DEVELOPMENT OF ACCELERATOR-BASED THz SOURCES AT TOHOKU UNIVERSITY*

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Abstract

Terahertz radiation sources based on electron accelerators have been developed at Laboratory of Nuclear Science, Tohoku University, Sendai. As a broadband source, coherent synchrotron radiation from very short electron pulses is going to be developed by employing a novel isochronous ring toward multi-user facility. On the other hand, free electron lasers (FELs) are considered to be unique narrowband source. Two different types of FELs have been discussed, such as Smith-Purcell backward wave oscillator (BWO) using a very low emittance DC gun and novel pre-bunched FEL employing shorter electron bunches than FEL wavelength.

INTRODUCTION

Recent remarkable progress of Terahertz (THz) technology based on laser and semiconductor physics produces new aspect of potential applications in many scientific fields [1]. Significant feature of accelerator based THz sources is of course high power in both regimes of peak and average. Since emission of coherent synchrotron radiation requires very short electron bunch length, radiation pulse is inevitably short that is another specific feature of the accelerator based THz source. Though combination of femto-second laser and photoconductive switch can produce ultra short THz pulse, the power is not high as well.

It is obvious the accelerator-based source is one of requisites for further development of THz science. We report on recent progress of radiation sources at Tohoku University.

TERAHERTZ COHERENT SYNCHROTRON RADIATION FROM EXTREMELY SHORT BUNCHES

Coherent radiation produced with the very short electron bunches is widely examined as typical accelerator-based THz source. Particularly coherent transition radiation is considered to be a promising tool for very high intensity source [2]. However this beam-destructive source is not suitable for establishment of multi-user hub facility of THz science. Coherent synchrotron radiation (CSR) has been also investigated as broadband source. Average power of ~ 50 W was demonstrated at a superconducting accelerator, ERL-FEL, Jefferson laboratory [3]. The corresponding micropulse peak power was observed ~ 1.4 MW. If the radiation is confined within an area of 1 mm^2, the electric field reaches 0.23 MV/cm, which may open a door for strong-field science in long wavelength region.

Assuming Gaussian distribution for the bunch shape, sufficient bunch form factor for producing CSR around 1 THz requires the bunch length of 100 fs (σ). Spectrum of form factor is very sensitive to the bunch shape, so that bunch-by-bunch stability of the bunch shape is quite important for stable production of THz CSR. In this sense, bunch compress scheme in a linac has to be carefully designed.

Short Bunch Production

To create appropriate longitudinal phase space of the beam for bunch compression, we have developed an independently tunable cells (ITC) RF gun [4]. The ITC-RF gun consisted with two cells and thermionic cathode can manipulate particle distribution in the longitudinal phase space by varying valance of feeding powers and phase difference as shown in Fig. 1(b) which is simulated using a 3-D finite difference time domain (FDTD) particle-in-cell code developed in our group [5].

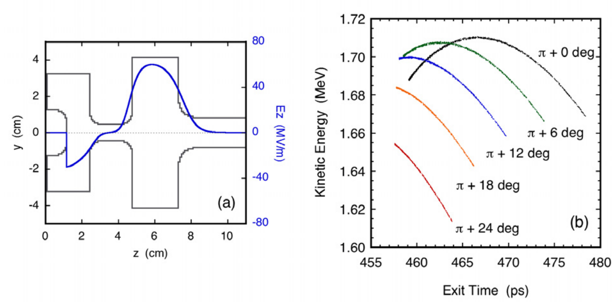

Figure 1: (a)Schematic of the ITC-RF gun and distribution of the accelerating filed of π-mode. (b)Longitudinal phase spaces at the exit of the gun. Peak electric field on the cathode surface is 30 MV/m and that in the 2nd cell is 60 MV/m. Plotted range of the momentum is 2 % from the top. Phase differences between the 2nd cell and the 1st cell are denoted.

In general, the longitudinal particle distribution produced from the thermionic RF gun is unique to a certain operating point. By choosing appropriate phase difference, nonlinear property of the phase space distribution can be suppressed as one can see in Fig. 1(b). Although the momentum is decreasing, that is not so much. Taking look at the phase space distribution, the phase difference apparently dominates the nonlinear property.

Schematic layout of injector, linac and chicane is shown in Fig. 2. Simulation results for the longitudinal phase space employing a code GPT are shown as well.

*Work supported by Grant-in-Aid for Scientific Research (S), the Ministry of Education, Science, Technology, Sports and Culture, Japan, contract No. 20226003.
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The space charge effect is considered. Although off-crest beam acceleration has been not optimized yet, the bunch length arounf 55 fs was obtained, where the bunch charge is 20 pC. Since the energy of the beam extracted from the gun is not sufficiently high, effects of space charge and wakefield are not negligible. Particularly the effects in the α-magnet are difficult to be evaluated.

