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GENERATION OF SUB-fs ELECTRON BEAMS AND ELECTRON BUNCH TRAINS WITH HIGH FORM FACTOR USING WAKEFIELD STRUCTURES

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Abstract

In this paper, we propose two beam manipulation methods with wakefield structures in a photo-injector. First, we propose a simple scheme to compensate nonlinear effects during ballistic bunching by using a wakefield structure. Simulations have shown beams of 1 pC charge can be compressed to 1.56 fs rms, and even shorter beams (a few hundred attoseconds) can be obtained with bunch charge well below 1 pC. In the second part, a method of producing bunch trains with high form factor is proposed by using multiple wakefield structures. Simulation results have shown the production of a train with a form factor of 0.5 using a 1 nC beam at few-MeV energy.

INTRODUCTION

Wakefield structures have been extensively studied in recent years as phase space manipulators for their simplicity. In this paper we explore two possible applications of wakefield structures. We consider specifically planar corrugated metallic structures for their adjustability.

Figure 1 gives the geometry of a corrugated structure. For a large aspect ratio w/2a, the short-range longitudinal wake can be approximated as a single-frequency oscillation, with the Green function [1]

$$w_z(z) = \frac{\pi^2}{16}\frac{Z_0 c}{\pi a^2} H(z)\cos(kz), \qquad (1)$$

where Z_0 is the impedance of free space, c is the speed of light, $H(z)$ is unit step function, and the effective wave number $k = \sqrt{p/ahg}$. The transverse quadrupole wake, on the other hand, can be effectively cancelled with two corrugated structures orthogonally aligned [2].

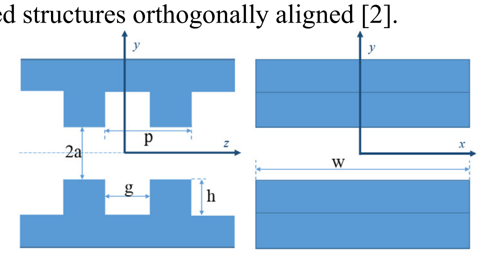

Figure 1: Geometry of a corrugated wakefield structure.

PRODUCING ULTRASHORT BEAMS

Generation of ultrashort electron beams has been a heated topic for its essential position in UED, FEL and advanced accelerator concepts. In the past two decades, velocity compression methods, including ballistic bunching [3] and velocity bunching [4], have been proven successful in low-energy electron beam compression. Nevertheless, some effects during compression, such as space charge force, RF curvature and nonlinear relation between energy and velocity, impose a limit on the shortest obtainable bunch length to the order of 10 fs, as is discussed in previous literatures [5].

In this study, we use *ASTRA* [6] to simulate the process of ballistic bunching. Beamline layout is shown in figure 2. Electron beam is emitted from an S-band 1.6π photocathode gun, followed by wake structures. Then a 9-cell buncher introduces a negative chirp required for the beam to be ballistically bunched in the drift tube downstream.

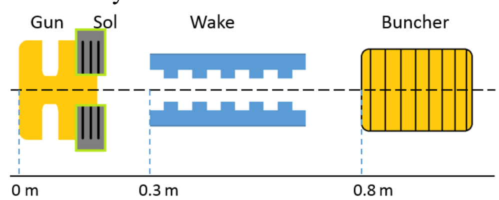

Figure 2: Beamline layout in simulation.

It is firstly studied the impact of the initial bunch distribution on the final bunch length. To start with, for a cylindrical beam, longitudinal charge density should satisfy parabolic distribution in order to induce linear space charge field. Secondly, for a 1-pC bunch it was found through parameter scanning that an initial length of 0.8 ps might be appropriate, in that shorter bunches suffer greater space charge effects, which leads to a rise in slice energy spread and thus lower compression factor; and for longer bunches stronger nonlinear effects are induced through rf-curvature and mostly the nonlinear relation between energy and velocity, as

$$\begin{aligned}\frac{\Delta\beta}{\beta} &= \frac{1}{\beta}\frac{\partial\beta}{\partial\gamma}\Delta\gamma + \frac{1}{2\beta}\frac{\partial^2\beta}{\partial\gamma^2}\Delta\gamma^2 + \cdots \\ &= \frac{1}{\beta}\frac{1}{\beta\gamma^3}\Delta\gamma + \frac{1}{2\beta}\frac{2-3\gamma^2}{\beta^3\gamma^6}\Delta\gamma^2 + \cdots. \qquad (2)\end{aligned}$$

Meanwhile transverse size needs to be reasonably small, due mainly to nonlinear space charge effect. Longitudinal space charge force within a slice varies for different radii, thus contributing to an increase of slice energy spread.

