

Amplitude and Phase Control of RF Pulse Using IQ Modulator to Improve Electron Beam Quality

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Abstract: A test-Accelerator as Coherent Terahertz Source (t-ACTS) has been under development at Tohoku University, in which an intense coherent terahertz radiation is generated from the short electron bunches. Velocity bunching scheme in a traveling wave accelerating structure is employed to generate the short electron bunches. The in-phase and quadrature (IQ) modulator and demodulator were installed to the low-level RF systems of t-ACTS linac to control and measure the amplitude and phase of RF power. The amplitude and phase of the RF power applied to an RF electron gun cavities and the accelerating structure are controlled to produce the electron bunches with a uniform and small momentum spread suitable for the velocity bunching. By installing the feed-forward control system using IQ modulators for the beam conditioning, we have successfully generated flat RF pulses and improved beam quality, including the energy spectrum of the beam. The details of feed-forward control system of the amplitude and phase using the IQ modulator and the beam experiments are presented in this paper.

Keywords: electron linac; RF modulation; feed-forward control



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1. Introduction

Generation of coherent radiation in the terahertz range using the short electron bunches is one of the most promising candidates for high-intensity terahertz sources. In t-ACTS, short electron bunches of less than 100 fs can be generated by velocity bunching [1–3]. We are conducting fundamental studies on generation of intense coherent radiation from short electron bunches. Various high-intensity coherent terahertz radiation sources, such as transition radiation [4], Cherenkov radiation [5,6], Smith–Purcell radiation [7], and undulator radiation [8], have been developed using the short electron bunches.

The t-ACTS accelerator is composed of the thermionic cathode RF electron gun, the alpha-magnet, and 3 m long S-band traveling wave accelerating structure. A multi-bunch electron beam with a duration of typically several microseconds, called a macro-pulse, is used to generate the coherent radiation. The macro-pulse consists of a train of short electron bunches at intervals of 350 ps, which corresponds to one period of the S-band RF wave. To produce the short electron bunches, the longitudinal phase space distribution of the bunch injected into the accelerating structure is optimized for the velocity bunching. To manipulate the longitudinal phase space distribution, the ITC-RF gun (Independently Tunable Cells RF gun) with two cavities has been developed, which allows independent tuning of the phase and amplitude RF power feed to the RF gun cavities [1,3].

Variations in the amplitude and phase of the RF power fed to the RF gun cavities and the accelerating structure have a significant effect on bunching and energy spread of the macro-pulse of the electron beam. To improve electron beam quality, we installed the IQ modulator and detector to the low-level RF (LLRF) system to control and measure the amplitude and phase of RF power. We have developed a feed-forward control system

for the beam conditioning using the IQ modulator. The demonstration experiments using feed-forward control were conducted in t-ACTS linac.

2. Amplitude and Phase Control Using IQ Modulator

2.1. t-ACTS RF System

Figure 1 shows the high-power RF system for the t-ACTS linac. The RF power fed to the RF gun cavities and the accelerating structure is generated by S-band klystron (TOSHIBA, E3730A). The input RF parameters of the RF gun cavities can be adjusted independent of the accelerating structure using the variable attenuators and the phase shifters in the waveguide system. These variable attenuators and phase shifters are mechanical device, making it impossible to control RF amplitude and phase at high speed. Several directional couplers to measure the RF power are placed on the waveguide between the klystron to the RF gun cavities and the accelerating structure as shown in Figure 1.

