BEAM QUALITY LIMITATIONS OF PLASMA-BASED ACCELERATORS *

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Abstract

Plasma-based accelerators are a promising novel technology that could significantly reduce the size and cost of future accelerator facilities. However, the typical quality and stability of the produced beams is still inferior to the requirements of Free Electron Lasers (FELs) and other applications. We present here our recent work in understanding the limitations of this type of accelerators, particularly on the energy spread and bunch length, and possible mitigating measures for future applications, like the plasma-based FEL in the EuPRAXIA design study.

INTRODUCTION

Plasma-based accelerators (PBAs), driven by high-intensity lasers [1] or charged particle beams [2], can sustain accelerating fields orders of magnitude higher than conventional radio frequency (RF) accelerators [3] and therefore offer a path towards highly compact and cost-effective particle accelerators. Although the beam quality of these novel devices is not yet sufficient for applications, the potential reduction in footprint and cost makes this technology very attractive.

Of particular interest is the use of PBAs as drivers for a new generation of compact synchrotron light sources, such as Free Electron Lasers (FELs) [4], which currently rely on kilometer-long RF accelerators. Concepts for plasma-based FELs, such as the EuPRAXIA design study [5], are currently under development. However, FELs impose strict requirements over certain key beam parameters, such as a micron-level emittance, multi-kiloampere current, femtosecond-long bunches and a relative energy spread $\lesssim 10^{-3}$ [6]. Also of interest is the production of sub-femtosecond bunches to generate short x-ray pulses for ultrafast science [7].

Outstanding progress in PBAs over the past decades has led to the experimental demonstration of micron to sub-micron emittances [8–16], peak currents over tens of kiloamperes [17, 18] and bunches as short as a few femtoseconds [17–20]. Still, the achievement of energy spreads below the percent level has remained an issue. Prior to 2004, where three different groups demonstrated almost simultaneously the production of quasimonoenergetic beams with ~ 100 MeV energies [21–23], electrons accelerated in PBAs exhibited broad and continuous energy spectra [24–28]. Since then, the rapid advances in laser technology as well as the development of new techniques for controlled injection have led to the successful realization of multi-GeV beams with energy spreads as low as ~ 1%. These techniques typically rely on self-injection from wave breaking [29, 30], which can be enhanced by modulating the plasma density profile [31, 32]. Other methods include ionization injection [33–38] or the use of colliding laser pulses [39–41]. Experimental results from these different injection schemes can be seen in Fig. 1.

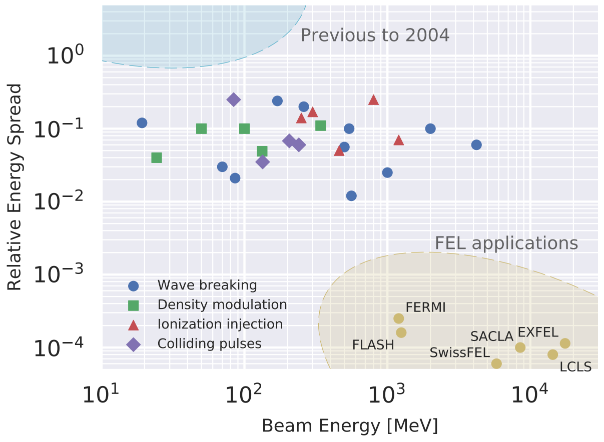

Figure 1: Overview of experimental results from laser-driven PBAs using different injection techniques, as obtained from Refs. [3, 17, 18, 20–23, 32, 42–56]. An illustrative range of parameters obtained in experiments prior to 2004 as well as for FEL applications is shown, including reference values of current FEL facilities [57–62].

We discuss here some general sources of energy spread in PBAs that currently limit the performance of these devices, as well as the difficulties in achieving sub-femtosecond bunches. Other issues such as the repetition rate or shot-to-shot fluctuations are not covered.

PARTICLE DYNAMICS IN PBAs

The perturbation caused by the driver in the plasma electron density generates a wakefield in which electrons can be trapped and accelerated. The motion of a relativistic electron within this wake is described by $\dot{\boldsymbol{p}} = -e\boldsymbol{W}$, where $\boldsymbol{p} = m\gamma\boldsymbol{v}$ is the particle momentum, m the electron mass, $\gamma = 1/\sqrt{1-|\boldsymbol{v}|^2/c^2}$ the relativistic Lorentz factor, $\boldsymbol{v}$ the particle velocity, e the electron charge and $\boldsymbol{W} = \left(E_x - cB_y, E_y + cB_x, E_z\right)$ the wakefield, in which E_i and B_i, for $i = x, y, z$, are the different components of the electric and magnetic fields and c is the speed of light. Depending on the intensity of the driver different accelerating regimes can

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be identified. In particular, analytical 3D expressions exist for the linear regime [63, 64], in which the laser strength parameter $a_0 \simeq 0.85 \times 10^{-9}\sqrt{\lambda^2(\mu\mathrm{m}) I_0(\mathrm{W/cm^2})} \ll 1$, with λ and I_0 being the laser wavelength and peak intensity, or the ratio between beam and plasma electron density $n_b/n_p \ll 1$ when a particle driver is used. Several models have also been developed for the blowout regime [65–67], in which the driver is able to completely expel all plasma electrons, leaving behind an ion cavity with uniform focusing gradient $K = \partial_x W_x = \partial_y W_y = m\omega_p^2/2e$ and accelerating fields with approximately constant slope $E_z' = \partial_z W_z$ towards the back of the wake, where $\omega_p = (n_p e^2/m\epsilon_0)^{1/2}$ is the plasma frequency and ϵ_0 the vacuum permittivity. In what follows, the blowout regime is assumed, as it offers ideal focusing properties and most experiments operate on it.

