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ROOM-TEMPERATURE BURST-MODE GHz AND THz PULSE-TRAIN PHOTOINJECTOR

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Abstract

In this paper, we report our study on a burst-mode GHz/THz pulse train photoinjector operating at room temperature. For the GHz operation mode, we illuminate the photocathode by a self-developed driver laser to generate tens of electron pulses at 2.856 GHz in an adjustable 5-10 ns temporal envelope repeating at 100 MHz. For the THz operation mode, we propose the use of a spatially modulated driver laser at the photocathode to generate an electron-pulse train with a bunching frequency in the THz-PHz range.

INTRODUCTION

A photoinjector usually generates an electron pulse with few ps pulse duration repeating at 10-100 Hz. The low-pulse rate usually limits the data rate in applications. Although high-repetition-rate operation is possible from a superconducting accelerator [1], the high cost and complexity of a superconducting system prevent it from being widely used.

The electron bunch structure from a photoinjector mimics that of the driver laser at the photocathode. We propose in this paper generation of a burst-mode GHz/THz electron-pulse train [2] from a photoinjector operating at room temperature by using a novel driver laser system rather than a superconducting accelerator. The idea is to tailor design the temporal and spatial profile of the driver to induce structured electron emission from the photocathode and accelerate the electron to obtain ultrafast temporal modulation on the current of the electron beam.

GIGAHERTZ OPERATION MODE

A typical photoinjector generates an electron bunch repeating at a 10~100-Hz rate. We propose a novel photoinjector that is driven by a laser amplifier system seeded with a GHz laser oscillator and switched by a partial-voltage Pockels cell [3].

Refer to Fig. 1 for the system layout. The main laser amplifier system consists of a 2.856-GHz Ti-Sapphire oscillator (GIGAJet30) and a regenerative laser amplifier pumped by a Q-switched Nd:YAG laser at 532 nm. The pulse rate of the laser oscillator is matched to the RF frequency of the accelerator. The first Pockels cell (PC1), functioning as a pulse picker, selects 10~ 20 laser pulses from the oscillator for amplification. Once the selected pulse train is injected into the regenerative amplifier cavity, the second Pockels cell (PC2) is turned on to its quarter-wave voltage to trap the pulse train for a duration long enough for laser amplification and then reduced to half of the quarter-wave voltage to partially and successively switch out the pulse train while the pulse train bounces back and forth in the amplifier cavity at ~100 MHz rate. During the switching-out time, the output coupling loss of the regenerative laser amplifier is compensated by the amplification gain, resulting in a bust-mode output pulses with constant amplitude. The repetition rate of the burst output is determined by the roundtrip time of the optical field in the regenerative cavity. In this design, the round-trip time is 10 ns and the burst-pulse repetition rate is 100 MHz.

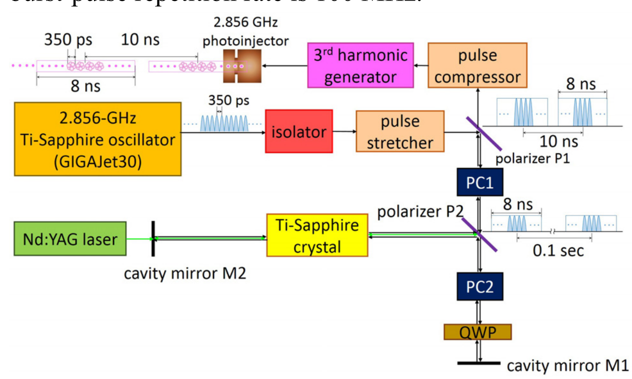

Figure 1: System layout of the proposed burst-mode 2.856 GHz photoinjector. QWP: quarter-wave plate, PC: Pockels cell.

A follow-up 3rd harmonic generator triples the frequency of the output laser to the UV wavelength to drive the photoinjector. With such a laser, the electron micro-pulse rate is effectively increased by ~100 million times from a conventional one. If such an injector is to be used to drive a free-electron laser (FEL) in the downstream, the average radiation power of the FEL can in principle increase by 100 million times, too.

TEMPORAL DISTORTION OF ELECTRON BUNCH DURING ACCELERATION

In a photoinjector, the electrons are accelerated by a standing wave in an RF cavity. Since the longitudinal acceleration field in the cavity is radially dependent [4], the transit time of an electron is dependent on its radial

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position in the accelerator. We have investigated the evolution of ultrafast electron bunches in an RF accelerator by PARMELA and found that the radially dependent acceleration field indeed distorts the electron bunch during acceleration [5]. In our simulation, we ignored the space charge effects and assumed the longitudinal bunch width is infinitely thin at the cathode. The simulation result is shown in Fig. 2(a- b), wherein the radial distribution of the particles r versus phase $\Delta\phi$ is changed from a thin disk to a curved bowl. The space charge effects can worsen the temporal distortion.

