THE EXTERNAL INJECTION EXPERIMENT

The route to external injection experiment can be logically divided into two parts. The first one concerns the generation and acceleration of proper high brightness electron beam up to the injector end. The second part consists in the design, realization and commissioning of the transport line down to the interaction chamber with the plasma wave and the subsequent diagnostic stations. Moreover, studies for designing the high power laser pulse transport line are underway. For each part, the planned activities are similar: after intensive numerical simulations to fix the machine working points, all the sub-systems (e.g. timing, diagnostics, beam transport, etc.) will be installed and tested independently, whenever possible, and eventually the whole accelerator will be commissioned. The main goal is to produce in a stable and reproducible way a beam with a charge up to 25 pC, an energy up to 1 GeV with a spread less than 1% and a normalized emittance of few mm-mrad.

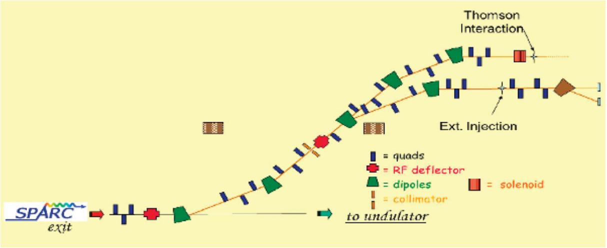

Figure 1: Layout of the dogleg.

High accuracy and precision diagnostic tools are compulsory for both transverse and longitudinal characterization of the electron beam; preferably non intercepting and single shot diagnostics should provide the required resolution of few tens of fs bunch length and few microns transverse beam size.

At SPARC_LAB a wide energy range spectrometer will provide means of measuring the beam energy and its spread. The emittance will be measured by the quadrupole scan technique, tough, if the beam energy spread is relatively large, the results could be unreliable due to chromatic effects [7]. As for the longitudinal diagnostics, we plan to insert an RF deflector downstream the plasma interaction chamber. Moreover, since the same line and interaction chamber will be used to perform PWFA experiments, we will profit of the non intercepting, longitudinal diagnostic tool which is the Electron Optical Sampling [8]. (e.g. Electron Optical Sampling). Finally, a device to measure the betatron radiation and the coherent transition radiation is foreseen.

Laser Pulse Guiding

The high brightness beam needed to feed the plasma wave must be short compared to the plasma wavelength λ_p ($\lambda_p > (30-40)\sigma_z$), in order to prevent an excessive energy spread after plasma interaction, since we plan to operate the plasma accelerator in the mildly non-linear regime. This choice comes from the need to prevent the possibility of self-injecting spurious charge, which can happen in the bubble regime, and exploiting, at the same time, the higher accelerating fields produced when the plasma wave is not linear. To ease the task, the plasma wavelengths should be in excess of 100 μm, meaning plasma densities up to $10^{17}\ cm^{-3}$. The expected accelerating fields can then be estimated to be of the order of few tens of GV/m. To meet the desired energy it is then necessary to guide the driving laser pulse over a length which is much greater then its natural one. There are two main strategies for achieving guiding: either by transverse tapering of the plasma density ($n_0 \propto r^2$) or by using a capillary as an optical waveguide [9]. Transverse tapering, though harder to properly manage, has the advantage of preventing any laser energy leakage from the plasma channel, allowing a longer acceleration; on the contrary, the capillary waveguide is easier to operate but, due to losses at the dielectric boundaries, allows acceleration lengths up to 6 - 8 cm (assuming a glass capillary) and severely constrains the laser spot-size w_0 and focus position [10]. We opted for the capillary waveguide, at least for the first part of the external injection experiment.

Start to End Simulations

Preliminary simulations, performed using the code QFLUID2, a cylindrical code that uses fluid approximation and QSA for plasma currents [11] and employing the transverse tapering guiding of the laser pulse, showed that it is possible to produce a beam with an energy up to 2 GeV (see Table 1), using a plasma density ranging from $8 \times 10^{16}\ cm^{-3}$ to $6 \times 10^{16}\ cm^{-3}$ over a length of 20 cm; the plasma density needed to be longitudinally tapered to overcome the de-phasing problem. The input bunch was 2.4 μm long with an energy of 150 MeV.

