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A Multi-Parameter Optimization of Plasma Density for an Advanced Linear Collider*

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Abstract

Recent plasma wakefield accelerator (PWFA) experiments showed that an accelerating gradient as high as 50 GV/m can be driven and sustained over a meter-long plasma [1]. Based on this result, a straw man design for a future, multi-stage, PWFA-based electron/positron collider with an energy gain of ~25 GeV/stage has been generated [2]. However, the choice of plasma density remains open. On one hand, high density means large accelerating gradients and possibly a shorter collider. On the other it means that the accelerating structure dimensions become very small, on the order of the plasma wavelength. Operating at high gradient and with such small structure imposes very strong constraints on the particle bunches: small dimensions and spacing, large current or limited charge, etc. These constraints result is challenges in producing the bunches (compression, shaping for optimum loading, etc.) and could limit the achievable collider luminosity. We explore the global implications of operating at a lower accelerating gradient with the goal of relaxing the beam and plasma parameters while meeting the requirements of a collider operating in the blowout regime.

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Recent plasma wakefield accelerator (PWFA) experiments showed that an accelerating gradient as high as 50 GV/m can be driven and sustained over a meter-long plasma [1]. Based on this result, a straw man design for a future, multi-stage, PWFA-based electron/positron collider with an energy gain of ∼25 GeV/stage has been generated [2]. However, the choice of plasma density remains open. On one hand, high density means large accelerating gradients and possibly a shorter collider. On the other it means that the accelerating structure dimensions become very small, on the order of the plasma wavelength. Operating at high gradient and with such small structure imposes very strong constraints on the particle bunches: small dimensions and spacing, large current or limited charge, etc. These constraints result is challenges in producing the bunches (compression, shaping for optimum loading, etc.) and could limit the achievable collider luminosity. We explore the global implications of operating at a lower accelerating gradient with the goal of relaxing the beam and plasma parameters while meeting the requirements of a collider operating in the blowout regime.

INTRODUCTION

Advanced accelerator concepts offer the potential to accelerate charged particles with a much larger gradient than radio-frequency (rf) based accelerators. Higher accelerating gradients can be reached for two main reasons. First, these new accelerators operate at higher frequencies ($\approx$THz) than rf accelerators ($\approx$GHz); second, they take advantage of the higher breakdown fields of either dielectrics (≈ 1 GV/m) or plasmas ($\gg 1$ GV/m) when compared to metallic cavity walls (a few 100's of MV/m). However, operating at higher frequencies means that the three-dimensional size of the accelerating structure becomes smaller, bringing new challenges in producing high quality particle bunches. For example, for high-energy physics applications high luminosity is required, which means that the charge of a single accelerated bunch must be maximized while its emittance must be minimized. At the same time, the average power transported by each of the colliding beams must also be maximized.

Among advanced acceleration techniques, plasma-based particle accelerators have made remarkable progress in the last decade. Electron bunches with GeV energy and relatively narrow energy spread have been produced in laser-driven plasma-based accelerators (or laser wakefield accelerators, LWFA) [3]. In the beam-driven plasma-based accelerators (or plasma wakefield accelerators, PWFA), the energy of 42 GeV electrons has been doubled in only 85 cm of plasma [4] and the acceleration of positrons has been demonstrated [5]. In the case of electron acceleration, the accelerating gradients were larger than 50 GV/m, far exceeding those rf structures can withstand. However, plasma densities n_e were larger than $2\times10^{17}\,\mathrm{cm}^{-3}$, which means that the size of the accelerating structures, on the order of the plasma collisionless skin depth c/ω_{pe}, were smaller than $\approx 20\,\mu$m. Here $\omega_{pe} = \left(n_e e^2/\epsilon_0 m_e\right)^{1/2}$ is the plasma electron frequency. Producing high charge, high quality accelerated bunches in such small scale structures is a challenge. This remains true even though no accelerating structure has to be manufactured.

In this paper, we briefly examine a few scalings for the PWFA that should be taken into consideration when outlining the parameters of a possible future PWFA-based linear collider. This is based on the premise that while very high-gradient acceleration would lead to a minimization of the length of such a collider by operating at very high frequencies, beam quality and power requirements may favor operating at lower frequencies and therefore also lower gradients. It is clear that the new accelerating technique will have to be fully integrated into the collider design and that compromises will have to be reached.

