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Test-accelerators as coherent terahertz source program (t-ACTS) at Tohoku University

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Abstract

The beam from thermionic RF gun is quite suitable for the bunch compression by means of velocity bunching. Since the thermionic gun is very stable in general, we anticipate very short electron pulses of the bunch length around 50 fs can be provided satisfactorily. The t-ACTS program has been developed toward updating terahertz science and technology in which intense coherent synchrotron radiation (CSR) from very short electron bunches will be employed. Careful numerical simulation showed possibility of the bunch length of less than 100 fs with a bunch charge of 20 pC, which will provide sufficiently large form factor for production of CSR in the THz wavelength region. The train of short bunches will be stored in an accumulator ring. The peak brilliance of THz radiation emitted from one bunch is expected to be 5×10^6 photons/mrad^2/0.1%bandwidth for each bending magnet of the ring.

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Keywords: coherent synchrotron radiation; terahertz; thermionic rf gun; velocity bunching; undulator; isochronous ring

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1. Introduction

At Electron Light Science Centre, Tohoku University, Sendai, a test accelerator complex towards high intensity THz radiation source, namely t-ACTS program schematically shown in Fig. 1, has been progressed. The injector of t-ACTS consists of a thermionic RF gun equipped with a single crystal LaB6

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cathode, an alpha magnet and a 3 m traveling-wave accelerating structure. Radiation sources are from an isochronous ring and an undulator employing coherent synchrotron radiation from very short electron pulses [1]. In addition, a novel oscillator free electron laser in THz region driven by the electron bunches shorter than the resonant wavelength (bunched-FEL) is also under consideration [2]. In order to achieve sufficient formfactor to radiate coherent THz wave, the bunch length less than 100 fs is required if the longitudinal profile is Gaussian or rectangular. Thus the key technology is how such extremely short electron pulse can be stably produced. In t-ACTS program, a method of velocity bunching proposed by Serafini and Ferrario is employed for bunch compression [3]. In the scheme of velocity bunching, the low energy beam injected into the traveling-wave accelerating structure slips backward relative to the RF phase and the longitudinal phase space is getting rotated and then accelerated. Since this method does not require other specific components for bunch compression at all, it is quite favorable for a compact injector system.

Coherent THz radiation of considerable average power is a possible tool for biophysics, molecular science and many other fields. In this article, we will discuss potential abilities of the short pulse electron linac together with the THz undulator and the compact accumulator ring by showing expected coherent radiation spectra.

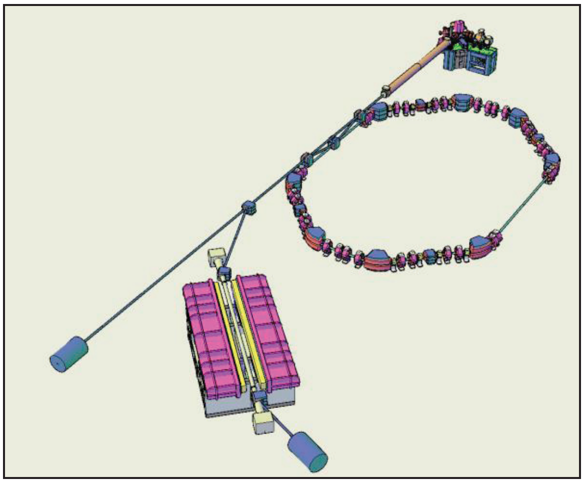

Fig. 1. Schematic apparatus of t-ACTS accelerator complex at Tohoku University. The system is consisted of a thermionic RF gun, a 3 m accelerating structure, an accumulator ring as a broad-band source and an undulator as a narrow-band source.

2. Outlook of t-ACTS

2.1. Injector linac

Thermionic cathode for the RF gun has been chosen in t-ACTS program because of stability, multi-bunch operation and cheaper cost. Since bunch charge in a micro-bunch will be small depending on acceptable energy spread, coherent enhancement of synchrotron radiation is not much stronger than photoinjectors. However, high repetition operation in multi-bunch mode will open another aspect of application experiments.

