STUDY OF FEMTOSECOND ELECTRON BUNCH GENERATION AT T-ACTS, TOHOKU UNIVERSITY

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Abstract

We are conducting a beam experiment of sub-picosecond electron bunch generation at t-ACTS (test accelerator as a coherent terahertz source), Tohoku University. In the t-ACTS, the intense coherent terahertz radiation will be generated from an undulator and an isochronous accumulator ring via producing sub-picosecond bunches. The accelerator is composed of a thermionic cathode RF gun, an alpha magnet and a 3 m-long accelerating structure. Velocity bunching scheme in accelerating structure is applied to generate the short electron bunch. The thermionic RF gun consists of two independent cavities has been developed, which is capable of manipulating the beam longitudinal phase space. To produced femtosecond electron bunch, the longitudinal phase space distribution of the beam entering the accelerating structure is optimized by changing the RF gun parameters. The bunch length is measured by observing an optical tradition radiation using a streak camera. In the study of femtosecond electron bunch generation, a relation between the RF gun parameters and the bunch length after compression was investigated. The preliminary results of experiments are described in this report (Fig. 1).

INTRODUCTION

The intense coherent THz source is a powerful tool for many scientific fields such as biophysics and molecular science. The t-ACTS has been proposed as a test accelerator complex towards intense THz source at Electron Light Science Centre, Tohoku University. The t-ACTS accelerator consists of a compact linear accelerator with a thermionic RF-gun, an isochronous accumulator and undulator [1]. A wide band THz coherent synchrotron radiation (CSR) is emitted from circulated electron beam in the isochronous accumulator ring [2] and a narrow-band one from the undulator has been considered [3, 4]. The t-ACTS project employs the velocity bunching scheme [5] in its compact linear accelerator to produce the femstosecond electron bunches for generating THz CSR [6]. The injector adopts a thermionic cathode RF gun deliberately chosen for stable multi-bunch operation and for cost efficiency. The compressed beam is much shorter than the wavelength of THz radiation, and has a sufficient large form factor for coherent enhancement of radiation power.

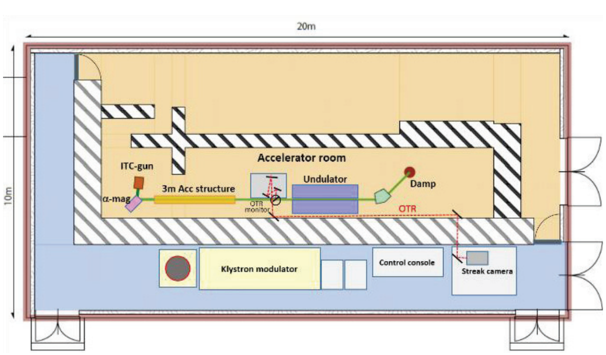

Figure 1: Accelerator-based light source house (t-ACTS).

SHORT BUNCH GENERATION

Velocity Bunching

In the velocity bunching, the non-relativistic electron bunch is injected into zero-cross phase ($\psi = 0$) of an accelerating structure. Since the phase velocity of the accelerating structure is equal to the speed of light, the non-relativistic electron bunch slips backward to the direction of crest phase and starts to accelerate as rotating its 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

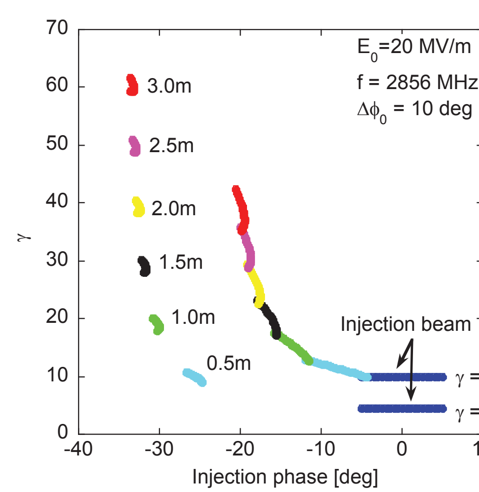

Figure 2: Equi-potential lines for the peak accelerating field E_0 = 20MV/m. Evolutions of electron distributions injected at 0 degree are plotted with colored lines.

