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BUNCH LENGTH MEASUREMENT BY USING A 2-CELL SUPERCONDUCTING RF CAVITY IN cERL INJECTOR AT KEK

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Abstract

The development of future light source and linear collider require high quality electron beams with short bunch length. In general, the bunch length was measured by using deflecting cavity which has the time dependent transverse electromagnetic field. It is shown that the transverse electric field of 2-cell superconducting RF (SRF) cavity can also provide the correlation between the bunch length and beam size as like the role of the deflecting cavity in bunch length measurement. The deflection strength was calibrated by changing the RF phase and the beam offset because the strength of transverse electric field of RF cavity depends on the phase of RF field and the beam offset in the cavity. We will present new way to measure the bunch length by using 2-cell SRF cavity, which has the acceleration field of 7.21 MV/m, and the measured result with the bunch length of 3.3 ps (rms) in cERL injector.

INTRODUCTION

The measurement of the bunch length is significant technique for achieving the designed performance of the future electron accelerators. Many instrumentation and technologies such as streak camera, transverse deflecting cavity, electro-optic probe and devices based on coherent radiation were developed for providing and measuring picosecond and subpicosecond electron bunches [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. These methods, however, require the complex and expensive equipment such as optical elements or a deflecting cavity with the spare klystron power supply modulators. We suggest a simple method for measuring the bunch length of a ps level with low energy by using the radial electric field of radio frequency (RF) cavity is installed in linear accelerators. This method only required a RF cavity, a steering magnet installed in the upstream of the RF cavity for providing the proper beam offset inside the RF cavity and a profile monitor installed in the downstream of the RF cavity for measuring the variation of the beam size as a function of the beam offset. Therefore injectors of the accelerators which has the RF cavity can apply this technique for measuring the longitudinal profile with a few ps bunch length without any additional devices. The theoretical formula was driven and the method is verified by experiments using 2-cell superconducting radio frequency (SRF) cavity installed in the injector at cERL.

COMPACT ERL INJECTOR

The compact ERL (cERL), which is a test ERL accelerator to acquire the technology for the future GeV machine, was constructed in the ERL development hall of KEK and the commissioning of the cERL injector system was started from April 2013. The injector system in cERL consists of the 500 kV photo-cathode DC gun [12], two solenoids, a 1.3 GHz normal-conducting buncher, three 1.3 GHz 2 cell super-conducting injector cavities, 5 quadrupole magnets, and a beam diagnosis beam line consisting of a dipole magnet and several beam diagnosis devices. In this commissioning phase, the injector system produced electron bunches with a repetition rate of 1.3 GHz, a beam current of a few fC and a beam energy up to 5.6 MeV. Fig. 1 [13] shows the beam line for the gun part of a compact-ERL injector system.

Figure 1: Picture of the gun part of cERL injector system at KEK.

The injector cryomodule contains three 2-cell superconducting cavities. Each cavity is driven by two input couplers to reduce the required power handling capacity and compensate for the coupler kick [14]. Fig. 2 shows the 2-cell superconducting injector cavity. The longitudinal and transverse field maps of the injector cavity is shown in Fig. 3 that is calculated based on the cylindrical symmetry of the structure.

During our experiments, the electron beam was generated from DC gun with the gun voltage of 390 kV and

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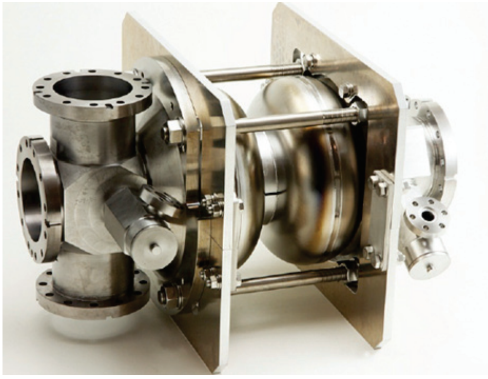

Figure 2: 2-cell superconducting injector cavity.

the beam was accelerated to 2.06 MeV using the first 2-cell cavity, while the beam is accelerated to 5.6 MeV using three 2-cell cavities in a normal operation.