We have developed an RF gun consists of two independent cavities to manipulate the longitudinal beam phase space as shown in Fig. 2(a), named the ITC (Independently-Tunable Cells) RF gun [4]. A small size (ϕ = 1.85 mm) cathode of single crystal LaB_6 is employed, which can provide a current density of more than 50 A/cm^2. The ITC-RF gun has been designed so as to produce appropriate longitudinal particle distribution by changing the relative RF phase and field strengths, as shown in Fig. 2(b). One indicates the phase difference of $\pi + 0°$ (usual RF gun) leads to higher energy (red dots) at the gun exit. Meanwhile, linear-chirped particle distribution can be obtained by detuning the RF phase (blue dots). Those projections onto the time axis are plotted by solid lines.

Considerable amount of charge are populated at the head part of the beam, which means the space charge effect is so strong that the particle distribution in the longitudinal phase space is very likely to be distorted. The extracted beam from the ITC-RF gun goes into the alpha magnet that does not work as a bunch compressor. The longitudinal phase space of the beam is rotated in the alpha magnet to choose appropriate particle distribution for velocity bunching in a conventional $2/3\pi$ traveling-wave 3 m accelerating structure. Applying an S-band 50 MW klystron system for the driver linac, the maximum beam energy is expected to be more than 50 MeV with the crest acceleration. Detail of velocity bunching is described later.

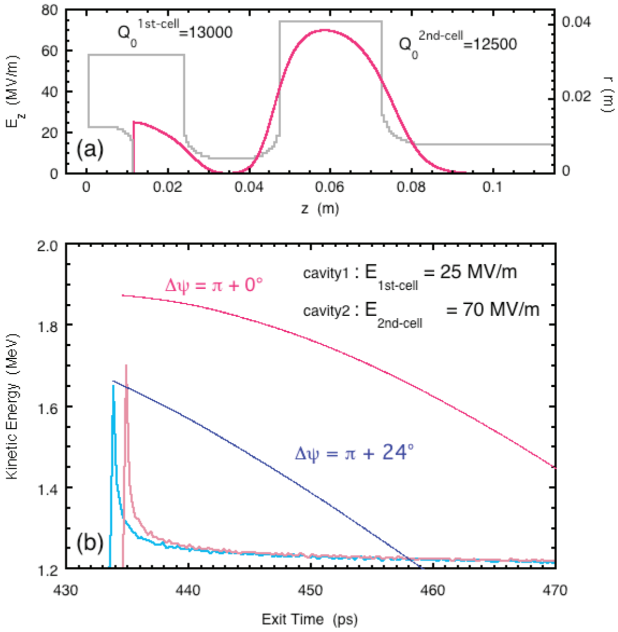

Fig. 2. (a) Cavity structure and field distribution in the ITC-RF gun; (b) Particle distribution in the longitudinal phase space simulated by an FDTD code [5].

2.2. Undulator; narrow-band THz source

A wide-gap Halbach type undulator will be used as narrow-band THz radiator. The THz undulator of which the period length is 0.1 m and the number of period is 25 has been already completed. Employing a peak magnetic field of 0.41 T at a gap of 54 mm with a 19 MeV electron beam, the resonant frequency of 1 THz is achieved [6]. To avoid diffraction loss for the longer wavelength, we have adapted very large magnetic gap to secure sufficient size of the beam pipe. Calculated spectrum from the undulator is shown in Fig. 3, and the bunch form factor is also plotted as a function of the wavelength in the figure. As one notices, only the fundamental radiation may be coherently enhanced.

