SUPER COHERENT THZ LIGHT SOURCE BASED ON AN ISOCHRONOUS RING WITH VERY SHORT ELECTRON BUNCHES*

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Abstract

A project to develop a coherent Teraherz (THz) light source has been progressed at Laboratory of Nuclear Science, Tohoku University. The coherent synchrotron light in the THz region is emitted from electron bunches with very short bunch less than 100 fs (rms) created by a thermionic RF gun and a sophisticated bunch compressor. The beam can circulate through the nearly complete isochronous ring for many turns, so that the average radiation power may be considerably enhanced. As an injector of this ring, we have developed an independently tunable cells (ITC) RF gun, which consists of two independent cavities to manipulate the longitudinal phase space. In order to generate short bunch with a significant bunch charge, a magnetic compressor is needed at downstream of ITC-RF gun. Two kinds of bunch compressor have been studied. This paper presents the isochronous THz ring design and describes ITC-RF gun, the magnetic bunch compressor and results of simulations. From simulation of the bunch compressor, we got a very short bunch length about 42 fs (rms).

INTRODUCTION

In these years, the coherent radiation in THz region has been observed in some 3rd generation light sources like BESSY-II [1]. However, it seems to be difficult on the storage ring to realize and/or maintain the short bunch with a significant beam current against bunch lengthening or other instabilities. On the other hand, when we focus on the condition of an isochronous beam transport, there is another possibility to generate the coherent radiation [2]. A very short electron bunch length around 100 fs is required to generate coherent THz radiation. To realize a coherent THz source based on the isochronous ring, total technologies of accelerators are required.

In this paper, a design study of an electron source and the bunch compressor for a novel coherent THz radiation source are described.

COHERENT THZ LIGHT SOURCE

Design of Isochronous Ring

The isochronous ring is the one of the candidates of the light source of coherent THz light [3]. Since this isochronous ring must keep a very short bunch length less than 100 fs (rms) from an injector in every place, it has been designed to have very small dispersion function. To keep bunch length for many turns at everywhere, the path difference for one turn should be much smaller than the bunch length. So that, the momentum spread of the injection beam must be order of 10^{-4} taking into account the momentum compaction factor which is designed as 0.0002. This ring has advantages; (1) multiple beam lines can be utilized, (2) a high average power of THz light can be generated since the electron beam can circulate ring for many turns. However, a betatron initial phase difference affects on the bunch lengthening larger than the effect of momentum compaction factor relatively. In order to reduce this bunch lengthening, an appropriate design of the phase advance in arcs is required [3]. We have designed the lattice of isochronous THz ring, then the effect of bunch lengthening in the bending arc has been calculated, and it is less than 40 fs which satisfies a condition to generate a coherent THz light. The major designed parameters of the isochronous ring are as follows. Tentative design parameters of this ring are shown in Table 1.

Table 1. Tentative design parameters of isochronous THz ring.

Circumference	C	45.691 m
Beam energy	E	200 MeV
Lattice type	-	Racetrack modified FODO
Bending radius	ρ	3 m (normal cell), 2 m (dispersion suppressor)
Momentum compaction factor	α	< 0.0002
Emittance of injection beam	ε_{rms}	5 π nmrad
Momentum spread of injection beam	$\Delta p/p$	2×10^{-4}

Coherent Synchrotron Radiation

The peak power of a coherent radiation from this ring has been calculated, and then it becomes about 100 kW with the bunch length of 100 fs (rms). This peak power of THz light is larger than other THz light sources (ex. FEL, other Lasers). This ring also has high performance in the average power of THz light. Radiation power of THz light sources is summarized in Table 2.

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Table 2. Radiation power from different THz light sources.

Source	Peak power (Micropulse length)	Average power
p-Ge Laser	1 W (10 ms)	100 mW
YAG + NOE	300 mW (4 ns)	60 nW
FEL	10 kW (1 ps)	10 mW
Isochronous THz ring	100 kW (250 fs)	350 mW