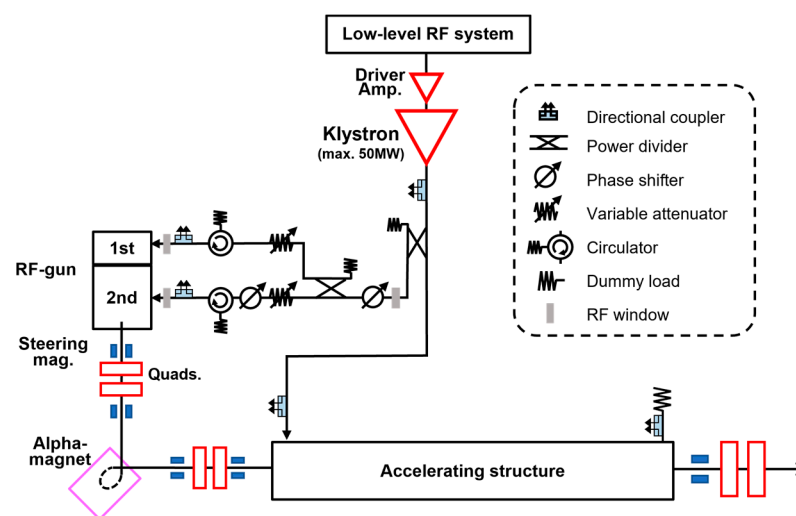


Figure 1. RF system of the t-ACTS linac. The output power from one klystron is fed to the RF electron gun cavities and accelerating structure. To control the amplitude and phase of the RF, the variable attenuators and phase shifter are instrumented in waveguide system. Directional couplers are also installed in the waveguide system as monitor.

The amplitude and phase of the klystron output power depend on the voltage applied to the klystron, V_k [9]. The RF frequency of the klystron used for the linac is 2856 MHz, and the typical klystron voltage is around 250 kV. The pulse-to-pulse klystron voltage and its ripple on the flat top of the square pulse should be small. Figure 2 shows a measured klystron high-voltage pulse shape, and the pulse duration is 7 μ s (FWHM). A drive RF pulse with a 3.5 μ s time duration is input to the klystron. The klystron voltage peak-to-peak variation is about 5.6 kV, which corresponds to 2.3%. This variation in klystron voltage results in a fluctuation of RF amplitude and phase, as shown in Figure 3. The amplitude and phase of the RF power vary by 9.8% and 6.9° in 3.3 μ s.

2.2. Control System

We have developed a feed-forward control system of the amplitude and the phase for the t-ACTS linac. Figure 4 shows the block diagram of the low-level RF (LLRF) system. The 2856 MHz of continuous wave (CW) RF signal generated by a stable master oscillator is converted using a high-speed RF switch to the pulsed RF signal with the duration of several microseconds. The pulsed RF signal is amplified by the solid-state amplifier for driving the 2856 MHz, 50 MW klystron. The timing and the duration of the RF pulse can be changed by using a pulse generator. The duration of the RF pulse is typically 3.5 μ s.

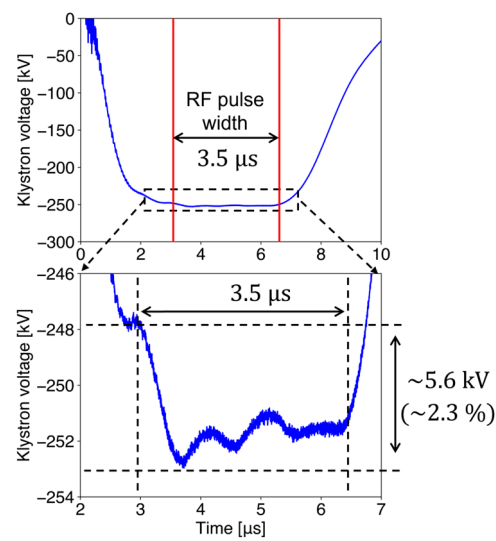


Figure 2. Waveform of a high-voltage pulse applied to the klystron: the full picture (**up**) and an expansion of the plateau (**down**). The pulse height is ~ 252 kV, and the pulse duration is $7 \mu\text{s}$ (FWHM).

