VERTICAL TEST OF PEFP PROTOTYPE SRF CAVITY*

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Abstract

The PEFP Proton linac is a 100-MeV machine which consists of a proton injector, RFQ and DTL. For the extension of the machine beyond 100 MeV, SRF technology is under consideration. As a prototyping activity, a superconducting RF cavity with a geometrical beta of 0.42 and a resonant frequency of 700 MHz has been designed, fabricated and tested.

The cavity is an elliptical shape with 5 cells stiffened by double-ring structure. A design accelerating gradient is 8.0 MV/m at the operating temperature of 4.2 K and maximum duty factor is 9 %. For the vertical test of the cavity, a cryostat with vacuum jacket and multi-layer insulation was prepared. The RF system for driving the cavity is based on PLL to track the resonant frequency. In case of lack of RF power, a two-way RF power combiner based on split coaxial transmission line is considered. The details of the vertical test setup and test results will be presented in this paper.

PROTOTYPE CAVITY

To gain an experience and check the design concept, we developed the prototype cavity which has following design parameters [1].

- Frequency: 700 MHz
- Operating mode: TM010 PI mode
- Cavity shape: Elliptical
- Geometrical beta: 0.42
- Number of cells: 5
- Accelerating gradient: 8 MV/m @2.0K
- Epeak/Eacc: 3.71
- Bpeak/Eacc: 7.47 mT/(MV/m)
- r/Q: 102.3 ohm
- Epeak: 29.68 MV/m
- Field flatness: better than 8.0 %
- Cell to cell coupling: 1.41 %
- Geometrical factor: 121.68 ohm
- Cavity wall thickness: 4.3 mm
- Lorentz force detuning: 0.4 Hz/(MV/m)^2
- Stiffening structure: Double ring structure
- Effective length: 0.45 m

The geometrical beta of the prototype is 0.42, which is lower than that of the PEFP SC linac (0.50) and the number of cell in a prototype cavity is five, not six as for PEFP SC linac. These differences are because the transition energy from normal conducting section to superconducting section used to be 80 MeV, not 100 MeV at the very initial phase.

In an elliptical cavity with a reduced beta, mechanical stabilities are issues to be addressed, especially for a pulsed operation machine. We chose to attach double-ring stiffening structure around dumbbell in center cells to reduce Lorentz force detuning. In addition, the cavity wall thickness is 4.5 mm before chemical processing for better mechanical stability. The ANSYS simulation showed that the Lorentz detuning factor can be as high as 19.2 Hz/(MV/m)^2 with a single-ring stiffening structure, which is unacceptably high. By using double-ring stiffening structure with thick cavity wall, the Lorentz detuning factor can be reduced below 1 Hz/(MV/m)^2.

The diameter of the cavity is about 380 mm and total length including the NbTi flange is about 860 mm. There is no fundamental power coupler port or HOM coupler port to shorten the prototyping period as shown in Fig. 1.

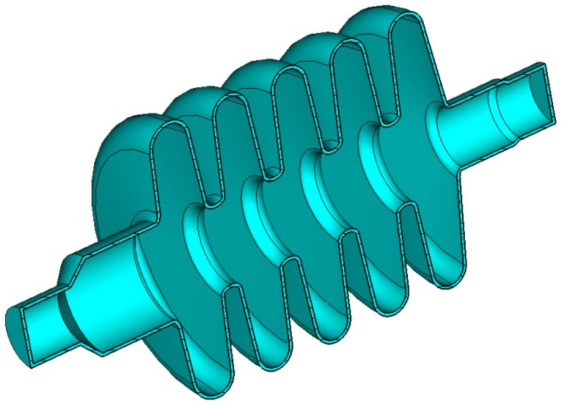

Figure 1: Five-cell prototype cavity.

CAVITY PREPARATION

The cavity fabrication mainly consists of the deep drawing process to make each components and the electron beam welding process to join them in one piece. We made the half cells with the deep drawing process [2].

After deep drawing, we trimmed the equator edge and iris edge to suitable length. In addition, the grooves on the outside wall of the half-cell are machined for welding the stiffening rings. The beam pipe transition parts were also fabricated by using similar deep drawing process.

