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PRODUCTION AND PERFORMANCE EVALUATION OF A COMPACT DEFLECTING CAVITY TO MEASURE THE BUNCH LENGTH IN THE cERL*

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Abstract

At the KEK compact energy recovery linac, we have generated an infrared free-electron laser (FEL) using the process of self-amplified spontaneous emission. To generate the FEL, an electron bunch should be compressed along the longitudinal direction. The measurement of the bunch length is a key to optimize the bunch compression. We plan to measure the bunch length by deflecting cavities in the burst mode. The deflecting cavities are required to be a time resolution of 33 fs in order to not only measure the bunch length but also resolve the structure inside the electron bunch. To achieve the requirement, we have developed a c-band cavity whose RF input port is compact. The deflecting cavity is a single cell and normal conducting cavity. The deflection mode of the cavity is TM110. The 12 cavities will be located at the exit of undulators. In this presentation, we reported the production of the first cavity. We also performed the evaluation of the resonance frequency, the unloaded Q and the external Q of the cavity.

INTRODUCTION

At KEK compact energy recovery linac(cERL) [1], an infrared free-electron laser (FEL) has been generated by the process of self-amplified spontaneous emission. In the generation process, the position of the micro-bunch formation and the purity of the micro-bunch localization affect the monochromaticity and intensity of the infrared FEL [2]. To optimize the micro-bunch formation, an electron bunch should be compressed along the longitudinal direction. We plan to confirm the bunch compression by measuring the bunch length in the burst mode. For this purpose, We newly developed a c-band deflecting cavity whose RF input port was compact. The deflecting cavity was a single cell and normal conducting cavity. In this thesis, we explained the requirements of the deflecting cavity first. Second, we introduced the design of the prototype cavity. Third, we reported the production and performance evaluation of the prototype cavity.

REQUIREMENTS FOR THE PROTOTYPE CAVITY

At the cERL, the deflecting cavity will be located entrance of undulators as shown in Fig. 1. In the deflecting cavity, the TM110 mode is resonated. Its RF phase is adjusted so that amplitude becomes zero when an electron bunch goes through the center of the deflecting cavity. As a result, the longitudinal distribution is rotated and projected on the rear screen as shown in Fig. 2. We plan to measure the longitudinal distribution with a time resolution of 33 fs in order to not only measure the bunch length but also resolve the structure inside the electron bunch. The time resolution is described as [3]

$$\sigma_{\mathrm{res}} = \frac{E\sigma_{\mathrm{off}}}{eL}\frac{1}{\omega_{\mathrm{RF}} n\sqrt{PR_T}}. \tag{1}$$

Here, e is the elementary charge. The definition of other parameters are shown in Tables 1 and 2. Table 1 shows the beam parameters assumed in this study. Table 2 shows the parameters of the deflecting cavity to satisfy the requirement of the time resolution. These parameters were designed to minimize the cost which was dominated by the power supply of the cavity. From Eq. (1), the high resonance frequency and multi cavity were essential to reduce the input power. The small input power enabled the cavity to have a small input coupler. The small coupler was useful to increase the time resolution since the transverse shunt impedance could be decreased by the large input coupler. The specific design was described in the next section.

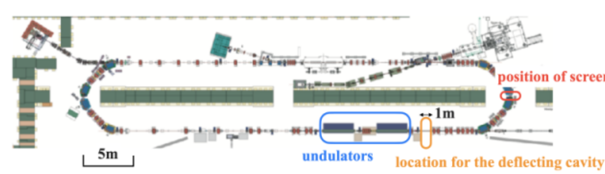

Figure 1: Schematic view of the cERL.

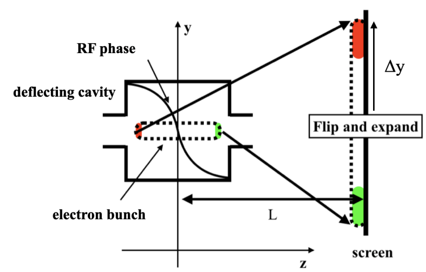

Figure 2: Schematic of the bunch-length measurement.

