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Ultra-short electron bunches by Velocity Bunching as required for plasma wave accelerations

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ABSTRACT

The generation of ultra-short bunches is nowadays a critical requirement for plasma wave accelerators, on which many laboratories world-wide are investigating or are close to starting with experimental activities. This requirement is true for both: external injection into "laser wake field accelerators", where injected beams need lengths around or shorter than 10 fs; and the "plasma wake field accelerators", where the wake field intensity scales like the driver bunch charge over the square of the rms bunch length (Q_b/σ_z^2). This work presents beam dynamic simulations, which show how to use the Velocity Bunching (VB) technique to obtain ultra-short bunches. The VB technique is applied to small bunch charges (0.5–15 pc) and it is driven with a proper control of the bunch density versus the bunch energy gain, which permits one to control the transverse beam emittance, the bunch length and the correlated longitudinal energy spread, in a peculiar manner. The compression optimizations by VB, shown in this work, are obtained using a layout very similar to SPARC's Linac one, which is a Linac designed to maximize VB performances.

1. Introduction

The electron acceleration in plasma wave, after years of R&D and some challenging experiments [1–4], is considered the roadmap to open a new electron acceleration era. Several laboratories worldwide are pursuing projects to develop such advanced technology, while many others are investing efforts in developing new codes (and algorithms) to simulate the electron plasma wave acceleration [5–8], providing to the scientific community the necessary tools and the know-how to design new experiments and applications.

Ultra-short electron bunches are of critical importance for the two main plasma acceleration schemas: external injection in Laser Plasma Wake Field Acceleration (LWFA) and in Plasma Wake Field Acceleration (PWFA); both require bunch lengths ranging from a few tens of femtoseconds down to few femtoseconds.

The external injection into LWFA, where a short intense laser pulse propagating through a plasma excites a plasma wave in the laser pulse's wake, requires bunches much shorter than the plasma wave length, in the way to maintain a good bunch quality (in terms of energy spread and emittance). The plasma wave length depends on plasma density as $\lambda_p \sim 1/\sqrt{n_e}$; while the acceleration gradient scales like $\sqrt{n_e}$. As a consequence, considering relevant gradients of few GeV/m up to some tens of GeV/m, the plasma waves length results shorter than 100 fs.

In the PWFA the driving laser pulse is replaced by a driving electron beam. In a simple configuration a single driving bunch enters a plasma exciting a plasma density wave; then a second trailing bunch, usually called "witness", is accelerated by the wake field. The amplitude of the wake field scales like Q_b/σ_z^2 [4] (Q_b is the driving bunch charge and σ_z the driver rms length). Considering a linear accelerating regime [2], where the best energy transfer is for $2\sigma_z \approx \lambda_p \propto 1/\sqrt{n_e}$ and $n_e \le Q_b/\sigma_r^2\sigma_z$, it can be assume that $1/\sigma_z^2 \approx Q_b/\sigma_r^2\sigma_z$ and as a consequence the wake amplitude can be rewritten as $E_{acc} \propto Q_b^2/\sigma_r^2\sigma_z$ in the way to define the following driver bunch figure of merit (in terms of energy gain):

$$\Delta T \propto E_{acc}\beta^* \propto \frac{Q_b^2\gamma}{\varepsilon_{x,n}\sigma_z}$$

with $\beta^* = \gamma\sigma_r^2/\varepsilon_{x,n}$, $\varepsilon_{x,n}$ the rms normalized transverse emittance (for round beams) and γ the relativistic parameter. This figure of merit shows that the ability to produce ultra-short bunches makes possible to perform PWFA experiments at lower energy. The witness bunch length in the PWFA has the same considerations as those for the LWFA.

It is worth noting the importance of ultra-short bunches also for single spike X-ray Free Electron Lasers (XFELs) operating in Self

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Amplified Spontaneous Emission (SASE), where the request bunch length is shorter than the cooperation length: $\lambda_r/2\sqrt{3\rho_{1D}}$ (λ_r the resonant wave length, ρ_{1D} the one-dimension FEL parameter), e.g. the SPARX project ($\rho_{1D}\approx 2\times 10^{-3}$) with σ_z=0.5 μm (~1.65 fs) [9] or the LCLS project, operating at 20 pC with σ_z=1.0 μm (~3.3 fs) [10].

More generally the femtosecond beam science is a leading technology dedicated to dynamic microscopy, as the visualization of atomic motions, chemical reactions, protein dynamics, and much more.

This paper is presents an analytical work, completed by simulations, which proves that by using the Velocity Bunching (VB) technique [11] is possible to produce ultra-short electron bunches (in fs scale). The following paragraph begins by introducing the VB from the transverse envelope equations point of view, showing that the VB makes it possible to produce a high brightness electron beam, then a new analysis, considering the longitudinal envelope equation, is presented. It is worth noting that the longitudinal envelope equation, in case of an electron, is usually discharged. Ultra-short electron bunches show a peculiar behavior where the terms contained in the longitudinal envelope equation give important information, both for the VB optimization and to explain space-charge effects that appear in the longitudinal phase spaces of such compressed bunches.

2. VB and longitudinal dynamic

The VB is an electron beam compression technique that works in rectilinear trajectories at low relativistic energies, typically the energy at RF photo-injectors exit (S-band 4–6 MeV). It is a relatively new method that has been experimentally tested in the last decade [11], and which has been used to drive different experiments [12–15]. The peculiarity of this method is the possibility to merge bunch compression and emittance compensation, in a way to produce very high brightness electron beams. VB is a valid alternative to magnetic compressors, which suffer from beam emittance degradation due to coherent synchrotron radiation emission in the dispersive path.

