ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA040

GENERATION AND RADIATION OF PHz RING-LIKE ELECTRON-PULSE TRAIN

Fu-Han Chao [2], Chia-Hsiang Chen [1,3], Yen-Chieh Huang [1,2], Ping J. Chou[2,3]

[1]Institute of Photonics Technologies/Department of Electrical Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan

[2]Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan

[3]National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan

Abstract

In this paper, we propose a multi-ring structured photocathode to emit a set of longitudinally packed electron rings with a bunching frequency of 1 PHz during particle acceleration. We also present in this paper the beam dynamics and radiation of the structured electron-pulse train.

INTRODUCTION

In an electron radiation device, the constructive interference of the radiation fields from a periodic electron-pulse train [1] can rapidly increase the spectral radiation power at the fundamental or harmonics of the pulse frequency.

To generate radiation in the EUV or X-ray spectrum, the required pulse frequency of the electron beam should be few tens or even few hundreds of PHz. The repetition rate of electron pulses generated from an ordinary RF photoinjector is usually at 10-100 Hz, which is far below that for efficient EUV or X-ray radiation.

In this paper, we propose a technique to generate a PHz ring-like electron-pulse train from an RF photoinjector with a structured photocathode. Our study using the ASTRA simulation code confirms that a PHz 3-D electron-pulse train can be generated from a photoinjector with an excellent bunching factor [1].

In this paper, we also study the interference of the radiation fields of a 3-D structured electron-pulse train.

BUNCH DISTORTION DURING ACCELERATION

Since the acceleration fields in the RF cavities of a photoinjector or a Linac are radially dependent [2], the transit time of an electron in an accelerator is dependent on its radial position in the accelerator. We have investigated the evolution of ultra-short electron bunches in an RF photoinjector by using the particle tracking codes, PARMELA and ASTRA, and found that the different transit time of the electrons can distort the electron bunch during acceleration [3]. When the space charge effects are insignificant, the transit time of the electron is only influenced by its radial position in the cavity. A delta-function like layer of electrons in the longitudinal direction allows us to exploit the impulse response of the accelerator system for bunch distortion during particle acceleration. Fig. 1(a) shows a delta-function input beam of an RF photoinjector and Fig. 1(b) shows the impulse response at the injector exit simulated by PARMELA, where r is the radial position and $\Delta\phi$ is the acceleration phase of the electron. To plot Fig. 1, the peak acceleration field in the 1.6 cell, S-band photoinjector is 80MeV/m.

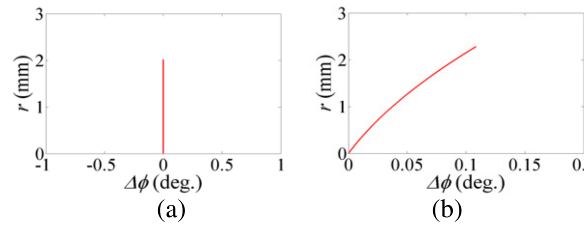

Figure 1: $r-\Delta\phi$ electron distributions of a delta-function like electron bunch (a) at the cathode and (b) at the exit of a typical S-band photoinjector. Results obtained from simulation in PARMELA.

GENERATION AND ACCELERATION OF PHz RING-LIKE ELECTRON-PULSE TRAIN

The impulse response of the accelerator reveals a transverse-to-longitudinal relation of the accelerated electron bunch. With a specified transverse-to-longitudinal relation of particles for an accelerator, it is possible to modulate the longitudinal density of an accelerated electron beam by properly modulating the transverse electron density at the cathode. To reduce the azimuthal bunch distortion resulting from the space charge force, we implement a cylindrically symmetric transverse density modulation for the electrons at cathode. A multi-ring structure can be used for generating such a symmetrically distributed electron bunch, as shown in Fig. 2(a). The transverse bunch profile consists of a set of concentric particle rings laid in the plane of the cathode, as shown in Fig. 2(b). After being accelerated by the radially dependent RF field, the electron rings with different radiuses are separated and become an electron-pulse train in the longitudinal direction, as shown in Fig. 2(c). The longitudinal distances between the accelerated electron rings are affected by the initial radius of and the total charge in each electron ring.

The flux of electrons emitted at the cathode depends on the driver laser power and the material of the cathode. Fabricating a series of concentric metal rings on a dielectric coated cathode or vice versa is a way to spatially modulate the electron density and generate ring-like electron micro-bunches. Such a multi-ring-structured cathode, as shown in Fig. 2(a), can be manufactured by electron beam lithographic patterning. It is possible to

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA040

pattern substrates of up to 200 mm diameter with a resolution as high as 10 nm. The rms radius of the driver laser is usually in the sub-mm region, which is much larger than the linewidth of the metal rings that can be fabricated by lithographic patterning.

