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TEMPORAL ELECTRON-BUNCH SHAPING FROM A PHOTOINJECTOR FOR ADVANCED ACCELERATOR APPLICATIONS *

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Abstract

Advanced-accelerator applications often require the production of bunches with shaped temporal distributions. An example of a sought-after shape is a linearly-ramped current profile that can significantly improve the transformer ratio in beam-driven acceleration, or produce energy-modulated pulse for, e.g., the subsequent generation of THz radiation. In this contribution we discuss the possibility of generating ramped bunches directly via photoinjection; and discuss the longitudinal shaping of the laser-pulse to accommodate for the early space charge dominated time experienced by the bunch. Finally, we demonstrate via particle-in-cell simulations the production of a quasi-ramped 6.9-MeV/c electron bunches suitable for beam-driven acceleration.

INTRODUCTION

Longitudinal bunch shaping of electron beams has a wide range of applications and is subject to intensive research. An application considered in this paper is the tailoring of a distribution to follow a linear ramp as a function of the longitudinal coordinate. This type of "ramped" distribution is sought after to improve the transformer ratio – the maximum accelerating wakefield over the decelerating field experienced by the driving bunch – in collinear beam-driven dielectric wakefield acceleration (DWA) schemes [1].

To date, several techniques have been proposed to generate longitudinally ramped bunches for DWA, and rely on complicated and expensive beam manipulation techniques. More recently, the use of a 3.9 GHz linearizer to generate a ramped bunch was demonstrated at DESY's FLASH facility [2]. In this method, a dual-frequency linac was used to impart nonlinear correlations in the longitudinal phase space (LPS), thereafter a dispersive section was used to impress a nonlinear correlation in the longitudinal phase space (LPS) and was tailored to produce a ramped current profile. Other recently proposed methods include the use of a transverse-to-longitudinal phase space exchanger [3] and a dispersive section with controllable high-order longitudinal dispersion [4]. The purpose of this paper is to investigate a relatively simple method to generate a longitudinally ramped bunch directly from photo-injection. The scheme could employ a large-bandwidth laser system combined with a dazzler to control the temporal shape of the laser onto the photocathode [5]. The temporal shape of the laser pulse has to be selected to account for the early moments of acceleration in a highly space-charge-dominated regime. Although this method is scalable within the limits of the laser system, the large space-charge forces after photo-emission blows up the longitudinal bunch shape; therefore, the use of higher accelerating field radio frequency (RF) gun significantly improve our method. This leads to the possibility of forming ramped bunches that are shown to produce a wakefield in a dielectric-lined waveguide with large transformer ratios and large accelerating field.

SPACE CHARGE IN 1D

For a given distribution, there is no general solution to the evolution of a charge distribution. However, there are some elementary examples, such as the inverted parabola, which can be understood nearly completely due to the linear nature of the electric fields and forces within the bunch. The asymmetry of the ramped bunch destroys the possibility of preserving its shape with linear space charge fields. Therefore we must investigate a nonlinear asymmetric bunch shape with nonlinear space charge fields.

The simplest example is given by the power distribution

$$\rho(z) = \begin{cases} z^n, & \text{for } 0 < z < 1 \\ 0, & \text{elsewhere,} \end{cases} \tag{1}$$

where z is the dimensionless longitudinal coordinate ($0 \leq z \leq 1$ in this section). The calculation of the longitudinal electric field in the rest frame of the distribution is usually calculated via [6] $E(z) = -\frac{g}{4\pi\epsilon_0}\frac{\partial\rho(z)}{\partial z}$, where g is a geometry factor and ϵ_0 the vacuum electric permittivity. Therefore to investigate such space charge effects, we develop a very simple 1-D model from elementary principles. Working in the bunch reference frame and assuming a "cold" beam with no energy spread, we consider the unitless 1-D Green's function for electrostatics

$$G(z, z') = \frac{1}{2}|z - z'|, \tag{2}$$

and compute the scalar potential via the convolution

$$\Phi(z) = \int_0^L \frac{1}{2}|z - z'|\rho(z')dz'. \tag{3}$$

This method recovers very similar fields for the familiar inverted parabola [7] in dimensionless units $I(x) = x(1-x)$. in particular the corresponding potential is found to be

$$\Phi(z) \quad = \quad \frac{1}{24}[1 - 2(z - 2z^3 + z^4)], \tag{4}$$

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giving rise to the electric field $E(z) = \frac{1}{12}(-1+6z^2-4z^3)$ and force dependence $F(z) = \frac{z}{12}(1-6z^2+4z^3)(z-1)$ as illustrated in Fig. 1.

