Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 89 (2016) 346 – 352

Energy Procedia

CoE on Sustainable Energy System (Thai-Japan), Faculty of Engineering, Rajamangala University of Technology Thanyaburi (RMUTT), Thailand

Proof-of-Principle Experiment of Velocity Bunching for Ultra-short Electron Pulse Production

S. Kashiwagi*, S. Nagasawa, F. Hinode, T. Muto, H. Saito, T. Abe, K. Nanbu, I. Nagasawa, K. Takahashi, C. Tokoku, E. Kobayashi and H. Hama

Research Center for Electron Photon Science (ELPH), Tohoku University, 1-2-1 Mikamine, Taihaku-ku, Sendai 982-0826, Japan

Abstract

An accelerator test facility, t-ACTS, established at Research Center for Electron Photon Science, Tohoku University, equips an injector consisted with a thermionic RF gun together with an energy filter and a 3 m traveling wave accelerating structure. A long-period undulator has been also installed for provide THz superradiance. Velocity bunching scheme proposed by Serafini and Ferrario is employed for ultra-short electron pulses production. A non-relativistic electron bunch, which is slightly slower than the velocity of light, is injected into the accelerating structure, and then the longitudinal phase space of the bunch is being rotated during acceleration. According to a numerical simulation, ~ 50 fs bunch can be produced by using the t-ACTS accelerator configuration. Proof-of-principle experiment of velocity bunching has been carried out by observing sub-picosecond electron pulse using a streak camera. We have succeeded in producing a sub-picosecond electron pulse in the t-ACTS. The details of the experiment for ultra-short electron pulse are described in this paper.

Peer-review under responsibility of the organizing committee of the 12th EMSES 2015

Keywords: short electron beam, coherent radiation, terahertz, Superradiance

1. Introduction

Intense coherent THz source is a powerful tool for many scientific fields such as biophysics and molecular science. The t-ACTS (test accelerator as coherent terahertz source) has been developed towards intense THz source at Research Center for Electron Photon Science, Tohoku University [1]-[2]. Superradiance (or coherent radiation)

* Corresponding author. Tel.: +81-22-743-3434; fax: +81-22-743-3402.
E-mail address: kashiwagi@lns.tohoku.ac.jp

Peer-review under responsibility of the organizing committee of the 12th EMSES 2015
doi:10.1016/j.egypro.2016.05.045

can be emitted from the electron beam when its form-factor is sufficiently large. Assuming Gaussian shape for the electron longitudinal distribution, the longitudinal form factor of 0.7 is obtained for which an optical wavelength is tenth of the bunch length. Since 1 THz radiation's wavelength (λ) is 300 μm and the intrinsic photon emittance is $\lambda/4\pi$ (24 μrad), the bunch length less than 30 μm (100 fs) and a normalized transverse emittance less than $24\beta\gamma$ μrad are required for superradiance.

The t-ACTS accelerator system consists of a compact linac with a thermionic RF-gun and an undulator [3]. A narrow band THz coherent radiation is obtained from the undulator has been considered [4]. The t-ACTS project employs the velocity bunching scheme [5] in its linear accelerator to produce the ultra-short electron bunches [6]. The injector adopted a thermionic cathode RF gun which was deliberately chosen for stable multi-bunch operation and for cost efficiency. The thermionic RF gun consists of two independent cavities has been developed, which is capable of manipulating the beam longitudinal phase space. The longitudinal phase space distribution of a beam entering an accelerating structure is optimized by changing the RF gun parameters to produced ultra-short electron pulse.

At present, the t-ACTS completed the construction of the linear accelerator part as shown in Fig. 1 and the facility was approved for the regulation of radiation safety on December 19th 2013. Proof-of-principle experiment of velocity bunching has been performed by measuring a pulse length of electron beam observing OTR by a streak camera. A relation between the compressed electron pulse length and an injection phase of beam to an accelerating structure was investigated. The preliminary results of the experiments are described in this paper.