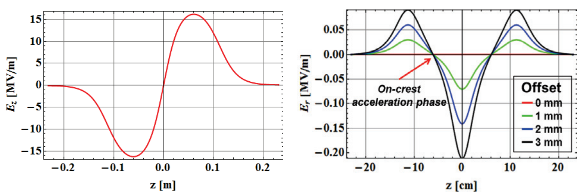

Figure 3: The electric field map of longitudinal (left) and transverse (right) with various transverse offsets of the 2-cell superconducting injector cavity.

The strength of the radial electric field of the injector cavity well corresponds to the offset inside the cavity and the direction of the deflecting force was opposite to the head and tail parts of the bunch when the particle was laid on the on-crest acceleration phase.

BASIC THEORY FOR BUNCH LENGTH MEASUREMENT USING A RF CAVITY

The method is based on the radial electric field of the RF cavity in which the strength of the field is proportional to the beam offset inside the RF cavity. The radial electric field of the RF cavity can be driven by considering the constrains of the Maxwell equations to obtain [15]

$$E_r = -\frac{r}{2}\frac{\partial E_z}{\partial z}, \text{ and } cB_\phi = \frac{r}{2c}\frac{\partial E_z}{\partial t}, \quad (1)$$

where r is the beam offset inside the RF cavity and c is speed of light. The crests of the electric and magnetic field are 90 deg apart. The deflecting force by the radial electric field of the RF cavity imparts a transverse momentum on the bunch which varies in time over the passage of the bunch. The small kick angle, $\Delta r'(<< 1)$, as a function of longitudinal position along the bunch, ζ, is given by $(k = 2\pi/\lambda)$ [16]

$$\Delta r'(\zeta) = \frac{eV_r(\zeta)}{pc} = -\frac{eE_0 r}{pc}\sin(k\zeta + \Delta\phi) \quad (2)$$

$$\approx -\frac{eE_0 r}{pc}\left(\sin\Delta\phi - \frac{2\pi}{\lambda}\zeta\cos\Delta\phi\right), \quad (3)$$

where ζ is the relative longitudinal position from synchronous particle, $\Delta\phi = \phi - \phi_0$, ϕ_0 is the synchronous phase of a RF field in the cavity, E_0 is a effective accelerating gradient of the RF cavity, λ is the wave length of the field, r is the beam offset inside the RF cavity and pc is the momentum at the entrance of the RF cavity. The radial voltage, V_r, can be calculated as $-E_0 r\sin(k\zeta + \Delta\phi)$when $E_z(z,t) = E_0\sin(kz)\sin(\omega t + \phi)$, $\zeta = z - z_0$ and z_0 is the longitudinal position of the synchronous particle. The displacement of the beam orbit by deflecting due to the radial electric field at the profile monitor is given by

$$\Delta r(\zeta) = -\frac{eE_0 r}{pc}\left(\sin\Delta\phi - \frac{2\pi}{\lambda}\zeta\cos\Delta\phi\right)\sqrt{\frac{E_c}{E_p}} \times\sqrt{\beta_p\beta_c}\sin\Delta\psi, \quad (4)$$

where $R_{12} = \sqrt{E_c/E_p}\sqrt{\beta_p\beta_c}\sin\Delta\psi$, β_p and β_c are the amplitude of the betatron oscillation at the profile monitor and the RF cavity position, respectively, $\Delta\psi$ is the phase advance between the RF cavity and profile monitor, E_c is the beam energy at the RF cavity entrance and E_p is the beam energy at the profile monitor. We assume that the electron beams on longitudinal phase space is Gaussian distribution and that it is transversally small compared to the transverse RF cavity radius. In these conditions the effect on the transverse direction such as the wake-field in the RF cavity are negligible and it is allowed to describe the transverse beam size at the profile monitor as a function of bunch length and RF cavity parameters as

$$\sigma_r = \sqrt{\sigma_{r0}^2 + \sigma_z^2\frac{E_c}{E_p}\beta_p\beta_c\left(\frac{2\pi eE_0 r}{\lambda pc}\sin\Delta\psi\cos\Delta\phi\right)^2}, \quad (5)$$

where σ_z is the bunch length and σ_{r0} is the beam size when the electron beam passing the center of the RF cavity. The beam size at the profile monitor proportional to the root of the square of bunch length. Therefore the energy of the beam at the entrance and exit of the RF cavity, effective accelerating gradient and beam offset,r, should be defined in the experiment.