Then an optimization algorithm is performed in search

Table 1: Main Parameters of the Simulation

Parameters	Values
Bunch charge	1.0 pC
Init. long. length	0.78 ps rms, Parabolic
Init. trans. diameter	15.0 μm rms, 2D Gaussian
Emission phase	2.1 °
Buncher phase	-88.8 °

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for the shortest bunch length. Optimized parameters are listed in Table 1. For the wake structure, a gap of 1 mm is applied with a full length of 37 cm, and the fundamental wake period is 1.49 mm. Figure 3 shows the evolution of the longitudinal phase space. At the exit of the gun the beam has a kinetic energy of 4.77 MeV, with a notable second-order energy chirp. Inside the buncher a positive chirp is induced for the ballistic bunching process to commence in the drift tube afterwards, meanwhile beam energy is slightly increased to 5.0 MeV. For a beamline without wake structures, the minimum bunch length, 24 fs rms, is obtained at 2.54 m. The longitudinal phase space indicates a compensation of the 2^{nd}-order nonlinear effects could significantly enhance the compression factor.

By introducing wake structures, an additional second-order chirp of the opposite sign is induced. Due to the nonlinear relation between energy and velocity, the 2^{nd}-order chirp need to be overcompensated so as to produce a linear velocity distribution with respect to relative position. Afterwards in the drift a shortest bunch of 1.56 fs rms is achieved. It is worth noting that wake field is weaker at the head of the beam and stronger at the tail, thanks to the charge distribution, so a subtle 3^{rd}-order modulation is introduced. At the focus of compression, the particles are aligned nearly in a straight line in the phase space, and slice energy spread is the main limiting factor under such circumstances.

It is also explored in the simulation work that an 80-fC beam with an initial length of 0.3 ps rms and transverse diameter 4.9 µm could be compressed down to 0.34 fs after energy modulation in wake structures, compared to 5.3 fs without high-order chirp compensation. However, a driver beam ahead with higher charge is required due to the insufficiency of the wake in amplitude for a beam well below 1 pC [7].

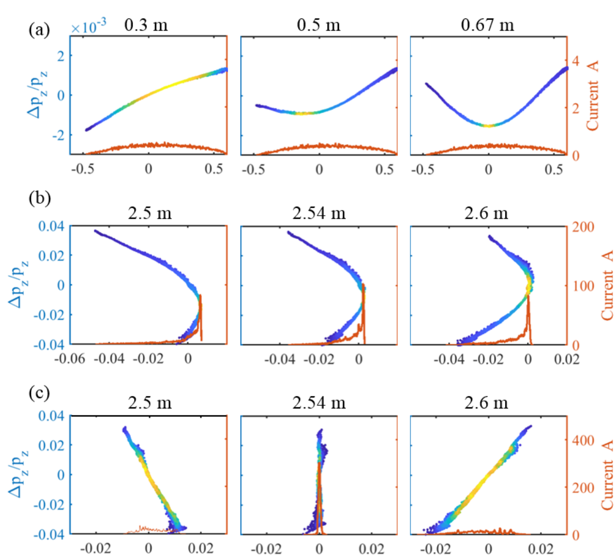

Figure 3: Longitudinal phase space evolution (head to the right). (a) through wake structure. (b) phase space at focus of compression without wake structure. (c) phase space at focus with wake structure.

PRODUCING HIGH-FORM-FACTOR BUNCH TRAINS

Electron microbunches or bunch trains have a wide range of applications, such as UED, generation of coherent radiation, and excitation of wakefield in advanced-concept accelerators. Recently it was proposed and experimentally demonstrated to use wake structures to produce electron microbunches [8]. Meanwhile a method was presented using two modulator-chicane modules to produce high-energy bunch trains with higher form factor [9]. Here we use two wake-drift modules (a wake structure followed by a drift tube) to achieve the same goal in the low energy regime.