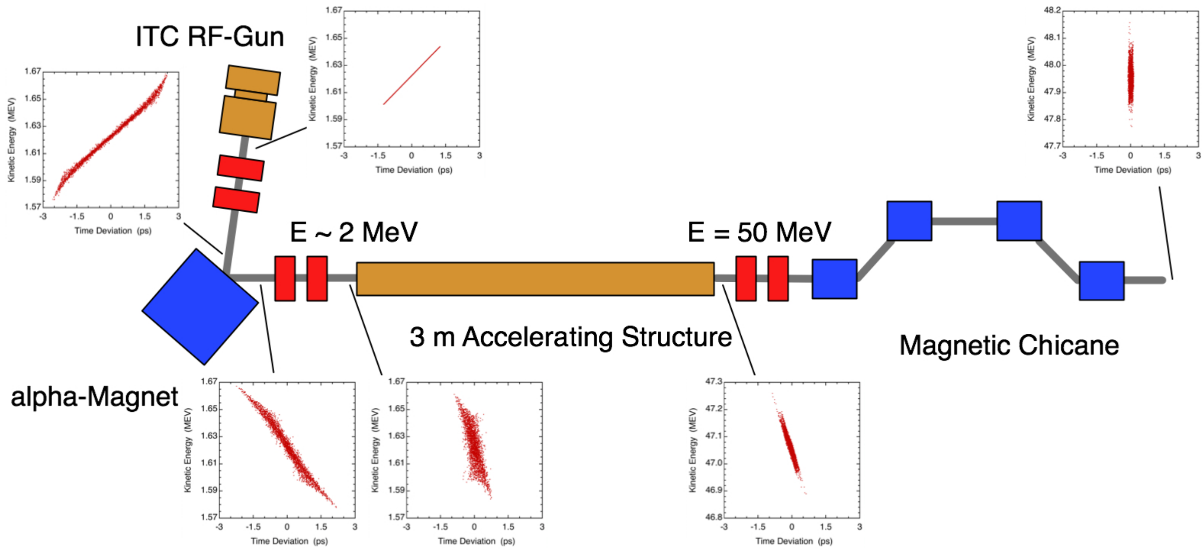

Figure 2: Configuration of the accelerator system including injector, accelerating structure and bunch compressor for producing extremely short bunch. Longitudinal phase spaces at respective positions are also indicated, which are simulated by GPT code. The role of adiabatic damping in the linac is quite important.

Formfactor and CSR

The bunch formfactor is calculated by a formula

$$f(\omega)=\left|\int_{-\infty}^{+\infty} S(\vec{r})e^{i\omega\vec{n}\cdot\vec{r}/c}d\vec{r}\right|^2. \quad (1)$$

If the bunch shape is Gaussian, the formfactor can be evaluated as $f(\lambda)=\exp\left[-2\pi^2(\sigma_b/\lambda)^2\right]$, where λ and σ_b are the wavelength and the bunch length, respectively.

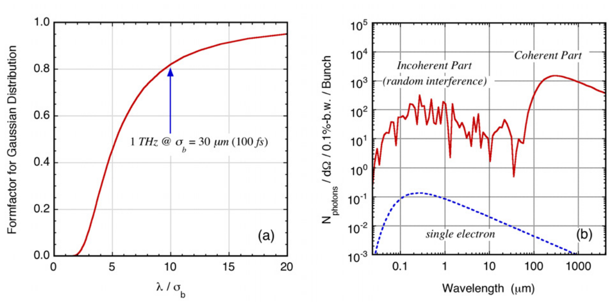

Figure 3: (a)Bunch formfactor for the Gaussian bunch shape. (b) Calculated spectrum of synchrotron radiation from the beam of 200 MeV. The bending radius is 3m and the number of particle is 1000. The coherent part is enhanced by a factor of 1000.

As shown in Fig. 3(a), the bunch length 10 times shorter than the wavelength is, at least, required for CRS production. By introducing higher frequency component in the bunch form such as rectangular shape, the bunch compression would be much more gentle. However we do not know how to manipulate the bunch shape as we like, so that sufficient shorter bunch length has to be essentially produced.

Fig. 4(b) shows a CSR spectrum calculated by integrating the Lienard-Wiechert potential, where the number of electrons in a bunch is only 1000. While we can see the random interference in a incoherent part clearly, coherent enhancement around 1THz is clearly arose.

Taking proper effects of space charge and wakefield into account in the FDTD simulation, we are going to confirm the bunch compression scheme.

ISOCHRONOUS RING AS A THz CSR SOURCE

In order to obtain CSR at multi ports and to increase the average power by extending macropulse, we are gong to introduce a complete isochronous ring as a THz source [6]. Path length deviation in the beam transport is coursed by the dispersion function with momentum spread and the betatron function with amplitude difference of oscillation. However we have already pointed out that the path length differences can be compensated employing right lattice functions, that is isochronous ring. In the isochronous ring, THz CSR is produced in every bending magnet since the bunch length is not varied by passing trough the arcs. Of course the bunch would be deteriorated due to energy loss and scattering with residual molecular. It is very difficult to tell how much longer the beam can circulate in the ring, the degraded beam can be kicked out from the ring and fresh beam is then injected.

