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THE PRELIMINARY STUDY OF A PRE-BUNCHED TERAHERTZ FREE ELECTRON LASER BY A VELOCITY BUNCHING SCHEME*

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Abstract

Terahertz (THz) radiation has broad applications in biological sciences, materials imaging and radar communications and so on. High-power, frequency tunable THz radiation sources are desired. An electron beam, generated in a photoinjector and bunched at THz frequency, can excite a coherent THz radiation in an undulator. The radiation power mainly depends on the particle number and the bunching factor of the electron beam, which is limited by the space charge effect among the microbunches and the total rf phase width the macrobunch occupied. Previously we have designed a pre-bunched THz free electron laser (FEL) with the radiation frequency covering 0.5-5 THz. While the radiation intensity for the lower frequency (below 1 THz) is not very high because of the large energy spread and the low bunching factor. We will report a THz FEL by a velocity bunching scheme, which could realize more highly bunched beam especially in the low THz frequency region. The physical design of the electron source is described in detail.

INTRODUCTION

The undulator-based terahertz (THz) source is a promising way to generate an intense narrow-band THz radiation with a broad frequency tuning range. For instance, a single-pass free electron laser (FEL) driven by a THz-pulse-train photoinjector, in which the electron beam is pre-bunched before entering the undulator and will excite coherent emission during the whole radiation process. The fundamental radiation frequency can be easily tuned by varing the time interval between the electron microbunches (laser micropulses). With the harmonic generation technique, the radiation could be further extended to higher frequency.

Previously, we have introduced a pre-bunched THz FEL by a linear accelerator which is composed of a photocathode rf gun and a short travelling wave (TW) tube [1]. The electron source can launch 16 microbunches with 15 pC charge for each bunch. This project is designed to have a tunable frequency range of 0.5-5 THz. One of the issues is their limited bunching factor at the frequency below 1 THz, since the large pulse width of the whole electron beam. The bunching factor is critical to determine the total radiation power, which will be discussed later. The most straight forward method to achieve a higher bunching factor at a shorter macropulse width is to reduce the microbunch number and increase its charge at the same time.

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BUNCH TRAIN GENERATION BASED ON VELOCITY BUNCHING

It is possible to produce electron pulse trains with several hundreds pC charge within the same accelerating bucket [2]. When each pulse is linearly chirped in energy, it can be longitudinally compressed either by a velocity bunching (VB) scheme, or by a magnetic compression scheme [3, 4]. In the VB procedure, the electron beam performs a rectilinear motion, which is free from the emittance degradation in a magenetic compressor. Moreover, the VB scheme is associated with the emittance compensation by focusing solenoids surrounding the accelerating section and as well as an energy increase. In short, the VB technique may be more suitable to maintain a high-brightness electron pulse train in the low-energy situation. In this section, we investigate the possible VB scheme for the pre-bunched THz FEL.

The scheme is illustrated in Fig. 1, which utilizes a typical setup for an S-band photoinjector. A 51-cell TW accelerator (TWA) is placed about 0.7 meters after a 1.6-cell BNL-type photocathode gun. A femtosecond laser followed by a proper optical system provides the required laser pulse train on the cathode. The TW tube operates at a brake-applied VB mode [5] which is also known as the over-compression regime. The whole compression is served by the TW tube together with a downstream drift segment. Three solenoids and four quadrupoles are used to focus the beam into the undulator. Three solenoids are 0.2 m, 0.5 m and 0.5 m long, respectively. And the quadrupoles are 0.05 m long with a maximum strength of 30 m^{-2}. A short undulator is located approximately 4.5 meters downstream of the TW tube. It should be indicate that the parameter setup is not the optimization result, but just a typical example instead. The designed parameters of this instance are shown in Table 1.