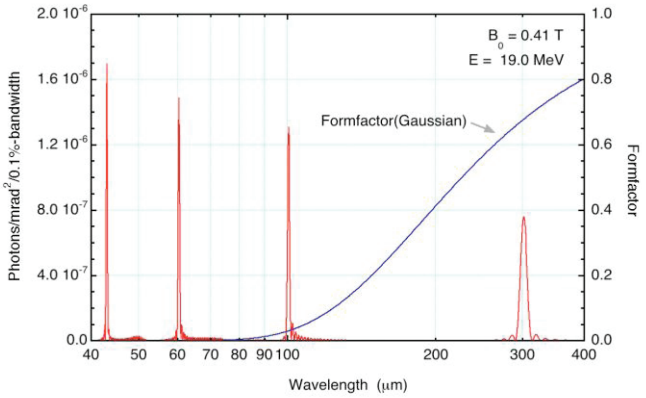

Fig. 3. Calculated spectrum for the resonant wavelength of 300 μm. The bunch form factor for 100 fs Gaussian pulse is also indicated.

Table 1. Basic parameters of THz undulator.

Undulator type	Halbach type (planar)
Magnet material	Nd-Fe-B (TiN coated)
Magnet block size	110×65×25 mm
Period length	0.1 m
Number of periods	25
Total length	2.532 m
Peak magnetic field	0.41 T (@54 mm gap)
Maximum K value	3.82 (@ 54 mm gap)

2.3. Isochronous ring; wide-band THz source

To extract maximum performance of such short pulse train in a macropulse, a compact accumulator ring is a candidate device for potential applications. Coherent THz radiation of considerable average power will be a possible tool for biophysics, molecular science and many other fields. In addition, short pulse x-ray via Thomson scattering induced by an external laser can be considered if a low beta colliding point is inserted into the lattice of the ring.

The accumulator ring consists with 4-fold Chasman-Green lattice, and the circumference is 16.795 m that is corresponding to harmonic numbers of 160 and 28 for the RF frequencies of 2856 MHz and 499.8 MHz, respectively. An inverted bend is inserted to the center of cell to achieve isochronous optics. Although the first order momentum compaction factor is corrected to be 0, the octupole magnet is considered to be indispensable for suppression of 3rd order term that is not negligible. In order to cancel out the path length deviation due to the betatron motion in the unit cell, the phase advance in the bending magnets is carefully tuned. Estimated bunch lengthening per unit cell is roughly less than 10 fs depending on the transverse emittance and the energy spread of the injected beam. Design work for optimization is still under way. The lattice functions of the isochronous accumulator ring are shown in Fig. 4.

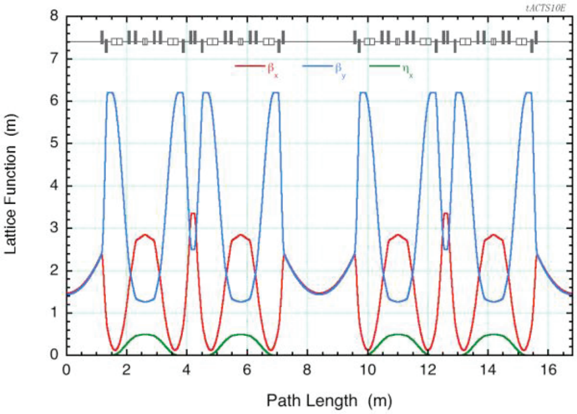

Fig. 4. The lattice functions of the isochronous ring. The betatron tune numbers for the horizontal and the vertical directions are 4.14 and 1.21, respectively.

The nominal energy of the ring is considered to be around 50 MeV, which is coming from a compromise between performance of the injector linac and beam lifetime in the ring. Coherent synchrotron radiation from a bending magnet is simulated for the particle number of 1000 and the bunch length of 100 fs employing Lienard-Wiechert potential [7]. In Fig. 5, the intensity of the radiation is plotted in linear scale. Note that the simulation is for only 1000 particles, so random interference can be seen in the incoherent part. We have expected the charge of 20 pC (1.25×10^8 electrons) in a micropulse, so the intensity of the coherent part should be multiplied by $\sim 10^{10}$.

