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Geometric Optimization of the 56MHz SRF Cavity and its Frequency Table

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Abstract

It is essential to know the frequency of a Superconducting Radio Frequency (SRF) cavity at its "just being fabricated" stage because frequency is the key parameter in constructing the cavity. In this paper, we report our work on assessing it. We can estimate the frequency change from stage to stage theoretically and/or by simulation. At the operating stage, the frequency can be calculated accurately, and, from this value, we obtain the frequencies at other stages. They are listed in a table that serves to check the processes from stage to stage. Equally important is optimizing the geometric shape of the SRF cavity so that the peak electric-field and peak magnetic-field are as low as possible. It is particularly desirable in the 56MHz SRF cavity of RHIC to maximize the frequency sensitivity of the slow tuner. After undertaking such optimization, our resultant peak electric-field is only 44.1MV/m, and the peak magnetic-field is 1049G at 2.5MV of voltage across the cavity gap. To quench superconductivity in an SRF cavity, it is reported that the limit of the peak magnetic-field is 1800G [1], and that of the peak electric-field is more than 100MV/m for a SRF cavity [2]. Our simulations employed the codes Superfish and Microwave Studio.

1 Introduction

The function of the 56MHz SRF cavity is to compress the RHIC ion beam longitudinally. Hence, the voltage across the cavity is a critical parameter for its use. The higher the voltage, the better is the compression. RHIC applications require that the voltage is 2.5MV. However, voltage is limited by the peak magnetic- and electric-fields that a superconducting cavity can reach. Here we know that to quench superconductivity, the magnetic field must be more than 1800G. The electric field can be more than 100MV/m.

Another important parameter must be considered simultaneously, viz., the frequency sensitivity to the slow tuner's movement. Figure 1 shows the slow tuner. We require as high sensitivity as achievable, such that the slow tuner, with its limited physical-adjustment range, covers as much as possible of the frequency range. An increase in the slow tuner's sensitivity raises the frequency tolerance of the cavity. In this paper, we describe our studies to satisfy these criteria.

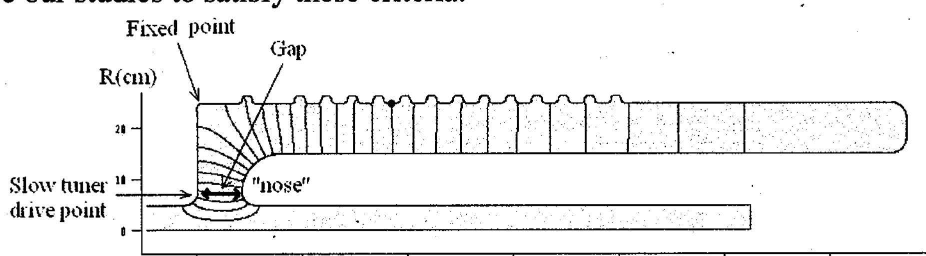

Fig.1 Geometry of the 56MHz SRF cavity

The maximum peak electric field can be lowered by decreasing the curvature of the surface at the location of the peak field, while the slow tuner's sensitivity is increased by decreasing the gap shown in Fig.1. Accordingly, we aimed to optimize the shape of the "nose" and the gap to reduce the ratio of the peak field to the accelerating field, and also increase the slow tuner's frequency sensitivity.

SRF cavities experience different physical processes, from their primary fabrication stage to their final operating stage. Since the 56MHz cavity is a Superconducting RF cavity and, therefore, has a very high Q. Its operating frequency can be controlled very accurately (<1Hz). The slow tuner's range is about ±8kHz around the operating point, and therefore, the frequency error of the fabrication stage should be smaller than this range. Thus, it is essential to know accurately the frequency of the cavity at its different stages. There are six stages from initially fabricating the cavity to operating it: 1. The cavity is fabricated: 2. the HOM dampers are installed; 3. the cavity is chemically cleaned and some of its material is lost; 4. the cavity is pumped down; 5. the cavity is cooled down and becomes the SRF cavity; and, 6, the slow tuner is adjusted to the operating point. The frequency varies in each of these stages. The changes are assessed either theoretically or by simulation. We can calculate the frequency at the operating stage accurately and so precisely derive the frequency at each stage.

2 The operating frequency

The speed of light is 299792458m/s. The RHIC's circumference is 3833.845m. We assume that the ion beam's energy is γ of 100, and the revolution frequency of one bunch is 78.19238076 kHz. Since there are 120 beam bunches in the ring, their frequency is 9.3830856912MHz. Then, the 56MHz cavity's frequency is 56.298514 MHz. Similarly, we calculate that the beam frequency is 56.299374 MHz for γ=120, and 56.296931 MHz for γ=80. The change in beam frequency is only 2.4 kHz from γ=80 to γ=120. For our optimization, we will assume that the beam frequency is 56.2985MHz. This frequency also is the cavity's resonance frequency.

