STATUS OF PLASMA-BASED EXPERIMENTS AT THE SPARC_LAB TEST FACILITY*

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Abstract

The current activity of the SPARC LAB test-facility is focused on the realization of plasma-based acceleration experiments with the aim to provide accelerating field of the order of GV/m while maintaining the overall quality (in terms of energy spread and emittance) of the accelerated electron bunch. External injection schemes, both laser-driven and particle-driven, are considered. The current status of such an activity is presented, together with results related to the applicability of plasmas as focusing lenses in view of a complete plasma-based focusing, accelerating and extraction system.

INTRODUCTION

High brightness electron beams are the future goal of plasma-based accelerators in order to compete with conventional RF-based ones. The current goal of the worldwide plasma, laser and photo-injector communities is to demonstrate the stable and repeatable acceleration of high brightness beams [1, 2]. Therefore the next step is the extraction and transport of the beam, preserving its quality, i.e. 6D high brightness, stability and reliability to drive a plasma-based user facility [3, 4].

A great theoretical and experimental effort is ongoing at the SPARC_LAB test facility [5] to achieve such a goal. In the following sections we will discuss experiments planned and performed at SPARC_LAB with the aim of providing a full comprehension of the accelerating and focusing processes in a H_2-filled plasma discharge capillary.

SPARC_LAB is based on a high brightness photo-injector and a high power laser (200 TW, <30 fs pulse) to drive Thomson back-scattering [6] and THz radiation [7] sources, Free-Electron Laser (FEL) experiments [8] and plasma-based acceleration experiments, both laser-driven [9] and particle-driven [10]. The updated photo-injector layout consists of

two S-band traveling wave (TW) accelerating structures and one TW, constant impedance, C-band structure [11], followed by the plasma interaction chamber designed for both plasma lens and particle-driven plasma wakefield acceleration (PWFA) experiments. The current layout, with a focus on the plasma chamber, is shown in Fig. 1.
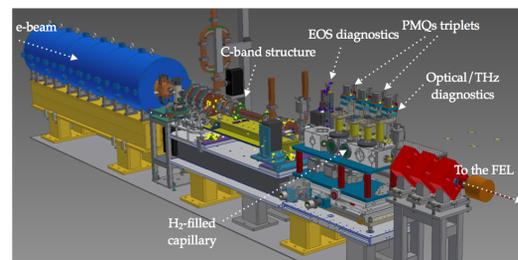
Figure 1: Layout of the SPARC photo-injector and the plasma interaction chamber.

The plasma interaction chamber is fully equipped with diagnostics, both transverse and longitudinal, with a H_2 plasma discharge capillary [12] and permanent magnet quadrupoles for matching the beam in and out from the plasma [13]. The photo-injector can be set, depending on the experiment, to provide energy between 30 and 170 MeV, with bunch charge ranging between ten and multi-hundreds of pC in fs up to ps bunch duration. A train of ultra-short bunches [14], i.e. a comb beam, can be also generated at the photo-cathode and manipulated through the linac to provide a multi-driver bunches and witness configuration for resonant PWFA schemes [10].

PLASMA-BASED ACCELERATION

The first plasma acceleration scheme we are experimentally studying is the one based on the external injection of a train of high brightness electron beams (HBEB) into a pre-formed plasma in the quasi non-linear or weakly non-linear regime, defined through the so-called reduced charge: $\tilde{Q} = \frac{N_b k_P^3}{n_0} \approx 1$, and $\alpha = \frac{n_b}{n_0} > 1$; n_0 is the unperturbed plasma

density, N_b the driver number of electrons, k_p^{-3} the cubic plasma skin-depth and n_b the beam density [15, 16].

By properly tailoring the driver bunch shape, e.g. using a train of multiple bunch trains with a ramp of charge, the witness beam energy can be more than doubled, resulting in a transformer ratio $R > 2$ [17]. The use of a train of bunches allows to gently transfer the energy first from one bunch to the following then to the resulting wake, piling up the total energy.