GENERATION OF VERY SHORT BUNCH

Design of a Thermionic RF Gun

As an injector of the isochronous ring, it is required to generate an electron beam with a very short bunch length less than 100 fs (rms) and with a very small normalized rms emittance less than 2 π mm mrad. To achieve high average power of coherent radiation, macropulse duration of the injector should be about 1.5 μs taking into account the circumference of the isochronous ring. In addition, the bunch charge should be as large as possible. To gather high bunch charge, the injector should have a large acceptance of momentum deviation. An acceptable momentum deviation is limited by acceptance of coherent THz ring. The coherent THz ring requires a momentum spread of the order of 10^{-4} for the injection beam. Because the beam is accelerated from 2 MeV to 200 MeV in the Linac, $\Delta p/p$ is limited to the order of 10^{-2} at the injector. To realize above parameters, a thermionic RF gun has been adopted for the injector. As a cathode material, a small single crystal of LaB_6 with a diameter 1.75 mm has been chosen. This cathode has a higher current density than conventional dispenser cathode. The normalized emittance can achieve a small value because of the small diameter. To reduce back-bombardment effect [4], this small diameter may be effective. In order to control a distribution of a longitudinal phase space at the exit of this RF gun, we employed independent two cells which don't couple with each other [5]. Parameters of ITC-RF gun are listed in Table 3.

Table 3. Design parameters of ITC-RF gun.

RF frequency	2,856 MHz (S-band)
Cathode material	LaB_6
Current density @ cathode	100 A/cm^2
Cathode diameter	1.75 mm
Number of cells	2
Feeding total power	～5 MW
E_{total} @ exit of gun	～2 MeV
Bunch length (rms)	～100 fs
Bunch charge	～several tens pC
$\varepsilon_{norm.\ rms}$	< 2 π mm mrad
$\Delta p/p$	< 2 %
Macropulse duration	1.5 μs

3D FDTD Simulation of ITC-RF Gun

In order to study the beam dynamics in ITC-RF gun and to design this geometry, we have used a 3D FDTD simulation code [6]. This code can include effects of the beam wakefield and of the space charge self-consistently. We have to design an appropriate distance between the cells and the strength of the accelerating field in each cell, because the longitudinal phase space strongly depends on these parameters. Since it is difficult for 3D FDTD code to calculate a precise geometry because of the mesh size, a 2D code: SUPERFISH [7] has been used to decide the precise geometry for manufacturing of ITC-RF gun. Because the RF coupling is a very small, accelerating fields are independent from each other. The prototype of ITC-RF gun is shown in Fig. 1.

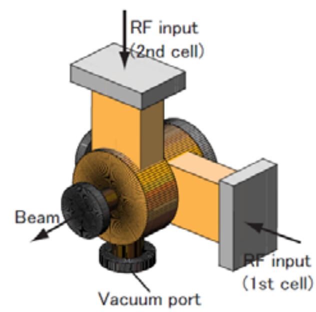

Figure 1. The prototype of ITC-RF gun. The RF input port is separated each other. This is now under manufacturing.

ITC-RF gun is designed to drive at π-mode basically. Peak accelerating fields of 1st cell E_1 [MV/m], 2nd cell E_2 [MV/m] and relative phase between cells Δθ are three degrees of freedom to control this gun. So as to compress the bunch length easier at the downstream of the gun, we have searched an optimum operating point of the gun to generate a beam with a linear dependence in the longitudinal phase space. At the optimization, the bunch charge from the gun should be as large as possible. The strength of E_1 was fixed around 25 MV/m in this gun, because the head of emitted electrons from a cathode must arrive at the middle point of between cells in time of a half RF cycle. With applying some suitable parameters (E_1, E_2) = (25, 50) MV/m and $\Delta p/p_{max}$ = 2 %, longitudinal and transverse phase spaces at exit of this gun are shown in Fig. 2 and Fig. 3 respectively.

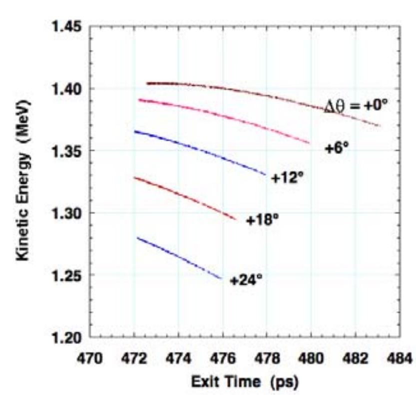

Figure 2. longitudinal phase space. Δθ is a variable in this simulation. (E_1, E_2) = (25, 50) MV/m.