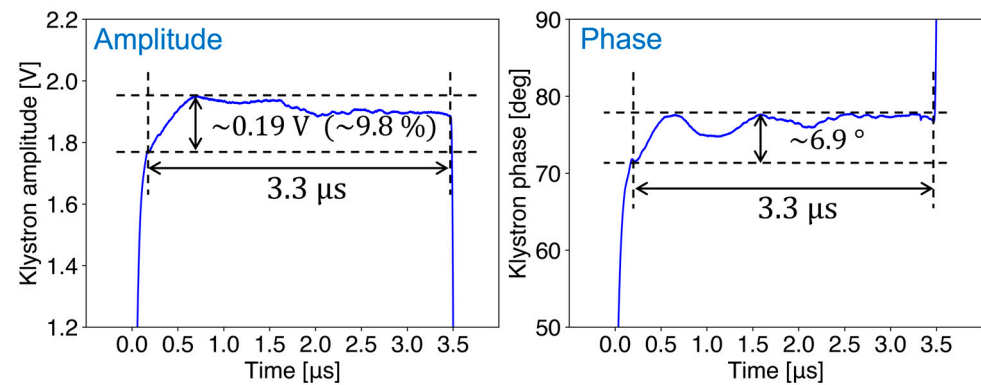


Figure 3. Amplitude (**left**) and phase (**right**) of the klystron output RF power. The amplitude varies by 9.8% in $3.3 \mu\text{s}$, and the phase varies by 6.9° .

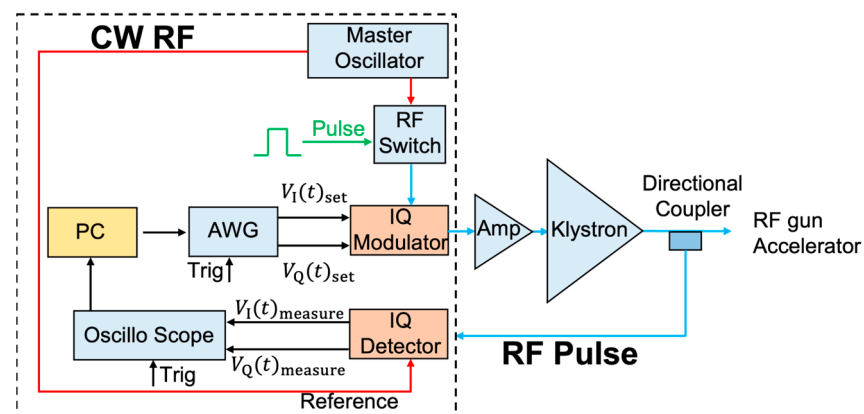


Figure 4. Block diagram of low-level RF system for feed-forward control.

The IQ modulator was implemented in the LLRF system for fast feed-forward control of amplitude and phase of the RF power with a duration of several microsecond. In the IQ modulation, arbitrary amplitude and phase are realized by composing the in-phase and quadrature vectors. In other word, the IQ modulation is based on the summation of two signals in quadrature. The IQ detector is also installed to measure the amplitude and the phase of the RF pulse. The input RF signal is directly demodulated to baseband analog

in-phase and quadrature signals that are subsequently converted to digital signal data using a digital oscilloscope.

2.3. Amplitude and Phase Modulation of Klystron Output Power

Amplitude and phase modulation is performed by the following procedure. First, target values for amplitude and phase (A_{target} , ϕ_{target}) are given, which in this case are constant values. The RF power is picked up from the directional coupler for monitoring the klystron output power. The RF signal is demodulated into two orthogonal components, $V_I(t)_{\text{measure}}$ and $V_Q(t)_{\text{measure}}$, using the IQ detector. The output signals of the IQ detector are measured with a digital oscilloscope, and the measured data are converted to amplitude $A(t)$ and phase $\phi(t)$ by a personal computer (PC). The measured data is subtracted from the target values to construct the data sets for the feed-forward control of the amplitude and the phase. The resulting data is transformed into the control voltages ($V_I(t)_{\text{set}}$ and $V_Q(t)_{\text{set}}$) for the IQ modulator using the klystron response curve, which are input–output properties of the klystron in amplitude and phase. These control voltage signals, $V_I(t)_{\text{set}}$ and $V_Q(t)_{\text{set}}$, are generated using an arbitrary waveform generator (AWG).

The feed-forward control is based on the linear response of the system and cannot compensate for the non-linear response of the control device in the system. To overcome these difficulties, the modulation procedure must be repeated alternatively several times for the amplitude and the phase until the measured waveform become equal to the target waveform [10]. Figure 5 shows the result of feed-forward control for the amplitude of RF pulses, and iteration numbers are indicated along with the measured waveform. The variations are significantly reduced, and the amplitude converge to flat and constant value. Figure 6 shows the amplitude and phase of the RF power from the klystron before and after feed-forward corrections. Finally, the amplitude and phase variations were compensated to 0.8% and 0.9° in 3.3 μs , respectively.