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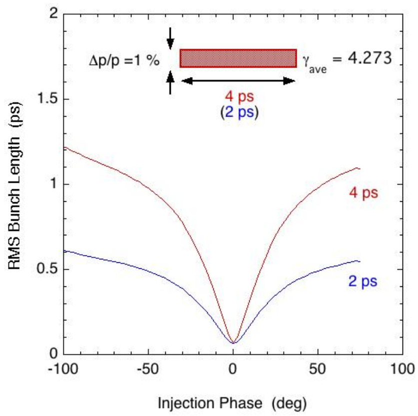

Figure 3: RMS bunch length via velocity bunching versus the beam injection phase to accelerating structure. (E_0 = 20MV/m) Initial electron bunch has uniform charge distribution with = 4.273, $\Delta p/p$ = 1%, Δt = 4ps (2ps).

mono-energy electron distribution in the longitudinal phase space is helpful to relieve the nonlinear effect (Fig. 2). The bunch length after acceleration strongly depends on the longitudinal phase space distribution of injection bunch into accelerating structure.

Figure 3 shows the calculation results of the relation between the injection phase and rms bunch 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 2ps and 4ps, a uniform charge distribution. As shown in Fig.3 the minimum bunch length is achieved at zero- crossing of the RF phase.

ICT RF-Gun

An S-band RF gun has two independent cells named ITC (Independently Tunable Cells) RF-gun [7]. The two cavities of the ITC RF gun have no electrical coupling, therefore two RF cavities can be independently controlled. It was designed to manipulate the electron

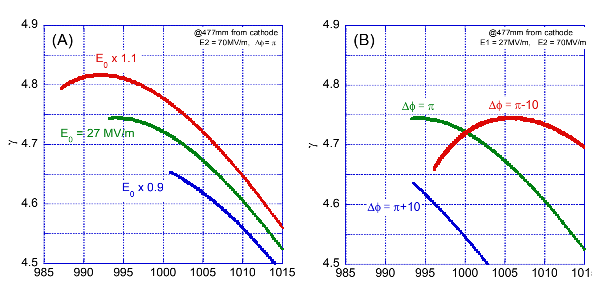

Figure 4: Simulation results for the electron distribution in the longitudinal phase space at the position of 477mm from the cathode for different combinations of the field strength (left) and the phase (right). (A) The E_1 dependence at the fixed E_2 = 70MV/m with the π-mode. (B) The phase dependence at the fixed field strength E_1 = 27MV/m and E_2 = 70MV/m.

distribution in the longitudinal phase space for the velocity bunching [6]. 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 bunch head.

Figure 4 shows the numerical simulation results of the longitudinal phase space distribution of the beam at the RF gun exit (at 433 mm from the cathode) 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 bunch head is selected using a slit installed in the alpha magnet, and subsequently injected into the accelerating structure.

BEAM EXPERIMENT

A t-ACTS was approved for the regulation of radiation safety at Dec. 19th 2013 and started first experiment of velocity bunching. In this experiment, the bunch length was measured as a function of beam injected phase to accelerating structure.

Experimental Setup

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

Bunch length measurement was performed by observing the optical transition radiation (OTR) using streak camera (Hamamatsu Photonics, FESCA 200). Al plate is inserted to beam line downstream of the accelerating structure to obtain OTR. The OTR was

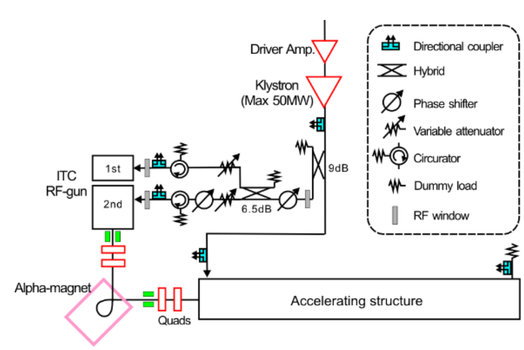

Figure 5: High power RF system for the t-ACTS injector.