DESIGN OF THE DEFLECTING CAVITY

The schematic view of the prototype cavity was shown in Fig. 3. The cavity had a loop antenna, three tuners, RF-decoupler and RF monitor. We designed the cavity using

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Table 1: Beam Parameters of the cERL Assumed in This Study

Parameters	Symbole	Value
Energy	E	20 MeV
Beam size at the undulator exit	σ_{off}	200 µm
Distance between the screen and the cavity	L	10 m
Bunch length	–	500 fs
Micro-bunch length	–	50 fs
Fundamental RF frequency	–	1.3 GHz
Beam hole radius	–	8 mm

Table 2: Parameters of the Deflecting Cavity to Satisfy the Requirement of the Time Resolution

Parameters	Value
Resonance frequency	5.2 GHz
Deflecting mode	TM110
Unloaded Q	14800
Transverse shunt impedance per single cavity	0.98 MΩ
Coupling β	1
Input power per single cavity	1 kW
Resolution per single cavity	400 fs
Number of cavity	12

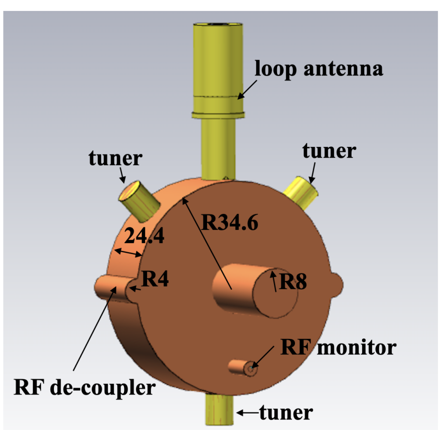

Figure 3: Schematic view of the prototype cavity.

3D electromagnetic simulation (CST) [4]. In this section, we explained the characteristics of each component.

The loop antenna was input coupler for the RF power. The RF power was input to the antenna through a N-type connector. The RF coupling of the loop antenna was set to be 1 with the rotation angle of 33 degree. To insert the antenna, the cavity had a hole whose radius was 7 mm. By inserting the antenna, the shunt impedance decreased to be 93 % of that without the loop antenna. The three tuners could push and pull the wall of the cavity with a range of ±0.2 mm. By moving all tuners, the resonance frequency was changed with a range of ±2 MHz. The RF de-coupler was designed to separate the resonance frequency of two TM110 modes. One was a horizontal deflection and the other was a vertical deflection. The RF de-coupler could decrease the resonance frequency of the vertical deflection to be 5.19 MHz, while it did not change that of the horizontal deflection. The RF monitor was a rod antenna to monitor the frequency of the TM110 mode. The RF signal was output through a SMA-type connector. The length of the rod antenna was decided so that the transmission coefficient of the rod antenna was −35 dB.

In Fig. 3, the external shape of the cavity was a simple Pill box shape and had no nose corn. These shapes were designed as simple as possible to simplify the production of the cavity. With the coupling hole and the simple shape, the estimated shunt impedance was same as the value shown in Table 2.

PRODUCTION AND PERFORMANCE EVALUATION OF THE PROTOTYPE CAVITY

Photo of the prototype cavity was shown in Fig. 4. The cavity was divided into three parts in order to simplify manufacturing and brazing. The loop antenna and RF monitor were weld on bases which were brazed on the center part of the cavity. Water pipes to warm the cavity were also brazed to front and rear side parts of the cavity. The radius of the cavity was 70 µm larger than that one with the resonance frequency of 5.2 GHz. Since the absolute value of the resonance frequency in the simulation was insecure, the external wall of the cavity was scraped after the measurement of the resonance frequency. The the cavity was produced by three steps: scraping of the external wall of the cavity, brazing of the cavity and a test in vacuum. In this section, we reported the production and performance evaluation of the prototype cavity along the production process.

Figure 4: Photo of the prototype cavity.

