REAL TIME BUNCH SHAPE MEASUREMENTS IN THE OSAKA SINGLE BUNCH ELECTRON LINAC

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Abstract

A bunch compressor with four dipole magnets has been installed in the ISIR-Osaka single bunch electron linear accelerator. In order to investigate the compression effects, a real time bunch shape measurement system with the time resolution of 2.4 ps has been developed. The single bunch with a full length of 40 ps is compressed into 12 ps, whereas the bunch width of 16 ps in FWHM is compressed into 9.5 ps. The maximum compression rate is estimated to be about 30 % for the single bunch with the charge of 10 - 40 nC.

Introduction

The performance of a linear collider is strictly limited by the deleterious effects of the longitudinal and the transverse wake fields generated by high-current bunches in the linear accelerators.[1-2] The longitudinal wake fields affect the energy spread of the bunch, whereas the transverse wake fields increase the beam emittance. These two wake fields depend on the longitudinal charge distribution of the bunch. The lower energy spread is required to focus the beam at the interaction point. The longer bunch length results in less energy spread than the shorter bunch length, since the longitudinal wake potential decreases with the increase of bunch lengths. On the other hand, shorter bunch lengths are preferable to reduce emittance growth due to the transverse wake fields, since a large transverse emittance leads directly to large beam diameter at the interaction point and gives rise to reduction of the luminosity.

If the charge distribution of the bunch can be controlled, the optimum ballance of two deteterious effects will be obtained. A bunch compressor is one of the useful tool to control the charge distribution of the bunch.[3-4] In order to investigate the effect of bunch compression, the real time bunch shape measurement system with time resolution less than picosecond should be developed.

Single Bunch Electron Linear Accelerator

The ISIR-Osaka single bunch electron linear accelerator[5] produces a high-current single bunch by means of the subharmonic prebuncher (SHPB) system. The linear accelerator consists of a 120 keV electron gun, three SHPBs, a prebuncher, a buncher, a 3 m long accelerating waveguide, a bunch compressor and a transport system. The accelerating waveguide is driven by a 20 MW L-band klystron, and both the prebuncher and the buncher are driven by a 5 MW L-band klystron.

The subharmonic prebuncher system consists of a 12th SHPB followed by a 180 cm drift tube, a 12th SHPB followed by a 120 cm drift tube and a 6th SHPB with a 80 cm drift tube. These three SHPBs are coaxial single-gap cavities independently connected with the rf-amplifiers. The rf-phases and the rf-powers can be independently controlled to obtain the optimum subharmonic bunching. The subharmonic prebunchers and the drift tubes are confined by the Helmholtz coils. The axial magnetic fields are tapered from 150 Gauss at the entrance to 540 Gauss at the output in order to keep the beam at Brillouin flow condition as the charge density increases due to subharmonic bunching.

The single bunch of 16 - 20 ps bunch length, with the maximum charge of 67 nC, with the energy spread of 0.7 - 2.5 % over the range of 24 - 34 MeV, and the repetition rate from a single shot to 720 pps can be accelerated. The normal operating energy and the energy spread depend on the single bunch charge, since the energy spread is determined both by the accelerating field and by the longitudinal wake potential. The single bunch of 67 nC, 16 - 20 ps with a long tail, 24 - 28 MeV, 2.5 % energy spread is obtained. However, the single bunch of 25 - 45 nC in charge are used for the experiments in routine work, since the minimum energy spread of 0.7 % is obtained at 33 nC. The beam emittance of π mm-mR is observed for the single bunch of 10 nC, 16 ps, 24 - 34 MeV, 1 % in energy spread.