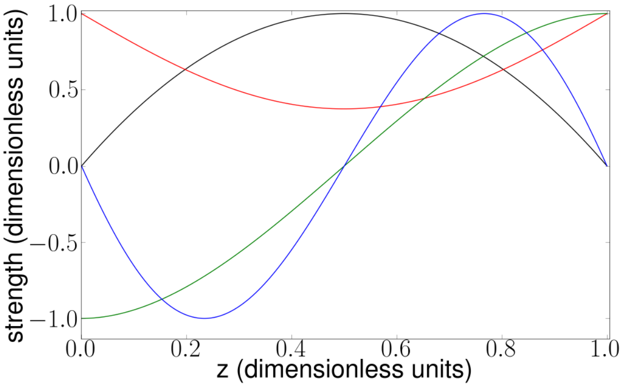

Figure 1: Inverted parabola distribution (black trace), and corresponding electrostatic potential (red trace), electric field (blue trace) and resulting force (blue trace) as a function of the longitudinal coordinate.

Considering the distribution from Eq. 1 the electrostatic potential, electric field and force within the bunch are respectively given by

$$\begin{aligned} \Phi(z) &= \frac{1+n-2z-nz+2z^{2+n}}{4+6n+2n^2}, & (5)\\ E(z) &= \frac{2z^{1+n}-1}{2(1+n)}, \text{ and} & (6)\\ F(z) &= z^n\frac{2z^{1+n}-1}{2(1+n)}. & (7) \end{aligned}$$

In Figure 2 we explore the electrostatic potential, field and force associated to power-law distributions with $n = 1$, 2, and 5. In particular, we notice for values of $n > 1$ the fields scale and maintain their shape across the distribution; moreover, the asymmetry of the fields will “push" the bunch apart about the zero-force point. Considering the case of $n = 2$, the maximum force in -$\hat{z}$ occurs near $z \simeq 0.6$. During the bunch longitudinal expansion, this portion of the bunch is smeared toward the left which help forming a quasi-linear shape. The nonlinear nature of this shaping process and its intricate dependence on space-charge effects renders an accurate prediction quite complicated and requires numerical simulations.

SIMULATION AND ANALYSIS

The previous section elaborated on a simple motivation to investigate a power-law initial distribution as a possible candidate to form ramped bunches. Here we carry particle-in-cell (PIC) simulations of the beam-dynamics using the program ASTRA [8] to demonstrate that a radio frequency (RF) gun with a properly shaped photocathode drive laser can produce a quasi-ramped bunch with characteristics consistent with the requirements of beam-driven acceleration with an enhanced transformer ratio.

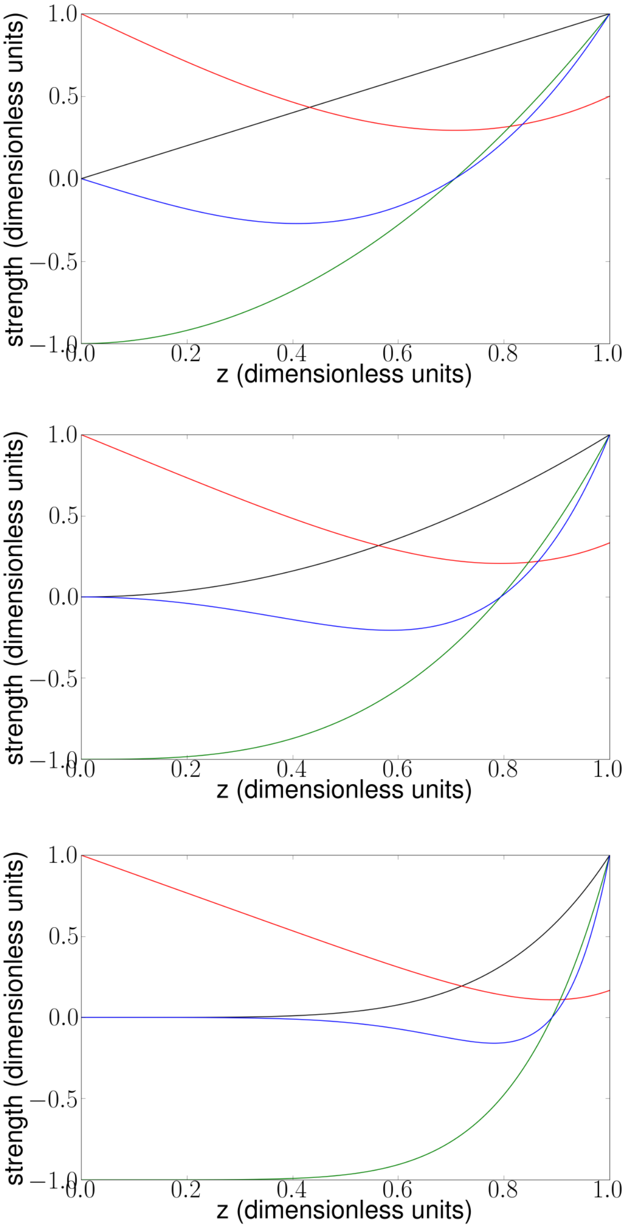

Figure 2: Charge distribution (black trace), and corresponding electrostatic potential (red trace), electric field (blue trace) and resulting force field (blue trace) for $n = 1$ (top), $n = 2$ (middle), and $n = 5$ (bottom).