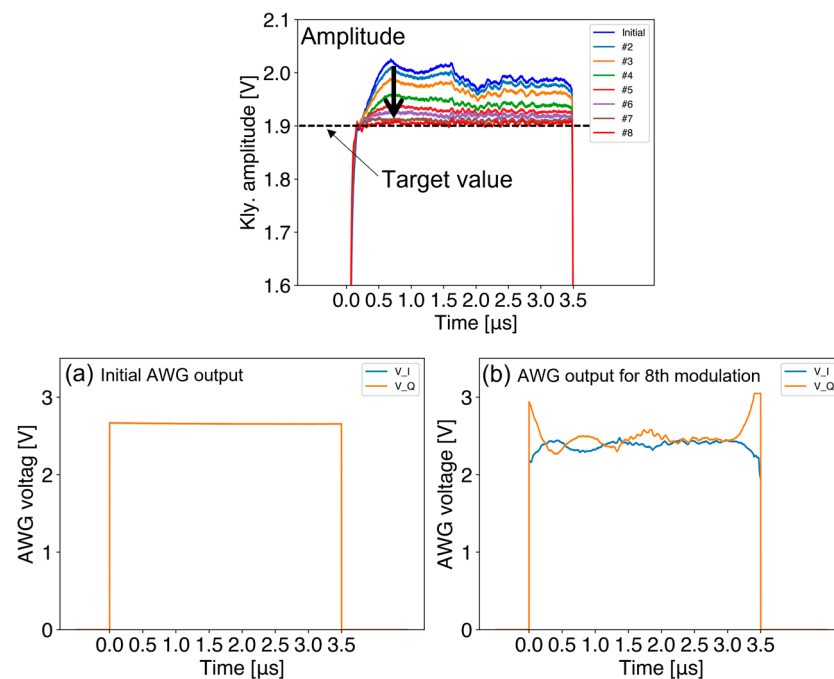


Figure 5. (Up) Amplitude variations in the RF pulse with increasing number of iterations of the feed-forward control. (Down) AWG output voltages to control IQ modulator, for the initial setting (a) and for the 8th setting (b).

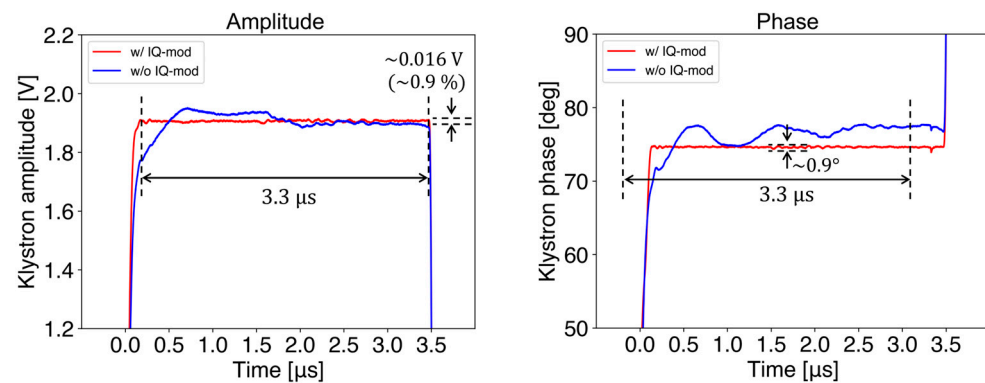


Figure 6. Amplitude and phase of the RF power from the klystron with and without IQ modulation.

3. Beam Experiments

Beam experiments were performed with RF power of uniform amplitude and phase, corrected by the feed-forward control, and applied to the RF gun cavities and the accelerating structure. The RF parameters for the gun and the injection phase of the beam into the accelerating structure were adjusted to maximize the intensity of the coherent transition radiation (CTR) measured downstream of the accelerating structure. In this experiment, a spectral measurement [11] of the CTR using a Michelson interferometer was performed, and the bunch length was derived to be approximately 80 fs.

