EXPECTED PERFORMANCE CHARACTERISTIC OF ACCELERATOR-BASED THz SOURCE AT TOHOKU UNIVERSITY*

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Abstract

Sources of coherent synchrotron radiation (CSR) at THz wavelength region have been constructed at Electron Light Science Centre, Tohoku University, Sendai, Japan. Bunch train of extremely shorter electron pulse less than 100 fs will be provided by an injector linac employing thermionic rf gun. Bunch compression will be performed by means of velocity bunching in an accelerator structure. Radiation sources under development are a Halbach type planar undulator and an accumulator isochronous ring. The undulator employs large gap and long period length configuration to secure sufficient free space for propagation of radiation. A resonant frequency around 1 THz is achieved by employing a lower beam energy of ~ 20 MeV. Since spectrum of CSR is depending on longitudinal bunch form factor, we have calculated CSR spectra for various conditions of the beam to evaluate the performance of the THz sources. Numerical simulation with multi-particle system has been carried out to understand the radiation power and angular distribution as well. The beam transport in the undulator is crucial for quality of the radiation because the beam energy is very much low relative to strong focusing power.

INTRODUCTION

A test accelerator complex towards high intensity THz radiation source, namely t-ACTS program, has been developed, which is schematically shown in Fig. 1. The injector linac of t-ACTS consists of an rf gun equipped with a single crystal LaB_6 cathode, an alpha magnet and a 3 m S-band traveling-wave accelerating structure [1]. An rf power source can provide a peak power of 50 MW with 3 μs pulse, which is distributed to two cells of the rf gun and the accelerating structure. Expected maximum beam energy at crest acceleration is 50 MeV, while beam energy of 20 MeV will be achieved for velocity bunching scheme [2].

Thermionic cathode for the rf gun has been chosen in t-ACTS injector because of stability, multi-bunch operation and cheaper cost. Although the bunch charge in a microbunch may be small depending on acceptable energy spread, characteristics such as particle distribution in the longitudinal phase space and the relatively lower beam energy (~ 2 MeV) produced by the thermionic rf gun are preferable for velocity bunching. In velocity bunching scheme, after passing through the α-magnet, energy filtered electron bunch is injected onto near zero-cross phase of the rf field. Because of non-relativistic beam energy, the bunch slips in the rf field and its longitudinal phase space distribution is rotated at the early stage of traveling in the accelerating structure, then shortening of the bunch length and the acceleration are simultaneously performed. We have anticipated the micropulse train of sub-picosecond bunch length, such as 50 fs, is possibly produced in our injector system [3].

The CSR sources are an isochronous accumulator ring (IAR) and a wide gap undulator (WGU). 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 [4].

In general, photo cathode rf gun provides large amount of charge (~nC/bunch). In this sense coherent enhancement of synchrotron radiation is not much stronger than the beams from photoinjectors. However, high repetition beam in multibunch mode will open another aspect of application experiments.

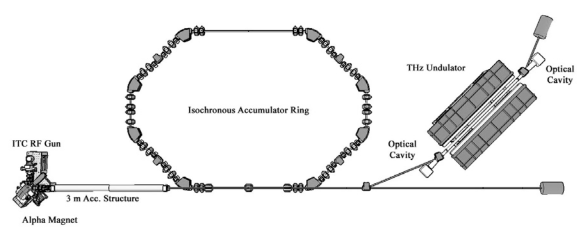

Figure 1: Schematic layout of the t-ACTS accelerator and radiation sources.

SOURCE APPARATUS AND RADIATION CHARACTERISTICS

Multi-particle Simulation for CSR

The intensity distribution of radiation from a multi-particle bunch with a number of electrons N can be calculated by a formula

$$\left.\frac{d^2 I}{d\omega d\Omega}\right|_{\text{multi-particle}} = \left\{N\left[1-f(\omega)\right]+N^2 f(\omega)\right\}\left.\frac{d^2 I}{d\omega d\Omega}\right|_{\text{single-particle}}, \quad (1)$$

where $f(\omega)$ is the bunch form factor. The intensity of the synchrotron radiation can be derived by integration of Lienard-Wiechert potential as

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$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c} \int_{-\infty}^{\infty} \frac{n \times \{(n-\beta)\times\dot{\beta}\}}{(1-\beta\cdot n)^2} e^{i\omega(t-n\cdot r(t)/c)} dt \cdot \qquad (2)$$

Here symbols e, c, β and n are a charge of the electron, the speed of light, a relative velocity of the electron and a unit vector in the direction to observation point from the particle position, respectively. In order to evaluate the CSR intensity, the form factor of the bunch has to be known. However if we can calculate the integration in Eq. (2) for multi-particle system, the radiation field is spontaneously enhanced according to the particle distribution. Certainly, in general, the number of electrons in a bunch is too many to calculate entirely. However performing multi-particle simulation by reducing the number of particles is significant to understand characteristics of CSR together with the beam dynamics in guide magnetic fields.