For the particular use of generating coherent THz radiation, a key parameter is bunch form factor,

$$F(k) = \left| \int S(z) e^{ikz} dz \right|^2, \tag{3}$$

where $S(z)$ is longitudinal charge distribution and k is the wave number. Suppose a beam is uniform in longitudinal direction and has a certain energy distribution $f_0(\delta_0)$. A sinusoidal energy modulation being induced, the energy turns $\delta_1 = \delta_0 + A_1 \sin(k_0 z_0)$. After a drift tube, the longitudinal coordinate transforms under linear approximation as $z_1 = z_0 + R_{56}\delta_1$. At this point the form can be calculated, using change of variable and Jacobi-Anger expansion,

$$\begin{aligned} F(nk_0) = F_n &= \left| \iint dz_0 d\delta_0 e^{ikz_1} f(z_1, \delta_1) \right|^2 \\ &= J_n^2(nk_0 R_{56} A_1) \left| \int d\delta_0 f_0(\delta_0)\, e^{ink_0 R_{56}\delta_0} \right|^2 \\ &= J_n^2(nk_0 R_{56} A_1) \exp(-n^2 k_0^2 R_{56}^2 \sigma_\delta^2), \end{aligned} \tag{4}$$

where in the last equation an initial Gaussian energy distribution with variance σ_δ^2 is considered. In the second wake-drift module a similar procedure follows where $\delta_2 = \delta_1 + A_2 \sin(k_0 z_1)$ and $z_2 = z_1 + R'_{56}\delta_2$, after which the form factor may not be analytically expressed but numerically calculated.

Consider a typical case where a 1-nC, 9-ps and 5-MeV beam with 0.5‰ energy spread goes through two stages of wake modulation and drift, with wake frequency 0.5 THz. With one stage only, a maximum form factor of 0.34 can be achieved at fundamental frequency (i.e. $n = 1$) for $R_{56}A_1 = 1.76 \times 10^{-4}$. In the two-stage scenario, an optimization process finds that the highest form factor for $n = 1$ reaches 0.76, when $A_1 = 0.90\%, R_{56} = 0.029, A_2 = 5.4\%, R'_{56} = 2.7 \times 10^{-3}$. It should be noted that space charge effects are not taken into consideration, which in practice cause severe beam quality degradation at low energy.

A simulation study is carried out using the beam parameter in Table 2. The beamline is composed of the same gun and solenoid as before, with two wake-drift modules afterwards, with the first one located at 0.4 m. Each wake structure measures 10 cm in length and has a fundamental frequency of 1 THz. Parameter optimization shows that the highest form factor for fundamental frequency is 0.49.

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Figure 4 shows longitudinal phase spaces at the end of each module. A moderate energy modulation is induced in the first section. Then the pre-bunched beam produces a stronger wake field in the second structure, resulting in a maximum energy difference of ± 20%. At the end the head and tail overlap within each microbunch, in that despite the decrease in peak current, more electrons are accumulated at the center, thus contributing to a higher form factor. It can be seen however that phase space is notably distorted owing to space charge effects, limiting a higher form factor.

Table 2: Optimized Parameters of Wake-drift Modules

Parameters	Values	
	Module 1	Module 2
Structure gap	0.59 mm	0.89 mm
Drift tube length	0.258 m	0.011 m

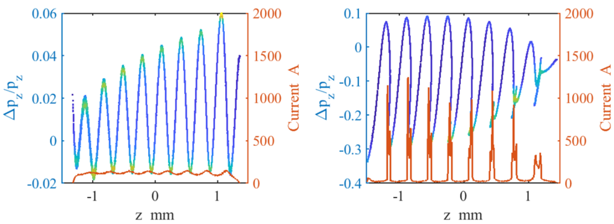

Figure 4: Longitudinal phase space at the end of each module (head to the left).

CONCLUSION

Two possible applications of wake structures are proposed. First, nonlinear effects in ballistic bunching can be compensated by self-induced field. Simulation indicates a 1 pC beam can be compressed down to 1.56 fs rms, and even shorter beams are achievable at lower charges. Second, multiple wake modules can significantly improve form factor in bunch train generation. Preliminary simulation studies show that a bunch train with a high form factor of 0.49 at low energy can be obtained via two wake-drift modules.

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