The linear focusing forces in this regime allow the transverse motion of the particles to be described as:

$$\ddot{x} + \frac{\mathcal{E}}{\gamma}\dot{x} + \frac{\mathcal{K}}{\gamma}x = 0, \tag{1}$$

where $\mathcal{E} = \dot{\gamma} = -eE_z/mc$ is the rate of energy gain and $\mathcal{K} = eK/m$. This implies that particles will perform transverse oscillations, known as betatron motion, with a frequency $\omega_\beta = \sqrt{\mathcal{K}/\gamma}$ while propagating throughout the accelerator. If the betatron frequency is a slowly varying function [65], i.e. $\dot{\omega}_\beta/\omega_\beta^2 = \mathcal{E}/2\sqrt{\gamma\mathcal{K}} \ll 1$, these transverse oscillations can be analytically found to be

$$x(t) \simeq A_0 \Gamma(t)^{-1/4} \cos\left(\phi(t) + \phi_0\right), \tag{2}$$

where $\Gamma = \gamma/\gamma_0 = 1 + \mathcal{E}t/\gamma_0$ and $A_0 = \sqrt{x_0^2 + \left(v_{x,0}/\omega_{\beta,0}\right)^2}$ is the initial oscillation amplitude, with γ_0 being the initial particle energy while x_0, $v_{x,0}$ and $\omega_{\beta,0}$ are the initial transverse position, velocity and betatron frequency. The initial phase is given by $\phi_0 = -\arctan\left(v_{x,0}/x_0\omega_{\beta,0}\right)$ and the phase advance $\phi = \int_0^t \omega_\beta(t')\,\mathrm{d}t'$ is

$$\phi(t) \simeq 2\frac{\sqrt{\mathcal{K}\gamma_0}}{\mathcal{E}}\left(\Gamma(t)^{1/2} - 1\right). \tag{3}$$

The longitudinal particle position is assumed to be fixed in the speed of light frame $\xi = z - ct$, and therefore the experienced $\mathcal{E}$ is constant.

In order to discuss the beam energy spread it is useful to introduce the normalized RMS longitudinal emittance, defined as $\epsilon_L = \sqrt{\langle\xi^2\rangle\langle\gamma^2\rangle - \langle\xi\gamma\rangle^2}$, where $\langle\rangle$ denotes the second central moment of the distribution. From here one can identify the bunch length as $\sigma_\xi = \sqrt{\langle\xi^2\rangle}$ and the absolute energy spread as $\sigma_\gamma = \sqrt{\langle\gamma^2\rangle}$.

SOURCES OF ENERGY SPREAD AND BUNCH LENGTH

The main source of energy spread in PBAs is typically the steep slope of the accelerating fields within the focusing region of the wake, $\mathcal{E}' = -eE_z'/mc$, which induces a longitudinal energy correlation along the bunch [68]. Assuming a constant $\mathcal{E}'$, the slope (or chirp) of this correlation for a beam with an initially uncorrelated energy distribution ($\langle\xi\gamma\rangle_0 = 0$) can be expressed as $\delta(t) = \mathcal{E}'\bar{\gamma}_0(\bar{\Gamma}(t) - 1)/\mathcal{E}$, where $\bar{\Gamma} = \bar{\gamma}/\bar{\gamma}_0$ with $\bar{\gamma}$ and $\bar{\gamma}_0$ being the current and initial mean beam energy. From this expression it follows directly that the induced correlated energy spread is given by

$$\sigma_\gamma^c(t) = \delta(t)\sigma_\xi = \frac{\mathcal{E}'\bar{\gamma}_0\sigma_\xi}{\mathcal{E}}\left(\bar{\Gamma}(t) - 1\right). \tag{4}$$

Assuming that the bunch length is preserved during acceleration, this correlated energy spread can be shown not to have any impact on the longitudinal emittance. In terms of δ, the correlation term in ϵ_L can be expressed as $\langle\xi\gamma\rangle = \delta\sigma_\xi^2 = \sigma_\gamma^c\sigma_\xi$, and since the total energy spread is given by $\sigma_\gamma = [(\sigma_\gamma^0)^2 + (\sigma_\gamma^c)^2]^{1/2}$, where σ_γ^0 is its initial value, the longitudinal emittance at any time can be found to be constant, $\epsilon_L = \sigma_\gamma^0\sigma_z = \epsilon_L^0$. This means that the increase in energy spread due to σ_γ^c can be compensated, as proposed in [69, 70], and thus it does not fundamentally limit the achievable energy spread.