3 Frequency change from stage to stage

The HOM dampers are installed from stage 1 to stage 2. Simulation by Microwave Studio yielded a frequency change in this step of 5.6 kHz/damper. Since we are going to use two dampers, the overall frequency will increase 11.2 kHz. We used the Microwave Studio because of the axial asymmetry of the HOM dampers.

From stage 2 to stage 3, the cavity is cleaned chemically, and it is assumed that there is a 100um thick material loss throughout the inside of the cavity. Simulation gives a frequency change of 15 kHz per mm of material loss (Superfish), so the frequency change in this step is 1.5 kHz.

There are two effects on the cavity from stage 3 to stage 4 where the air is pumped out. One reflects the deformation of the cavity due to the change in pressure. We found that the frequency change due to the deformation is -0.914Hz per mbar decrease of pressure in the cavity. Hence, the total frequency change from air to vacuum is 0.924 kHz.

Another effect is from the change of permittivity from air ($\varepsilon_{r(air)}$=1.00054) to vacuum ($\varepsilon_{r(vac)}$=1). This is estimated as follows:

$$f_{Vac} / f_{Air} = \sqrt{\varepsilon_r(air)} \approx 1.00027 .$$

That causes an increase in frequency of 15.2 kHz.

The cavity is cooled down to the temperature of liquid helium from stage 4 to stage 5, during which the cavity shrinks due to the thermal-expansion effect. We calculated the integrated thermal-expansion coefficient from room temperature (293K) to liquid-helium temperature (4.2K or 2K). The coefficient is found to be 0.00143. Therefore, the frequency change in this step is 80.5 kHz.

Before the last stage, the slow tuner is in a position where the cavity is detuned. This position also is the tuner's free-standing state. During this last step, the slow tuner is pulled out from its free-standing state and its frequency increases to the operating point. Simulation (Superfish) give a value of 17 kHz/mm for the frequency sensitivity due to the slow tuner's movement, assuming that the distance between the free-standing state to the operating point is 1.5mm. So, the frequency change in this step is 25.5 kHz.

4. The frequency table

Table 1, below, is the frequency table of the 56MHz SRF cavity derived from the above analysis.

Table 1

Status					Actions	Frequency [MHz]	Frequency change [kHz]
Operating position (0mm)	Cooling down (4.2K)	Vacuum	After chemical treatment	With 2 HOM dampers	[redacted]	56.2985	
Detune position (1.5mm)	Cooling down (4.2K)	Vacuum	After chemical treatment	With 2 HOM dampers	[redacted]	56.2730	-25.5 (17kHz/mm)
Detune position	Room temp.	Vacuum	After chemical treatment	With 2 HOM dampers	[redacted]	56.1925	-80.5 (α=0.00143)
Detune position	Room temp.	In air	After chemical treatment	With 2 HOM dampers	[redacted]	56.1934	0.9 From deformation
Detune position	Room temp.	In air	After chemical treatment	With 2 HOM dampers	[redacted]	56.1782	-15.2 From air to vacuum
Detune position	Room temp.	In air	Before chemical treatment	With 2 HOM dampers	[redacted]	56.1797	1.5 (-15kHz/mm)
Detune position	Room temp.	In air	Before chemical treatment	Without HOM dampers	[redacted]	56.1685	-11.2 (5.6kHz /damper)

It should be pointed that before the operating point and after the cavity is cooled to liquid-helium temperature, the fundamental damper is inserted into the cavity to allow the beam's frequency to surpass the cavity's frequency. This action might affect the cavity's resonance frequency but is deemed unimportant, as the Q is very small when it is inserted, and eventually it will be completely removed at operation. The error for each step is smaller than 1 kHz. The above parameters may vary depending on the final configuration. For example, three HOM dampers may be used instead of two, and then the frequency change in this step will be 16.8 kHz rather than 11.2 kHz.

5. Gap optimization

To optimize the cavity's geometry, we first explored the accuracy of the simulations. Fig.2 gives the results of simulations of the peak field a 56MHz cavity with the same geometry but with various mesh sizes. It reveals that the simulations converge when the mesh is smaller than 1mm. We used a 0.5mm mesh in our optimization.

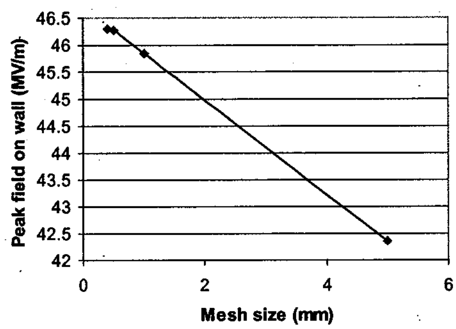

Fig.2 Peak-field results for the cavity with various mesh size

Our next step was to optimize the gap. In principle, keeping the voltage unchanged, then the smaller the gap is, the higher is the peak electric-field. . On the other hand, the smaller the gap becomes, the higher is the slow tuner's frequency sensitivity due to the increased capacitance. Fig. 3 shows that the peak field does not change much when the gap size is above 8.5cm. Fig.4 illustrates the rapid increase in the slow tuner's frequency sensitivity when the size of the gap is falling. We chose a gap of 8.5cm.