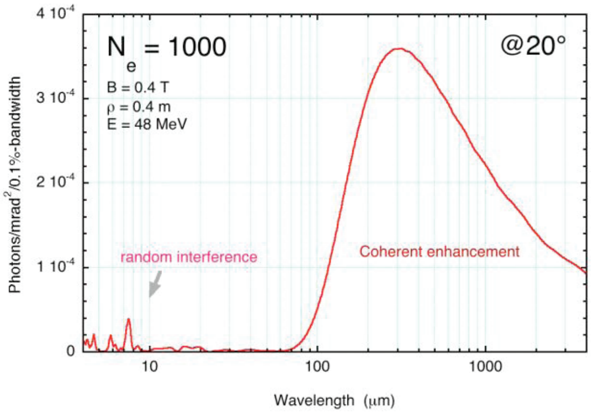

Fig. 5. Simulated spectrum of the synchrotron radiation from a bending magnet of the isochronous ring. An rms bunch length of 100 fs for the Gaussain pulse is used for the simulation.

3. Velocity Bunching in Accelerating Structure

A Hamiltonian, which describe longitudinal motion of the particle in a traveling-wave accelerating structure whose phase velocity is equal to the speed of light, can be written as

$$H = \left(\gamma - \sqrt{\gamma^2 - 1}\right)k - \alpha k \cos(\psi) , \tag{1}$$

where γ is Lorentz factor, k is an RF wave number ($= \omega / c$) and $\alpha \equiv eE_0 / mc^2 k$ is a dimensionless amplitude factor of the RF field [3]. Thus the Hamilton's equations are

$$\begin{aligned} \frac{d\psi}{dz} &= \frac{\partial H}{\partial \gamma} = k\left(1 - \frac{\gamma}{\sqrt{\gamma^2 - 1}}\right) \\ \frac{d\gamma}{dz} &= -\frac{\partial H}{\partial \psi} = -\alpha k \sin(\psi) \end{aligned} , \tag{2}$$

where the particle phase ψ and the energy γ are canonical conjugate variables. In the $\psi - \gamma$ phase space, the injected particle follows the equi-potential line derived from Eq. (1) as shown in Fig. 6. If the particle distribution can be manipulated for proper injection phase as shown in the figure, the bunch is compressed along with acceleration. Because the injection energy is not so high and the alpha magnet can tilt the beam in the longitudinal phase space, in this sense, the phase space distribution of the beam from the thermionic RF gun shown in Fig. 2 is suitable for velocity bunching. From deliberate theoretical and numerical simulation works, the bunch length of around 50 fs is possibly achieved by employing combined system of thermionic injector and velocity bunching [8].

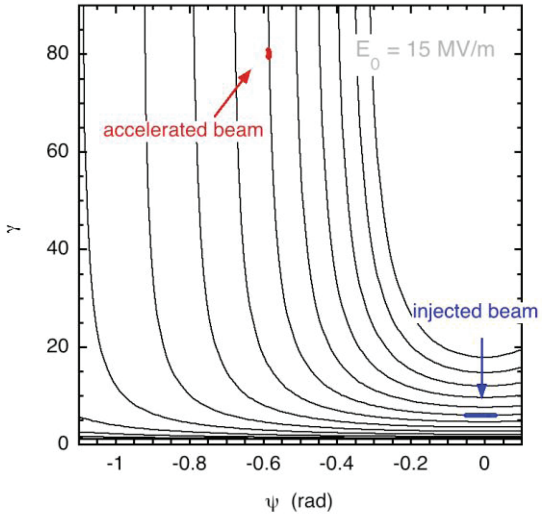

Fig. 6. Equi-potential line of the traveling-wave accelerating structure for the accelerating gradient of 15 MV/m. Blue area indicates the injected bunch at near the zero-cross phase and red area is the accelerated and compressed bunch after traveling for 3 m in the accelerating structure.

4. Conclusion and Prospect

We have developed novel accelerator-based THz radiation sources, t-ACTS. By employing velocity bunching, intense coherent radiation from the extremely short electron pulse will be stably obtained in a compact accelerator system. Currently the RF gun is under testing and the beam extraction will be started soon. Radiation source will be hopefully established in the near future.

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