Isochronous Accumulator Ring, IAR

An accumulator ring with isochronous optics will provide THz-CSR from bending magnets for multi-user. The ring with no rf cavity stores the femtosecond bunches and storage them for a short time. Besides the storing time of the beam may depend on the vacuum and intra-beam scattering, a significant obstacle is higher order momentum compaction factors, particularly the second order one. Although the path length deviation brought by the betatron motion (in beam transport, that is R_{51}) is mostly cancelled out in a unit cell, the bunch shape is distorted by the third order momentum compaction factor in a couple of hundred turns, so that THz-CSR might be generated for a few tens μs. Major parameters of IAR at present are shown in Table 1, and the isochronous optics is still under investigation [5].

One of simulated CSR spectra from a bending magnet of IAR is shown in Fig. 2. A bunch contains 1000 electrons and the Gaussian bunch shape with σ = 100 fs is employed in the simulation. Since the number of electrons is not sufficient, random interference can be seen at the incoherent wavelength region. However THz-CSR is clearly arisen. We have expected the charge of 20 pC (1.25×10^8 electrons) in a micropulse from the t-ACTS

Table 1: Important Parameters of IAR

Nominal beam energy	E	54 MeV
Circumference	C	16.7951 m
Betatron tune	(ν_x, ν_y)	(4.14, 1.21)
Natural chromaticity	$(\xi_x, \xi_y)^{nat}$	(-5.47, -10.0)
Corrected chromaticity	$(\xi_x, \xi_y)^{cor}$	(-0.05, -0.05)
0^{th} momentum compaction	α_0	0.00000155
1^{st} momentum compaction	α_1	-0.00640
2^{nd} momentum compaction	α_2	2.03
Normal bending radius	ρ^n	0.4 m
Normal bending angle	θ^n	50º
Inverted bending radius	ρ^i	-0.8 m
Inverted bending angle	θ^i	10º

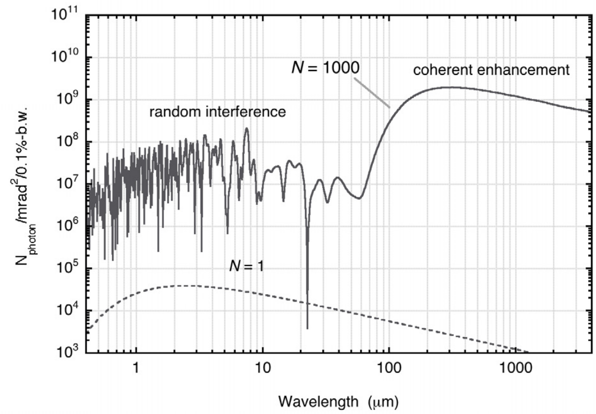

Figure 2: Calculated spectrum from a short bunch for a beam energy of 48 MeV. Number of electron in the bunch is 1000 and the bending radius of IAR dipole magnets is 0.4 m.

injector linac, so the intensity of the coherent part shall be multiplied by ~ 10^{10}. Accordingly the micropulse energy of ~ 10 mJ/mrad^2/0.1%-bandwidth at the 1 THz frequency region will be provided to users. Since the maximum repetition rate of the injector linac is 25 Hz (viz. normal conducting), the isochronous optics has to be improved to secure longer storage time for increase of the average THz-CSR power.

Wide Gap Undulator, WGU

A THz undulator has developed to supply narrowband CSR. Because we have considered FEL oscillation at longer wavelength region, a wide gap and long period length undulator has been chosen to avoid waveguide mode. Employing 19 MeV beam, a resonant frequency of 1 THz is achieved at the minimum gap. Since the height of accelerator beamline is as low as 0.7 m from the floor, the deflection plane was chosen to be vertical. Note the direction of the deflecting plane is defined to be x for the further discussion. Parameters of WGU are summarized in Table 2 [6].