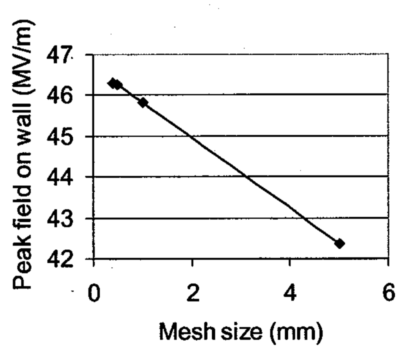

Fig.3 Peak electric-field on the cavity's wall as a function of the gap's size

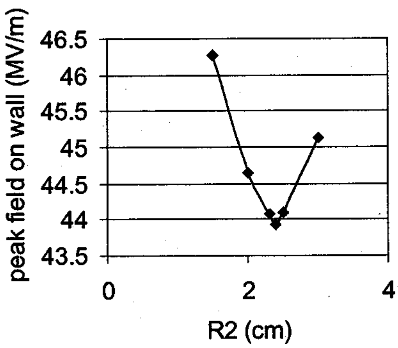

Fig.4 Slow tuner's sensitivity as a function of the gap's size

6. Optimization of the shape of the "nose"

Figure 5 depicts the shape of the "nose". In our optimization, we kept R1+R2 a constant. We first optimized the shape assuming that the upper half of the nose is an ellipse; the optimized result demonstrated that the shape actually is a circle.

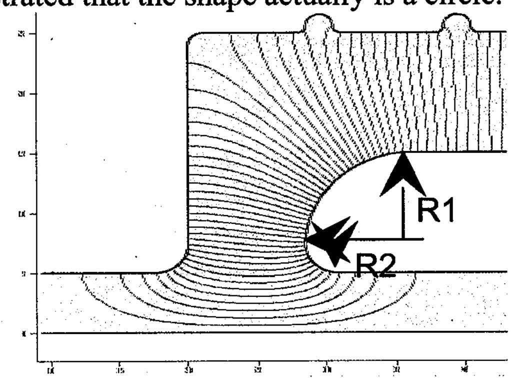

Fig.5 Peak electric-field vs. gap size

Fig.6 plots the peak electric-field as a function of the size of the radius, revealing that the optimized point is R2=2.4cm. However, this does not constitute a big difference to R2=2.5cm that we selected.

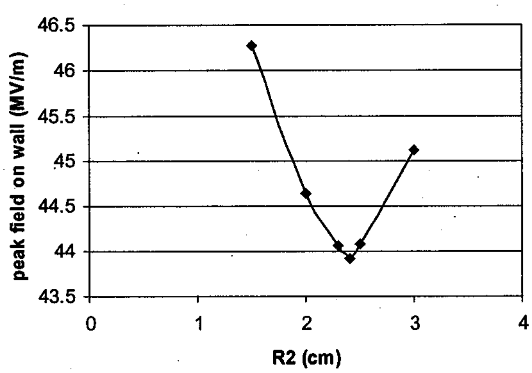

Fig.6 Peak electric-field as a function of the radius R2

The following lists some parameters of our optimized cavity.

Frequency	= 56.29903 MHz
Stored energy	= 214.43 Joules
Operating temperature	= 4.2000 K
Power dissipation	= 42.23 W
Q	= 1.796E+9
Shunt impedance	= 74002 MOhm/m
r/Q	= 81.95 Ohm
Maximum H (at Z,R = 151.27,14.97)	= 83483.4A/m
Maximum E (at Z,R = 30.12,12.15)	= 44.09 MV/m

7. Conclusion

We generated a frequency table by simulations and calculations. The error is expected to be within 1 kHz in each step calculation, and the final error is within the range of the slow tuner's frequency coverage. The frequency of the fabricated cavity should be 56.1685MHz under these present assumptions.

We optimized the cavity gap and the nose shape to achieve a low peak electric-field, and low peak magnetic-field, and a slow tuner with high frequency sensitivity. The resulting gap is 8.5cm, and the radii for the nose are 7.5cm for its upper part, and 2.5cm for its lower part. The peak electric field is 44.1MV/m at voltage of 2.5MV, and the slow tuner's frequency-sensitivity is 17 kHz/mm.

References:

[1] K. Saito, Proc. of the PAC.03, p.462, Portland, Oregon, USA, May12-16, 2003

[2] P. Kneisel, "LATEST DEVELOPMENTS IN SUPERCONDUCTING RF STRUCTURES FOR BETA=1 PARTICLE ACCELERATION", proc. of EPAC06, Edinburgh, Scotland, July, 2006