Generation of 37 MeV Subpicosecond Electron Single Bunch at S-Band Linear Accelerator

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Abstract

Subpicosecond 37MeV electron single bunch was generated at the S-band linear accelerator of University of Tokyo. An original single bunch with a pulse width (Full Width of Half Maximum; FWHM) of less than 10 picosecond was successfully compressed to a subpicosecond time domain by magnetic pulse compression. The energy modulation was optimally matched to the magnetic optics to achieve the most effective compression by tuning RF power and phase of the microwave. A femtosecond streak camera with a time resolution of 600fs was utilized to measure a pulse shape of electron bunches by one shot via Cherenkov radiation emitted by the electrons in air. Finally, the shortest and average pulse widths in FWHM are 0.7ps and 0.9ps in the best operating mode, respectively. The compressed bunches has electric charge of 0.15nC (9.4×10^8 electrons) in average. Prior to the experiment , numerical tracking analysis for electrons in the pulse compressor was performed to investigate the matching between the energy modulation and the magnetic optics. Experimental and numerical results with respect to pulse widths was compared with each other and discussed. The subpicosecond electron single bunch is going to be utilized for exploration of ultrafast and fundamental radiation physics and chemistry.

Introduction

A 10ps(FWHM) electron single bunch was first generated at the 35MeV S-band linear accelerator (linac) with the subharmonic buncher and the pulseradiolysis system was established in 1977[1]. Since then the system has been contributing to the research of ultra-fast and basic process of radiation chemistry in pico- and nanosecond time domains by measuring light emission or absorption of a matter irradiated by the 10ps electron bunch. In particular the twin linac and stroboscopic absorption measurement system were built in 1986[2]. Here the bunch generated by the first linac irradiates a specimen and the Cherenkov radiation pulse emitted in air by the bunch generated by the second linac is used as a probe light. The twin linac system has enabled the absorption measurement in a picosecond time domain. Last year the 10ps electron single bunch was compressed to 2ps by using a preliminary magnetic compressor at the linac of University of Tokyo[3]. Considering the above progress and achievement, we have entered the stage seeking a new system to investigate ultra-faster phenomena of beam-matter interaction in a femtosecond time domain. For this purpose a femtosecond electron single bunch is necessary. The main objective of this paper is to report and discuss how to generate and measure a femtosecond electron single bunch with a certain amount of electric charge at the S-band linac. Numerical tracking analysis was also done to determine the operating parameter for the magneic pulse compression experiment.

Experimental Setup

The S-band twin linac consists of the two linacs named as 28L and 18L. The maxmum energy is 38MeV. The magnetic pulse compression experiment was carried out at 28L. 28L has two accelerating tubes (ACC1, ACC2) into which RF power is fed by two klystrons (KLY1,KLY2), independently. The magnetic pulse compressor consists of the two accelerating tubes (ACC1, ACC2), a bending magnet, which is normally used as an energy analyzer magnet, two quadrupole magnets and another bending magnet as shown in Figure 2. ACC1 and ACC2 were used for acceleration and energy modulation, respectively. A single bunch is accelerated up to 19.1 MeV in ACC1 and the RF phase in ACC2 is tuned in such a way that it rides on a specified RF phase of the traveling accelerating electric field wave. The energy modulation is converted to a pulth length modulation by the magnet assembly so that the pulse compression, namely the bunch compression in the longitudinal direction, is achieved. The variation of the longitudinal phase space of the compressed bunch is also schematically depicted in the figure. The connection of the waveguides between the accelerating tubes and klystrons was made so that the klystrons can feed the RF power independently into ACC1 and ACC2 with tunable phase shift. Hereafter we use the peak electric field and RF phase as an indicator of the energy modulation.

Pulse shapes were obtained by measuring Cherenkov radiation by one shot emitted by the electrons of a bunch in air at the end of the 45° bent beam line, namely the compressor. At the experiment the single bunches ride on the RF phase from 45° through 72° so that the best matching between the energy modulation and magnetic optics is obtained for best