BUNCH LENGTH MEASUREMENT AT CERL INJECTOR

In order to verify the effectiveness of the method for a short bunch length, a few ps, the measurement with a bunch length of 3.3 ps (rms) was performed [17]. The electromagnetic center was estimated by using the measurement of $dX_C/d\phi$ and $dY_C/d\phi$ which is expressed in Ref. [18]. To measure the a bunch length of 3.3 ps (rms) using this method, the beam offset inside the RF cavity should be large than 6 mm. Therefore the variation of the horizontal beam profile as a function of the horizontal beam offset was measured with various beam offset up to ± 7 mm inside the RF cavity that is shown in Fig. 4.

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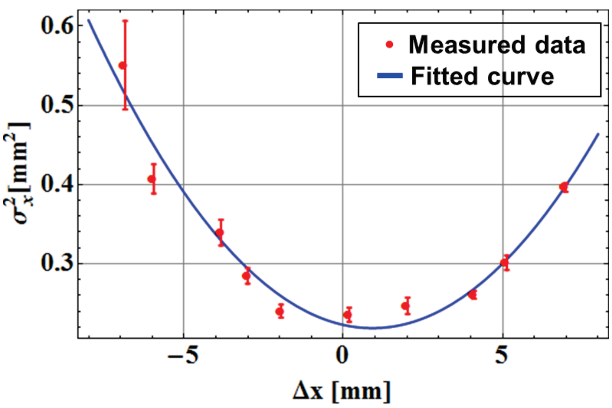

Figure 4: The bunch length measurement using a radio frequency cavity with an effective accelerating gradient of 1.62 MV/m and the laser duration on the cathode of 3.3 ps.

In order to calculate the bunch length from the measured result, the acquired data was fitted by the formula given by

$$\sigma_r^2 = \xi(r+\chi)^2 + \sigma_{r0}^2, \tag{6}$$

where $\xi = \sigma_z^2\beta_p\beta_c E_c/E_p \left(2\pi e E_0 \sin\Delta\psi \cos\Delta\phi/(\lambda p c2)\right)^2$ and χ is constant which represents the minimum beam size position. Using the fitted curve plotted in Fig. 4, which is derived from Eq.(6), the ξ value was calculated to be 0.00488 ± 0.000471. In this experiment, the E_p, E_c, R_{12}, E_0 and $\Delta\phi$ are 2.01 MeV, 0.39 MeV, 2.308 m, 1.62 MV/m and 0°, respectively. Then the measured bunch length was calculated to be 3.08 ± 0.145 ps. Since the duration of the laser pulse on the cathode is 3.3 ps (rms) [17], it also shows a very good agreement with the measured result.

CONCLUSION

We suggest an experimental methodology for the measurement of the bunch length by using combinations of the beam offset inside the cavity and a radial electric field of RF cavity. This method requires a steering magnet installed in the upstream of the cavity, a RF cavity and a profile monitor installed in the downstream of the cavity. The theoretical model for the bunch length measurement using a RF cavity was presented. It was verified by experiment in cERL injector with the bunch length of 3.3 ps (rms) and the injected energy of 390 keV. The measurement shows a very good agreement with the duration of the laser pulse which was irradiated on the photo cathode to produce electrons. Since the resolution of the method mainly depends on the injected beam energy, the amplitude of the electric field of cavity and beam offset inside the cavity and the cavity with more strong electric field are required to measure the shorter bunch length than a ps.

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