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Beam dynamics in resonant plasma wakefield acceleration at SPARC_LAB

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ABSTRACT

Strategies to mitigate the increase of witness emittance and energy spread in beam driven plasma wakefield acceleration are investigated. Starting from the proposed resonant wakefield acceleration scheme in quasi-non-linear regime that is going to be carried out at SPARC_LAB, we performed systematic scans of the parameters to be used for drivers. The analysis will show that one of the main requirements to preserve witness quality during the acceleration is to have accelerating and focusing fields that are very stable during all the accelerating length. The difference between the dynamics of the leading bunch and the trailing bunch is pointed out. The classical condition on bunch length $k_p\sigma_z=\sqrt{2}$ seems to be an ideal condition for the first driver within long accelerating lengths. The other drivers show to follow different longitudinal matching conditions. In the end a new method for the investigation of the matching for the first driver is introduced.

1. Introduction

Plasma wakefield acceleration beam driven is a promising scheme for the future compact accelerators. The beam driven experiment performed at SLAC [1] has proved that it is actually possible to create plasma accelerated bunches with energy spreads lower than few percents. During the experiment, two bunches, both with an energy of ≈ 20.3 GeV, were injected inside plasma and the witness gained an energy of about ≈ 2 GeV, with a total final energy spread $\approx 2\%$ and an effective accelerating gradient of 4.4 GV/m.

In order to achieve high accelerating gradients with beam driven scheme where the incoming bunches have lower energy (≈ 120 MeV actually used at the SPARC_LAB facility), the ramped charge bunch train (a train composed of N drivers where the Nth driver has a charge of $(2N-1)Q_0$ with fixed Q_0) has been originally proposed to increase the transformer ratio beyond 2 [2]. Within this scheme we will have N different drivers located at a longitudinal distance $\approx \lambda_p$ (plasma wavelength) and the field will be increased proportional to the number of drivers. Within this experiment we are considering different charge profiles of drivers (i.e. ramped charge). In this paper we considered a constant charge profile, N different drivers having all the same charge.

SPARC_LAB facility is able to produce very high quality bunch trains ($\sigma_E<0.1\%$, $\epsilon_r \approx 1$–2 mm mrad). This high quality of the beams permits us to focus on low charge drivers (50–200 pC) to high densities ($n_b>10^{16}$) because with this emittance and energy, the required transverse spot size ≈ 4 µm can be achieved with relative high β-function at the entrance of the plasma capillary (≈ 1 mm). Furthermore, the very low energy spread makes chromatic effects negligible.

The case in which the normalized bunch charge as it has been defined in [3] $\tilde{Q}=\frac{N_B k_p^3}{n_0}$ (where $N_b=Q/e$ is the number of the electrons inside the bunch and k_p is the skin depth of the plasma) is <1 and the bunch density is greater than the background plasma density ($n_b>n_0$) is very well known as quasi-non-linear regime. This regime has been deeply investigated because it presents many positive aspects of the blowout regime, for instance the linear focusing field, but the frequency of the oscillations still depends only on plasma density [4]. In these conditions it is possible to preserve a resonant behavior of plasma oscillations. In last instance, what is going to be obtained is a resonant bubble regime where the field is pumped by different drivers injected and the witness is the only accelerated bunch.

Within the experiment we try to achieve an accelerating beam driven structure with one and more drivers. The background

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plasma density will be $n_0 = 10^{16}\ \text{cm}^{-3}$, the driver train will have a total charge of ≈ 200 pC and the witness will have a charge of ≈ 10 pC. The final aim of the experiment is to preserve the high quality of the beams accelerated in the plasma (controllable emittance growth and final energy spread $< 1\%$).

Within this paper we will study the impact of longitudinal driver matching, evaluating what is the best longitudinal injection condition to preserve witness emittance.

Looking at the rms envelope equation [5,6]

$$\sigma_x'' + \frac{p'}{p}\sigma_x' - \frac{1}{\sigma_x}\frac{\langle xF_x \rangle}{\beta c p} = \frac{\epsilon_{n,rms}^2}{\gamma^2 \sigma_x^3} \qquad (1)$$

(where σ_x is the transverse spot size, p is the momentum of the beam, ϵ is the transverse emittance and, F_x is the focusing force acting on the beam) we see that the oscillations of a bunch depend on the term $\langle xF_x \rangle$ that consists of the resulting of all forces acting on the bunch itself. For a witness inside plasma this is just the sum of driver(s) wake and beam loading.

A consequence that can be shown from the envelope equation is that rapidly changing matching conditions cause very fast betatron oscillations of the beam itself. In this context "rapidly" means that in the space of a single betatron oscillation there is a non-negligible change in the matching conditions. Mehrling et al. [7] showed that these oscillations can cause emittance growth.

