PROTOTYPING ACTIVITIES OF LOW-BETA SRF CAVITY FOR THE PEFP PROTON LINAC EXTENSION

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Abstract

A superconducting RF cavity with a geometrical beta of 0.42 and a resonant frequency of 700 MHz has been under consideration for an extension program of Proton Engineering Frontier Project (PEFP) to accelerate the proton beam above 100 MeV. A five-cell prototype was fabricated and tested to confirm the fabrication procedure and to check the RF and mechanical properties. High RRR niobium sheets (RRR > 250) were used for the cavity material, whereas reactor grade niobium and NbTi were used for the beam pipe region and the flange, respectively. Double-ring stiffening structure was adopted to reduce the Lorentz force detuning effect. For the vertical test of the prototype cavity, a cryostat with operating temperature of 4.2 K was designed and fabricated. The cryostat was thermally insulated with 40 layers of MLI and the vacuum jacket and equipped with temperature monitors and liquid level sensors. The RF system for driving the cavity is based on PLL to track the resonance condition. The status of the prototype development and the vertical test results will be presented in this paper.

PROTOTYPE SRF CAVITY DESIGN

The operating frequency of the RFQ and DTL of PEFP linac is 350 MHz. Therefore, we chose the operating frequency of the SRF cavity as 700 MHz. In the previous study performed by PEFP, we developed the two-cell niobium cavity for prototyping purpose [1]. Based on the experience of developing the two-cell prototype, we designed the five-cell cavity which can be used as a PEFP linac extension. Because the beam energy of PEFP linac is 100 MeV, the design beta of the SRF cavity is 0.42, which is quite low for elliptical cavity shape. The major parameters of the prototype five-cell elliptical niobium cavity for PEFP are like followings.

- Frequency:	700 MHz
- Cavity type:	Elliptical
- Number of cell:	5 per cavity
- Geometrical beta:	0.42
- Accelerating gradient:	8 MV/m
- Epeak/Eacc:	3.71
- Bpeak/Eacc:	7.47 mT/(MV/m)
- R/Q:	102.3 ohm
- Epeak:	29.68 MV/m (1.21 Kilp.)
- Geometrical factor:	121.68 ohm
- Cavity wall thickness:	4.3 mm
- Stiffening structure:	Double ring
- Effective length:	0.45 m

The five-cell prototype cavity is composed of three parts; the center cells, a fundamental power coupler (FPC) beam tube and a field probe beam tube as shown in Fig 1. We adopted a double-ring stiffening structure to reduce Lorentz detuning effect. The diameter of the cavity is 379.02 mm and the total length including the NbTi flanges is 860.0 mm.

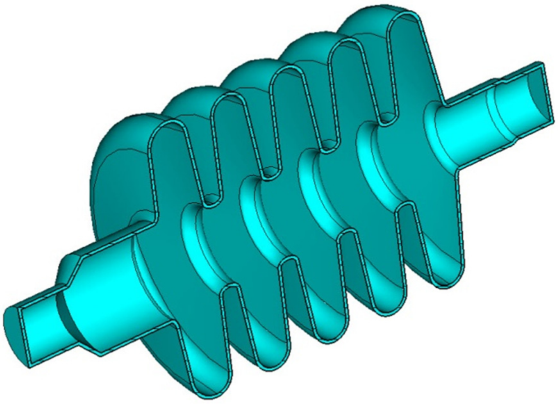

Figure 1: Five-cell elliptical cavity for PEFP.

FABRICATION OF CAVITY

Various processes such as machining, deep drawing and electron beam welding are required for fabrication of the elliptical cavity. Especially, we etched the surface of each part by using an acidic solution before every electron beam welding process. The acidic solution consists 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 um/min by using a specimen. The original niobium sheet thickness was 4.5 mm and after several etching steps, the final cavity wall thickness was reduced to 4.3 mm. After etching, each part was cleaned with DI water.

Following the etching, each part is joined by electron beam welding process. We tried many specimens to find out the optimum welding condition. Figure 2 shows the five-cell cavity with fixing jigs during the final equator welding step.

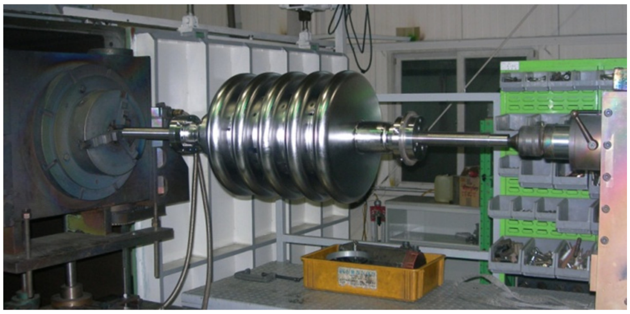

Figure 2: Electron beam welding process.