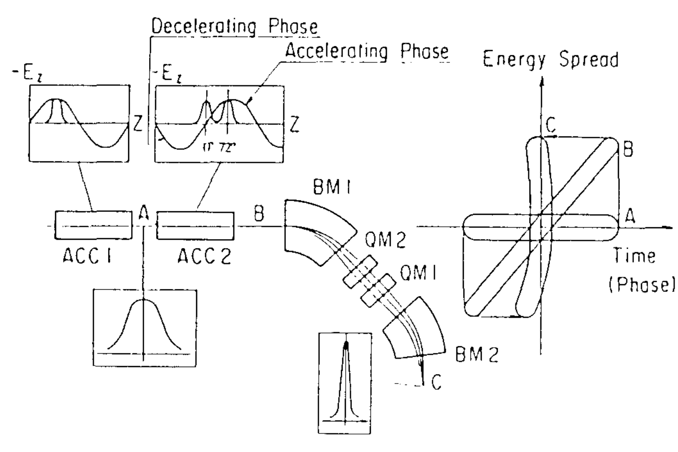

Fig.1 Magnetic pulse compression system and longitudinal phase space diagram

pulse compression. We used three mirrors, a convex lens and an optical filter. In particular we utilized a femtosecond streak camera which has a time resolution of 600fs (HAMAMATSU FESCA-500; courtesy of Free Electron Laser Institute, INC, Japan). We chose a slit width of less than 30μm in order to avoid the pulse broadening due to space charge effect in the camera. Furthermore, an optical band-pass filter which is centered at 465nm and has a half width of 12.5nm was used to avoid the pulse broadening due to optical dispersion in the convex lenses used in the measurement. All data of compressed pulse shapes were acquired by single shot measurements. The electric charge per bunch was measured by using the Faraday cage, which is represented as a beam catcher.

Electron Tracking Analysis

To find the optical peak electric field and phase for a bunch in ACC2 and the field gradient in the quadrupole magnets for most effective pulse compression, the numerical electron tracking analysis was carried out beforehand. The transformation matrix method is based on the perturbation theory where all quadratic or higher order terms are neglected. Actually, an error of 0.3mm in the path length of an electron corresponds to 1ps time difference which is inacceptable for the discussion of pulse compression in a subpicosecond time domain. For a more rigorous discussion we have numerically tracked electrons in a bunch passing through the pulse compressor by solving the following three-dimensional equation of motionin the dipole and quadrupole magnets and drift space,

$$\frac{d(mv)}{dt} = -ev \times \boldsymbol{B}. \qquad (1)$$

Beam parameters used in the analysis are summarized in Table.1. All values are previously measured ones. The initial distributions of electrons in the horizontal, vertical and longitudinal phase spaces at the entrance of ACC2 are assumed to be Gaussian with standard deviations obtained from the values in Table 1. The shape of the distributions in the horizontal and vertical phase spaces is assumed to be circular for simplicity. 1000 electrons are generated according to the Gaussian distributions and their positions in the phase spaces are calculated at the end of each cell by making use of the tracking method. Pulse width and energy spread are evaluated as the FWHMs of the density distributions of the electrons in the horizontal and vertical directions in the longitudinal phase space, respectively. The calculated phase space distribution of the 1000 electrons in the bunch at the exit of ACC2 and at the first mirror is shown in Figure 2, where the bunch is supposed to ride on the 72° phase of the RF wave with a peak field of 9.3MV/m. It is clear that the shape becomes rather straight and parallel to the vertical axis. The analysis tell us the prospect that a subpicosecond single bunch might be generated at this linac.

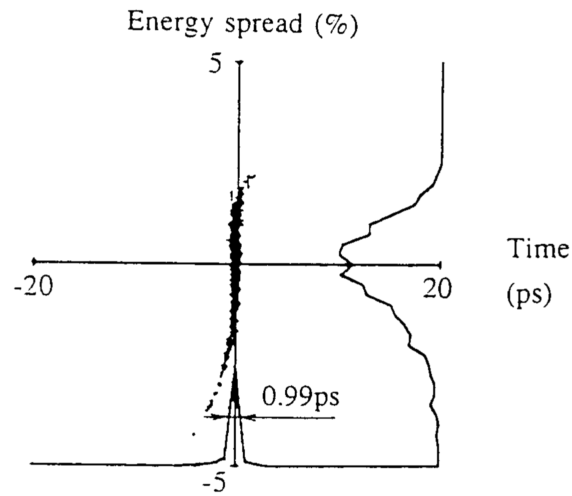

Fig.2 Calculated longitudinal phase spacedistribution after the compression.

Table.1 Beam parameters used in the numerical tracking analysis

Initial Energy acceleated by ACC1	19.1MeV
BeamProfile	Gaussian
Original Pulse Width (FWHM)	6.5psec
Energy Spread (FWHM)	0.2%
Horizontal and Vertical Emittance (90%normalized)	100πmm· mrad

Results and Discussion

The peak electric field in ACC2 was fixed to be 9.3MV/m. Typical measured pulse shapes of 36.8MeV original and compressed single bunches riding on the phase of 72° are shown in Figure 3. It is found that the 6.5ps pulse width of the original single bunch was shorter than the 10ps of the 19.1MeV original single bunch. The best matching between the energy modulation and trajectory modulation and the above shorter initial pulse width yielded the compressed single bunch of the pulse width of 0.7ps. The average pulse width among 10 shots was 0.9ps. Based on the careful investigation on measurement error, we have so far concluded that the time resolution of this measurement is limited by the band width of the optical filter which is used to eliminate the optical dispersion. For better time resolution, we plan to use the optical filters with a band-width of less than 10nm. Measured pulse width as a function of the RF phase in ACC2 are shown in Figure 4. Calculated pulse width by the tracking method is added to the figure. Good agreement between the experiment and calculation was achieved. The reason why the calculated pulse width is shorter than the measured one for the phase of 45° can be also ascribed to the loss of electrons at the