Experimental studies on beam manipulation have been performed to optimize a multi-bunch ramped charge distribution in terms of temporal spacing, charge ratio, bunch length and transverse emittance. Figure 2 shows the longitudinal phase space (LPS) of a four ramped drivers and a witness bunch train in the RF deep over-compression region [14], corresponding to -100 deg from the phase of maximum acceleration. The witness bunch (24 pC) is at $3\lambda_p/2$ from the last driver (named as D4); the driver separation is 270 − 240 − 420 μm ($\lambda_p = 330$ μm with a plasma density $n_0 = 10^{16}$ cm^{-3}). The total charge is 220 pC.
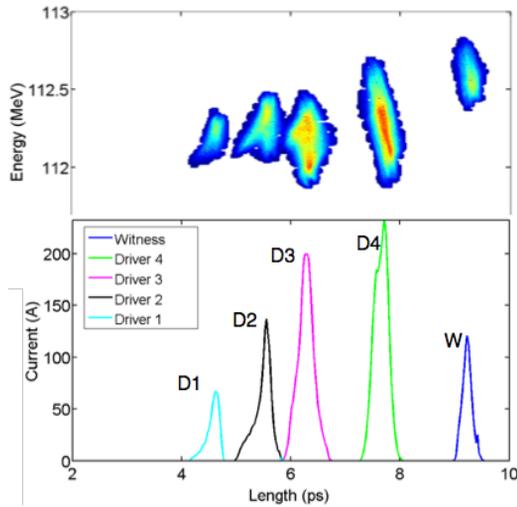
Figure 2: Measured LPS (top) and current profiles (bottom) of a comb-like beam.

The effect of a real, i.e. measured, multi-bunch train on transformer ratio and accelerating gradient, in the interaction with the plasma, has been investigated and it is reported in Fig. 3 [10]: the calculated transformer ratio for the realistic case is slightly larger than 3; it means that, while the first three bunches, spaced $\approx \lambda_p$ apart, drive a 1.5 GV/m wake, the spacing of the last driver bunch, $\approx 1.5\lambda_p$, contributes to preserve the transformer ratio. Hybrid spacing, or adjustable separation, might be a good compromise for the optimization of both accelerating gradient and energy transfer.

PLASMA-BASED FOCUSING DEVICES

Once accelerated in the plasma, electron beams must be captured and transported along the beam line. When exiting the plasma region, electrons move from an extremely intense focusing field, generated inside the bubble, to a free space where the focusing effect suddenly vanishes. Indeed,
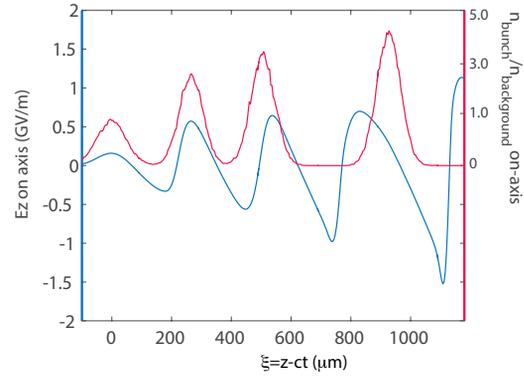
Figure 3: Longitudinal electric field on axis (blue curve) and normalized bunch density profile (red curve) for the measured ramp charge profile (ratio 1:3:5:7) in the weakly non-linear regime: $\alpha >> 1$ and $\tilde{Q} = 0.75$.

plasma fields are stronger, $10^2 − 10^3$ times, than in conventional accelerators, depending on the plasma density n_p as [18]: G(MT/m)$\approx 3\,n_p\,(10^{17}$cm$^{-3})$. Typical plasma densities considered in these experiments are of the order of $10^{16} − 10^{17}$ cm^{-3}, resulting in $G \approx 1$ MT/m. Therefore, because of mrad-scale angular divergence, the beam experiences a huge transverse size variation when propagating from the plasma outer surface to the following beam line element. Under these conditions, the particle transverse motion becomes extremely sensitive to the energy spread: the betatron frequency of a particle critically depends on its energy, therefore particles with different energies, in a drift, rotate with different velocities in the transverse phase space, resulting in a wider bunch trace space area. As a consequence, the resulting projected normalized emittance becomes a function both of drift length and energy spread. In this regard, the beam angular divergence has to be reduced and the transverse spot size increased to limit the chromatic induced emittance degradation in free space [19–21]. A proper distance where any capture and transport system should be placed to avoid emittance growth of a factor $\sqrt{2}$ because of the energy spread is defined by the chromatic length, $L_c = \frac{\sigma_x}{\sigma_{x'}\sigma_E}$ [22]. If the energy spread is not mitigated below 1%, the chromatic length can be of the order of cm. For the reasons above mentioned, a radially symmetric focusing gradient of the order of kT/m, and eventually higher, is needed at the injection of the plasma accelerating module to guarantee the matching condition, and at the extraction from it to limit the emittance growth in the transition from the plasma module and the free space. Plasma lenses satisfy these requirements and in addition they feature a focusing strength scaling proportionally to $1/\gamma$, to be effective even at ultra-relativistic energies, and a focusing field varying linearly with the radius, to prevent emittance degradation due to geometric aberrations (γ is the relativistic Lorentz factor). In particular, an active plasma lens is a current carrying conductor, realized by means of a discharge applied between the electrodes at the edges of a capillary [23, 24]. The bunch is focused by the azimuthal magnetic field, $B_\phi = \frac{\mu_0}{r} \int_0^r J(r')r'dr'$, generated by the discharge current according to Ampere's law: μ_0 is the vacuum

