THz ELECTRON-PULSE-TRAIN DYNAMICS IN A MeV PHOTOINJECTOR*

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Abstract

In this paper, we study the beam dynamics of ultra-short electron bunches in an RF photoinjector and propose illumination of temporally shaped laser pulse at the photocathode to restore the distorted electron bunches during particle acceleration.

INTRODUCTION

A periodic electron-pulse train is important for generation of coherent radiation. For example, coherent radiation power from a pre-bunched electron beam [1, 2] can grow up rapidly from a short undulator in a free electron laser (FEL). To have an appreciable value of the electron bunching factor [1] in an electron pulse train, the longitudinal electron micro-bunch width in the time domain should be significantly smaller than the inverse of the electron pulse rate. For example, for an electron-pulse train with a pulse rate of 30 THz, the longitudinal bunch width of the electron micro-bunch should be much smaller than 33 fs. The longitudinal bunch width of an accelerated electron bunch can be sensitively influenced by the bunch radius, space charge effect, acceleration gradient, and acceleration phase in an accelerator.

In this paper, we first point out that the primary debunching mechanism of the electron micro-bunch is the radial dependence of the RF fields in a photoinjector. We then proposed a temporal laser-pulse shaping technique to correct the acceleration-distorted electron micro-bunch. Finally we include the space charge effects into our study by using the PARMELA simulation code.

ELECTROMAGNETIC FIELDS IN AN RF ACCELERATOR

In a photocathode RF gun, the electrons are accelerated by a standing wave in the RF cavity. The field components of the dominate mode in a cylindrically symmetric accelerator cell are given by [3]:

$$\mathrm{E}_z(r,z,t) = E_0 J_0(\eta_0 r)\cos(k_0 z)\sin(\omega t + \phi_0), \quad (1)$$

$$\mathrm{E}_r(r,z,t) = E_0 k_0 r \frac{J_1(\eta_0 r)}{\eta_0 r}\sin(k_0 z)\sin(\omega t + \phi_0), \quad (2)$$

$$\mathrm{B}_\theta(r,z,t) = E_0 \frac{\omega r}{c^2}\frac{J_1(\eta_0 r)}{\eta_0 r}\cos(k_0 z)\cos(\omega t + \phi_0), \quad (3)$$

where c is the speed of light, $\omega = 2\pi f$ is the angular frequency with f being the resonant frequency of the cell, ϕ_0 is the initial acceleration phase, E_0 is the accelerating gradient of the RF cavity, $k_0 = \pi / L$ with L being the cell length, $\eta_0 = \sqrt{(\omega/c)^2 - k_0^2}$, and the RF phase is defined as $\phi = \omega t - k_0 z + \phi_0$. The RF fields are standing waves with radial-dependent field amplitudes. The longitudinal field E_z decreases as r increases. On the other hand, the transverse fields E_r and B_θ increase as r increases. Since the acceleration fields are radial-dependent, the transit time of an electron is dependent on its radial position in the RF cavity. The electrons emitted at the cathode at a time may not reach the exit of the accelerator at the same time, and the longitudinal bunch width of the electron bunch could be broadened. In the following, we consider a 1.5 cell RF photoinjector with the relevant parameters shown in Table 1.

Table 1: Parameters of the RF Photoinjector

Parameter	Value
RF resonance frequency f	2.856 (GHz)
Accelerating gradient E_0	80 (MV/m)
Cell length L	6.76 (cm)
Entrance position	z = 0 (cm)
Exit position	z = 10.14 (cm)

EVOLUTION OF AN ULTRA-SHORT ELECTRON BUNCH

Firstly, it will be interesting to see how a delta-function like electron pulse in time is broadened during acceleration. Consider an ultra-short electron bunch generated by illuminating the cathode with an ultrafast laser pulse. Since the laser spot size is not infinitely small, the electrons are generated at different radial positions at the cathode. Assume that the initial longitudinal bunch width of such an ultra-short electron bunch is infinitely small, all the electrons have the same initial phase ϕ_0 , and the longitudinal distribution function of the electrons can be expressed as $n_i(\phi) = \delta(\phi - \phi_0)$ at the cathode. The particle dynamics in the photoinjecor is simulated by the PARMELA code. Figure 1 shows how the ultra-short electron pulse is distorted by the radial-dependent RF fields for (a) ϕ_0 = 210 and (b) ϕ_0 = 250°. Δϕ in the figure

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denotes the phase of an electron with respect to that of the reference particle at r =0. In PARMELA simulation, the delta-like electron pulse at the cathode is modelled as an infinitely thin particle layer with a Gaussian distribution of 10000 charged particles in the r direction (RMS radius σ_r = 0.5 mm) . To simplify, the result in Fig. 1 does not include the space charge effects. During the acceleration process, the radial non-uniformity of the RF fields causes the longitudinal phase spread and radial position spread of the electron bunch. This spread transforms the electron distribution in the radius-phase plane from a straight line to a curve, as shown by the plots in the first two rows of Fig. 1. The 3rd row shows a linear relationship between the particle's initial radial position r_i and final radial position r_f with a distribution slope $M = dr_f/dr_i > 1$ due to particle spreading. The on-axis electrons exit the accelerator earlier than the off-axis ones. The spread of the particles or effectively debunching of the particles is related to the initial phase ϕ_0 .