The VB compression is the result of a longitudinal phase space rotation, which occurs inside a TW RF cavity, where the beam is accelerated and chirped. This rotation is possible if the injected beam is slightly slower than the RF phase velocity, so when the beam is injected at the zero crossing field phase, it slips in back to phases where the field is accelerating and simultaneously it is chirped and compressed. In order to prevent irreversible emittance degradation, during compression, the beam laminarity has to be preserved in a way to control slices envelope oscillations that cause normalized emittance oscillations. The envelope propagation has to be as close as possible to a Brillouin-like flow [16], with an invariant envelope. These assumptions, generalizing to the compression regime and considering a current increase of the same factor of the energy gain (i.e. $I=I_0\gamma/\gamma_0$), give rise to a new equilibrium stated by the following matching condition:

$$\sigma=\frac{1}{k}\sqrt{\frac{I_0}{4\gamma_0 I_A}\left(1+\sqrt{1+\left(4\frac{\varepsilon_n\gamma_0 k I_A}{I_0}\right)^2}\right)}, \tag{1}$$

where $k=eB_{SOL}/2mc$ is the solenoid focusing strength, with B_{SOL} the field intensity of long solenoids around first accelerating structures (where the compression takes place), $I_A=17$ kA the Alfvén current and ε_n the normalized emittance. The long solenoids around TW cavities provide additional external focusing, which is necessary to compensate the current rise (the RF ponderomotive focusing force results too weak).

Eq. (1) represents an exact equilibrium solution of the transverse beam envelope equation, considering an ellipsoidal bunch distribution with a constant volume density charge:

$$\sigma''+\frac{\gamma'}{\gamma}\sigma'+\left(\frac{k}{\gamma}\right)^2\sigma=\frac{Qc}{2I_A\gamma^3\sigma_z\sigma}+\frac{\varepsilon_n^2}{\gamma^2\sigma^3} \tag{2}$$

where $\gamma'\approx 2E_{acc}$, E_{acc} [MV/m] being the accelerating field.

So far we have seen the transverse electron beam dynamic, which is of crucial importance for this work, but that can be read, also with further details, in other works (cited above). The originality of the work presented here lies in an extension of the VB analysis using longitudinal beam dynamic considerations.

The longitudinal rms envelope equation can be written as follows, as in Ref ([17], Appendix A) considering $\gamma=\gamma(z)$ and for an ellipsoidal bunch distribution with a constant volume density charge:

$$\sigma_z''+K_z\sigma_z+\frac{3\gamma'\sigma_z'}{\beta^2\gamma}=\frac{Q_b c}{5\sqrt{5}I_A\beta^2\gamma^4\sigma_z\sigma}+\frac{\varepsilon_{nz}^2}{\beta^2\gamma^6\sigma_z^3} \tag{3}$$

with σ_z is the rms bunch length, β the normalized velocity, ε_{nz} the normalized rms longitudinal emittance, σ the rms bunch transversal dimension $\sigma=\sigma_x=\sigma_y$ (which couples the two envelope Eqs. (2) and (3)), $\gamma_0'=eE_{acc}/m_0c^2$ the normalized acceleration gradient and K_Z the RF longitudinal strength ([17], Chapter 5):

$$K_z=\frac{2\pi\gamma_0' \sin|\varphi_0(z)|}{\lambda_{RF}(\beta\gamma)^3} \tag{4}$$

with $\varphi_0(z)=z/c(1-(\gamma/\sqrt{\gamma^2-1}))$ (maximum acceleration at $\varphi_0=0$).

The third term on the left-hand side of Eq. (3) is a velocity damping term, always in contrast with focusing or defocusing. The two terms on the right-side of Eq. (3) represent internal forces, the space charge and the emittance longitudinal pressure. The space charge term has been obtained considering a geometry factor g_0, which for small eccentricities ($0.8<\sigma_z/\sigma\le 4$) – as for the simulations presented in this work (and more generally for typical σ_z/σ values in rf gun) – gives a good approximation of $g_0\approx(2/3)(\gamma\sigma_z/\sigma)$ [17]. From internal forces is possible to define the longitudinal laminar parameter ρ_z:

$$\rho_z=\frac{Q_b c(\gamma\sigma_z)^2}{I_0\sigma\varepsilon_z^2}. \tag{5}$$

This parameter, which is the longitudinal laminar parameter, is of crucial importance; if it is greater than one ($\rho_z>1$) the bunch maintains its longitudinal laminarity and also pushing the compression to its highest values in the longitudinal "cross-over" is forbidden [18]. One main limitation of VB is the over-compression regime (by cross-over), as reported in Ref. [18] as "wave breaking" in the longitudinal phase space. It follows that by maintaining $\rho_z>1$ different longitudinal slices are not allowed to overlap or to crossover each other. The key idea is to control the VB in a near equilibrium process, avoiding cross-over, damping both energy spread and longitudinal space charge, in the way to generate ultra-short electron bunches. The over-compressions by bouncing, after a "longitudinal waists", is avoided from longitudinal space charge damping, which is given by acceleration. Different from ballistic bunching [18], here the compression is performed together with acceleration.

The laminar parameter has to be considered as a knob to control the VB, termed Laminar Velocity Bunching (LBV), and to improve its performances; for example, with $\rho_z\gg 1$, going close to the maximum compression, the bunch becomes stiff and hard to be compressed, different from $\rho_z\cong 1$ some bunch's regions can lose laminar property and undergo in cross-over, thereby limiting the final compression. This laminar parameter is thus useful to drive optimization codes; nowadays the use of optimization codes