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GENERATION OF ATTOSECOND ELECTRON BUNCHES THROUGH TERAHERTZ REGULATION

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Abstract

Obtaining ultrashort electron bunches is the key to the studies of ultrafast science, yet second and higher order nonlinearities limits the bunch length to a few femtoseconds after compression. Traditional regulation methods using rf higher order harmonics have already optimized the bunch length to sub-fs scale, yet the energy loss and rf jitter are not negligible. In this paper we demonstrate the second order regulation with THz pulses through a dielectric-loaded waveguide. Simulations suggest that with higher order regulations, the MeV electron bunches with tens of fC charges can be compressed to sub-fs rms and the second order distortion can be compensated. The transverse beam size is also optimized to less than 20 um rms. This scheme is feasible for a wide range of electron charges. The relatively short bunch length is expected to find a better time resolution in UED, UEM and other ultrafast, time-resolved studies.

INTRODUCTION

Producing ultrafast electron beams with sub-femtosecond (fs) level bunch length is the core challenge in the electron-laser involved applications such as ultrafast electron diffraction (UED) [1] [2], laser-plasma driven acceleration [3], and X-ray free-electron laser [4]. One of the most commonly used compression techniques is velocity bunching using the RF compressor. It is the most compact scheme which is only employed with a standing wave cavity operating at the zero crossing so that the beam is compressed while the central energy remaining unchanged. Although the RF compressor successfully delivers the femtosecond electron bunch, the achievable beam length is limited by the rf-curvature.

Several approaches have been proposed to correct higher order effect including using additional higher order harmonics [5] and utilizing accelerating and bunching procedure [6]. However, These approaches come at the cost of reducing the energy of the electrons by several hundred keV, and introducing additional phase jitter between the RF fields. In this work, we present THz regulation scheme. Our compensation scheme uses a central frequency of 0.46 THz. With a higher frequency, the field strength needed for the compensation process is reduced, bringing a negligible energy reduction of only 0.5 keV for 10 fC bunch. Because the THz pulse is generated from the laser system, the THz field technically does not introduce additional phase jitter.

PRINCIPLE

In this paper, we identify a regime to regulate and further compress a relativistic electron beam by using the longitudinal electric-field-components of a single-cycle THz pulse through a dielectric-loaded waveguide. The schematic layout is shown in Fig. 1.

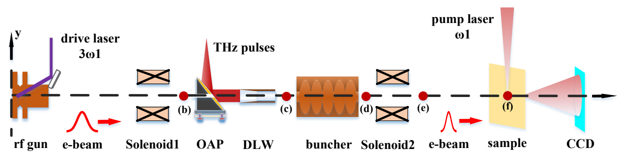

Figure 1: The schematic layout of the beamline.

The basic outline of the beam consists of a radio-frequency (rf) photoemission source (rf gun) consisting of a 1.6-cell, 2.856 –GHz standing-wave (SW) resonant cavity operating at the TM_{010} mode. The rf gun is followed by a solenoidal lens to control beam size. The electron bunches are produced by ultraviolet light pulses which have a tunable FWHM length from a few hundred fs to a few ps. The electron bunches reach an energy of 3.3 MeV downstream of the rf gun and are then injected into a dielectric-loaded waveguide (DLW) made of a quartz capillary, in which the electron bunches interact with single-cycle THz pulses (focused by a OAP mirror) operating at TM_{01} mode. The thickness of the quartz layer is carefully optimized so that the phase velocity of THz pulses matches with the velocity of the electrons. The THz phase velocity and the the electric field seen by the electrons are shown in Fig. 2. After being regulated in the DLW, the bunches are injected into a buncher consisting of a 5-cell SW resonant rf cavity operating at the TM_{010} mode at zero-crossing phase. The shortest bunch length is obtained on the sample after a free drift downstream of the buncher.

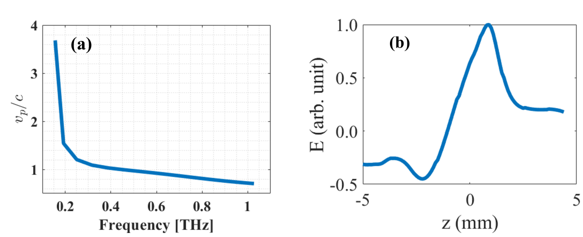

Figure 2: (a) Phase velocity inside the DLW and (b) the electric field seen by the electrons in the structure.