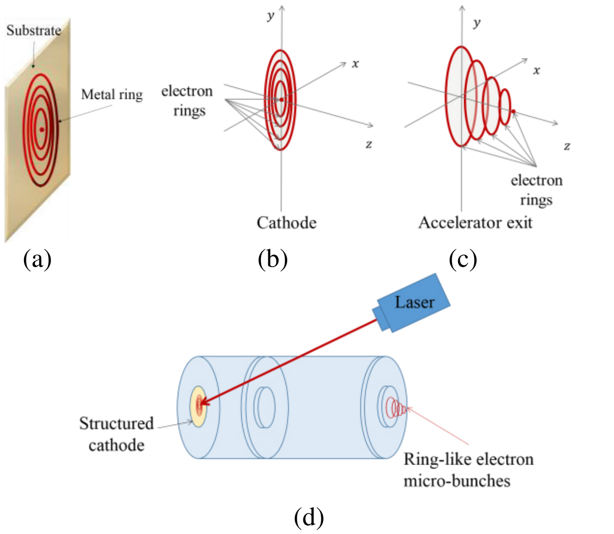

Figure 2: (a) A multi-ring structured photocathode.3-D particle distributions of the concentric ring-like electron micro-bunches (b) at the cathode and (c) at the accelerator exit. (d) Illustration of a photoinjector generating ring-like bunches.

Given an acceleration field, the longitudinal period of the generated ring-like electron-pulse train is determined by the radial distances between electron rings at the cathode. Therefore, the bunching frequency of the electron-pulse train can be adjusted by varying the radius of electron rings at the cathode. We designed an electron macro-bunch which is composed of 120 electron rings. Those rings are non-uniformly distributed in a 2-mm radius at the cathode. To simplify, we assumed in our simulation the linewidth of the rings to be infinitely small. We simulate the generation of a 400-MeV electron-pulse train from a 23 m-long accelerator system with the particle tracking code, ASTRA. The accelerator system consists of a photoinjector and 4 sections of Linac. The system layout is shown in Fig. 3. Each Linac is mounted in a solenoid coil, which helps compensate the emittance growth of the beam and confine the transverse dimension of the electron beam. The design parameters of the cathode, photoinjector, Linac, and coils are listed in Table 1. Fig. 4(a) shows the $x-y$ distribution of the electrons at the cathode. Fig. 4(b, c) show the $r-\Delta\phi$ distributions of the output electron macro-bunches with total charges of 0 (without space charge) and 1 pC at z = 23 m. The $x-y$ distribution of the electrons at the cathode is designed for optimizing the longitudinal periodicity of the ring-like electron-pulse train at z = 23 m. The longitudinal bunching factor spectra of those pulse trains are shown in Fig. 4(d). The simulation results indicate that the space charge effects can deteriorate the periodicity and bunching factor of the electron-pulse train, as shown in Fig. 4 (c, d). However, a ~20% bunching factor is retained at 1PHz for the 1-pC electron beam.

ANALYSIS OF THE RADIATION BEHAVIOR FOR THE RING-LIKE ELECTRON-PULSE TRAIN

In this section, we discuss the interference of the radiations from such an electron-pulse train under the assumption that each electron is an independent radiation emitter and there is no energy spread in the beam.

Consider a ring-like electron-pulse train with a continuously tempo-spatial distribution $f(r,t)$ at the output plane $z=0$, where r and t are the transverse coordinate and temporal variable for the electrons. Based on the Huygens-Fresnel principle [4], the interference of the radiation fields seen by an on-axis observer at $z=d$ can be expressed as:

$$E(k_r,\omega)=E_0\int\int_0^\infty f(r,t)\exp(j\omega t)\exp[j\frac{\omega}{c}\sqrt{r^2+d^2}]drdt \quad (1),$$

where E_0 is the field amplitude emitted by a single electron, ω is the angular frequency of the radiation, and c is the speed of light. In the far field $r^2<<d^2$, the superposition integral of the fields can be approximated as:

$$E(k_r,\omega)\simeq E_0\exp(j\frac{\omega}{c}d)\int\int_0^\infty f(r,t)\exp(j\omega t)\exp(j\frac{\omega}{2cd}r^2)drdt \quad (2),$$

It indicates that not only the longitudinal bunch distribution but also the transverse distribution has influences on the output radiation field. From Eq. (2), a 3-dimensional (3-D) bunching factor can be defined as:

$$M_b(k_r,\omega)=\int\int_0^\infty f(r,t)\exp(j\omega t+j\frac{\omega r^2}{2cd})drdt \quad (3),$$

If the electron beam is confined to a small aperture with a radius b and the Fresnel number [4] $N_F=\omega b^2/2\pi cd<<1$ is small enough, the radius dependence is dropped from the integration $\int_0^\infty f(r,t)\exp(j\frac{\omega}{2cd}r^2)dr\cong\int_0^\infty f(r,t)dr$. In such a limit, the 3-D bunch factor reduces to the usual 1-D factor:

$$M_b(\omega)\simeq\int_0^\infty f_l(t)\exp(j\omega t)dt=\mathbb{F}\{f_l(t)\} \quad (4),$$

where $\mathbb{F}\{f_l(t)\}$ represents the Fourier transform of $f_l(t)$. Therefore, as long as $N_F=\omega b^2/2\pi cd<<1$, the on-axis radiation field of a ring-like electron-pulse train is similar to that of a solid electron-pulse train. However, it is advantageous to use our scheme to generate very high frequency bunching in an electron ring-pulse train.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA040