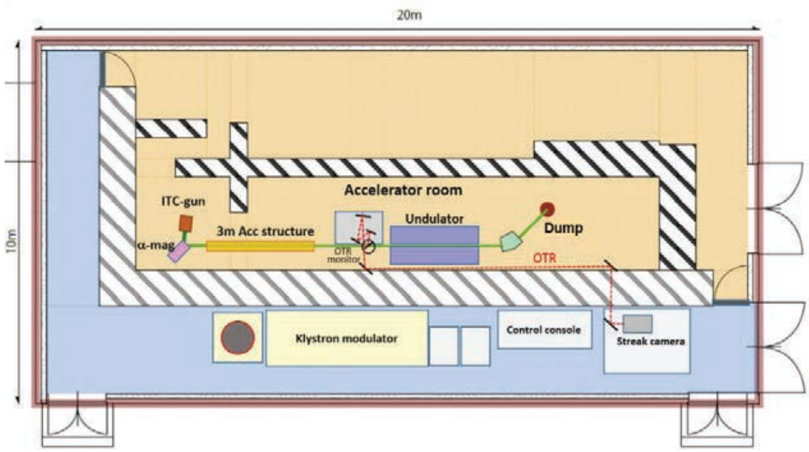

Fig. 1 Accelerator test facility (t-ACTS).

2. Ultra-short electron pulse production

2.1. Velocity bunching

In the velocity bunching, the non-relativistic electron bunch is injected into zero-cross phase (ψ = 0) of an accelerating structure to obtain the minimum pulse length. Since the phase velocity in the accelerating structure is equal to the speed of light, the non-relativistic electron bunch slips backward to the direction of crest phase and they will be accelerated and rotated in longitudinal phase space as shown in Fig. 2. Injected electron bunch moves along the equi-potential line in the longitudinal phase space. Ideally, the compression factor becomes maximum when the injected electron distribution is exactly on the same equi-potential line. Since nonlinearity of the equi-potential line at higher injection energy is stronger, a lower energy beam with mono-energy electron distribution in the longitudinal phase space is helpful to relieve the nonlinear effect (Fig. 2). The pulse length after acceleration strongly depends on the longitudinal phase space distribution of injection beam into accelerating structure.

Figure 3 shows the simple calculation results of the relation between the injection phase and rms pulse length after the velocity bunching. Its initial distribution is simplify as the momentum width ($\Delta p/p$) 1 %, γ_{ave} = 4.273, the pulse width of 2 ps and 4 ps, a uniform charge distribution. As shown in Fig.3 the minimum bunch length is achieved at zero- crossing of the RF phase.

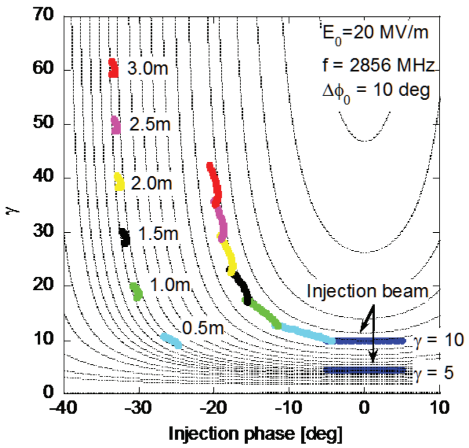

Fig. 2. Equi-potential lines for the accelerating field 20 MV/m. Evolutions of electron distributions injected at 0 degree are plotted with colored lines.

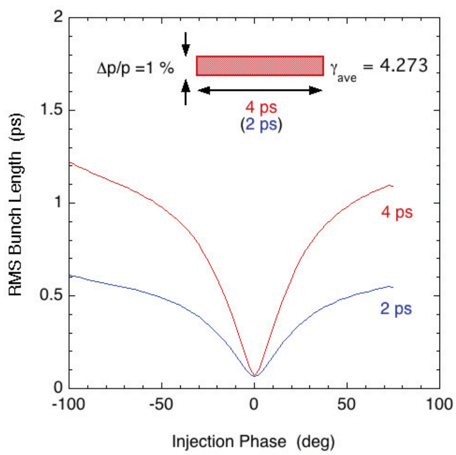

Fig. 3. RMS bunch length via velocity bunching versus the beam injection phase to accelerating structure. (E = 20MV/m) Initial electron bunch has uniform charge distribution with γ = 4.273, $\Delta p/p$ = 1%, Δt = 4ps (2ps).

2.2. Longitudinal phase space manipulation

An S-band RF gun had been developed to manipulate a longitudinal phase space distribution of electron beam for velocity bunching. The S-band RF gun has two cells and they have no electrical coupling, therefore the two RF cells can be independently controlled. It is named ITC (Independently Tunable Cells) RF-gun [8]. It was designed to manipulate the electron distribution in the longitudinal phase space for the velocity bunching. In general the thermionic RF gun produces a beam with strong energy-time correlation. The electrons are continuously extracted from the cathode in the duration of half RF cycle, and it is densely populated at the pulse head.