The electric field in a standing wave rf-gun along the axis can be assumed to be a simple cosine function [7]:

$$E_z = E_0 \cos\left(k_0 z + \phi_0\right) \tag{1}$$

Where k_0 is the wave number of the electric field and E_0 is the electric field intensity. For a 2.856 –GHz rf gun, k_0 = 59.8. Expanding equation (1) to the second order, we have

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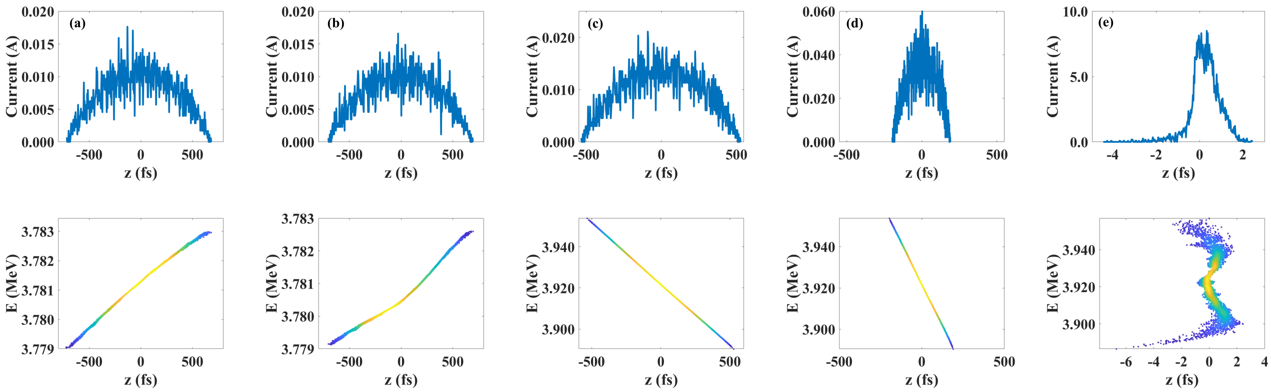

Figure 3: The evolution of current distribution and longitudinal phase space along the beamline. The five sets of images from left to right correspond to the current distribution and longitudinal phase space at points (b) before the DLW, (c) right after the DLW, (d) after the buncher, (e) after the second solenoid, and (f) at the sample in Fig. 1.

the transfer matrix of the rf gun:

$$R_G = \begin{vmatrix} 1 & 0 \\ -\frac{2\phi_0 k_0}{\cos\phi_0} & 1 \end{vmatrix}, \quad T_{655} = -\frac{k_0^2}{2} \tag{2}$$

Without higher order regulations, the final bunch length will be strongly related to the square of the initial bunch length for any compression schemes with only one compression component, such as buncher. In our compression schemes with THz regulation, the final longitudinal position z_f compared with the initial longitudinal position z_i for an individual electron in the bunch is:

$$\begin{aligned} z_f = &\left(1 - k\frac{L_B}{\beta^2\gamma^2}\right) z_0 + \frac{L_B}{2\beta^2\gamma^2}\left(\frac{k_H^2}{n^2} - k_0^2\right) z_0^2 \\ &+ \frac{L_B}{\beta^2\gamma^2}\delta_0 + O(\delta_0^2) + O(\delta_o z_o) \end{aligned} \tag{3}$$

Where k_B is the wave number of the buncher, V_B is the equivalent voltage of the buncher, L_B is the drift length between the buncher and the sample and $k = \frac{eV_B k_B}{E_0}$. k_H is the wave number of the THz central frequency and n is the proportion of the buncher and THz field strength. $O\left(\delta_0^2\right)$ and $O\left(\delta_o z_o\right)$ are induced by the non-linear compression process. By choosing proper L_B and k, the first item on the right can be set to 0; by choosing proper THz field strength, the second item on the right can be set to 0.

Figure 3 shows the evolution of current density and longitudinal phase space along the beamline. As shown in Fig. 3 (a), due to the space-charge effect, an initial 0.2-ps electron beam is quickly broadened to more than 0.3 ps rms. Then, the electron beam experiences the electron-magnetic field of the THz at the central frequency of 0.46 THz and the second order curvature is compensated, as shown in Fig. 3 (b). The beam then goes through the rf buncher and gains a negative energy chirp, as in 3 (c). Finally at the sample position, the bunch length is minimized, as in 3 (f).

SIMULATION

In this section, we demonstrate the proposed scheme by using a three-dimensional relativistic particle-tracing simulation with the ASTRA code [8] and CST microwave studio (MWS) [9]. The space-charge effect is included in both simulation softwares and 5000 macroparticles are used in the simulations. The main parameters are summarized in Table 1. All the parameters are optimized with multi-objective optimization using genetic algorithms (MOGA).