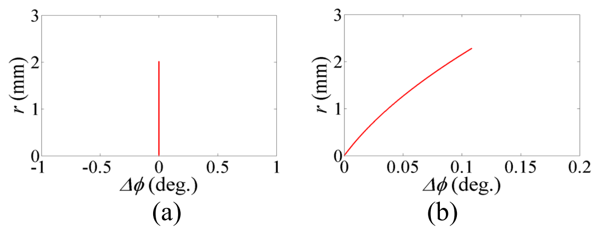

Figure 2: $r-\Delta\phi$ distributions of the particles in an accelerated electron bunch (a) at the cathode and (b) at the exit of a typical S-band photoinjector. Results obtained from simulation in PARMELA.

TERAHERTZ OPERATION MODE

The $r-\Delta\phi$ curvature in Fig. 2(b) shows a transverse-to-longitudinal relationship of particles in the accelerated electron bunch. With a given transverse-to-longitudinal relationship of particles, it is possible to modulate the transverse density of electron bunch at the cathode to yield an accelerated electron bunch with a modulated longitudinal density on the electron bunch at the accelerator exit. Figures 3(a-d) show the simulation results of generating a 200 THz electron-pulse train by using such a scheme. Specifically, to reduce the azimuthal bunch distortion resulting from the space charge force, we design a cylindrical bunch profile consisting of a set of coaxial rings at cathode. The distributions of electrons in the $x-y$ and the $r-\Delta\phi$ planes at the cathode are shown in Fig. 3(a) and (b), respectively. In this case, there are 9 rings at the cathode, and the radius of the outermost ring is 1 mm. After acceleration, the electrons at different radial positions are separated by the radially dependent field and distributed periodically along the longitudinal direction, as shown in Fig. 3(c). Figure 3(d) shows the bunching spectrum of such a ring-like electron-pulse train at the accelerator exit.

The ring-like distributed electron micro-bunches, or the concentric electron rings, are initially laid in the same plane at the cathode, as shown in Fig. 4(a). As the electron rings propagate in the photoinjector, the radially dependent acceleration field separates them gradually to form a longitudinal pulse train. The longitudinal separation between micro-bunches is determined by the radius of the electron ring in a radially dependent acceleration field. We propose two ways to generate concentric ring-like electron bunches at the cathode. One is to illuminate the cathode by the interference pattern of a laser transmitting a properly designed optical phase mask, as shown in Fig. 4(c). Another way is to fabricate a series of concentric metal rings on the cathode for generating ring-like electron micro-bunches with the same structure. Such a multi-ring-structured cathode can be manufactured by lithographic patterning.

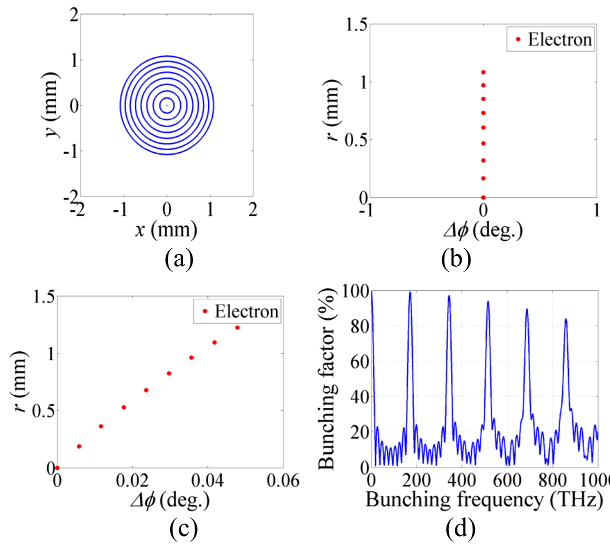

Figure 3: (a) Distribution of the electrons in the $x-y$ plane at the cathode. $r-\Delta\phi$ distributions of the electrons (b) at the cathode and (c) at the photoinjector exit. (d) Bunching factor spectrum of the electron-pulse train at the accelerator exit.

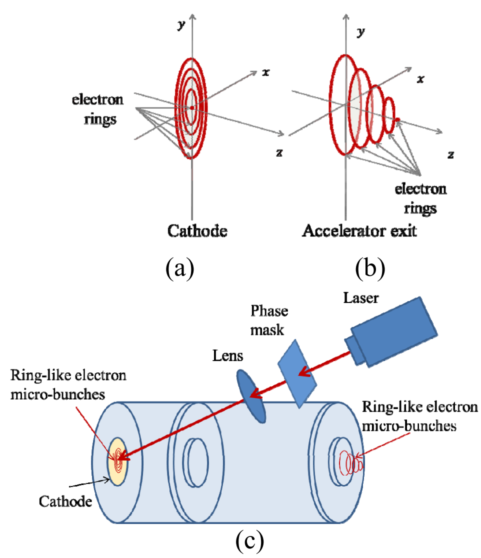

Figure 4: 3-D particle distributions of the concentric ring-like electron micro-bunches (a) at the cathode and (b) at the accelerator exit. (c) Illustration of a photoinjecor generating periodic ring bunches of electrons.