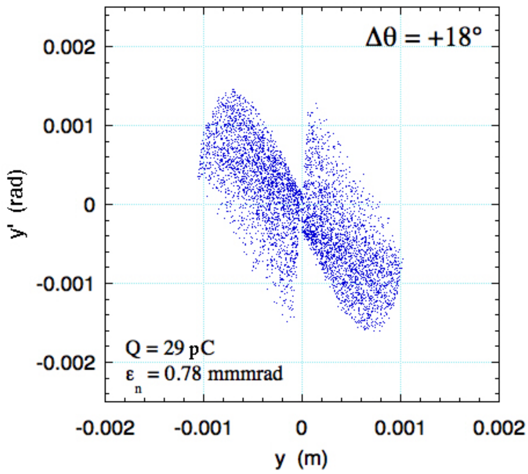

Figure 3. transverse phase space. (E_1, E_2) = (25, 50) MV/m, Δθ = +18 degree.

As shown in Fig. 2, a linearity of momentum distributions depends on the Δθ. From Fig. 3, the normalized rms emittance $\varepsilon_{norm.\ rms}$ = 0.78 π mm mrad satisfy the design value < 2 π mm mrad. Normalized rms emittances in other conditions also satisfy the design value. On the other hand, the bunch charge of this beam with momentum deviation $\Delta p/p$ = 2 % is about 30 pC which almost satisfy the design value. However the bunch lengths of these beams are far from the design value, so that the beams must be compressed at the downstream of the gun.

Magnetic Bunch Compressor

To compress the rms bunch length from several ps to less than 100 fs, a magnetic bunch compressor is needed. Magnetic bunch compression uses a difference of time of flight (TOF) for particles of different momenta p_0 and p_1 where these particles move from s_1 to s_2 along the beam axis. For these particles, the difference of TOF can be written as

$$\Delta t = t_1 - t_0 = \frac{L_1}{c\beta_1} - \frac{L_0}{c\beta_0} = \frac{L_1}{c\beta_0\beta_1}\left\{-L_0(\Delta\beta) + \beta_0(\Delta L)\right\} , \qquad (1)$$

where t is TOF from s_1 to s_2, L is a path length from s_1 to s_2, β is a relative velocity, index: 0, 1 represent particles with p_0 and p_1 respectively, $\Delta\beta = \beta_1 - \beta_0$ and $\Delta L = L_1 - L_0$. When we assume $p_0 < p_1$ and the longitudinal distribution in Fig. 2, a condition of the bunch compression leads $\Delta t > 0$. The first term of eq. (1) represents a difference of TOF caused by a difference of each particle velocity, and become negligible small when β goes to unity. The second term is caused by a difference of path lengths. In case of ITC-RF gun, the effect of the first term can not be negligible. When a total beam energy is 2 MeV, $s_2 - s_1 = 1$ m and $p_1/p_0 = 1.02$, the first term becomes about -5 ps. ΔL of the second term can be represented as

$$\Delta L = \Delta L_{\Delta p/p} + \Delta L_\beta = \left\{\int \frac{\eta(s)}{\rho(s)} ds\right\}\frac{\Delta p}{p} + \int \frac{x_\beta(s)}{\rho(s)} ds \quad . \qquad (2)$$

The first term of eq. (2) means a path difference produced by an energy dispersion at bending section, and this term can be used for bunch compression. The second term of eq. (2) represents a path difference which comes from a different value of initial phase of a betatron motion, and this term can be suppressed by reducing the beta function and designing appropriate phase advances along lattice.

We have considered two kinds of magnetic compressor. The first is an α-magnet [8], and the second is a triple-bend achromat (TBA) lattice. An advantage of α-magnet is that this system has a larger energy acceptance, and has a possibility to gather larger bunch charge for a large $\Delta p/p$. An advantage of TBA lattice is that this system has a possibility to manipulate the higher order term of $\Delta p/p$ by adjusting optics. Each magnetic bunch compressor can apply different slopes of $(\Delta p/p)/\Delta t$ in longitudinal phase space. In case of TBA lattice, this system can vary the R_{56} by changing a dispersion function of the 2nd benging magnet without changing its reference orbit. When the α-magnet changes the field strength, reference orbit in it is changed correspondingly. Each system can be an achromat for the beam energy. At manufacturing the magnet of each system, it is easier for TBA lattice than α-magnet to design magnets. In order to select the method of a suitable bunch compression, studies have been continued. In the following, basic studies are shown.