Table 1: Main Parameters of the Beam Line

Parameter	Value
Gradient of the rf gun	115 MV/m
Phase of the rf gun	20°
Gradient of the TWA	~ 12 MV/m
Phase of the TWA	~ -150°
Solenoid strength	~ 0.2 T (in the gun)
	0.03~0.07 T (in the TWA)
Quadrupole strength	~ 30 m^{-2}
Undulator length	0.432 m for 8 periods
Drift segment length downstream the TWA	4.5 m

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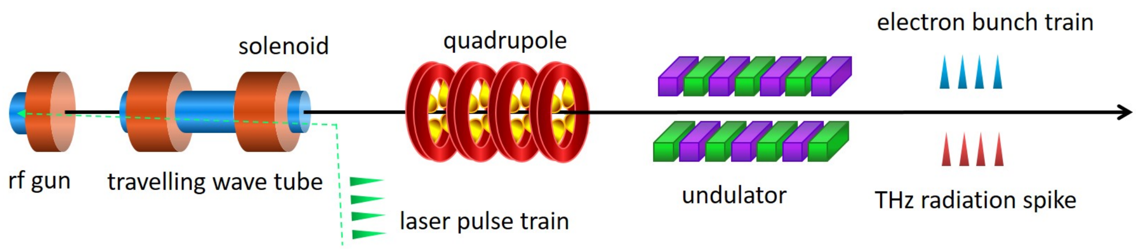

Figure 1: A schematic layout of the pre-bunched THz FEL based on velocity bunching.

A laser pulse train with four Gaussian longitudinal profiles that are 0.1 ps rms long separated by about 7 ps with 2 mm transverse spot size. The extracted charge for each pulse is 200 pC. To avoid a strong destructive force from the space charge, the time interval between the initial pulses is relatively long. The bunch charge and time interval can be adjusted to fine tune the radiation pulse structure.

The rf gun is set to 115 MV/m and a 20° off-crest phase to trade off between a good space charge control and a proper energy chirp. An electron pulse train with an average energy of above 5 MeV is obtained in the gun and then injected into the TW tube at a deep deceleration phase ($\ll$ -100 degrees). A strong over-compression regime occurs, the beam energy largely declines and then climbs up along the TW tube (dash line in Fig. 2). The beam length goes through a plunge to a minimal value then a steep rise and finally a gradual decrease which continues in the drift segment (solid line in Fig. 2).

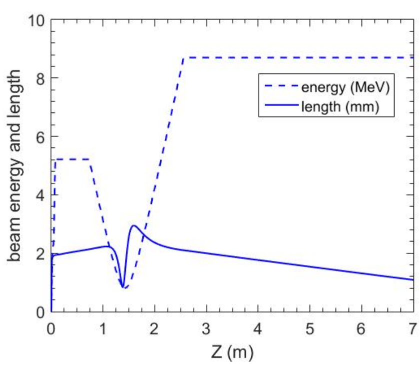

Figure 2: The evolution of the kinatic energy (dash line) and the rms beam length (solid line).

The longitudinal phase space configurations at different location are compared in Fig. 3, as computed by ASTRA code. Each micropulse is labled with a serial number based on the initial sequence. The corresponding rotation in the longitudinal phase space of the bunch train is clearly visible. The four pulses are rotated clockwise, overlapped in an instant and then flipped over and separated again, which happens in a short section of the TW tube (a distance of about 0.4 m as shown in (c-e) of Fig. 3). A persistent and gradual beam compression occurs after rollover and lasts until the end of the drift segment. At last, the bunch train is shrunk in each micropulse width and shortened in the separation time. The micropulses in average are about 0.15 ps rms long separated by 3.2 ps with 470 µm of horizontal spot size. A horizontal emittance is about 12 mm mrad which is less important in THz FEL.