We etched the surface of each part by using an acidic solution before every electron-beam welding process for better welding performance. The acidic solution consisted of HF, HNO_3 and H_3PO_4 with a volume ratio of 1:1:2. The etching rate was estimated to be about 2.5 μm/min, which was confirmed by several tests using specimens. After etching, each part was cleaned with DI water.

Following the etching, each part was joined by using an electron-beam welding process. Figure 2 shows the five-

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cell cavity with fixing jigs during the final equator welding step.

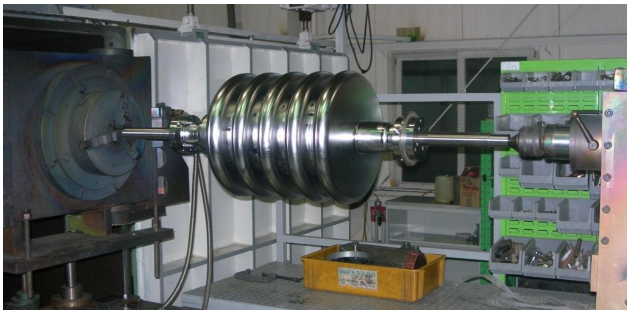

Figure 2: Electron-beam welding of five-cell cavity.

After the cavity fabrication, we tuned the cavity to make the field profile uniform along the beam axis. The field flatness used to express how uniform the field profile is in an N-cell cavity is defined as following;

$$\eta_{\mathrm{ff}} = \frac{V_{\mathrm{cmax}} - V_{\mathrm{cmin}}}{\frac{1}{N}\sum_{i=1}^{N} V_{\mathrm{c}i}} \times 100\% \cdot \tag{1}$$

Here, V_{ci} is the accelerating voltage of the ith cell. V_{cmax} and V_{cmin} is the maximum and minimum cell voltage in a cavity, respectively. The accelerating voltage in Eq. (1) can be expressed as a phase shift during a bead-pull test.

The initial field distribution was far from uniform. The fields in the 4th and the 5th cells were almost negligible compared with that in the 1st cell. Before applying the theory-based tuning algorithm, we performed a manual tuning based on the fact that the local field is increased by increasing the local frequency (stretching the cell) and vice versa. By manual tuning, we obtained a field distribution better than the initial profile. Following the manual tuning, we applied the perturbation theory and obtained an almost uniform field distribution after two iterations. The final field flatness is uniform within 4%, which is good enough, considering the requirement is about 8%. The inner surface of the fabricated cavity was treated through the standard buffered chemical polishing (BCP) process and the high pressure rinsing (HPR) process with ultra-pure water. Total material removal was estimated to be about 200 um during the surface treatment.

VERTICAL TEST PREPARATION

RF System

The RF system is based on the phase locked loop (PLL) to keep driving the cavity on resonance and to minimize the reflected RF power. The block diagram of the RF system for the vertical test is shown in Fig. 3. A vector signal generator (E4432B, Agilent) is used as VCO (voltage controlled oscillator). A phase comparator that generates a voltage signal proportional to the phase difference between the forward RF power and cavity RF power is used to drive the signal generator frequency modulation function. For adjusting the initial phase, a trombone-type phase shifter is used due to its large phase shift range (over 360 degrees at 700 MHz).

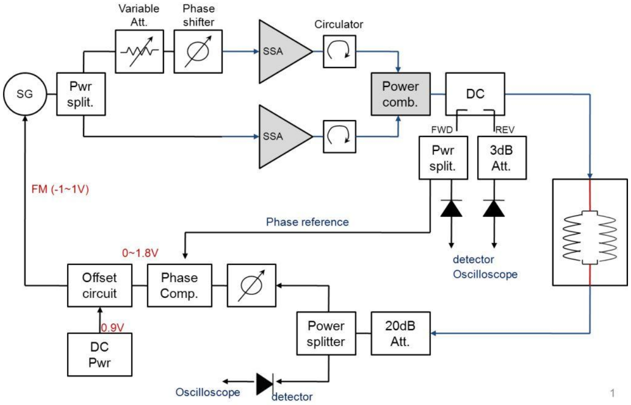

Figure 3: RF System setup for the vertical test.