SCALING

Here we only consider the scaling with accelerating gradient. We express this scaling with respect to the plasma density n_e assuming that the accelerating gradient scales proportionally to the cold plasma wave breaking field $E_{WB} = m_e c\omega_{pe}/e \propto n_e^{1/2}$. Note that the accelerating gradient may exceed E_{WB}. For a fixed energy gain, the plasma length L_p thus scales as $n_e^{-1/2}$. We assume that the drive and witness bunch length σ_z are a (fixed) fraction of the plasma skin depth c/ω_{pe}, and therefore also scale as $n_e^{-1/2}$. In order to minimize energy loss to synchrotron radiation and to cancel the betatron envelope oscillation of the bunches along the plasma, the beam size is assumed matched to the plasma's very strong focusing force. In this case, the beam transverse size remains constant along the plasma since the focusing force is also constant in both transverse dimensions. The beam radius matched to the

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plasma focusing force is given by [8]:

$$\sigma_r = \left(\frac{2\epsilon_0 m_e c^2}{e^2}\frac{\gamma\epsilon^2}{n_e}\right)^{\frac{1}{4}} \propto n_e^{-\frac{1}{4}} \quad (1)$$

where $\epsilon_N = \gamma\epsilon$ is the normalized emittance. We also assume that the ratio of the two bunches' density to plasma density n_b/n_e is kept constant to keep up with the above scalings and the number of particles per bunch scales as $N_b \propto \sigma_r^2\sigma_z n_b = cst$. Therefore, according to this scaling, the number of particles per bunch is independent from the plasma density. The increase in beam density is negated by the decrease of the bunches' dimensions.

Beam Matching

Note that the above matching condition between the plasma focusing force and the beam leads to extremely small transverse beam dimensions. Focusing the beam to the entrance of each plasma section is a challenge that can be relaxed by operating at lower gradient and therefore lower plasma density. The bunch transverse size has strong implications for synchrotron radiation emission and plasma ion motion, as discussed below. With the normalized emittance typically expected for the ILC ($\epsilon_{xN} = 10^{-5}$ and $\epsilon_{yN} = 3\times10^{-8}\,\mathrm{m-rad}$) the transverse sizes matched to a plasma with $n_e = 10^{16}\,\mathrm{cm}^{-3}$ are $\sigma_{x0} \cong 1\,\mu\mathrm{m}$ and $\sigma_{y0} \cong 57\,\mathrm{nm}$. The matched beta function (equal in both planes) $\beta_{matched} \cong 17\,\mathrm{cm}$ at an initial injection point into the plasma at $25\,\mathrm{GeV}$, and $\cong 76\,\mathrm{cm}$ at $500\,\mathrm{GeV}$ energy.

Synchrotron Radiation

The plasma provides a very large focusing force that allows for the electron beams to propagate over a long distance and to gain/lose large amounts of energy. With the beam density larger than the plasma density, the witness bunch propagates in a pure ion column of density $n_i = n_e$. The focusing strength of the ion column is $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\epsilon_0 c}$ and reaches MT/m for plasma densities in the $10^{17}\,\mathrm{cm}^{-3}$ range. Under this focusing force the beam electrons experience betatron oscillations with a period $\lambda_\beta = \frac{2\pi}{k_\beta} = \frac{2\pi c\sqrt{2\gamma}}{\omega_{pe}} \propto n_e^{-1/2}$. Along that motion each electron emits synchrotron radiation (often called betatron radiation in this context) at a rate given by

$$W_{synchr} \cong \frac{e^5}{48\pi\epsilon_0^3 m_e^2 c^4} n_e^2\gamma^2 r_0^2 \propto n_e^{3/2}, \quad (2)$$

where $r_0 \propto \sigma_r$ is the maximum transverse excursion of the electron along its betatron trajectory. The power averaged over a beam with Gaussian transverse profile scales as σ_r^2. The total energy lost to synchrotron radiation along the plasma scales as $N_b W_{synchr} L_p/c \propto n_e$. The largest number of photons is emitted at an energy of $\approx 0.27\,\hbar\omega_c$, where $\omega_c = \frac{3}{4}\frac{e^2}{\epsilon_0 m_e c}\gamma^2 n_e r_0 \propto n_e^{3/4}$, corresponding to $10's$ of MeV with the above n_e, and the photon spectrum extends to about $10\,\hbar\omega_c$. The spectrum is broad because each electrons has a non-harmonic motion. The energy lost to synchrotron radiation may be a small fraction of the beam energy increases with n_e. The high energy synchrotron photon can generate significant parasitic signals in the detector. Note that in a multi-stage acceleration approach driven by $25\,\mathrm{GeV}$ bunches, synchrotron radiation from the accelerated witness bunch ($W_{synchr} \propto \gamma^2$) is of real concern ($\propto \gamma^2$).

Ion Motion

The matched bunch radius (Eq. 1) is very small ($\propto 1\mu\mathrm{m}$) for the low emittance beam considered for a future collider. The very dense bunches have large space charge fields that can pull the plasma ions toward the beam axis on the time scale of a plasma period ($\omega_{pi}^{-1} \propto n_i^{-\frac{1}{2}} = n_e^{-\frac{1}{2}}$). This results in nonlinear plasma focusing forces that lead to beam emittance growth. To lowest order the plasma ions of mass Am_p and ionization state Z execute a harmonic motion towards the axis and their phase advance over one plasma period is given by [6]:

$$\frac{\Delta\phi}{2\pi} = \left(\frac{2\pi Z r_a N_b \sigma_z}{A\epsilon_N}\right)^{1/2} (r_e n_e \gamma)^{1/4} \quad (3)$$

where r_e and r_a the classical radius of the electron and of the proton, respectively. The value of $\frac{\Delta\phi}{2\pi}$ must remain $\ll \frac{1}{4}$ for ion motion not to be an issue for emittance preservation. Therefore, under the assumption of constant beam to plasma density ratio, $\frac{\Delta\phi}{2\pi}$ is independent of n_e. Ion motion can only be mitigated by using lower charge and longer bunches (than assumed here for the scaling), or by using heavier ion plasmas and other techniques [7].