The correlated energy spread can also be minimized through beamloading [71, 72], in which the presence of the electron beam itself can modify the longitudinal field such that $\mathcal{E}'$ is minimized or suppressed along the bunch. However, achieving $\mathcal{E}' = 0$ imposes strict conditions on the bunch current profile which are difficult to realize in a controlled manner with internal injection schemes. This could be improved with externally injected beams produced in a conventional RF accelerator, as this more mature technology allows for a more precise bunch shaping that can be optimized for beamloading in a plasma stage. However, due to the short wavelength of the wakefields (~ 100 fs), sub-femtosecond precision in the injection phase of the external beam is necessary in order to achieve sufficient shot-to-short energy stability. Although this level of synchronization between laser driver and witness beam is beyond state-of-the-art, new concepts have been proposed for its realization [73].

Another source of energy spread in PBAs is the emission of synchrotron radiation, usually referred to as betatron radiation, arising from the transverse electron oscillations [74, 75]. Since not all beam particles oscillate with the same amplitude, they will radiate energy at different rates and therefore induce an energy spread which has been estimated as [76]

$$\sigma_\gamma^r(t) = \frac{2r_e}{15c^3}\frac{\mathcal{K}^2\sigma_{A^2}\bar{\gamma}_0^3}{\mathcal{E}}\left(\bar{\Gamma}(t)^{5/2} - 1\right) \tag{5}$$

where $r_e = e^2/4\pi\epsilon_0 mc^2$ is the classical electron radius, σ_{A^2} is the standard deviation of A_0^2 within the bunch and $\mathcal{E}$ is assumed constant. For a Gaussian beam matched to the plasma focusing fields [77, 78], σ_{A^2} can simply be written in terms of the normalized transverse emittance $\epsilon_x = \sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}/mc$ as $\sigma_{A^2} \simeq \sqrt{8c^2\epsilon_x^2/\mathcal{K}\bar{\gamma}_0}$.

This source of energy spread, as opposed to σ_γ^c, is not caused by a longitudinal correlation and therefore contributes to an increase of the longitudinal emittance, thus posing a more fundamental limit to the achievable energy spread. Furthermore, it has been proposed that the emission of betatron radiation could limit the maximum energy achievable in a PBA [79] since the radiated power increases with the beam energy. This could be relevant for collider applications where TeV energies are required. One way of mitigating this issue would be to decrease the focusing strength of the transverse fields, for which the use of hollow plasma channels [80] is particularly attractive.

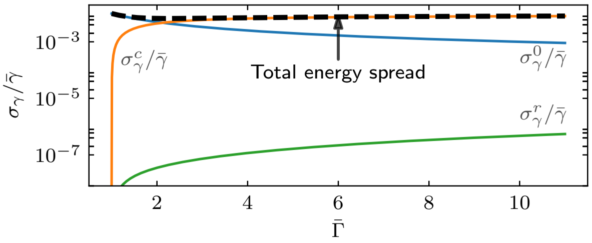

Figure 2: Comparison of the different sources of energy spread reviewed here for the beam and plasma parameters described in the text.

An additional contribution to the energy spread arises during electron injection, which determines σ_γ^0. For beams provided externally, this is simply the energy spread of the incoming beam. However, if the electron bunch is generated internally, the initial location and momentum of the trapped electrons, as well as the total duration of the injection process can greatly contribute to the energy spread [81]. This is also the process that limits the initial bunch length, which is typically on the femtosecond range. Several schemes have been proposed in order to reach sub-femtosecond duration by using sharp density transitions [82–84], although experiments have yet to demonstrate these ultrashort bunches.

Besides these different effects, we have recently investigated an additional source of energy spread and bunch length that could further limit the performance of PBAs. This contribution to the energy spread arises from the coupling of longitudinal transverse electron dynamics [85] and will be reviewed in detail in an upcoming publication [86].

The relevance of the different sources of energy spread reviewed here is compared in Fig. 2 using Eqs. (4) and (5) for the case of a beam with $\epsilon_x = 1\ \mu$m rad, $\sigma_\xi/c = 1$ fs, a matched transverse size and an initial energy of 100 MeV with a spread of 1%, parameters which could be achieved in the SINBAD facility at DESY [87–89]. A plasma stage with $n_p = 10^{17}$ cm^{-3} assuming a typical blowout with $\mathcal{E}' = \omega_p^2/2c$ and $\mathcal{E} = \omega_p$ is considered, providing a net energy gain of 1 GeV. It can be seen how the correlated energy spread quickly dominates and tends asymptotically to $\sigma_\gamma^c(t)/\bar{\gamma} \sim \mathcal{E}'\bar{\gamma}_0\sigma_\xi/\mathcal{E}$. The contribution of betatron radiation, although negligible in comparison to σ_γ^c, sets a lower limit for the achievable energy spread which could become relevant for FEL applications ($\sigma_\gamma^r/\bar{\gamma} \sim 10^{-5}$) at $\sim$ 10 GeV energies.

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