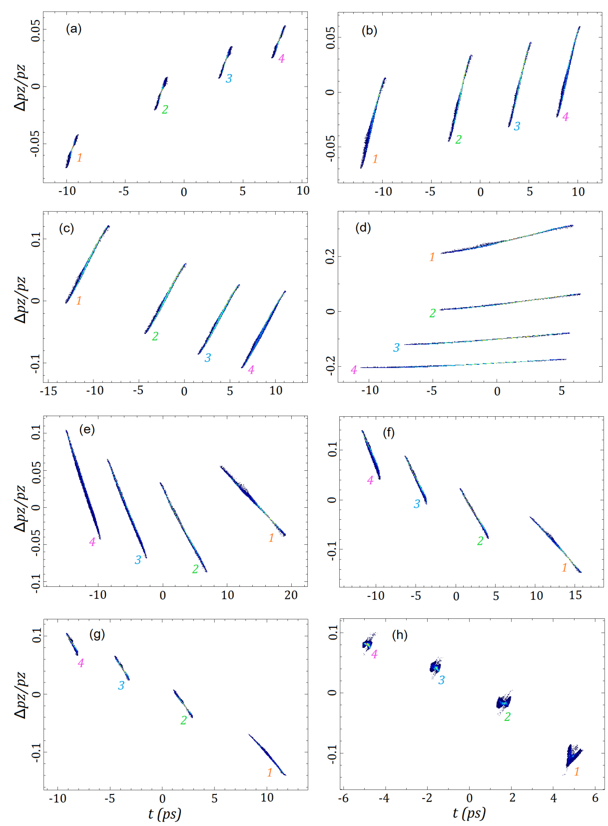

Figure 3: Longitudinal phase space of 4 micropulses. The corresponding locations are gun exit (a), TWA entrance (b), 0.5 m from TWA entrance (c), 0.7 m from TWA entrance (d), 0.9 m from TWA entrance (e), 1.1 m from TWA entrance (f), TWA exit (g), end of drift (h). Each micropulse is labled with a serial number based on the initial sequence.

It is known that a more highly bunched electron beam could achieve a more intense narrow-band THz radiation in the undulator. The bunching factor b describes the longitudinal density distribution in the electron beam. The bunching factor at a certain frequency ω can be expressed as

$$b(\omega) = \frac{1}{n}\left|\frac{\sin \pi n \omega \Delta t}{\sin \pi \omega \Delta t}\right| e^{(-(2\pi\omega\sigma_t)^2/2)}. \qquad (1)$$

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Assumed the electron bunch train is consist of n Gaussian microbunches with rms pulse width of σ_t, spacing by Δt temporal interval. One can find that each micropulse in the bunch train has a narrow width and a quasiequal spacing time, which contributes to a high bunching factor as given in the blue line of Fig. 4. Bunching factor in the previous scheme is also plotted in black line for comparison. In the first five harmonics of the VB scheme, the bunching factor is maintained above 0.4 with a quite narrow bandwidth. It is worth pointing out the initial separation time between each micropulse may be different to provide a uniform space inside the compressed bunch train, which is beneficial to obtain a high bunching factor.

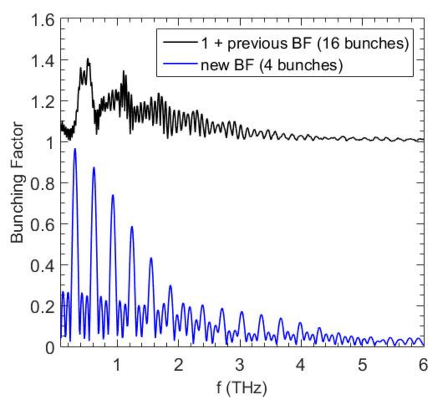

Figure 4: The bunching factor comparison before (black line) and after (blue line) improvement. In previous scheme 16 microbunches with 15 pC charge in each, while 4 microbunches with 200 pC charge in each is assumed in the VB scheme. The black line is entirely raised by 1 to make a legible comparison.

Therefore, it is demonstrated by simulations that electron bunch train with a short micropulse width and a large bunch charge can be generated in a photoinjector, and a good time structure of the beam may be preserved by the VB technique in a deep over-compression regime. Via an optimized compression scheme, a relatively uniform bunch train can be generated, which should have great potential for application in FELs, advanced particle accelerations and THz radiation sources [6].