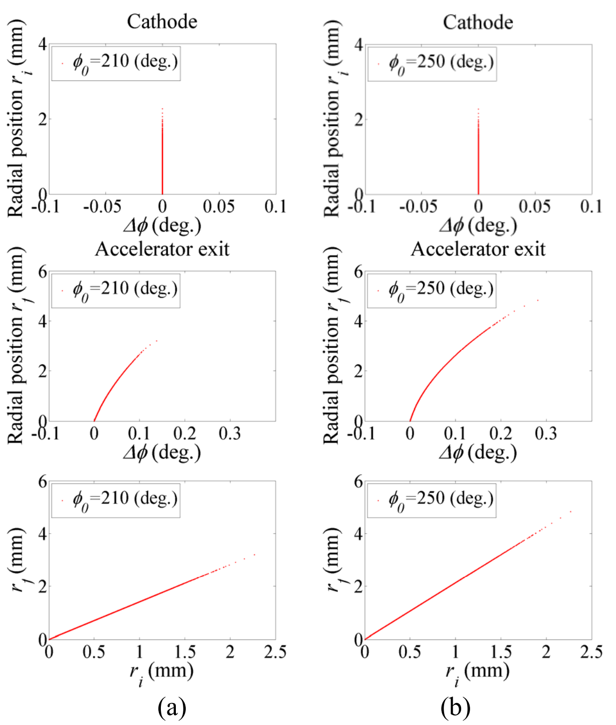


Figure 1: Evolution of an ultra-short electron bunch in the RF cavity. Every electron has initial phase (a) ϕ_0 = 210 and (b) ϕ_0 = 250° at the cathode.

Given the linear relationship between r_i and r_f found from the simulated acceleration process, the radial distribution of the electrons is expected to be uniformly broadened in r by M times. The radial probability density function of the electron bunch can be expressed as:

$$n_i(r) = \frac{\int_0^{2\pi} \exp(-r^2/2\sigma_r^2) r d\theta}{\int_0^{\infty}\int_0^{2\pi} \exp(-r^2/2\sigma_r^2) r d\theta dr} = \frac{r}{\sigma_r^2}\exp(-\frac{r^2}{2\sigma_r^2}). \tag{4}$$

At the exit of the accelerator, the RMS bunch radius has been broadened by M times, and the radial probability density function becomes:

$$n_f(r) = \frac{r}{M^2\sigma_r^2}\exp(-\frac{r^2}{2M^2\sigma_r^2}). \tag{5}$$

The longitudinal distribution of the particles can be derived from the radial probability density function with a known relationship between r and $\Delta\phi$. Figure 2 shows the evolution of the radial and longitudinal electron distributions before and after acceleration for an initial phase of 210°. With Fig. 2, the longitudinal and radial spreads of the electron pulse become evident after acceleration.

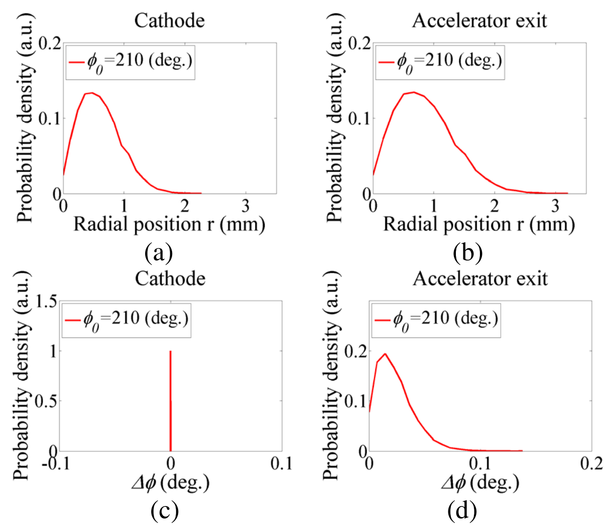


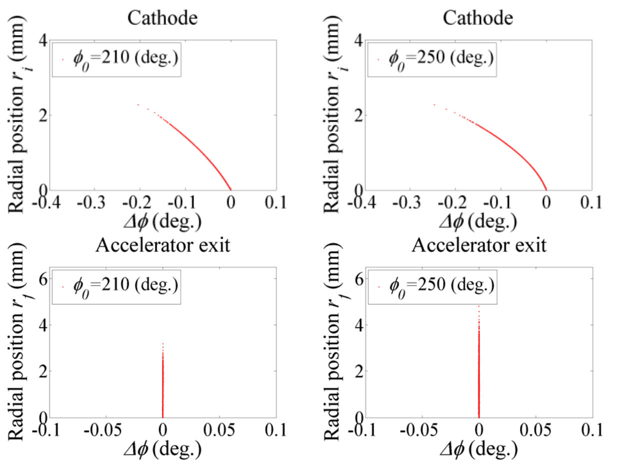
Figure 2: Radial electron distribution at (a) the cathode and (b) the accelerator exit. Longitudinal electron distribution at (c) the cathode and (d) the accelerator exit. The initial phase ϕ_0 is 210° for the plots.