permeability and $J(r)$ the current density within the aperture ($r < R$, with R is the capillary radius). Optimal focusing condition is reached when the current density is perfectly parallel to the capillary axis and transversely uniform: in this case, the magnetic field intensity has a linear dependence on the distance from the axis.

Both active [25] and passive [26] plasma lenses are under investigation at SPARC_LAB [27, 28]. The aim of these experiments is studying the effect on the transverse emittance for a better integration into conventional transport beam lines. We have observed experimentally that with the 3 cm long sapphire capillary and the high peak current discharge circuit (15 kV, 180 A), a higher (larger than 40%) and more uniform ionization degree within the capillary radius results in a current distributed approximately uniformly within the capillary aperture. This fact results in a more linear magnetic field, which contributes to preserve the transverse emittance at least in the horizontal plane as measurements reported in Fig. 4 confirm: the emittance, measured as function of the discharge current, is reported in Fig. 4 (data at 0 A correspond to a measurements with discharge off, i.e. no plasma).
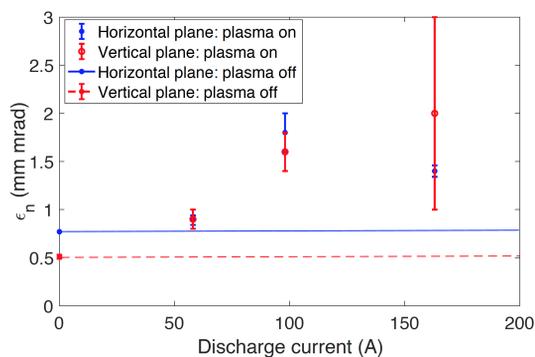
Figure 4: Measured normalized transverse emittance as function of the discharge current.

The arrival time of the electron beam is scanned with respect to the discharge pulse in order to change the active plasma lens focusing, since at different delays correspond different currents. The -800 ns delay from the beginning of the discharge corresponds to the current value that produces a beam waist at the screen, i.e. 58 A. The evolution of the transverse spot size, as measured on the YAG:Ce screen 20 cm downstream from the capillary, is reported in Fig. 5.

CONCLUSIONS

A future plasma-based user facility demands high brightness beams.At SPARC_LAB we are facing this challenge by studying with simulation and experiments both external injection acceleration schemes. Injection of HBEBs into the plasma module and extraction of plasma-accelerated beams from the the plasma module is also under investigation with the aim of preserving the 6D quality during the transport up to the pilot application, an FEL for instance. The resonant amplification of plasma waves by a train of HBEBs injected into the preformed plasma is one of the schemes proposed
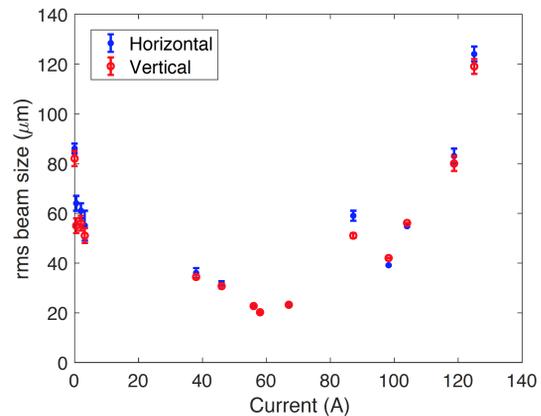
Figure 5: Evolution of the beam transverse size, as measured on the YAG:Ce screen placed at 20 cm from the capillary, for different discharge current.

to enhance the energy transfer and preserve the beam quality. A preliminary characterization of the electron beam, manipulated to resonantly excite plasma wakes, has been performed at the SPARC_LAB test facility and results have been shown. In addition, because of radial focusing with gradient of the order of kT/m, active plasma lenses allow for a compact, cm-scale, with low chromaticity system. Results from experiments at SPARC_LAB have been reported, showing a moderate emittance growth in the plasma-discharge capillary, mainly due to plasma plumes at the capillary exits.

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