In the planar undulator, averaged focusing power in the direction perpendicular to the deflecting plane is

Table 2: Parameters of WGU

Type		Halbach planar
Deflecting plane		vertical
Period length	λ_w	0.1 m
Number of periods	N_w	25
Total length	L_w	2.532 m
Minimum gap	g_{min}	0.054 m
Peak magnetic field @g_{min}	B_0	0.41 T
Deflection parameter @g_{min}	K	3.82
Magnet block size		110×65×25 mm^3
Magnet material		Nd-Fe-B

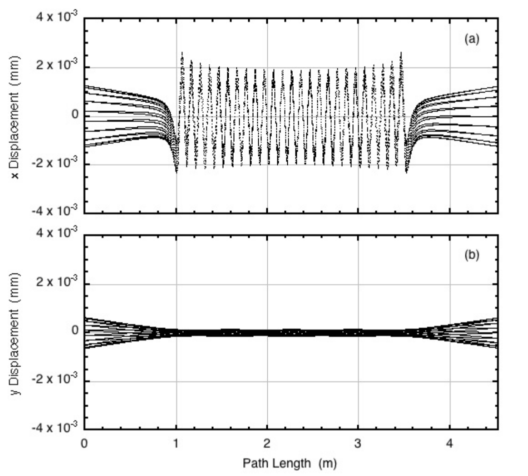

Figure 3: Particle trajectories in (a)x-plane and (b)y-plane with the matched condition of the beam optics. A tight focusing in the y-direction is required.

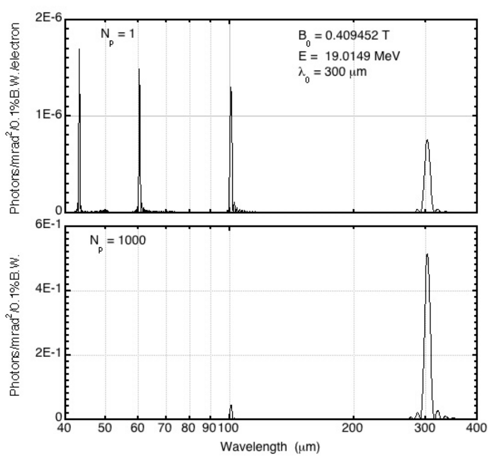

Figure 4: Calculated spectra of the radiation from WGU for single particle (upper) and mulit-particle (lower). A Gaussian bunch with σ = 100 fs is used in the simulation.

$$k_y = \frac{1}{2}\left(\frac{B_0}{B\rho}\right)^2 \ [\mathrm{m}^{-2}], \tag{3}$$

where $B\rho$ is the beam rigidity. For the 19 MeV beam, one obtains k_y = 20.9 m^{-2} at the minimum gap. If we assume a constant beta function in WGU, that is $2\pi/\sqrt{k_y} = 1.4$ m, so that the total phase advance of the beam would be ~ 4 π after passing through WGU. This value is considerably large, so the beam optics has to be matched with the strong focusing power for obtaining a smooth beam envelop in WGU. In addition, due to the large orbit displacement in the deflecting plane, there is some focusing power k_x. Performing calculations of the magnetic field and particle tracking, we found k_x = -0.84 m^{-2}. Using the transfer matrix of Twiss parameters and these focusing power per unit length, we have estimated the matching conditions in Twiss parameters at a position of 1 m this side of the undulator entrance. As one can see in Fig. 3, the beam envelope is mostly constant and well smoothed. The radiation spectrum from the single electrons is shown in Fig. 4(upper). Since a large value of the deflection parameter, the higher harmonics are intensely appeared. As described in the previous subsection, the CSR undulator radiation from the multi-particles system is also simulated, which is shown in Fig. 4(lower). Because the form factor of the 100 fs bunch arises around the wavelength of 100 μm, only the fundamental radiation is enhanced.

The radiation characteristics of THz-CSR from WGU are summarized in Table 3. Due to the slippage effect, the pulse duration is, of course, much longer than the electron bunch length.

Table 3: Characteristics of CSR around 1 THz

Micropulse duration	25 ps
Micropulse energy	0.15 μJ
Peak power	6 kW
Macropulse duration	2 μs
Macropulse energy	850 μJ
Macropulse power	430 W

The bunch charge of 20 pC is assumed.

PROSPECT

We have evaluated the radiation characteristics of THz CSR from IAR and WGU in the t-ACTS project. At the moment the bunch charge from the injector linac is presumed to be 20 pC, thus expected intensities of THz-CSR is apparently not much powerful comparing with that with photoinjectors. We have, however, anticipated increase of the bunch charge by a factor of 3, so the intensity will be increased by 10 times. The first THz-CSR production will be demonstrated in fiscal year 2012.

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