GENERATION OF BUNCHED ULTRA-SHORT ELECTRON PULSE

Single Electron Bunch

The previous simulation results on Figs. 1-2 indicate that the non-uniformity of the RF fields broadens the electron bunch during the acceleration process. To generate an electron bunch with no phase spread at the exit of the accelerator, we propose a control on the emission phase for the electron over r to compensate the longitudinal electron debunching due to the radial non-uniformity of the fields in the accelerator. For example, the curved phase distribution of the electrons at the accelerator exit, as shown in 2nd row of Fig. 1, could be compensated by using a properly counter-curved phase distribution of electrons at the cathode, as shown by the plots in the 1st row of Fig. 3. Indeed, with initial phases of 210 and 250° for the reference particle, the 2nd row of Fig. 3 shows that the results from our simulation, indicating the spread of the particle's longitudinal phase is fully compensated at the exit of the accelerator.

Generation of initially curved longitudinal phase distribution of electrons can be done by illuminating the photocathode with a temporally counter-curved laser pulse from the driven laser. The pulse front of an ultrafast laser can be transformed from a planar one to a curved one by using a series of optical lenses and deformable mirrors [4, 5].



(a) (b)

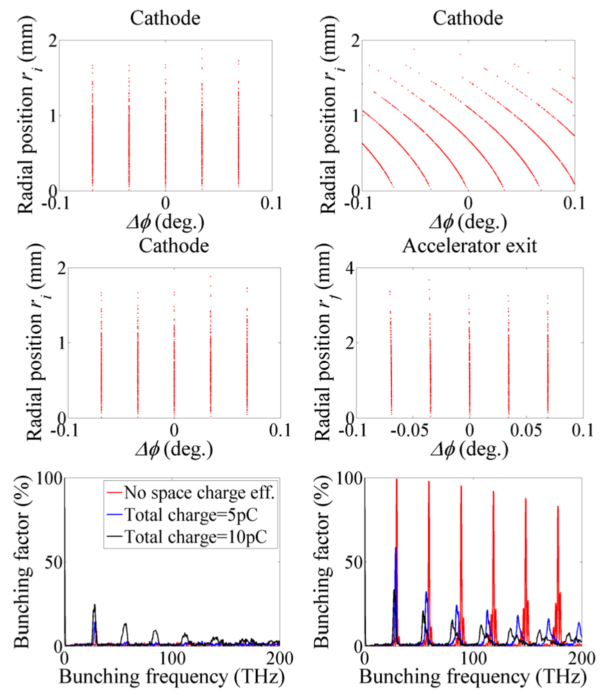
Figure 3: Evolution of an initial phase modulated electron bunch before and after the acceleration process of the RF cavity. The initial phase of the reference particle is ϕ_0 = (a) 210 and (b) 250°, respectively.

Electron-Pulse Train

As an electron-pulse train propagates in an RF accelerator, the radially non-uniform RF fields broaden the longitudinal bunch widths of the electron micro-bunches and reduce the bunching factor of the electron-pulse train, as shown in Fig. 4(a) without any initial longitudinal phase compensation at the cathode. As shown in Fig. 4(b), initial phase compensation at the cathode can overcome the debunching of individual electron bunches and retain an excellent bunching spectrum of an electron-pulse train at the accelerator exit. In this simulation, the longitudinal FWHM bunch width and bunching frequency of the electron-pulse train at the cathode are 1ps and 30 THz, respectively. With the aid of PARMELA simulation, we also estimated the bunching factor for the cases with space charge effects. The space charge force can degrade the bunching factor and is a subject of our future study. Nevertheless the initial phase compensation technique is useful to retain an ultra-short electron bunch during particle acceleration.

CONCLUSION

We have discussed the influence of the radially non-uniform RF fields to the bunch width of an accelerated electron bunch. With the non-uniform fields, it is hard to retain the width of an ultra-short electron pulse in the fs regime during acceleration. We proposed to modulate the initial phases of the electrons to compensate the phase spread of the electrons during the acceleration process. From the PARMELA simulation results, we confirm that the longitudinal bunch width of the accelerated electron bunch can be effectively retained with initial phase compensation when the space charge effects are not significant. With such a scheme, it is possible to produce a periodic electron-pulse train with a high bunching factor for a pulse rate at tens of THz.



(a) (b)

Figure 4: Evolutions and Bunching factor spectra of the electron-pulse train (a) without and (b) with the initial phase compensation. In the bunching factor spectra, the bunching factor of an electron macro-bunch with a total charge of 0/5/10 pC is represented by the red/ blue/ black line, respectively.

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