UNDULATOR RADIATION

After a proper manipulation in the photoinjector, the electron beam passes through a short undulator to generate the coherent radiation. The output wavelength of the undulator radiation is determined by a resonance condition as $\lambda = 0.5\lambda_u(1+K^2)/\gamma^2$, where γ is the relativistic factor, λ_u and K are the period and the strength parameter of the undulator, respectively. For a certain frequency $\omega = 2\pi c/\lambda$, the total radiation power P can be expressed by [7]

$$\frac{dP}{d\omega} = \frac{dP_0}{d\omega} N_e [1 + (N_e - 1) b^2(\omega)]. \tag{2}$$

N is the total electron number, $dP_0/d\omega$ is the radiation power from a single electron which is considered as incoherent radiation power. It is indicated that the electron beam could be bunched at the fundamental frequency ($\omega = 2\pi/\Delta t$) and the high harmonics ($\omega = 2\pi m/\Delta t$, m=2,3...). Thus, a highly bunched electron beam could significantly enhance the total radiation power.

A planar undulator with 8 periods and a period length of 54 mm is preliminarily designed, in which the gap can be tuned from 16 to 48 mm based on different harmonics. At the funamental frequency, the undulator with a strength of K=4.33 can output an FEL pulse with a peak power of 0.46 MW. The time structure of the output FEL pulses at the undulator exit for resonating at 0.31 THz is simulated by GENESIS, as shown in Fig. 5. The full length of the radiation pulse is about 35 ps. The other four harmonics of the FEL pulses also have radiation powers at MW level.

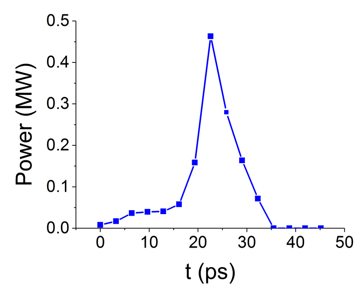

Figure 5: The time structure of the output FEL pulse at the undulator exit for resonating at 0.31 THz.

CONCLUSION

The strong overcompression regime of the velocity bunching scheme is greatly beneficial for bunch train compression due to its relatively large acceptance of longitudinal phase space and its uniformity of compression. The phase space of microbunches are reversed in the TW tube and maintained a linear chirp in energy. A considerable high bunching factor can be achieved especially in the low THz frequency region. With charges of several hundred pC, and a good tunability in time and energy space, the electron bunch train should have great potential for application as FELs and terahertz radiation sources.

REFERENCES

[1] R. Huang, *et al.*, Particles 1, 267 (2018). doi:10.3390/particles1010021

[2] M. Boscolo, *et al.*, *Nucl. Instrum. Methods Phys. Res.*, Sect. A 593, 106 (2008). doi:10.1016/j.nima.2008.04.069

[3] M. Boscolo *et al.*, "Laser Comb: Simulations of Pre-modulated E- Beams at the Photocathode of a High Brightness RF Photoinjector", in *Proc. 10th European Particle Accelerator Conf. (EPAC'06)*, Edinburgh, UK, Jun. 2006, paper MOPCH025.

[4] M. Ferrario, *et al.*, *Nucl. Instrum. Methods Phys. Res.*, Sect. A 829, 17 (2016). doi:10.1016/j.nima.2016.01.061

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP063

[5] R. Huang, *et al.*, *Nucl. Instrum. Methods Phys. Res.*, Sect. A 866, 65 (2017). doi:10.1016/j.nima.2017.05.022

[6] D. Wang, *et al.*, *Phys. Rev. Accel. Beams* 21, 024403 (2018). doi:10.1103/PhysRevAccelBeams.21.024403

[7] H. Li, *et al.*, *J. of IRMM and THz Waves* 37: 649 (2016). doi:10.1007/s10762-016-0258-9