We measured momentum distribution of the electron beam produced from the RF gun using the movable slit in alpha-magnet and the beam current monitor. The beam current of the macro-pulse injected into the accelerating structure was approximately about 20 mA, which corresponds to a bunch charge of 7 pC. Figure 7 shows the measurement results with and without beam conditioning using the feed-forward control of the amplitude and phase of the RF power using IQ modulator. Without the IQ modulation, the time duration of the beam pulse with uniform energy was only about 1.3 μ s. On the other hand, the electron momentum is constant in the portion of the spectrum, from 1.5 to 3.5 μ s, with beam conditioning as shown in Figure 7. The variation of momentum in the macro-pulse of the beam causes a difference of travel time of the electron beam from the RF gun cavities to the accelerating structure, therefore resulting in a difference in the injection phase of the beam into the accelerating structure. Velocity bunching is very sensitive with the injection phase of the electron beam into accelerating structure. Namely, the difference in the injection phase becomes a bunch length variation. Electron beams with uniform and small momentum spread have been generated by RF gun and are suitable for the velocity bunching in the structure.

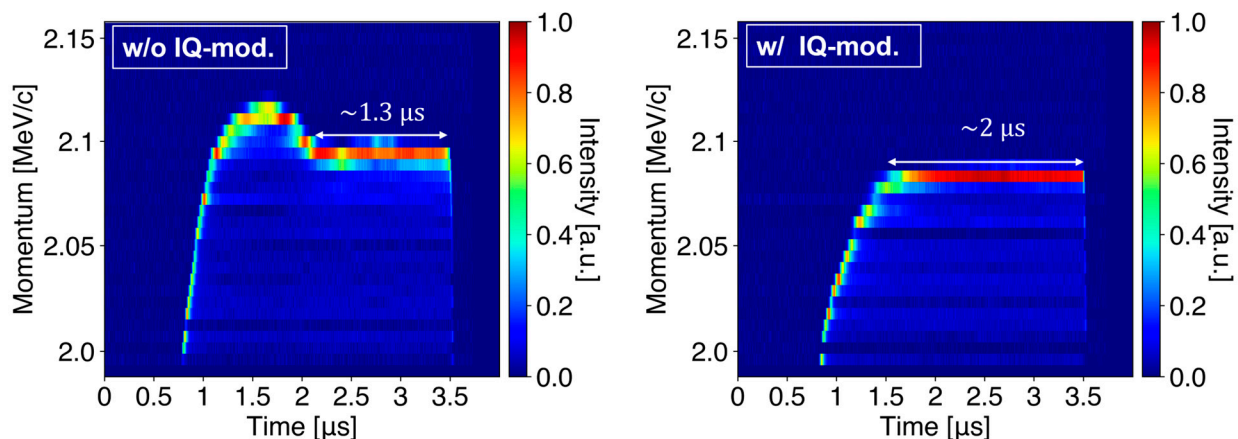


Figure 7. The time-resolved momentum spectra of the electron beam produced by the RF gun with and without beam conditioning using the feed-forward control using IQ modulator.

The time-resolved energy spectra measurement of accelerated electron beam with and without beam conditioning using feed-forward control was performed at the dispersion section downstream of t-ACTS linac. For the time-resolved measurements, an aluminum plate was installed as the screen for the beam profile monitor to generate optical transition radiation (OTR), since OTR is emitted in the time duration of the electron bunch. Beam profile measurements in the dispersion section using the OTR enable time-resolved energy spectra measurements. To acquire an image of the electron beam, we utilized gated image intensifier unit and a CCD camera. The gate pulse width for the image intensifier was set to 100 ns, and the beam profile was measured by changing the timing of the gate pulses in 100 ns steps. The dispersion function and β function in horizontal direction at the beam profile monitor were 0.49 m and 0.02 m, respectively. In the experiment, normalized horizontal emittance was 6.4×10^{-6} m. Figure 8 show the time-resolved energy spectra with and without beam conditioning using IQ modulator. In Figure 8, the energy deviation is derived with the reference energy as 22.2 MeV. The energy spectrum without beam conditioning indicates that the energy of electron beam varies considerably, whereas the energy of the electron beam with beam conditioning using IQ modulator is constant except for a transient part in the first 0.8 μ s, which is due to the filling time of the accelerating structure and the transient beam loading.