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converted to parallel light using a concave mirror (f =400) and transported a distance of about 10 m to the streak camera placed outside of accelerator room using reflective optics. Streak camera was operated at sweep time of 153.77ps/1024ch with 60 μm of opening slit for bunch length measurement.

Injection Beam to Accelerating Structure

The energy 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 as shown in Fig. 6. The measured distribution in energy spectrum such as the 15° (orange line) in Fig. 6 with small energy spread corresponds to the simulated distribution in longitudinal phase space such as $\Delta\phi = \pi$ in Fig.4(B) at the bunch head. To shape an electron distribution suitable for velocity bunching, only the bunch head with small energy spread should be injected to accelerating structure. Therefore a lower energy part of electrons distribution was cut out by the slit. The created bunch has a charge of 6pC.

Figure 7 shows the measured beam momentum downstream of the linac as function of relative phase between RF-gun and accelerating structure fixing the RF-gun parameters. The field gradient of accelerating structure was estimated to be about 16 MV/m from measured maximum momentum. Momentum of the beam became a maximum at 35° in measurement, and corresponding phase in calculation is -80°.

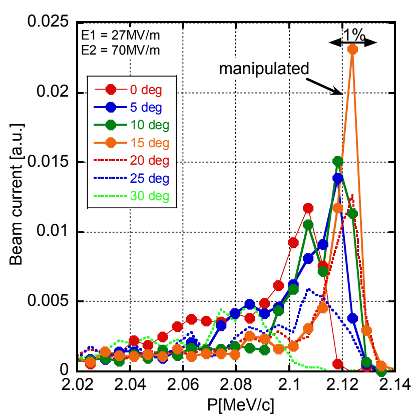

Figure 6: Measured momentum spectra for different phases of ITC RF-gun. These spectra were measured in the alpha magnet using the movable beam slit. The phase shifter set to 15 degrees (orange line) to make a spectrum with small energy spread.

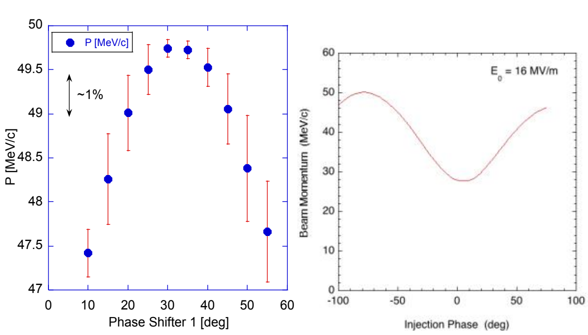

Figure 7: (Left) RF phase dependence of the beam momentum measured downstream of linac. (Right) Injection phase versus the momentum of accelerated beam (calculation).

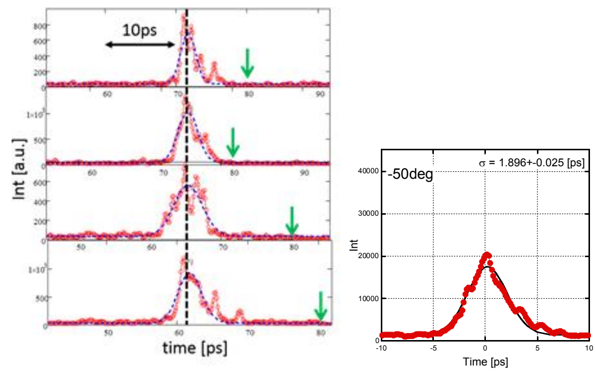

Figure 8: Measured time profile using streak camera. (Left) Samples of single shot measurement. (Right) Time profile superimposed of 30 shots.