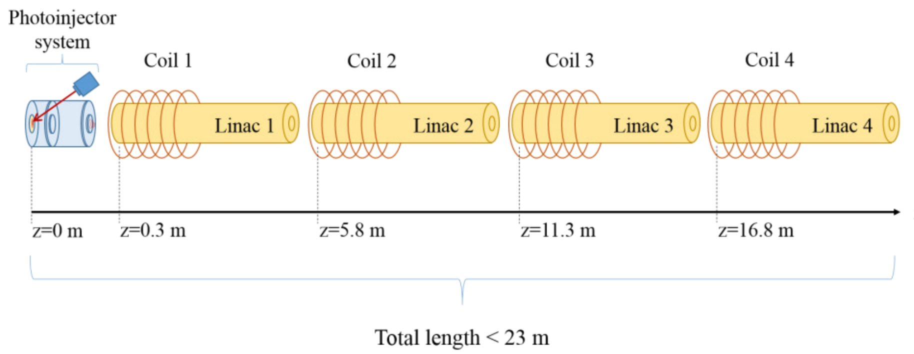

Figure 3: Layout of the accelerator system in our simulation.

Table 1: Parameters of the Electron Beam, Photoinjector, Linac, and the Coil

Parameter	Value
Photoinjector	2.856 GHz, 1.6 cell, standing wave
Linac 1-4	2.856 GHz, 147 cell, traveling wave
Acceleration gradient	80 MV/m (Photoinjector) 25 MV/m (Linac 1-4)
Peak B-field in the coil	7.5×10^{-2} T
Accelerator length	1.26×10^{-2} m (Photoinjector) 5.15 m (Linac 1-4)
Average energy at the output	~400 MeV
rms beam size of the output beam	~0.2 mm
Transverse emittance of the output beam	~0.15 $\pi mm\cdot mrad$.

CONCLUSION

In this paper, we have proposed to generate a ring-like electron-pulse train from a photoinjector with a very high pulse rate. We have also presented the simulation of such an accelerator system generating a 400-MeV beam with significant bunch factors in the PHz regimes. We concluded from our study that the transverse structure of the ring-like electron beam is not important to an on-axis application, as long as the outer radius of the ring-like beam b satisfies the condition $\omega b^2/2\pi cd \ll 1$, where d is the observation distance from the radiation device.

ACKNOWLEDGMENT

This work is supported by the Ministry of Science and Technology under Contract MOST 102-2112-M-007-002-MY3. F. H. Chao acknowledges a scholarship from National Synchrotron Radiation Research Center.

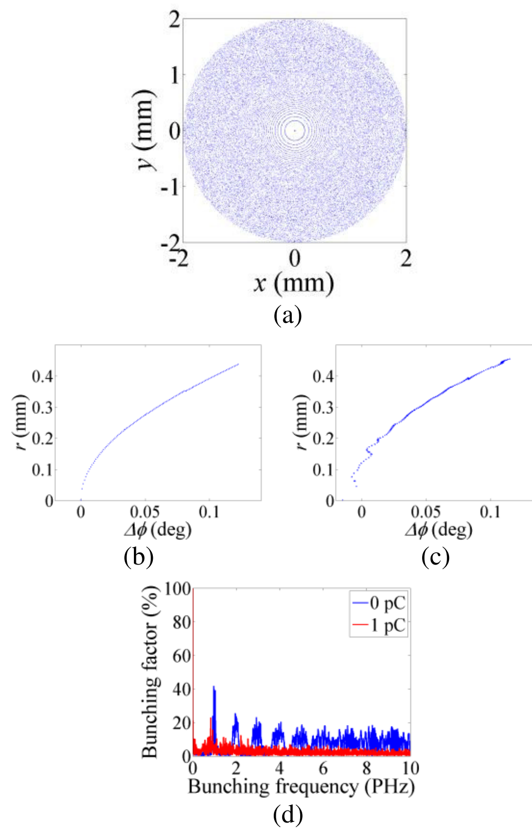

Figure 4: (a) Particle distribution of the electron bunch in the x-y plane at the cathode. (b) and (c) $r-\Delta\phi$ distribution of the electron-pulse trains with total charges of 0 and 1 pC, respectively, at z = 23 m. (d) Longitudinal bunching spectra of the electron-pulse trains for 0 and 1 pC charge at z = 23 m.

REFERENCES

[1] A. Gover, Phys. Rev. ST Accel. Beams 8 (2005), 030701.
[2] L. Serafini, Nucl. Instr. and Meth. Phys. Res. A 304, (1994) 40-51.
[3] F.H. Chao, C.H. Chen, Y.C. Huang, P.J. Chou, in Proceedings of International Particle Accelerator Conference, Shanghai, 2013, p.3109-3111.
[4] "Introduction to Fourier Optics", second edition, J.W. Goodman, p. 85.