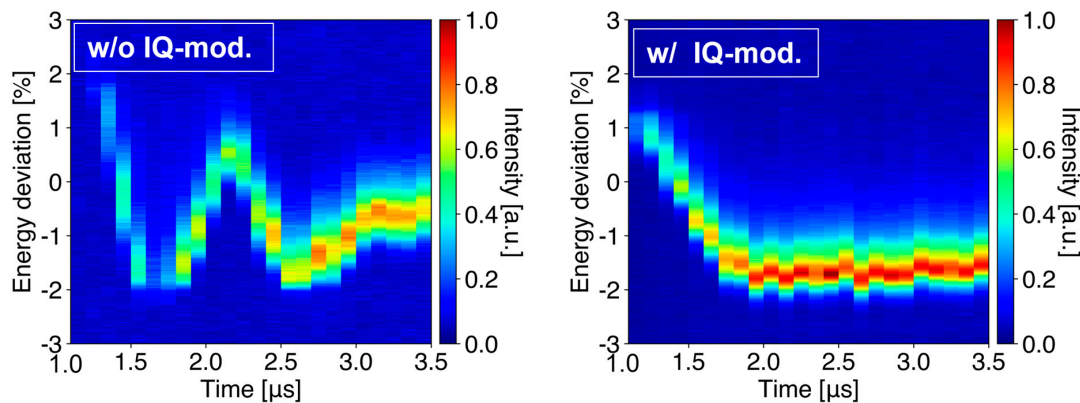


Figure 8. Measured energy distribution of the accelerated beam in dispersion section with and without IQ modulation. The spectra were measured using a gated image intensifier and a CCD camera. The 100 ns time-width gate was shifted in 100 ns steps.

Figure 9 shows the energy spectra of the electron beam integrated over the macro-pulse with 2.5 μ s of time duration. The energy spectra of the electron beam without beam conditioning have broad energy distribution. On the other hand, the peak in the energy spectra with beam conditioning using the IQ modulator becomes sharp, since the electron energy is constant and small energy spreads in the portion of the time-resolved energy spectrum, from 2.0 to 3.5 μ s.

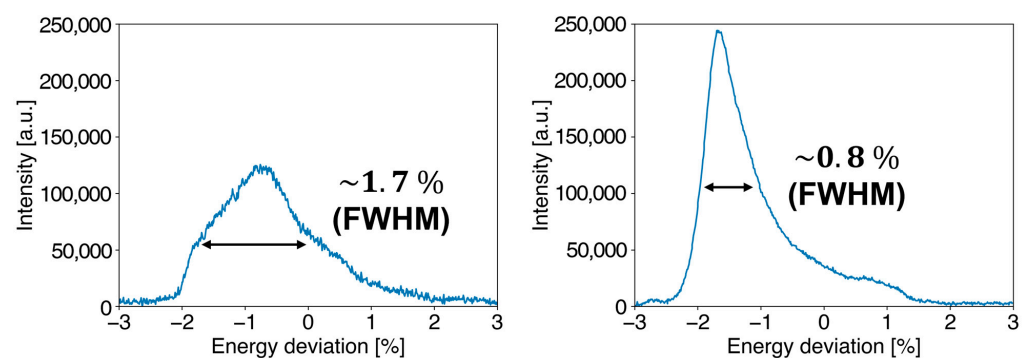


Figure 9. The energy spectra of the electron beam with and without conditioning using the IQ modulator.

4. Summary

The feed-forward control system of amplitude and phase using the IQ modulator for high-power RF pulses was applied to the t-ACTS linac to make the energy of the electron beam uniform and constant. With the feed-forward control, the peak-to-peak variation over 3.5 μ s in the RF power were reduced from 9.8% to 0.9% for the amplitude and from 6.9° to 0.9° for the phase. We have been able to produce an electron beam suitable for velocity bunching with a uniform and small momentum spread over 2 μ s from the RF electron gun. The time-resolved energy spectra of the accelerated beam in t-ACTS linac was measured, and the energy deviation of the electron beam was suppressed from 1.7% to 0.8% in FWHM. We have successfully improved beam quality, including the energy spectrum of the beam, by installing the feed-forward control of the amplitude and phase using IQ modulators into the LLRF system. The improvement of the beam quality leads to the generation of high intensity coherent radiation. We will clarify the effect of feed-forward beam conditioning by measuring the intensity of the coherent radiation.