Table 1: Beam Parameters for Transverse Tapering Laser Guiding.

Charge	13 pC
Energy	2.01 GeV
$\delta\gamma/\gamma$	0.8%
ϵ_n	0.6 mm-mrad

Employing the capillary as guiding device, constraints the acceleration length to be less than half of what previously considered, so that the final energy will be lower. Since the needed input bunch length is very demanding, a first set of simulation using ELEGANT [12] has been run in order to asses its feasibility. A 0.5-1 nC, 5 ps long bunch has been simulated from SPARC photo-cathode to interaction chamber. During the transport it has been compressed by velocity bunching and/or magnetic compression and longitudinally tailored by a slit collimator, after dispersion by means of the SPARC RF deflector. The produced beams had a length down to 7 μm, a charge in the range of 5-20 pC and emittance under 1 $mm - mrad$. Even if the length requirements were not met yet, such beams have been injected and accelerated in the capillary using QFLUID2. The transverse and longitudinal phase spaces of the accelerated beam are shown in figure 2 while figure 3 reports a slice analysis. The beam parameters are summarized in Table 2. The plasma density is $10^{17}\ cm^{-3}$, the acceleration length is 8 cm and the capillary inner diameter is 100 μm. We also assumed that a proper matching has been performed somehow and squeezed the transverse beam size "by hand" to about half its initial value (keeping the emittance constant). It is clear how the input bunch excessive length prevented to reach the desired performance in energy spread and final energy. These working conditions should be considered intermediate, easier steps toward the target parameters reported before that will be met when shorter bunches will be available.

Table 2: Beam Parameters for Capillary Laser Guiding.

Charge	5 pC
Energy	570 MeV
$\delta\gamma/\gamma$	2.7%
ϵ_n	1.4 mm-mrad

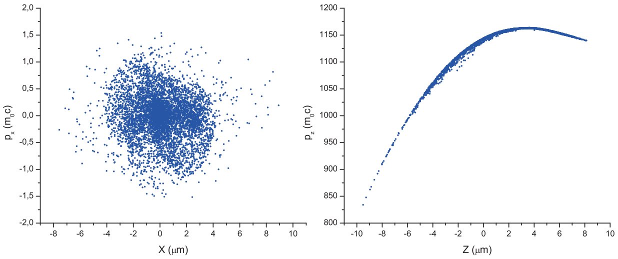

Figure 2: Phase spaces of the accelerated beam.

In order to reach the required bunch length, numerical studies are underway foreseeing to directly produce a short, low charge bunch from the photo-cathode, which will be then compressed by velocity bunching and, if needed, magnetic compression and a collimator. The goal is to yield a charge to length ratio close to 0.7 pC/fs. With such beams it seems to be possible achieving the desired beam energy and quality.

For preventing a huge normalized emittance dilution after the bunch leaves the plasma [13], a proper matching at plasma entrance end exit must be enforced [14]. This can be done by properly tapering the plasma density ramps at both ends of the capillary. Numerical studies are trying to asses if this can be achieved by properly shaping the capillary tips.

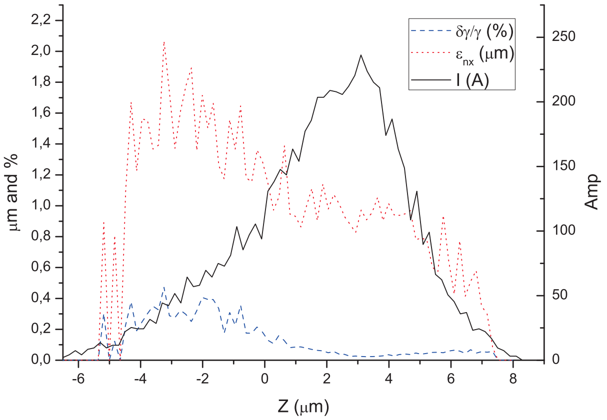

Figure 3: Slice analysis of the accelerated beam.

Another problem arises when trying to increase the bunch charge: since the focusing forces inside the plasma waves are very intense, the beam transverse equilibrium size is small and the bunch density can become comparable to the plasma's. When this happens the electron beam becomes the driver of another plasma wave, loosing energy to the plasma instead of gaining it.

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