Bunch Compressor

As shown in fig. 1, the bunch compressor consists of four dipole magnets which produce an achromatic bump in the bunch trajectory such as an energy compressor system (ECS).[3-4] The high energy electrons take a shorter path through the compressor than the low energy electrons. By placing the single bunch at the optimum phase-angle where the energy spectrum is minimized, the tail of the bunch will be higher in energy than the bunch head. The bunch tail will catch up the bunch head through the compressor,

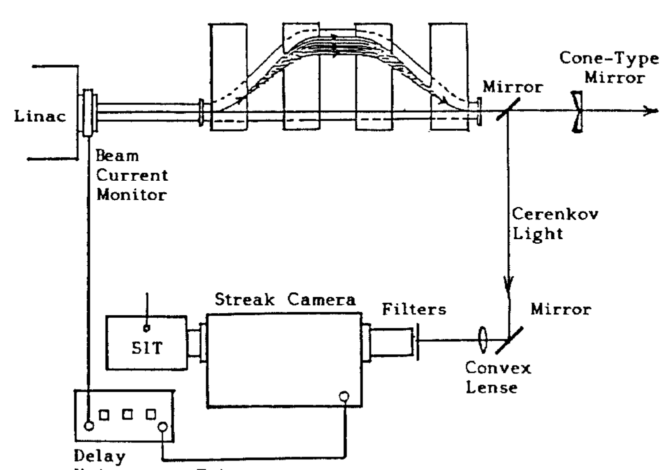

Figure 1. The real time bunch shape measurement System.

and then the bunch length will be shortend at the exit of the compressor. With magnetic strength higher than the optimum value, the bunch tail will pass by the bunch head, and then the bunch length will be prolonged.

Bunch Shape Measurement System

In order to investigate the compression effects, the bunch shape should be measured with the time resolution of the order of ps in real time. On such a short-time scale, the optical detection is more effective than the electric detection. By using streak cameras, the fine structure pulses of the mode-locked lasers can be measured with the time resolution of picosecond or sub-picosecond.

The real time bunch shape measurement system consists of Cerenkov radiators, cone-type mirrors, streak cameras, and a data processing system. The bunch shape can be observed on the video terminal in real-time at the repetition rate of 1.1 pps. The time resolution of the system is estimated to be 2.4 ps.

Cerenkov Radiators

The Cerenkov light generated by a relativistic electrons passing through a medium can be applied to the observation of the bunch shape. The Cerenkov light is generated with the angle

$$\theta_c = \cos^{-1}(1 / n(\lambda) \beta) ,$$

where $n(\lambda)$ is the refractive index in the medium and β is the electron velocity normalized to the light velocity in vacuum.

The medium suitable for Cerenkov radiators should be transparent even in the radiation enviroment. The following two mediums are utilized for Cerenkov radiators: gases and synthetic vitreous silica.

When the Cerenkov light is utilized to observe the bunch shape with the time resolution of ps, the following specifications should be taken in consideration:

1) The spectrum of the Cerenkov light consists not of the monochromatic wavelength but of the continuous wavelength. Figure 2 shows the typical spectrum of the Cerenkov light generated in the air by 30 MeV electron beam. The spectrum is observed by a multi-channel optical analyser with the sensitivity in wavelengths between 300 nm and 1000 nm. The cutoff wavelength is determined by the absorbers, such as a radiator, VUV lenses and an optical guide. Selection of the narrow band in wavelength enable to measurement the bunch shape with the picosecond time resolution, since the time delay due to the dispersive medium such as the radiators and the lenses.

2) The Cerenkov light is not a point source but a line source with the Cerenkov angle. The optical guide system should be designed to reduce the transit time spread due to the difference of the light path in the system.

Synthetic Vitreous Silica Cerenkov Radiators

The synthetic vitreous silica (Spectrosil-A) has optical homogeneity, free from bubbles, transmission in the range between 180 nm to 1200 nm, and the least amount of impurities. Even in the irradiation by beam electrons, the productions of color centers is negligible. As the refractive index is 1.47 at 400 nm, the Cerenkov angle is estimated to be 47.1° in the energy range from 2 MeV to ultra-relativistic.