Measurement Results

In the bunch length 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 superposed to analyze rms bunch length as shown in Fig. 8.

As shown in Fig. 3, the bunch length in calculation is shorten as the injection phase goes to zero. To verify the calculation, the bunch length measurement was performed changing the injection phase from -80° to +30° as shown in Fig. 9. The measured bunch length also change in the same manner as the calculated one. However, it was not possible to measure the bunch length near zero-crossing phase and the deceleration phase. Since beam focusing in accelerating structure changes as the injection phase goes to the RF zero-crossing, it was difficult to keep enough transmission of beam for the measurement.

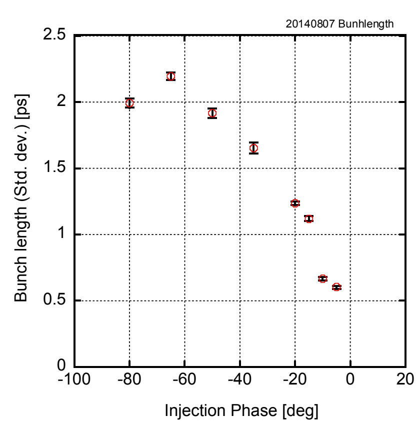

Figure 9: Measured bunch length plotted as a function of injection phase.

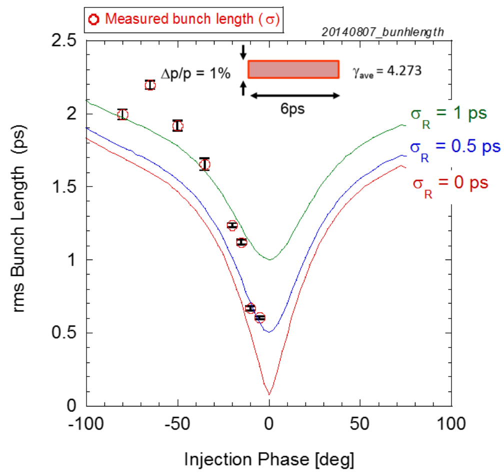

Figure 10: Measured bunch length versus beam injection phase. The solid lines show the calculation results of rms bunch length with time resolution of 0.0ps, 0.5ps, 1.0 ps.

In the velocity bunching scheme, an electron beam accelerated near RF crest keeps an initial bunch length. It was measured as 2ps of rms bunch length (Fig. 9). Experimental results were compared with the calculation of bunch length having uniform charge distribution in longitudinal phase space. Initial condition of calculation was 6ps bunch length (corresponds to rms bunch length ~ 2ps), a momentum spread ($\Delta p/p$) 1 %, and γ_{ave} = 4.273. Figure 10 shows the both of the measurement and the calculation results. Three lines with different colors represent the calculated bunch length to be measured with time resolution (σ_R) of 0ps, 0.5ps and 1.0ps. The experimental result is approximately consistent with the calculation result assuming the time resolution of 1.0ps from -90° to -20°. Assuming that the time resolution of 1.0 ps in measurement, the measured bunch length around -25° is sub-picosecond after deconvolution of a 1ps time resolution.

CONCLUSION

Electron bunch was manipulated of the longitudinal phase space distribution by the ITC RF-gun. The measured electron bunch length proved that the velocity bunching scheme in t-ACTS stands up to generate sub-picosecond electron bunch. However a transmission loss in accelerating stage makes a measurement in deacceleration phase difficult in a current setup, an installation of additional transverse focusing at injection into accelerating structure is our first priority for further experiment. In the measurement with streak camera, time resolution should be evaluated considering an opening slit width, a light intensity dependent space charge effect, and the streaking voltage linearity [8]. These will be investigated carefully now.

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