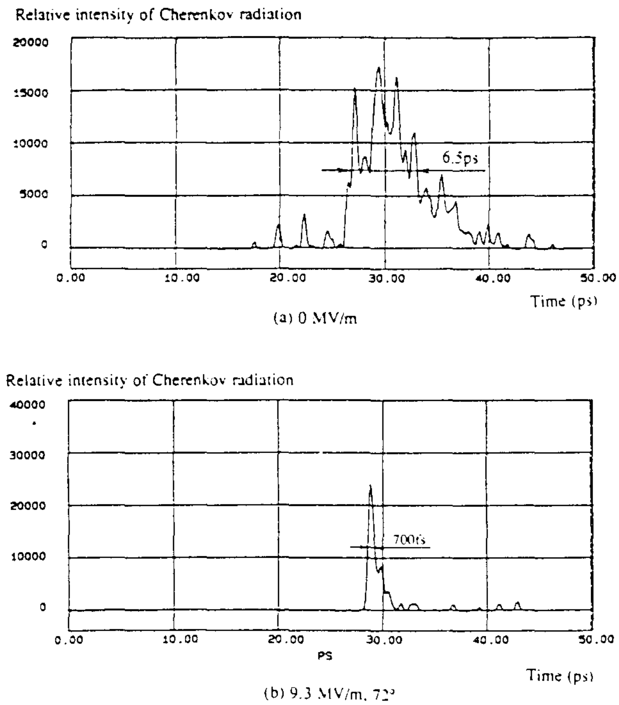

Fig.3 Measured pulse shapes of 36.8MeV original and compressed single bunches riding on the RF phase of 72° for the peak electric of 9.3MV/m in ACC2.

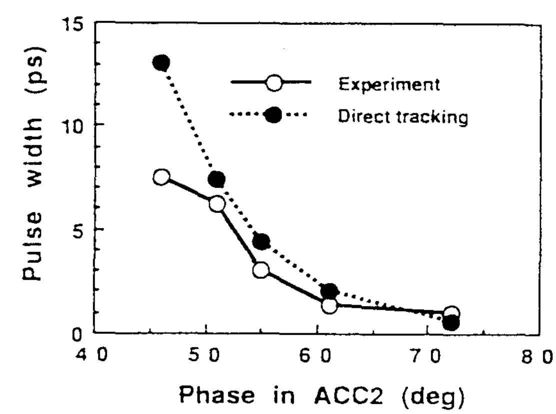

Fig.4 Pulse width, as a function of the RF phase in ACC2.

inner wall of the vacuum chamber due to large horizontal beam spread. Horizontal, vertical beam sizes in FWHM and electric charge per bunch were 6mm, 11mm and 0.15nC (9.4×10^8 electrons) Finally, the subpicosecond single bunches, where the shortest and average were 0.7 ps and 0.9ps, respectively, were generated for the RF phase of 72° and the peak electric field of 9.3MV/m in ACC2.

We are going to construct an achromatic magnetic pulse compressor to supply subpicosecond electron single bunches of higher luminosity to radiation physics and chemistry research in near future. Here we demonstrated the possibility to generate a subpicosecond electron single bunch at the S-band linear accelerator. As a future step we have to consider what we should do if a femtosecond single bunch with a pulse width of less than 100fs is needed. Considering our experience of the recent compression experiments with the 10ps original bunches, the compressed bunch looks to be close to the shortest limit at the S-band linear accerelator. We may be able to generate a femtosecond single bunch of about 100fs if we use such a short original bunch as a few picoseconds and its energy spread and emittance are much improved. For the former purpose we may have to choose an X-band (11.424GHz) accerelating system, which is now under development for linear colliders at SLAC and KEK.

Conclusion

Subpicosecond 37MeV electron single bunch was generated at the S-band linear accelerator of University of Tokyo. An original single bunch with a pulse width of less than 10 picosecond (FWHM) was successfully compressed to a femtosecond time domain by the magnetic pulse compression. The femtosecond streak camera with a time resolution of 600fs was utilized to measure the pulse shape of electron bunches from single shot Cherenkov radiation emitted by the electrons in or air. The specification of optical components was also optimized to avoid the pulse broading due to optical dispersion. Finally, the shortest and average pulse widths in FWHM are 0.7ps and 0.9ps in the best operating mode, respectively. A more efficient magnetic pulse compressor is planned to be constructed and the subpicosecond electron single bunch of higher luminosity is going to be utilized for exploration of ultrafast and fundamental radiation physics and chemistry in near future.

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