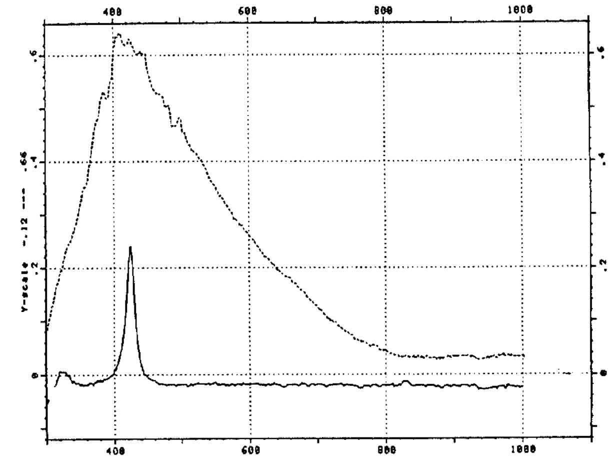

Figure 2. The spectrum of the Cerenkov radiation generated in the air by 30 MeV single bunch. With an interference filter of 430 nm in wavelength, the time resolution is reduced to 2.4 ps.

The streak camera (C1370-01, Hamamatsu Photonics) consists of VUV lenses and P11 photocathode. The sensitivity region in wavelength is 185 - 850 nm. As the refractive index of the VUV lenses is 1.551 at 200 nm and 1.452 at 850 nm, the time delay between two photons with different wavelengths is evaluated to be 2.1 ps/cm in the VUV lenses. The time resolution increases to several picoseconds by using silica-radiators and the lenses installed between the Cerekov radiator and the streak camera. In order to avoid the transit time spread, the narrow band in wavelength should be utilized, but the number of photons guided to the streak camera decreases. Therefore, the proper focusing at the slit of the streak camera is required to increase the S/N ratio.

Two types of Cerenkov radiators by using the synthetic vitreous silica are designed to minimize the transit time spread in the radiators. The geometrical diagram of the Cerenkov radiators are shown in fig. 3. The Cerenkov light generated on

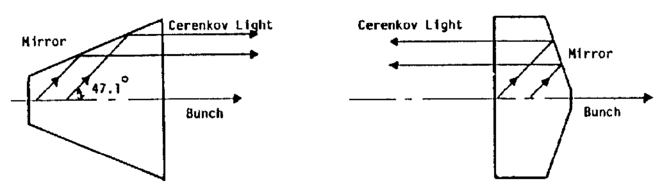

Figure 3. Two types of the synthetic vitreous silica Cerenkov radiators. The Cerenkov angle is 47.1°.

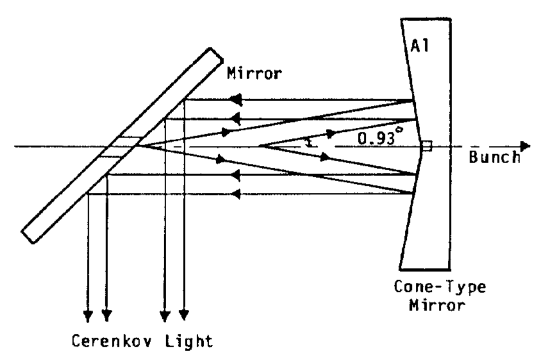

Figure 4. The gas Cerenkov radiator. The Cerenkov angle is 0.93°.

the axis of the radiators is converted to the parallel light beam inside the radiators. The radiators are settled at the exit of the beam window of the straight line.

Gas Cerenkov Radiators

In order to accelerate the single bunch without satellite bunches, the fine structure pulses from a Cerenkov radiator filled with X_e gas is usually observed at the controll desk.[6] The Cerenkov radiator is a cell in the shape of alphabet L, and it can be inserted into the beam transport tube. The Cerenkov light extracted into the air from the cell-window is converted to the quasi-parallel beam by a convex lenses. It is guided to the streak camera (Hamamatsu Photonics, C-979 and C-1098) with the time resolution of 10 ps. This system is not suitable to observe the effect of the bunch compression.