Given that space-charge effects are predominant close to the photocathode, we select an S-band ($f = 2.856$ GHz) $\frac{1}{2}$-cell cavity RF gun similar to the one currently in use at the linac coherent light source (LCLS) [9] which is capable of a maximum accelerating field of 140 MV/m. Applying a high-field at the cathode surface mitigate the space-charge induce distortion of the longitudinal distribution and insure the bunch distribution is promptly "frozen".

The simulations were carried for different values of n and for this preliminary study the laser spot size on the cathode was $\sigma_c = 1.0$ mm, with total pulse length $T = 5$ ps. The bunch charge was fixed to $Q = 1$ nC. For values of $n > 5$ the bunch blows out too rapidly to produce a ramped distribution and nearly follows parabolic distribution. Moreover, for $n \approx 2$, the resulting distribution downstream of the RF gun is close to a linearly-ramped bunch. Figure 3 presents the resulting LPS and associated current profiles for the case $n = 2$ and at three axial locations.

In beam-driven dielectric wakefield acceleration, longer ramped bunches covering many wavelength of the fundamental mode lead to larger transformer ratios, albeit with reduced accelerating fields. Therefore, to generate a useful ramped current profile that provide an enhance transformer ratio with reasonable accelerating field we operate the RF gun at the conservative peak field of ~ 100 MV/m.

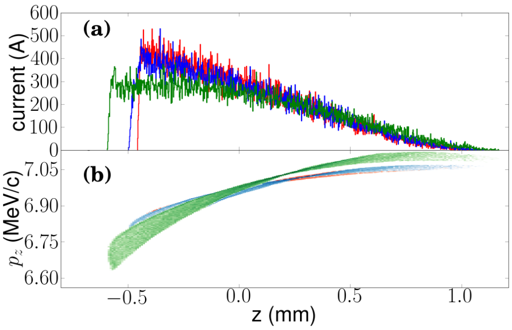

Figure 3: Current profiles (a) and longitudinal phase space (b) obtain with $n = 2$ at 10 (red), 30 (blue), and 95 cm (green) from the photocathode.

In order to explore the performances of the current profiles in beam-driven dielectric-wakefield acceleration, we considerer a diamond DLW with parameters listed in Tab. 1 and compute the electric field within and downstream the bunch via the convolution $E(z) = \sum_m \int_{-\infty}^{z} I(z-\tilde{z}) W_m(\tilde{z}) d\tilde{z}$ where $W_m(z)$ is the Green's functions associated to the m^{th} mode; see Ref. [10]. For our calculation we limit the summation to $m = 4$ modes. Once the axial field is obtained, the decelerating field is computed as $E_- = \max[E(z)]$ for z within the bunch and $E_+ = \min[E(z)]$ for z behind the bunch. The resulting wakefield is shown in Fig. 4 for the distribution located at 30 cm. We stress that the location of this distribution can be altered occur sooner, or later depending on the original choices of laser and gun parameters. For an ideal ramped bunch, the maximum transformer ratio is given by $\mathcal{R} = N\pi$ where N is the number of fundamental wavelength oscillations within the bunch. In this particular example, the structure was chosen to generate $N = 4$, which would ideally give $\mathcal{R} = 12.56$. However, the small "rolling" feature observed in the distribution leads to a slightly higher $\mathcal{R}$ as discussed elsewhere [11] compared the the ideal linear ramp.

Table 1: Parameters associated to the dielectric structure used for the dielectric-wakefield calculations of Fig. 4.

Parameter	Value	Units
inner radius a	165	μm
outer radius b	195	μm
relative permittivity ϵ_r	5.7	–
fundamental frequency f_0	0.83	THz

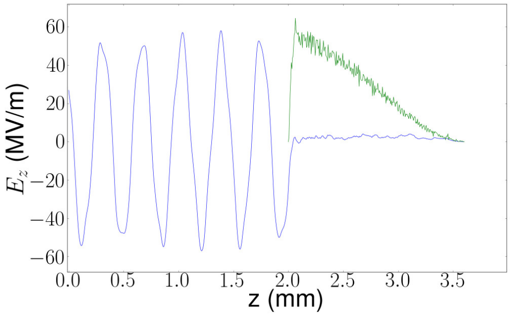

Figure 4: Longitudinal wakefield (blue trace) generated by the current profile (green trace) obtained at 30 cm from the photocathode; see Fig. 3. The maximum accelerating field $E_+ = 57$ MV/m and the transformer ratio $\mathcal{R} = 13.9$.

CONCLUSION

We have investigated a relatively simple method to produce enhanced-transformer ratio distributions by longitudinally shaping a photocathode drive laser. The technique does not rely on complicated beam manipulations and in princpal scales with the operating parameters of the photoinjector. In our range of parameters, we show that a photocathode-laser shape described by $I(x) = x^2$, leads to transformer ratios larger than the theoretical maximum for the ramped bunch.

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