The role of such multi-port THz facility is very significant to accelerate the THz science by gathering and accumulating the advanced technology and knowledge.

TERAHERTZ FEL SOURCES

To extend applicable experiments in the accelerator-based facility, narrowband source is highly required. Since the THz CSR source is wideband source, specific experiment such as time domain spectroscopy (TDS) will be very fascinate. On the other hand narrowband source is constantly in demand for molecular spectroscopy, because energy levels of rotation and vibration of the high molecular compounds exist in the spectral range of THz

Smith-Purcell BWO FEL

We have developed another electron gun, which is a DC (50 kV) gun and measured normalized beam emittance is less than 1 π mm mrad. Using a very small cathode of the single crystal LaB_6 cathode and employing no grid structure, we have achieved production of a very high brilliant beam. Although double-slit measurement for the transverse phase space was so noisy that uncertainty is a bit large, the measured normalized emittance was below 1 π mm mrad at 300 mA [7]. This DC gun seems to be very promising tool for Smith-Purcell BWO FEL. We have performed an FDTD simulation by taking the beam characteristics of the DC gun. Parameters of a model grating is as follows; period length 400 μm, groove width 200 μm, groove depth 300 μm and the number of period is 50. As shown in Fig. 4, Smith-Purcell BWO FEL was successfully lased in the simulation. When the normalized emittance of 5 π mm mrad was employed, obvious lasing was not observed. Radiation power is expected to be 300 W/mm^2.

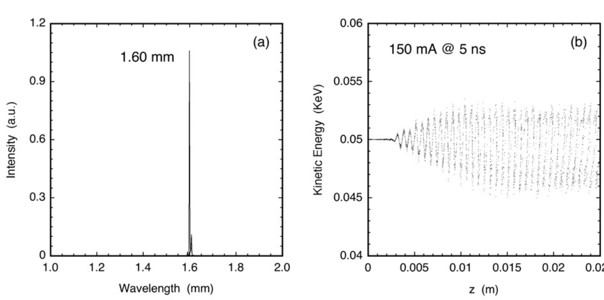

Figure 4: (a) Lasing spectrum of S-P BWO FEL, and (b) longitudinal phase space of the beam above the grating. Interaction with the evanescent wave can be seen clearly.

FEL with Shorter Bunch Length than Wavelength

In general FEL interaction can be understood with long beam pulse approximation, where the long pulse means sufficiently longer than wavelength. Phase space evolution of the beam in the FEL potential can be considered as sequence of energy gain of the radiation field. Exponential gain arises in this process stating from 0 bunching factor. If we adapt the very short bunch for the FEL process (here we call it " pre-bunched FEL"), we notice that the bunching factor starts from non-zero state. The bunch length of 100 fs is significantly shorter than the wavelength of the THz radiation. The growth of the radiation field per interacting time is proportional to the bunching factor, the pre-bunched FEL should have very large gain. In case of oscillator configuration, in each round trip a fresh bunched-electron interacts with non-zero bunching factor, so that the head of the FEL pulse is steeply amplified. Furthermore, because the bunch is going out from the separatrix of the FEL potentials, the tail of the FEL pulse is no longer amplified but the head part is simply increased without clear saturation. Typical phase space evolution in one path is shown in Fig. 5, which are calculated based on 1-D FEL equations. Detail of the calculation can be found in ref. 8.

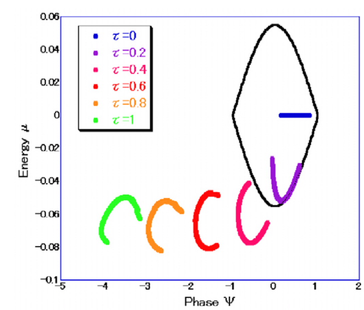

Figure 5: Typical evolution of the electron bunch in FEL field. Separatrix indicates the first one of the FEL pulse at the entrance of undulator. The beam quickly looses the energy and goes out of the separatrix.

PROSPECTS

The ITC RF-gun is now on commissioning stage. The beam property will be measured soon. Designing of lattice for the isochronous ring will be completed this year. Accelerator based THz facility at Tohoku University is now in progress.

REFERENCES

[1] M. Tonouchi, Nature Photonics 1 (2007) 97.
[2] H. Loss et al., presented at THz workshop at Jefferson Laboratory, Sept. 90 (2004).
[3] G. L. Carr et al., Nature 420 (2002) 153.
[4] T. Tanaka et al., Proc. 27th Int. FEL Conf., Stanford (2005) 371.
[5] H. Hama et al., Nucl. Instr. and Meth. in Phys. Res. A528 (2004) 371.
[6] H. Hama et al., N. J. of Phys. 8 (2006) 292.
[7] K. Kasamsook, Doctor thesis, Tohoku University (2008).
[8] M. Yasuda, Master thesis, Tohoku University (2009).