First, we mechanically compiled the cavity and measured the resonance frequency of the TM110 mode in the atmosphere. We connected the loop antenna and the RF monitor

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to a network analyzer, and measured their reflection coefficient and transmission coefficient. Figure 5 shows the measurement example of the reflection coefficient and transmission coefficient. A peak in each coefficient represented the resonance frequency of the TM110. We calculated the loaded Q of the cavity and the RF coupling of the loop antenna from the width of the reflection coefficient distribution. Using the loaded Q (Q_L) and the RF coupling (β), the unloaded Q (Q_0) is described as $Q_0 = (1 + \beta)Q_L$ since the RF coupling of the RF monitor was negligible small. The unloaded Q was used to estimate the transverse shunt impedance by multiplying itself to R/Q, which was calculated in the simulation. Since the R/Q should be only decided by the shape of the cavity, the estimated R/Q was expected to be reliable. After the measurement, we decided the scraping width of the cavity wall to make the resonance frequency near 5.2 GHz in vacuum of 35 °C. We estimated the change of the resonance frequency from the simulation. The radius of the cavity was scraped by three times. Total change of radius and resonance frequency was 71 µm and 10.45 MHz, respectively. While the estimated change of the resonance frequency was $10.20^{+0.31}_{-0.37}$ MHz and agreed well with the measurement.

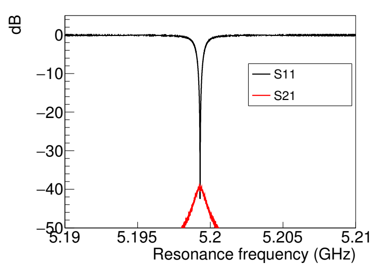

Figure 5: Measurement example of the reflection coefficient and transmission coefficient. Black line shows the reflection coefficient and red line shows the transmission coefficient.

After the scraping, all components were brazed by two steps. At the first step, the center part of the cavity was brazed with the rear part of the cavity, the three tuners, and the base to weld the loop antenna. At the second step, the front part of the cavity was brazed with the center part of the cavity and the base to weld the RF monitor. The water pipes were brazed on rear and front part of the cavity in each step. After the brazing, we adjusted the rotation angle of the loop antenna and rod length of the RF monitor by measuring the RF coupling and the transmission coefficient, respectively. Then, the loop antenna and the RF monitor were welded to the bases.

Finally, we checked an air leakage of the cavity in vacuum condition. The cavity was connected to a turbo pump and an air-leak detector through the beam hole. The degree of vacuum and the leak rate of was 3×10^{-6} P_a and 3×10^{-11} $P_a \cdot m^3/s$, respectively. There were no air-leakage in the vacuum test. In vacuum of 24.2 °C, we measured the reflection coefficient and transmission coefficient. The cavity parameters calculated from the measurement and that estimated from the simulation were shown in Table 3. The measured resonance frequency was 580 kHz smaller than that one expected. The resonance frequency was expected to be increased by 500 kHz after brazing, while that was decreased by 80 kHz after actual brazing. The resonance frequency was expected to be 5.2 GHz at 30 °C. We decided to use the cavity at 30 °C instead at 35 °C. In Table 3, the transmission coefficient was largely different from the expected value. We suspected that the input connector or antenna rod of the RF monitor was damaged in the vacuum test, since the transmission coefficient was −39.4 dB just after the welding. Nevertheless, we could measure the resonance frequency from the RF monitor and measured resonance frequency was stable. We decided to use the RF monitor without any treatment. Other cavity parameters were agreed well with the simulation. We succeeded to produce a new c-band cavity which satisfied our requirement to measure the bunch length.

Table 3: Comparison of the Cavity Parameters Between the Measurement and Simulation

Parameters	Measurement	Simulation
Frequency (GHz)	5.2005	5.2011
Transmission coefficient (dB)	-35.0	-58.2
Unloaded Q	14009	13981
Shunt impedance (MHz)	0.96	0.96
RF coupling	1.02	1.01

CONCLUSION

To measure the bunch length in the cERL, we newly developed a c-band deflecting cavity. The deflecting cavity was a single cell and normal conducting cavity. The deflection mode of the cavity was TM110. To achieve the time resolution of 33 fs, the resonance frequency of the TM110 mode was set to be 5.2 GHz and 12 cavities were expected to locate entrance of undulators. The RF power was input to the cavity by a compact loop antenna to prevent the decrease of the transverse shunt impedance. We produced the prototype of the cavity and evaluate its performance. The resonance frequency was 5.200 5 GHz in vacuum of 24.2 °C and estimated to be 5.2 GHz in vacuum of 30 °C. The transverse shunt impedance was estimated to be 0.96 MΩ by the expected R/Q and measurement of the unloaded Q. The time resolution was estimated to be 404 fs when the input RF power was 1 kW and the beam energy was 20 MeV. Using 12 cavities, we could achieve the time resolution of 33 fs.

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