Figure 4 shows the numerical simulation results of the longitudinal phase space distribution of the beam at the RF gun exit for different combinations of the field strength and the relative RF phase between two cells. This result strongly indicates that the ITC RF-gun can achieve the suitable manipulation of longitudinal phase space distribution for the velocity bunching. In actual operation, only the pulse head is selected using a slit installed in the alpha magnet, and subsequently injected into the accelerating structure.

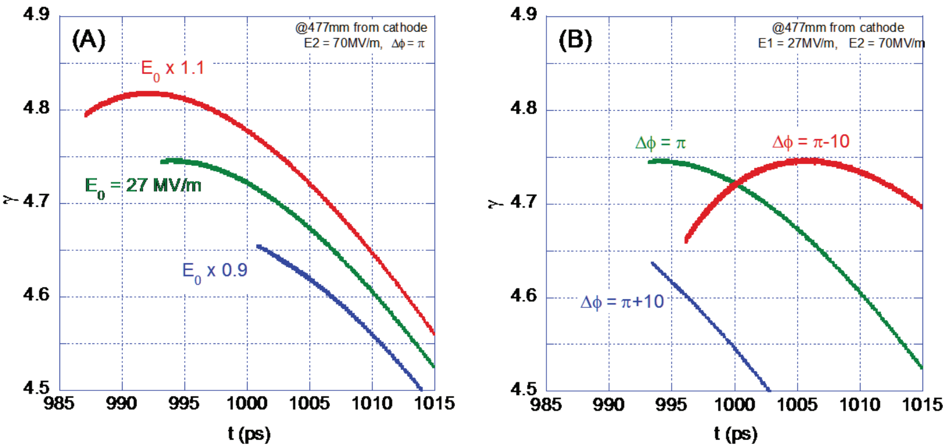

Fig. 4. Simulation results for the longitudinal phase space distribution at gun exit for different combinations of a field strength and the relative phase. (A) Changing the field strength of 1st cell. (B) Changing the relative phase between two cells.

3. Beam experiment

3.1. Accelerator system of t-ACTS

The t-ACTS linear accelerator consists of the ITC RF-gun, an alpha-magnet and 3m long S-band accelerating structure. Figure 5 shows the schematic diagram of a high power RF system. The ITC RF-gun cavities and an accelerating structure are driven by single klystron, and input RF parameters for the ITC RF-gun were adjusted using the RF attenuators and phase shifters independently. These makes it possible to manipulate a longitudinal distribution such as the simulation results as shown in Fig. 4. Since a direct measurement of longitudinal phase space distribution requires special techniques, it is carefully estimated from the comparison of the momentum spectrum measurements and simulation results in a nominal operation.

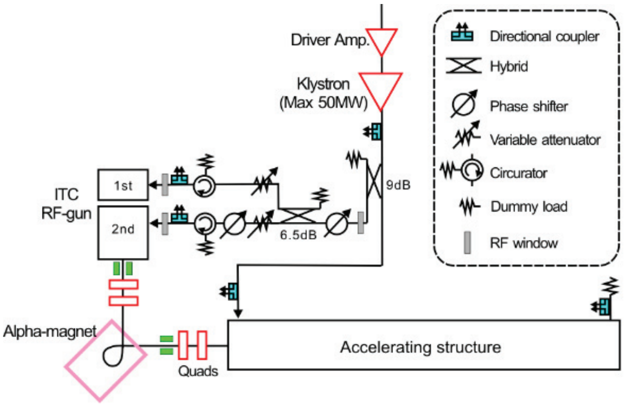

Fig. 5. RF system for the t-ACTS linear accelerator.

3.2. Experimental setup

Bunch length measurement was performed by observing an optical transition radiation (OTR) using streak camera (Hamamatsu Photonics, FESCA 200). Aluminum plate is inserted to beam line downstream of the accelerating structure to obtain OTR. The OTR was converted to parallel light using a concave mirror (focal length =250 mm, diameter = 50 mm) and transported a distance of about 10 m to the streak camera placed outside of accelerator room using reflective optics. Streak camera was operated with two different sweep time (50ps range: 53.99ps/1024ch, 100ps range: 153.77ps/1024ch.)