In order to estimate a bunch compression, particle distributions in Fig. 2 and Fig. 3 have been used for both methods. The operating conditions of the gun are (E_1, E_2) = (25, 50) MV/m and Δθ = +18 degree. In case of α-magnet method, a beam tracking simulation has been done. In case of TBA lattice method, a design of optics and tracking simulations have been done by using SAD [9]. Since the bending angle of dipole magnets of TBA lattice are the same angle 60 degree, TBA lattice is 180 degree bending transport system totally. In addition, TBA lattice has four families of quadrupole which are used for two purposes mainly. The dispersion function in the 2nd bending magnet is controlled by quadrupole magnets between bending magnets to change the R_{56}. The other quadrupole magnets are used for matching of horizontal and vertical Twiss parameters at exit and reducing the beta function in bending magnets. One example of the TBA optics is shown in Fig. 4.

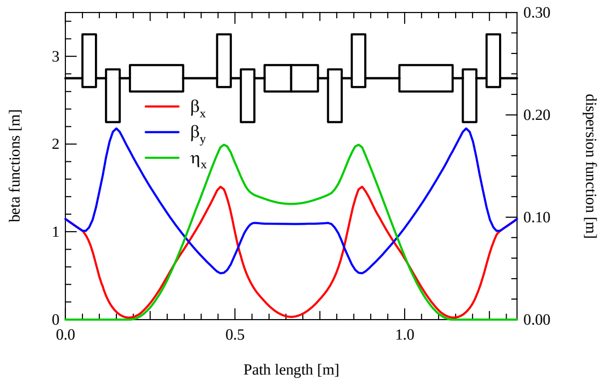

Figure 4. TBA optics. Left axis is for beta functions. Right axis is for dispersion function.

In case of an α-magnet, the first term of eq. (2) can be calculated by using following equation

$$\Delta L_{\Delta p/p} = \left\{ \int \frac{\eta(s)}{\rho(s)} ds \right\} \frac{\Delta p}{p}$$

$$= \frac{K_\alpha}{2} \sqrt{\frac{\beta\gamma}{g}} \frac{\Delta p}{p} \quad , \qquad (3)$$

where K_α = 191.655 Gauss$^{1/2}$cm$^{1/2}$ and g is the field gradient of α-magnet in Gauss/cm. The path length in α-magnet can be represented as $K_\alpha \sqrt{\beta\gamma / g}$. In order to estimate a difference of TOF in an α-magnet, the first term of eq. (1) and eq. (3) should be calculated, and then we can find the field gradient of an α-magnet for a suitable bunch compression. After optimizations of each bunch compressor, the longitudinal phase spaces and the particle time distributions are shown in Fig. 5.

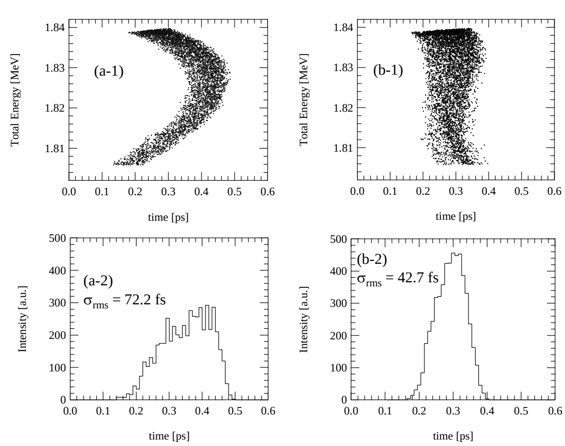

Figure 5. longitudinal phase space distributions and time distributions after bunch compression. (a-1), (a-2) α-magnet case, (b-1), (b-2) TBA lattice case.

As shown in Fig. 5, the compressed bunch lengths are 72.2 fs (rms) for the α-magnet system and 42.7 (rms) fs for the TBA lattice respectively. Both bunch compressors can achieve less than 100 (rms). TBA lattice can achieve shorter bunch length in this case, but more studies are needed for selecting a more suitable method.

SUMMARY

We have proposed the coherent THz light source by employing an isochronous THz ring and an injector which can generate a very short electron beam. From numerical calculations and simulations, the radiation power from the isochronous THz ring may achieve higher than other light sources of THz region. In order to generate the required short bunch beam for this ring, we have designed the injector which consists of ITC-RF gun and the magnetic bunch compressor. ITC-RF gun can generate a small normalized rms emittance value which satisfies the design parameter. For generating very short bunch, a magnetic compressor is needed at the downstream of ITC-RF gun. We have studied two kinds of bunch compressor: α-magnet transport and TBA lattice transport. Both of bunch compressors can achieve design bunch length less than 100 fs (rms). At a glance, TBA lattice seems to be better than α-magnet. However, we have continued to studied more detail about them including effect of the higher order momentum dependences and betatron initial phase difference.

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