The longitudinal period of the generated ring-like electron-pulse train is influenced by the radial distances between electron rings at the cathode. Therefore, the bunching frequency of the electron-pulse train can be adjusted from THz to PHz by varying the density of electron rings at the cathode. We designed an electron

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macro-bunch which is composed of 107 electron rings with a 2 mm outermost ring radius at the cathode, and confirmed the feasibility of generating a 1 PHz electron-pulse train from the photoinjector with a 5-fs driver laser pulse in PARMELA simulation. The relevant parameters of the electron bunch, laser, and photoinjector used in the simulation are listed in Table 1. Fig. 5(a) shows the $x-y$ distribution of the electrons at the cathode. Fig. 5(b-e) show the $r-\Delta\phi$ distributions of electron macro-bunches with total charges of 0 (without space charge), 5, 10 and 20 pC at the accelerator exit. Figure 5(f) shows the bunching factor spectra of those ring-like electron-pulse trains at the accelerator exit. The simulation results indicate that the irregular distortion of the electron macro-bunch induced by space charge effects degrades the periodicity and decreases the bunching factor of the electron-pulse train, as shown in Fig. 5 (c-f). Nonetheless, a bunching factor of a few percents is retained at PHz frequencies for an accelerated electron charge of a few tens of pC.

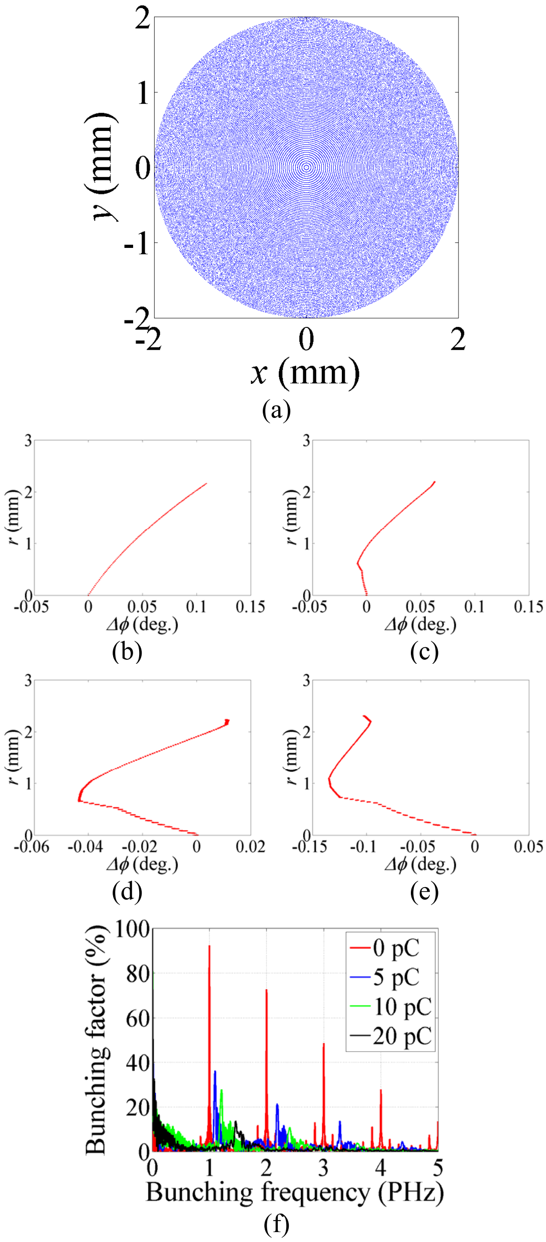

Figure 5: (a) Particle distribution of the electron bunch in the $x-y$ plane at the cathode. $r-\Delta\phi$ distributions of the electron-pulse trains with total charges of (b) 0, (c) 5, (d) 10 and (e) 20 pC at the accelerator exit. (f) Bunching factor spectra of the electron-pulse trains at the accelerator exit.

Table 1: Parameters of the Electron Macro-bunch, the Driver Laser, and the Photoinjector

Parameter	Value
Number of concentric rings	107
Radius of the outermost electron ring	2 mm
Dominant bunching frequency after acceleration	~1 PHz
rms temporal width of the driver laser	5 fs
Photoinjector	1.6 cell, S-band injector
Acceleration gradient	80 MV/m
Injection phase	180 (deg.)

CONCLUSION

In this paper, we present the concept of a room-temperature burst–mode GHz electron-pulse train photoinjector, and a THz-PHz ring-like electron-pulse train photoinjector. The former is useful to increase the data rate for applications using an accelerator, and the latter is useful to generate short-wavelength radiation from micro-, nano-bunched electrons. The GHz operation mode of the proposed photoinjector is driven by a laser system which is able to generate 2.856 GHz laser-pulse trains in a macro-envelope repeating at 100 MHz. For the THz-PHz operation mode, we have proposed a scheme to generate a ring-like electron beam from a photoinjector with ultrafast density modulation. Our PARMELA simulation confirms that such a scheme is useful to generate electron bunches with a high bunching amplitude in the THz and PHz frequency range.

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