The momentum spectrum of the beam from ITC RF-gun was measured by inserting a slit in alpha magnet, and by changing relative phase of its two cavities. The measured distribution in momentum spectrum such as the 15° (orange line) in Fig. 6 with small momentum spread corresponds to the simulated distribution in longitudinal phase space such as $\Delta\phi = \pi$ in Fig.4(B) at the pulse head. To manipulate an electron distribution in longitudinal phase space suitable for velocity bunching, only the pulse head with small energy spread should be injected to the accelerating structure. Therefore a lower energy part of electron distribution was filtered by the slit. The created bunch has a charge of 6 pC. The beam momentum was measured at a dispersion section the linac downstream as a function of accelerating phase. From the measurement, the field gradient of accelerating structure was derived approximately 16 MV/m.

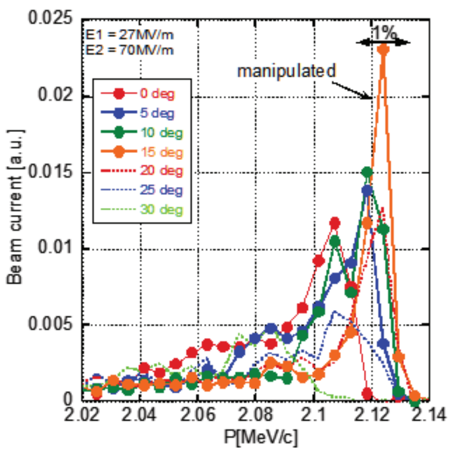

Fig. 6. Measured momentum spectrum with different phase of ITC RF gun. The phase shifter is set to 15 degrees (orange line) to make a spectrum with small energy spread.

3.3. Measurement results and discussion

In the velocity bunching, the pulse length is shorten while the injection phase goes to the RF zero-crossing as shown in Fig. 3. To verify the principle of velocity bunching, the pulse length measurement was performed changing the injection phase from -80° to +15°. In the measurement, the time profiles were taken 30 times at each injection phase using the streak camera. Each of them was fitted by Gaussian distribution to determine its center, and was superimposed to analyze rms bunch length as shown in Fig. 7. The pulse length of electron beam was derived using following equation

$$\sigma = \sqrt{{\sigma_m}^2 - {\sigma_R}^2} \tag{1}$$

where σ_m and σ_R are the measured pulse length and a temporal resolution of the system, respectively. In this measurement, a temporal resolution determined by the slit width of streak camera were 1.05ps and 0.37ps for the measurement time-range of 100ps and 50ps, respectively. Deterioration of temporal resolution due to the wavelength dispersion of OTR in the air was also considered in this optical setup and it corresponds to 0.16 ps with the wavelength range from 300 nm to 800nm.

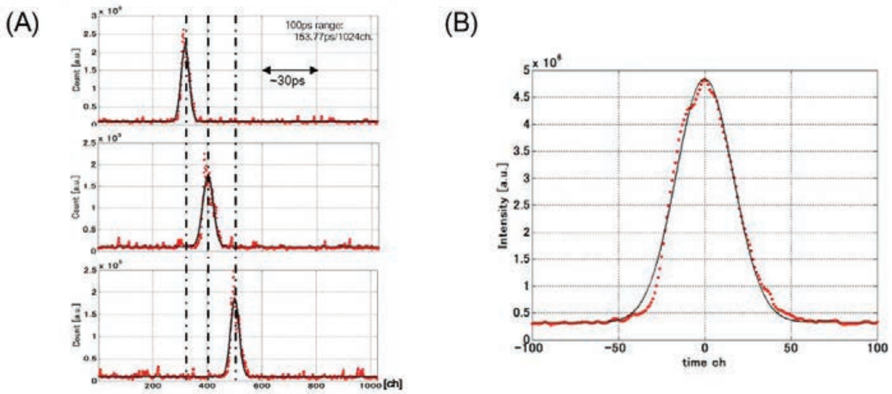

Fig. 7. Measured time profile using streak camera with 100 ps range. (A) Samples of single shot measurement. (B) Superimposed time profile.

Figure 8 shows the measured pulse length using the streak camera with two different time-ranges and a simulation result of GPT code [9]. The measured bunch length also change in the same manner as the simulation, and a sub-picosecond electron beam was successfully produced by velocity bunching. However, it was not in agreement with the simulation near the RF zero-crossing phase and it was not possible to measure the pulse length at deceleration phase. From the measurement result initial pulse length was estimated around 2 ps, because an electron beam accelerated near RF crest keeps an initial bunch length in the velocity bunching (Fig. 8).