Beam Scattering

Beam scattering is slightly different in a PWFA than in a neutral medium. Since the bunch density is chosen larger than the plasma density, the witness bunch propagates in a pure ion column. Therefore, as far as scattering is concerned, the bunch electrons "collide" with all the ions of the ion column, unlike the case of a neutral medium in which the collisions are only with single nuclei, or in neutral plasmas where the maximum impact parameter is the Debye length. Therefore, the emittance growth resulting from this extended scattering range must be recalculated and can be expressed in terms of the bunches initial γ_{in} and final γ_{fin} relativistic factors, (for a bunch radius matched to the ion column) [8]:

$$\Delta\epsilon_N = \sqrt{2} r_e S\left(\sqrt{\gamma_{fin}} - \sqrt{\gamma_{in}}\right) \quad (4)$$

where $S = Q^2\left(ln(\frac{R_b}{R_a}) + \frac{1.78Z(Z+1)}{Q^2} ln\frac{287}{\sqrt{Z}}\right)$, R_a is the atomic radius of the ions, $R_b = \sqrt{\frac{n_b}{n_e}}\sigma_r$ is the blowout radius, and r_e the electron classical radius. Note that for this case of an initially matched beam that remains matched as long as the emittance growth is small over one betatron wavelength, the emittance growth only depends on the type of plasma ions (S term) and the initial and final beam energy; it is essentially independent of the plasma density.

Beam Head Erosion

It was noted in recent experiments that head erosion of the drive bunch may limit the acceleration length and therefore the energy gain in a single plasma section [4]. This erosion occurs because the head of the drive bunch propagates either in a neutral vapor (field-ionized plasma case) and/or in a neutral plasma without focusing forces (pre-ionized plasma case). Therefore, the point along the bunch where the plasma focusing force counters the natural beam divergence recesses. This effect is significant only when the matched beam beta function $\beta_{matched} = \frac{c\sqrt{2\gamma}}{\omega_{pe}} \propto n_e^{-1/2}$ is shorter than the plasma length L_p. Note that head erosion appears to be an issue for beams with parameters typical ILC beams matched to meter-long plasma sections with densities in the $10^{16}\,\mathrm{cm}^{-3}$ since their beta function is on the order of 17 cm. However, head erosion is only an issue for the drive bunch that is discarded at the end of each of plasma section. In a multi-stage acceleration scenario the drive bunches only have a 25 GeV initial energy decreasing to close to zero. Therefore, they need not to be matched to the plasma focusing force. Their larger size will generate extra betatron radiation (form $25- \approx 0$ GeV electrons), but mitigate both the drive bunch head erosion and the effect of plasma ions motion from the drive bunches. An expression for the head erosion rate in a field ionizing plasma was derived that indicates that for head erosion not to be an issue, the following condition must be satisfied [9]:

$$\frac{1}{2466}\frac{c}{\omega_{pb}}(\mu m)\frac{\sigma_r(\mu m)E_{thresh}(GV/m)}{\frac{N_b}{2\times10^10}}\frac{1}{\beta^*} < 1 \qquad (5)$$

In this equation ω_{pb} is the beam plasma frequency, σ_r is the matched beam size and $\beta^* = \gamma\sigma_r^2/\epsilon_N$ is the matched beam beta function, and E_{thresh} is the electric field threshold for field ionization of the ambient gas (e.g., $E_{thresh} \cong 6\ GV/m$ for lithium). This limit scales as $n_e^{-5/4}$.

Summary

We have briefly considered the scaling of a few of the beam and plasma parameters with plasma density in the PWFA. As expected, most of the parameters are easier to achieve in a PWFA that operates at lower density. Indeed, other effects related for example to the interaction of the two bunches at the collision point (beam-strahlung, disruption parameter, etc.) are also strongly dependent on the plasma density through the bunch parameters. In order to evaluate the potential of the PWFA as a possible new acceleration method for a future e^-/e^+ collider, the plasma accelerator design must withstand the same scrutiny as radio-frequency accelerators do. This process is just starting, because of the recent experimental results obtained at SLAC [4] and because a new facility with a strong research emphasis on the PWFA, known as FACET [10], is currently under commissioning at SLAC. These new PWFA experiments will be dedicated to the study of PWFA collider-related issues, more specifically to the study of a single, meter-long plasma section that adds ≈ 25 GeV to an incoming witness bunch. These issues include final energy spread, beam loading, energy transfer efficiency, emittance and preservation [11]. The dependency of these parameters on plasma density will also be studied, although over a relatively small density range (factor of five). With the progress of these upcoming experiments the issue of scaling with plasma density and acceleration gradient will be further studied.

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