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Stability study for matching in laser driven plasma acceleration

A.R. Rossi [a,*], M.P. Anania [b], A. Bacci [a], M. Belleveglia [b], F.G. Bisesto [b], E. Chiadroni [b], A. Cianchi [c,b], A. Curcio [b], A. Gallo [b], D. Di Giovenale [b], G. Di Pirro [b], M. Ferrario [b], A. Marocchino [e], F. Massimo [e], A. Mostacci [e,b], M. Petrarca [e], R. Pompili [b], L. Serafini [a], P. Tomassini [d], C. Vaccarezza [b], F. Villa [b]

[a] INFN - MI, via Celoria 16, 20133 Milan, Italy
[b] INFN - LNF, v.le E. Fermi, 00044 Frascati, Italy
[c] Tor Vergata University, Physics Department, via della Ricerca Scientifica 1, 00133 Rome, Italy
[d] University of Milan, Physics Department, via Celoria 16, 20133 Milan, Italy
[e] La Sapienza University, SBAI Department, via A. Scarpa 14, 00161 Rome, Italy

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ABSTRACT

In a recent paper [14], a scheme for inserting and extracting high brightness electron beams to/from a plasma based acceleration stage was presented and proved to be effective with an ideal bi-Gaussian beam, as could be delivered by a conventional photo-injector. In this paper, we extend that study, assessing the method stability against some jitters in the properties of the injected beam. We find that the effects of jitters in Twiss parameters are not symmetric in results; we find a promising configuration that yields better performances than the setting proposed in [14]. Moreover we show and interpret what happens when the beam charge profiles are modified.

1. Introduction

The basic principles of Laser WakeField Acceleration (LWFA) [1] have been extensively studied and are routinely exploited worldwide [2]; plasma based acceleration is potentially one of the most promising techniques to build next generation, compact and cheap, high energy accelerators. However there still exist a considerable lag between the exploitation of plasma based acceleration and the practical realization of a working plasma accelerator.

The main difficulties, from a beam dynamics point of view, arise because of the extremely intense transverse fields present in plasmas. Among the problems generated by this simple feature we can list: a high sensitivity to jitters and asymmetries [3]; very demanding requirements for matching beams in plasma channels [4]; a large normalized emittance degradation occurring whenever the beam propagates through a conventional beam line downstream the plasma acceleration stage [5], even if this means a trivial drift in vacuum. This last phenomenon is rooted in the intrinsic properties of an electron bunch accelerated by plasma: because of the small scales lengths of plasma waves and of the intense focusing fields, the accelerated beam usually possess a rather large energy spread and high divergence [6,7]. This makes their management extremely awkward.

The solutions proposed so far make use of plasmas as optical elements (lenses) in order either to propagate the bunches from plasma acceleration to a "user" experiment or to couple different acceleration stages. It is possible to divide the conceived plasma optical devices in active and passive lenses: the former need some kind of independent power supply, whereas the latter are powered by the same driver that produces the accelerating plasma wave. Lenses belonging to the first category, such as the one reported in [8] and the "double-pulse" lens of [9], are usually conceived as stand alone devices: this implies some amount of drift, between the plasma acceleration stage and the lenses, that could potentially spoil beam properties before reaching the plasma optics; moreover synchronization is required, although this may not constitute a great difficulty. As for passive lenses, they can be both stand alone elements, such as the "single-pulse" lens of [9], or *integrated* devices. This means that they can be implemented as extensions of already needed devices, such as capillaries, gas-jets or plasma cells. The operating principles of passive-integrated plasma lenses have been suggested some years ago [5,7,10,11] and are based on a longitudinal tapering of plasma density; further investigations showed they can be successfully operated both in the bubble regime of the plasma wave [12] and, together with a judicious choice of laser focusing, in the linear regime [13], provided beam loading is negligible. In [13] it was also shown how the longitudinal tapering can reduce detrimental effects due to offsets in beam alignment.

* Corresponding author.
E-mail address: andrea.rossi@mi.infn.it (A.R. Rossi).

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In a recent paper [14], some of us demonstrated that the method of combining longitudinal tapering and laser focusing can yield interesting results also in a more appealing setting, where beam loading is not negligible and the plasma wave is in the quasi-linear regime. Use of passive, integrated solutions seems to constitute, at least in simulations, a choice that can match the performances of active lenses, with the further advantage of an easier implementation and operation.

In this paper we extend the numerical study presented in [14], in order to verify the stability of the results with respect to the beam charge density profiles and errors in the initial matching conditions in plasma. Moreover a couple of interesting features of beam dynamics are identified and analyzed, extending and integrating what was reported in [14].

The paper is organized as follows: in Section 2 we briefly review the results of [14], defining the reference setting, and showing how the beam transport downstream the plasma is less troublesome when the beam is properly extracted from the plasma; in Section 3 the results of the stability study are presented and commented. Moreover, we give some estimations on the jitters in matching conditions that can be tolerated; in Section 4 we present an heuristic explanation of interesting features shown by emittance evolution in some instances; finally, in Section 5 we draw some conclusions.