Table 1: Main Simulation Parameters

Parameters	Values
Gun field strength E_0	70 MV/m
Gun frequency	2.856 GHz
Gun phase ϕ_0	199.04°
Initial rms bunch size	11.9 µm rms
Initial rms bunch length	0.2 ps rms
Buncher field strength E_k	30 MV/m
Buncher phase ϕ_B	214.36°
THz maximum field strength	0.18 MV/m
Solenoid 1 field	0.141 T
Solenoid 2 field	0.1 T

In this optimized case, the electron energy is 3.3 MeV, and the bunch charge is 10 fC. In our simulations, the transverse profile of the bunch is also considered, since the transverse size of the bunch also affects the diffraction quality. Simulation results show that by choosing moderate solenoid fields, the minimum bunch length and bunch size can be simultaneously obtained at the sample. Fig. 4 shows the evolution of both transverse and longitudinal size of the beam. The final bunch length is 679 as rms, and the achievable beam size is 16 um rms. The transverse beam size is little effected by the THz pulse.

As shown in Eq.(1) and Eq.(2), the rf field of the gun induces a positive second order energy chirp T_{566} while the THz pulse induces a negative one. Fig. 5(a) shows the reduced curvature of the longitudinal phase space and Fig. 5(b) shows the energy spread at the sample with and without THz regulation. The bunch length after THz regulation is 5 times shorter compared to when the THz pulse is off.

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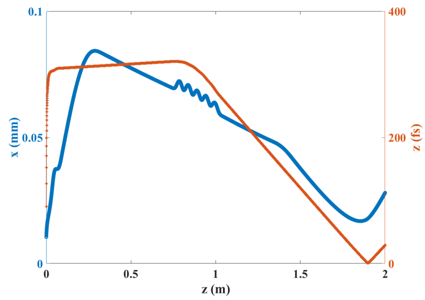

Figure 4: The longitudinal and transverse profile of the beam.

The energy spread slightly reduces from 0.584% to 0.571% during the compensation procedure, as the second order energy chirp is cancelled.

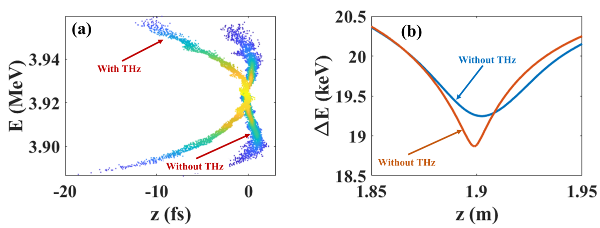

Figure 5: (a) The reduced curvature of the longitudinal phase space and (b) the energy spread at the sample with and without THz regulation.

With a second order regulation, the final achievable bunch length is mainly limited by space charge forces. Fig. 6 shows the longitudinal phase space with (color line) and without (red line) space charge force. The scattering particles at tail are contributed from the transverse space charge. In a TM_{010} mode rf structure, the particles with larger radius go through weaker electric field strength, which leads to a larger energy spread and longitudinal position. With a reduced bunch charge, the final bunch length can be further reduced. In our study, we also simulated the 0.1 fC case where the final bunch length can be optimized to 43 as rms. With such low space charge, the initial bunch size expansion at the cathod is reduced, leading to a shorter bunch length before the DLW and the buncher, reducing the effect of the third and higher order distortion induced by the THz pulse.

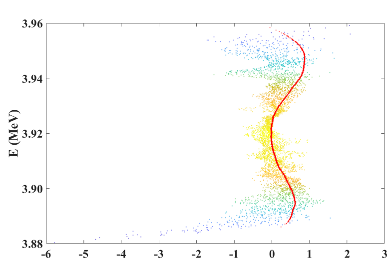

Figure 6: The longitudinal phase space at the sample with (color line) and withou space charge force (red line).

CONCLUSIONS

In conclusion, we demonstrate a scheme to reduce the pulse duration of a relativistic electron beam through buncher compression and THz regulation. This scheme is also capable of slightly reducing the energy spread and do not introduce additional time of flight jitter. Simulation results show that a 10-fC electron beam with an energy of 3.3 MeV and a pulse duration of 0.2 ps rms can be compressed to sub-fs at the sample position, while the transverse beam size is less than 20 um rms. This scheme can be extended to devices with charges being tens of fC and lower, such as UED, UEM and other alternative approaches. The scheme proposed in this work is, of course, not the only solution of further compressing the electron bunch length. Our results clearly show, however, significant enhancements can be made by regulating the longitudinal phase space profile using approaches that are practically feasible.

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