In case of measuring the length of extremely short electron pulses, it is necessary to measure meticulously. Especially, an estimation of temporal resolution of the measurement system is important to obtain the “true” pulse length. In this experiment, the pulse length of electron beam was measured using streak camera for observing OTR. An opening angle of OTR at source point is inversely proportional to electron energy (1/γ). Since an electron beam energy decreases as the injection phase goes to the RF zero-crossing, the opening angle of OTR become large. In order to keep the intensity of OTR guided to the streak camera, a large aperture is required in the optical transport system. For electron beam transport system, a beam focusing in accelerating structure may change depending on the injection phase. In the injection phase is near the RF zero-crossing, the electron beam is defocused by RF field at the entrance of accelerating structure. In this experiment, an intensity of OTR measured by streak camera decreased near the RF zero-crossing phase and a beam loss in accelerating structure occurred at deceleration phase. The transverse property of injection beam should be controlled at the accelerating structure upstream to maintain transmission of beam using quadrupole magnets or an additional focusing component such as solenoid magnet.

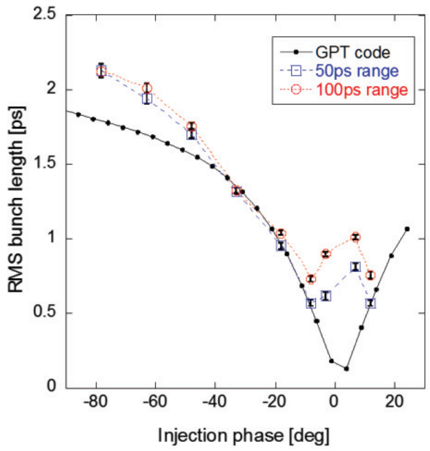

Fig. 8. Measured pulse length of electron beam as function of injection phase and the results of GPT simulation.

4. Conclusion

Longitudinal phase space distribution of electron beam was manipulated adjusting the RF parameters of ITC RF-gun to be suitable for velocity bunching. The measured pulse length of electron beam proved that the velocity bunching scheme in t-ACTS can be applied to generate sub-picosecond electron pulse. However the measurement results is not in agreement with the simulation near the RF zero-crossing and deceleration phase. Beam loss in the accelerating stage was observed in deceleration phase, it makes difficulties in measurement and operation in the present beam line setup. Installation of additional component for transverse focusing at the beginning of acceleration is necessarily for further experiment. In the measurement using the streak camera, the temporal resolution should be evaluated considering an opening slit width, a light intensity dependent space charge effect, and the streaking voltage linearity [10]. We will carefully investigate it to improve the reliability of measurement.

Acknowledgements

This work is partly supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (S) 20226003 and (B) 25286084.

References

[1] Hiroyuki Hama, Masayuki Kawai, Shigeru Kashiwagi, Fujio Hinode, Fusashi Miyahara, Ken-ichi Nanbu, Toshiya Muto, Yuu Tanaka, Xiangkun Li, Nuan-Ya Huang, Energy Procedia 9 (2011) 391-397.
[2] H Hama, H Tanaka, N Kumagai, M Kawai, F Hinode, T Muto, K Nanbu, T Tanaka, K Kasamsook, K Akiyama and M Yasuda, New J. Phys. 8 (2006) 292.
[3] Hiroyuki Hama, Mafuyu Yasuda, Masayuki Kawai, Fujio Hinode, Kenichi Nanbu, Fusashi Miyahara, Nucl Instr. and Meth., A637 (2011) S57-S61.
[4] H. Hama and M. Yasuda, Proc. of FEL2009, (2009) 394.
[5] L. Serafini and M. Ferrario, AIP Conf. Proc. 581 (2001) 87-106.
[6] Fujio Hinode, Masayuki Kawai, Kenichi Nanbu, Fusashi Miyahara, Hiroyuki Hama, Nucl Instr. and Meth., A637 (2011) S72-S75.
[7] F. Miyahara, F. Hinode, M. Kawai, T. Muto, K. Nanbu, H. Oohara, Y. Tanaka, and H. Hama,, Proc. of IPAC'10, (2010) 4509.
[8] F. Hinode, H. Hama, S. Kashiwagi, M. Kawai, K. Nanbu, F. Miyahara, T. Muto, H. Oohara,, Proc. of IPAC'10, (2010) 1731.
[9] http://www.pulsar.nl/gpt/
[10] H. Tomizawa, Proc. of the 5th Annual Meeting of Particle Accelerator Society of Japan, pp129-132.