2. Matching of electron bunches to/from a plasma stage

The matching condition for a given beam in any focusing system, can be derived starting from the transverse envelope equation. Assuming cylindrical symmetry, the matched size in a plasma channel turns out to be [4]:

$$\sigma_{\mathrm{tr,match}} = \sqrt[4]{\frac{2}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}} \tag{1}$$

where ε_n is the normalized phase space emittance, $k_p^2 = 4\pi n_0 e^2/mc^2$ the plasma wavenumber, n_0 the unperturbed plasma density, γ the beam average Lorentz factor, e is the electron charge, m its rest mass and c the speed of light. All analytical results derived so far [13,15,16] are exact only either when the focusing strength is constant along the bunch (i.e. in the bubble regime) or in the linear regime; moreover beam loading is considered negligible. The derivation of 1 implies that the beam Twiss parameter α is zero [17].

When Eq. (2) is evaluated for a typical high brightness beam delivered by a photoinjector ($E \approx 100$ MeV, $\varepsilon_n \approx 1$ μm) the matched size turns out to be $\sigma_{\mathrm{tr,match}} \approx 1.3$ μm for a plasma density $n_0 = 10^{17}$ cm^{-3}; this density value is considered to be a good choice in planned and ongoing external injection experiments [18,19]. Such a small spot-size for a high brightness beam requires a matched Twiss beta function of the order of few hundreds of μm, an unfeasible task even for state of the art permanent magnets quadrupoles [20].

The exploitation of plasma tapering (plasma ramps) and laser focusing allows us to gently bring the beam transverse size σ_{tr} from a value manageable by conventional beam lines optics, to the tight focusing needed in plasma acceleration stages; the reverse is true when the beam leaves the plasma and needs to be coupled to an experimental line or another stage of plasma acceleration. If an adiabatic matching [16] is realized, those processes occur without a significant emittance increase, as shown in [13] with numerical simulations. This requires the plasma ramps to be much longer than the electrons betatron wavelength $\lambda_\beta = \sqrt{2\gamma}\lambda_p$, where $\lambda_p = 2\pi/k_p$. The effective ramp length can be shortened if a specific, optimized tapering profile could be implemented [16]; however, different profiles can still provide adiabatic matching if the ramp length is increased accordingly.

Table 1
Input bunch parameters. The reported transverse size is the one attaining matching.

Charge	10 pC
$\sigma_{x,y}$	1.3 μm
σ_z	2 μm
$\epsilon_{x,y}$	1 μm
Energy	80 MeV
$\Delta E/E$	0.2%

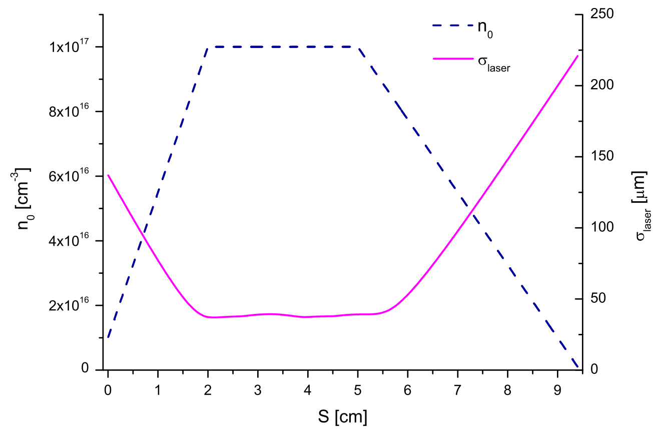

Fig. 1. Laser average radius (solid line) and plasma density profile (dashed line). The three stages of the transport (insertion, acceleration, extraction) with relative lengths and densities. Throughout acceleration the laser is guided by the capillary, while it evolves freely in both matching sections. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

In [14] we showed how it is possible to perform the matching task, for a bi-Gaussian beam whose properties are summarized in Table 1, employing an experimental setting as shown in Fig. 1 (blue line). Such a plasma density configuration could be produced by proper shaping of the capillary geometry and tuning the pressure of the gas applied to the inlet(s). An insertion linear plasma ramp of length $L_1 = 2.0$ cm, and plasma density varying from $n_i = 10^{16}$ cm^{-3} to $n_0 = 10^{17}$ cm^{-3}, brings the beam to an acceleration stage whose length L_{acc} is 3 cm; after acceleration, the bunch is coupled back to vacuum by means of an extraction ramp with length $L_2 = 4.4$ cm and density going from n_0 to $n_f = 10^{15}$ cm^{-3}. In the accelerating stage, the plasma wavelength is $\lambda_p \approx 100$ μm. We used linear ramps for sake of simplicity. The distance between the barycenters of driver and witness is set to be $\Delta z = 50$ μm.

A laser pulse with $\lambda_L = 800$ nm drives the plasma wave. The pulse is Gaussian transversally, while the longitudinal profile is a squared sine. It is focused at the beginning of the acceleration stage, Fig. 1 magenta line, down to an rms size $\sigma_L = 38.6$ μm in order to be matched in a dielectric capillary hollow waveguide whose inner radius is $R_{cap} = 60$ μm [21]. After guiding in the capillary, the laser is allowed to defocus freely in the extraction ramp. The pulse length is 35 fs FWHM and the energy is 3.5 J, so that at focus we have $a_0 \approx 1.4$. This value allows us to drive a quasi-linear plasma wave. The choice of laser and capillary parameters has been detailed in [18].

For simulations, we used the hybrid fluid/Particle in Cell (PIC) code QFLUID [18]. The plasma component is modeled as a cold fluid while the accelerated bunch is fully kinetic. Cylindrical symmetry is assumed and the laser evolves under the envelope approximation. QFLUID makes also use of the quasi-static approximation and evolves the plasma component by solving