As the refractive index of air is 1.00027311 at 1 atm and 20°C, the electrons with the energy higher than 21.4 MeV radiate the Cerenkov light at the beam window. The Cerenkov angle slightly depends on the energy and it is estimated to be 0.69° at 25 MeV, 0.93° at 30 MeV, and 1.05° at 35 MeV. In the ultra-relativistic region, the Cerenkov angle is saturated at 1.34°.

The diameter of the Cerenkov light generated in air is estimated to be 3.2 cm at the distance of 1 m. The reflected Cerenkov light by the plane mirror is the optical hollow beam with the 3.2 cm of thickness and increasing diameter with the rate of 32 cm/10 m. The VUV convex lenses are required to converge the hollow light beam. As the Cerenkov light is a line source along the beam axis, the focus point at the streak camera depends on the source position from the convex lenses. Therefore, a cone-type mirror is designed to convert the Cerenkov light to the parallel light beam. The mirror is made of Aluminum with the surface angle of 0.47°. The roughness of the surface is estimated to be about 50 nm which is 1/8 of the interest wavelength.

Optical Guide System

The parallel light converted from the Cerenkov light is guided by the plane mirrors to the streak camera in the controll room. The light is focused at the slit of the streak camera. In order to avoid the transit time spread, an interference filter which transfers 38 % of photons in the wavelength between 425 - 435 nm is installed in fron of the slit of the streak camera. The high cut filter is also installed to cutoff the higher mode of the interference filter. The slit width of the streak camera is adjusted to be 4 μm so as to obtain the time resolution of 2 ps.

The size of focussing spot is 1 - 2 mm for the gas Cerenkov radiators and 5 mm for the silica Cerenkov radiators. Therefore the total number of photons through the slit for the gas Cerenkov radiators is larger than the silica radiators. The gas Cerenkov is preferable to measure the bunch shape with one shot operation.

Streak Camera System

The streak image on the fluorescent screen of the streak camera is pictured by a SIT camera, and the video signal is transfered to a data processing system (Hamamatsu Photonix, C-1098). The streak camera is triggered by a signal detected from a beam current monitor at the exit of the linear accelerator. The jitter of the streak image is observed to be about 10 ps, which is caused by a internal jitter of the trigger circuit of the streak camera. As the decay of the SIT camera is about 0.6 s, the superimposed streak images increase the time resolution at the higher repetition rate than 1.5 pps. In order to avoid the internal jitter of the streak camera, the one shot operation is preferable. Therefore, the beam injection from the gun is operated at 1.1 pps so as to obtain the one shot streak image, while the rf power is supplied to the linear acceleratorwith the repetition rate of 10 pps to obtain the stable operation.

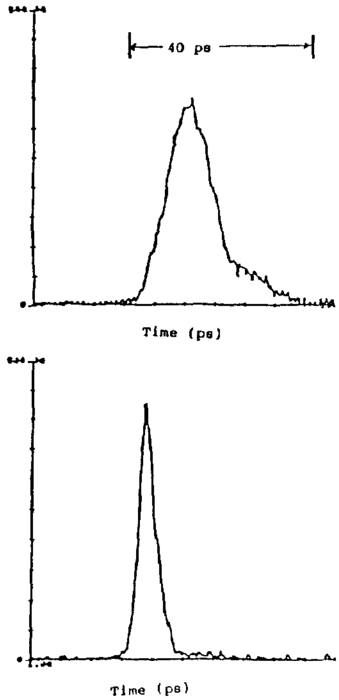

Figure 5. The shape of the single bunch with / without the bunch compressor. The single bunch is accelerated at the phase angle 0.242 radian, and the magnetic strength of the compressor is 0.96 kG.

Compression Effects

Figure 5 shows the observed bunch shapes with or without the bunch compressor. The single bunch charge is 20 nC and accelerating phase is 0.242 radian ahead of the crest. The figure shows that the single bunch of 16 ps in FWHM is compressed to 9.5 ps. The maximum compression rate of full width is about 30 % for the single bunch with the charge in 10 - 40 nC.[4]

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