Furthermore, as showed by Floettmann in [8], high energy spreads introduce emittance growth during drifts. Supposing that the effect of the beam loading stays constant during all the accelerating length, a full compensation of energy spread growth could be achieved only if the accelerating wake by driver(s) is kept as constant as possible.

The consequence is that the optimal matching conditions for witness implicitly presuppose a great stability of the accelerating and focusing fields. So, the study of matching conditions inside the plasma regards not only the witness but also all the bunches. Matching of driver(s) is a necessary condition in order to make possible a perfect matching of witness.

While the trailing bunches feel a preexisting focusing field as those in a conventional RF cavity, the first driver or leading bunch generates and experiences the fields at the same time.

In other words, the matching for the leading bunch requires a self-consistent treatment in which the distribution generates the fields and the fields will act on the distribution and on the energy of the beam.

At high energies, this feature is not crucial. Despite the so-called 'head erosion effects' have been treated by several authors [9,10], in many aspects the bunch can be considered a rigid bunch for relatively short distances, especially if the plasma is pre-ionized. At low energy, this aspect becomes one of the main issues. The bunches are not rigid and the field is a function of the position inside the plasma. So the longitudinal optimal matching condition for drivers we are looking for is the one that generates the most stable wakefields within all the accelerating length.

2. Architect code

Simulations have been performed with a time-explicit hybrid kinetic fluid code called *Architect* presented by the authors in these proceedings [11,12].

Beams are treated kinetically in a 3D space with conventional particle-in-cell schemes, while the background plasma electrons are modelled as a cold relativistic fluid.

The electromagnetic fields that move the particles both of the fluid and beams are generated by the sum of the currents of the beams and the background plasma.

Electromagnetic fields and fluid equations are solved in cylindrical symmetry on a moving window following the bunch.

The code, due to its hybrid nature, allows for fast systematic scans. Each simulation, for a realistic case, runs in a few hours on a single core.

3. Matching of drivers

The bunch we simulated is a Gaussian driver with $\gamma = 215$, $\sigma_x = 6\ \mu$m, a transverse normalized emittance of $\epsilon_n = 4$ mm mrad injected with various lengths inside a plasma with a density $n_0 = 10^{16}\ \text{cm}^{-3}$.

Transverse matching conditions for the driver are chosen according to the following equation

$$\sigma_x = \sqrt[4]{\frac{3}{\gamma}}\sqrt{\frac{\epsilon_n}{k_p}}, \qquad (2)$$

obtained starting from Eq. (1) and using the definition of fields inside plasma given by [13].

In the literature the condition $k_p\sigma_z = \sqrt{2}$ provides the length that guarantees the best beam–plasma coupling [14] (in our case $\approx 75\ \mu$m).

To verify this result we performed a scan of bunch length keeping constant all the other parameters, including charge, so varying bunch density. As a figure of merit for the matching we chose the peak accelerating field and we looked for the configuration that guarantees the highest and most stable field. In Fig. 1 we plotted the peak accelerating field versus the position of beam centroid inside capillary z.

A bit shorter bunch seems to give a better field than the bunch with the length given by the classical formula. So we extended the accelerating length in order to verify this outcome. What we obtained is shown in Fig. 2. The classical matching condition guarantees the most stable bunches but for short accelerating lengths it is actually possible to use shorter bunches in order to increase the accelerating field. On the other side, if the bunch is too short, the head erosion effects will increase dramatically and the accelerating field will decrease immediately. As it is easy to show, a driver that observes the longitudinal matching conditions inside the plasma fills completely the first bubble letting no space

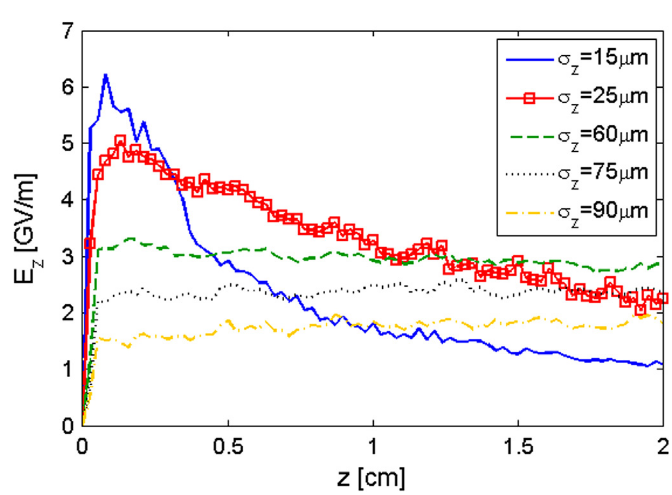

Fig. 1. Peak field evolution at different bunch lengths. For different bunch lengths, the first driver generate wakefields that evolve in a different way within all the accelerating length. Within 2 cm of accelerating length we find that the best condition for driver's injection (green line, 60 μm) is different and shorter than the classical longitudinal matching condition $k_p\sigma_z = \sqrt{2}$ (black line, 75 μm). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

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