Author Contributions: S.Y., S.K. and I.N. conceived the physics concept and developed the feed-forward control system; K.-i.N., T.M., K.T., K.K. (Ken Kanomata) and K.S. developed data acquisition and control system; F.H., S.M., H.Y. and K.K. (Kohei Kumagai) prepared the beam energy measurement system with the downstream beamline; H.H. supervised the experiment; S.Y. and S.K. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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References

1. Hama, H.; Kawai, M.; Kashiwagi, S.; Hinode, F.; Miyahara, F.; Nanbu, K.I.; Muto, T.; Tanaka, Y.; Li, X.; Huang, N.Y. Test-accelerators as coherent terahertz source program (t-ACTS) at Tohoku University. *Energy Procedia* **2011**, *9*, 391–397. [\[CrossRef\]](#)
2. Serafini, L.; Ferrario, M. Velocity bunching in photo-injectors. *AIP Conf. Proc.* **2001**, *581*, 87–106.
3. Kashiwagi, S.; Nagasawa, S.; Hinode, F.; Muto, T.; Saito, H.; Abe, T.; Nanbu, K.; Nagasawa, I.; Takahashi, K.; Tokoku, C.; et al. Proof-of-Principle Experiment of Velocity Bunching for Ultra-Short Electron Pulse Production. *Energy Procedia* **2016**, *89*, 346–352. [\[CrossRef\]](#)
4. Hama, H.; Abe, T.; Kashiwagi, S.; Hinode, F.; Muto, T.; Nanbu, K.-i.; Takahashi, K.; Nagasawa, I.; Kanomata, K.; Saito, H.; et al. Demonstration of Coherent Radiation Generation up to 3 THz from Femtosecond Electron Pulses. *Int. J. Opt. Photonic Eng.* **2017**, *2*, 004.
5. Nanbu, K.I.; Saito, Y.; Saito, H.; Kashiwagi, S.; Hinode, F.; Muto, T.; Hama, H. Bunch Length Measurement Employing Cherenkov Radiation from a Thin Silica Aerogel. *Particles* **2018**, *1*, 305–314. [\[CrossRef\]](#)
6. Nanbu, K.; Kashiwagi, S.; Hinode, F.; Muto, T.; Nagasawa, I. Study of Cherenkov Radiation from Thin Silica Aerogel. *Int. J. Magn. Electromagn.* **2017**, *3*, 471–473. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Yamada, H.; Hinode, F.; Kashiwagi, S.; Muto, T.; Miura, S.; Nanbu, K.; Kanomata, K.; Nagasawa, I.; Saito, H.; Shibata, K.; et al. Study of Bunch Length Measurement by Forward Coherent Smith-Purcell Radiation. In Proceedings of the 13th International Particle Accelerator Conference, Bangkok, Thailand, 12–17 June 2022; pp. 1125–1128.
8. Kashiwagi, S.; Abe, T.; Saito, H.; Hinode, F.; Kanomata, K.; Miura, S.; Muto, T.; Nagasawa, I.; Nanbu, K.I.; Ninomiya, S.; et al. Observation of coherent undulator radiation in THz region. *Infrared Phys. Technol.* **2018**, *93*, 335–339. [\[CrossRef\]](#)
9. Hogg, H.; Lebacqz, J.V. *Linear Accelerators*; Lapostolle, P.M., Septier, A.L., Eds.; North-Holland Publ. Co.: Amsterdam, The Netherlands, 1969.
10. Kawase, K.; Morio, Y.; Kon, Y.; Fujimoto, M.; Hirata, S.; Shen, J.; Kato, R.; Irizawa, A.; Isoyama, G.; Kashiwagi, S. Feed-forward control of the amplitude and the phase of a high-power RF pulse based on the overdrive technique. *Nucl. Instrum. Meth Phys. Res. A* **2012**, *679*, 44–53. [\[CrossRef\]](#)
11. Evtushenko, P.; Coleman, J.; Jordan, K.; Klopff, J.M.; Neil, G.; Williams, G.P. Bunch Length Measurements at the JLab FEL Using Coherent Transition and Synchrotron Radiation. *AIP Conf. Proc.* **2006**, *868*, 193–201.

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