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After the cavity fabrication, we tuned the cavity to make the field profile uniform along the beam axis. The field profile was measured by using a standard bead-pull method and Slater's perturbation theory. The initial field measurement result is shown in Fig. 3. As can be seen from Fig. 3, the field distribution is far from uniform. The fields in a 4th and 5th cell are almost negligible compared with 1st cell field. Before applying the theory based tuning algorithm, we performed 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 initial profile. Following the manual tuning, we applied the perturbation theory and obtained almost uniform field distribution after twice iterations. The final measurement result is shown in Fig. 4. The final field flatness is uniform within ±4%, which is good enough considering the requirement is about 8%.

Figure 3: Initial field distribution.

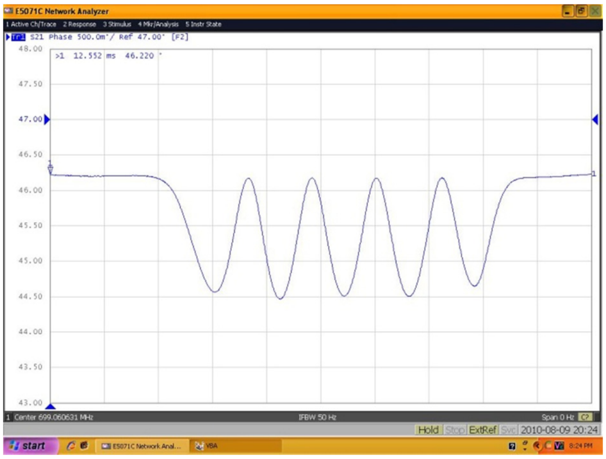


Figure 4: Final field distribution after tuning.

The inner surface of the fabricated cavity was treated through the standard BCP process and the high pressure rinsing (HPR) with ultra-pure water. The inner surface was inspected by using an endoscope. Figure 5 compares the inner surface condition at the electron beam welding region before and after BCP and HPR. Total material removal was about 200 um.

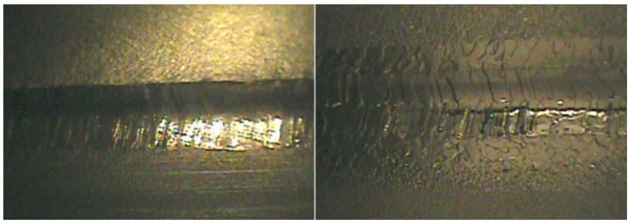


Figure 5: Inner surface condition at the welding region (left: Before BCP and HPR, right: After BCP and HPR).

VERTICAL TEST SETUP

To test the prototype five-cell cavity at low temperature, we prepared the cryostat and the RF system [2]. It is equipped with liquid helium and liquid nitrogen level meters (LM-500, Cryomagnetics) and the temperature sensors (218E, Lake Shore). The static heat loss is estimated to be about 12 W with superinsulation and vacuum jacket. Fig. 6 shows the prototype five-cell cavity installed in the insert of the cryostat.

The RF system is based on the phase locked loop (PLL) to main the cavity on resonance and to minimize the reflected RF power. The vector signal generator (E4432B, Agilent) is used as VCO (voltage controlled oscillator) and phase comparator which generates voltage signal proportional to the phase difference between the forward and cavity RF power is used to drive the signal generator frequency modulation function. The trombone type phase shifter is used due to its large phase shift range (over 360 degrees at 700 MHz).

Figure 6: Cavity installed in the insert of the cryostat.

TEST RESULTS AND DISCUSSION

To determine the power coupler length which makes critical coupling at low temperature, we measured the external Q value of the power coupler with varying the coupler length and compared the results with MicroWave Studio simulation as shown in Fig. 7. The power coupler length should be determined with care because the coupler used in this study was not the adjustable type. The measurement and simulations show reasonable agreement.