To build up the accelerating gradient of 8 MV/m in the cavity at 4.2 K without proper magnetic shielding, the required RF power was estimated to be about 1 kW. However, RF amplifier with such a high output power was not available during the test phase. Instead, there are two solid state amplifiers which can provide RF power up to 200 W. Therefore, we designed, fabricated and tested a RF combiner. The RF combiner is a split coaxial type based on the geometry of 1-5/8 inch rigid coaxial line.

Figure 4 shows the fabricated RF combiner. The fabricated RF combiner was tested at low power level as well as high power level. Measured S11 parameter is better than -35 dB, which shows good impedance matching. The VSWR is lower than 1.02 at design frequency of 700 MHz and better than 1.05 within ±20 MHz range. The amplitude balance between two input ports was measured to be better than 0.06 dB and phase difference was less than 0.3 degree.

Figure 4: Fabricated split coaxial type RF combiner.

Cryostat

The height of the cryostat for the vertical test is about 2550 mm and the outer diameter is about 840 mm. The cryostat is double-wall structure and the space between the inner chamber and outer chamber is filled with 40 layers of the multi-layer insulation and evacuated down to

3E-07 Torr. The cryostat system is equipped with a liquid helium level monitor (LM-500, Cryomagnetics) and a temperature monitor (218E, Lake Shore). Total 10 layers of stainless steel plate of 1 mm thickness are adopted as thermal reflectors. The insert structure with a prototype cavity is shown in Fig. 5.

Figure 5: Insert structure with a prototype cavity.

TEST RESULTS AND SUMMARY

The overall experimental setup is shown in Fig. 6. It took less than 1 hour to reduce temperature from 77 K to below 5 K. About 350 L of liquid helium was consumed to lower the temperature of the cavity and surrounding structures. Total liquid helium consumption was about 2000 L.

RF power was applied in pulsed mode with 250 ms pulsed width and 2 Hz repetition rate (duty factor: 50 %). From the pulse mode measurement, we obtained the unloaded Q as function of Eacc, as shown in Fig. 7. At low power level, the measured Q was about 2.9E+8. The BCS resistance was estimated to be about 155 nΩ and the magnetic resistance was estimated to be about 126 nΩ at the earth's magnetic field level of 500 mG.

When the accelerating gradient is about 2.7 MV/m, which amounts to a 10 MV/m peak field, the Q value starts to decrease with noticeable increases in radiation level. This decrease may be due to field emission.

Figure 6: Overall test setup for the vertical test.

The maximum accelerating gradient was 4.2 MV/m with 330 W RF power, which was limited by the available RF power. During the test, we could observe the conditioning effect by noticing the increase of the Eacc and Q value at the same RF input power level. However, the conditioning is considered to be not sufficient due to the limited test time. With enough RF power and sufficient high-power conditioning, we expect the cavity to meet the design accelerating gradient of 8 MV/m.

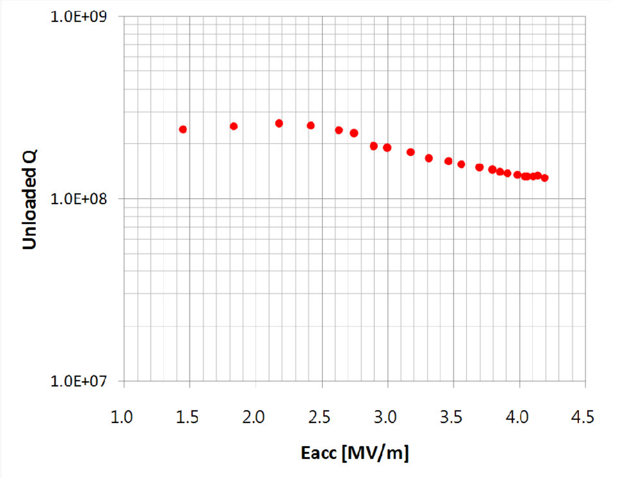

Figure 7: Unloaded Q vs. Eacc for the prototype cavity.

REFERENCES

[1] Sun An, Y. S. Cho and B. H. Choi, "PEFP Low-beta SRF Cavity Design", PAC'07, Albuquerque, 2007.

[2] H. S. Kim, H. J. Kwon, Y. S. Cho and Sun An, "Prototyping and Vertical Test for PEFP Low-beta Elliptical Cavity", SRF2009, Berlin, 2009.