Minimization of the Emittance Growth in a Superconducting Radio Frequency Cavity at cERL Injector

For the development of future light sources based on linear accelerators such as X-FEL and ERL, beam dynamics for the acceleration and transportation without degradation of ultra-low-emittance beams such as 0.1 mm-mrad for 7.7 pC/bunch in the cERL injector are an important research topic to provide high-brightness and high-quality synchrotron radiation. In particular, a radial electric field of the superconducting radio frequency cavity, which is proportional to the beam offset, can cause transverse emittance growth. We succeeded in compensating the transverse emittance growth in the SRF cavity by a new method of estimating the electrical center of a cavity and adjusting the beam trajectory inside the cavity.

In KEK, the compact energy recovery linac (cERL) was constructed and has been commissioned to demonstrate the production, acceleration, and recirculation of ultra-low-emittance and high-current beams before constructing a 3-GeV ERL that will be used as a super-brilliant and ultra-short pulse synchrotron light source as well as a driver for an X-ray free electron laser oscillator (XFEL-O) [1, 2].

The ERL injector, which is shown in the Fig. 1, requires a high-brightness electron gun, and high-power SRF cavities to generate and accelerate high-current and low-emittance electron beams. Using a GaAs photocathode DC gun, the generation of a low-emittance beam of 0.1 mm-mrad with a bunch charge of a few tens of fC was demonstrated [3]. After generating the high-quality beam, the next step is to accelerate it without deterioration in beam quality. SRF injector cavities, which are used to increase the energy of the beam up to 5.6 MeV, are one source of the emittance growth, since the particles in the head and tail parts of the bunch receive the transverse kick force in a direction opposite to the radial electric field of the cavity, when the bunch is laid on the on-crest acceleration phase. In order to avoid the degradation by injector cavities, it is essential to estimate the electrical center of the cavity and to adjust the beam trajectory inside the cavity, because the strength of the radial electric field depends on the orbit offset inside the cavity [4].

In general, the electrical center in an actual cavity is estimated by measuring the pick-up HOM signal digitized by a fast oscilloscope, and using TE111 thas is the 6th HOM mode of the cavity signal [5, 6]. This method, however, requires the fabrication of an additional monitoring system with electronics. Therefore, we proposed a simple new experimental methodology to estimate the electrical center of a cavity by using an orbit corrector magnet to adjust the trajectory inside the cavity and a screen monitor installed in the downstream of the cavity. When the beam does not pass through the electrical center of the cavity, the beam is kicked by the radial electric field, and the position of the kicked beam after the cavity (X_C and Y_C), which is measured on the screen monitor, depends on the phase of the RF field (φ), because it changes the strength of the radial electric field. On the other hand, when the beam passes through the center of the cavity, the beam position is not changed even though the phase of the RF field varies, because the radial electric field is zero at the electromagnetic center of the cavity. This means that the value of $dX_C/d\varphi$ for the horizontal direction and $dY_C/d\varphi$ for the vertical direction is zero. Thus, in our new method, the beam trajectory passing through the electrical center of the cavity is extrapolated by measuring the values of $dX_C/d\varphi$ and $dY_C/d\varphi$.

Figure 1: Photograph of a DC gun and cryomodule for injector cavities in a compact ERL injector.

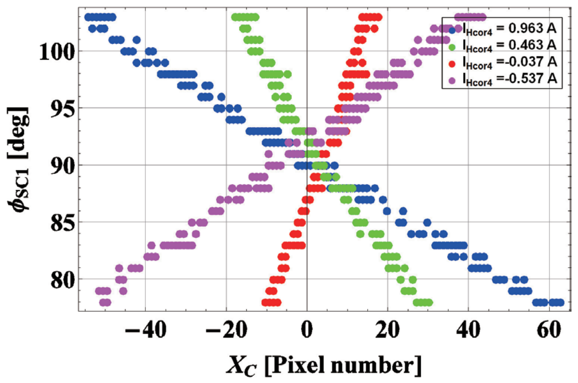

Figure 2: Measurement of $dX_C/d\varphi$ for the horizontal direction with various strengths of corrector magnet (I_{Hcor4}) to estimate the electromagnetic center of an injector cavity.

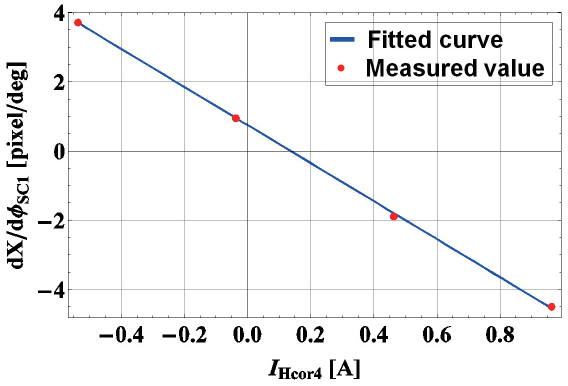

Figure 3: By measuring $dX_C/d\varphi$ with various strengths of the corrector magnet, the strength of the corrector magnet for passing the beam through the electromagnetic center of the cavity was estimated to be 0.136 A.

Table 1: Measured normalized transverse emittance with various beam offsets.

Δx (mm)	Δy (mm)	ε_{nx} (mm-mrad)	ε_{ny} (mm-mrad)
-12.4	0	1.070 ± 0.0533	0.970 ± 0.0337
0	0	0.212 ± 0.0064	0.259 ± 0.0229
0	-4.55	0.243 ± 0.0057	0.497 ± 0.0373
0	-9.10	0.240 ± 0.0151	0.665 ± 0.105

In order to verify the method, $dX_C/d\varphi$ and $dY_C/d\varphi$ were measured as a function of the orbit corrector magnet, which was used to adjust the trajectory inside the cavity. As shown in Fig. 2, the values of $dX_C/d\varphi$ were measured with different strengths of the corrector magnet, and the strength of the horizontal corrector magnet (I_{Hcor4}) for passing the beam through the electrical center of the cavity was estimated to be 0.136 A by fitting the measured $dX_C/d\varphi$ values as shown in Fig. 3. Based on this result, the normalized transverse emittance was measured as a function of the beam offset inside the cavity, because the transverse emittance is minimized when the beam passes through the center of the cavity. As shown in Table 1, the electrical center gives the minimum emittance growth due to the cavity. Using our method, we succeeded in minimizing the transverse emittance growth due to the radial electric field of the cavity.

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Ji-Gwang Hwang[1], Eun-San Kim[1] and T. Miyajima[2]
([1]Kyungpook National Univ. [2]KEK-PF)