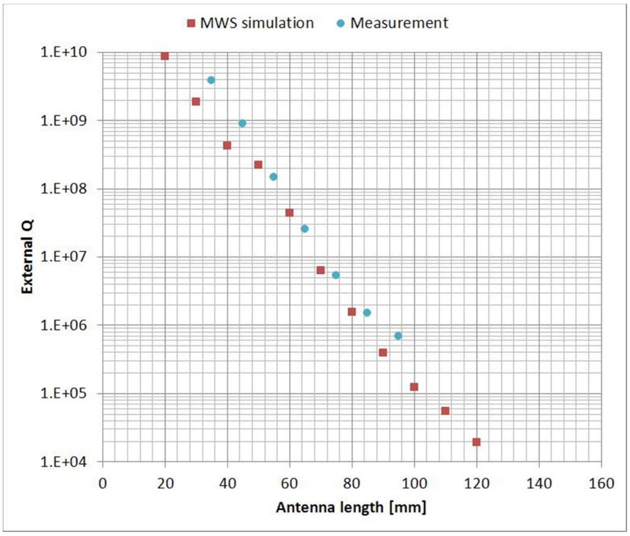
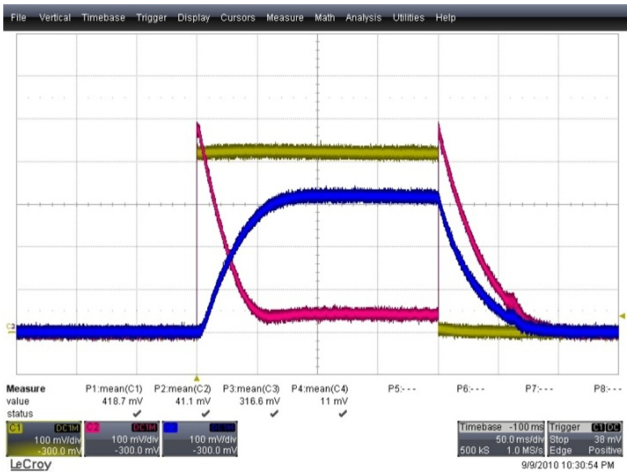


Figure 7: External Q of the RF power coupler.

The cavity was pre-cooled to 77 K by using liquid nitrogen of about 500 litters. After drain of the liquid nitrogen, the liquid helium was transferred to the cryostat. Total liquid helium consumption was about 1000 litters including cool-down process.

RF power was applied to the SRF cavity with pulsed mode up to 200 W, which was the maximum output power of the solid state amplifier. Pulse length was 200 ms. We measured the forward, reflected and transmitted RF power, respectively as shown in Fig. 8. Yellow, red and blue traces represent the forward power, reflected power and transmitted power, respectively.



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Measure   P1:mean(C1)  P2:mean(C2)  P3:mean(C3)  P4:mean(C4)   P5:- - -   P6:- - -   P7:- - -   P8:- - -
value        418.7 mV      41.1 mV     316.6 mV        11 mV
status              ✓            ✓            ✓            ✓
C1     DC1M   C2     DC1M          DC1M                       Timebase  -100 ms  Trigger     C1 DC
  100 mV/div    100 mV/div    100 mV/div                               50.0 ms/div  Stop      38 mV
  -300.0 mV     -300.0 mV     -300.0 mV                       500 kS    1.0 MS/s   Edge   Positive
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Figure 8: RF pulse waveform during the vertical test.

From the measurement, we obtained the unloaded Q versus Eacc as shown in Fig. 9. At low power level, the measured Q was about 2.9E+8. The BCS resistance at 700 MHz, 4.2 K is about 155 nΩ [3]. If we assume that the residual resistance is about 250 nΩ including magnetic resistance, total surface resistance is about 405 nΩ, which results in unloaded Q of about 3.1E+8.

When the accelerating gradient is about 2.5 MeV/m, which amounts to 10 MeV/m peak field, the Q value starts to decrease with noticeable increase in radiation level. This decrease is possibly due to the field emission. When the accelerating gradient is increased to about 3.2 MeV/m, the Q value is reduced to half of the initial value.

The maximum accelerating gradient was 3.2 MeV/m, which was limited by the RF amplifier output power. Note that this gradient was obtained without any conditioning, because the available liquid helium was not enough to perform the conditioning of the cavity. With enough RF power and some conditioning, it is expected that the cavity can meet the design specification without much difficulties.

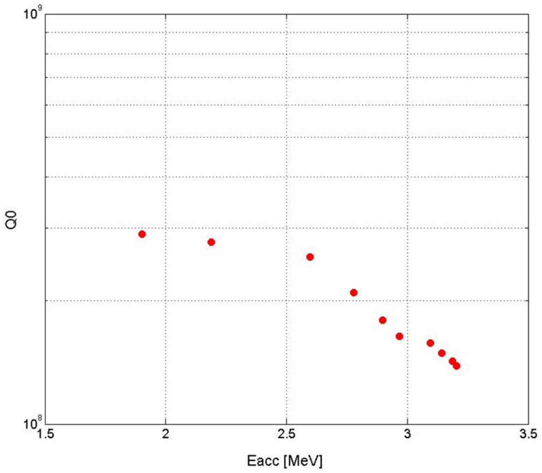

Figure 9: Unloaded Q versus Eacc.

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