Frequency Control and Pre-tuning of a Large Aperture 500 MHz 5-cell Superconducting RF Cavity Postprint

Authors: TANG Zheng-Bo, MA Zhen-Yu, HOU Hong-Tao, MAO Dong-Qing, FENG Zi-Qiang, WANG Yan, Kai Xu, LUO Chen, Li Zheng, SHI Jing, LIU Jian-Fei

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Abstract

The 500 MHz 5-cell superconducting RF (SRF) cavity was designed aiming to be a candidate cavity for high current accelerators. A copper prototype cavity and a niobium cavity were fabricated at SINAP in 2012. In order to ensure these cavities get the desired frequency and a good field flatness higher than 98%, frequency control was implemented in the manufacturing process and pre-tuning has been done using a simple pre-tuning frame based on the bead-pull pre-tuning method. Then, TM010-π mode frequency within 5 kHz from the target frequency was achieved and the field flatness reached 98.9% on the copper prototype cavity. Finally, the same procedure was applied to the niobium cavity to obtain a field flatness better than 98% which benefited the cavity performance in the vertical testing.

Full Text

Preamble

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TANG Zheng-Bo (唐正博),[1],[2],[3] MA Zhen-Yu (马震宇),[1],[3] HOU Hong-Tao (侯洪涛),[1],[3] MAO Dong-Qing (毛冬青),[1],[3] FENG Zi-Qiang (封自强),[1],[3] WANG Yan (王岩),[1],[3] XU Kai (徐凯),[1],[3] LUO Chen (罗琛),[1],[3] LI Zheng (李正),[1],[3] SHI Jing (是晶),[1],[3] and LIU Jian-Fei (刘建飞)[1],[3],*

[1]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Jiading Campus, Shanghai 201800, China

[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Shanghai Key Laboratory of Cryogenics & Superconducting RF Technology, Shanghai 201800, China

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The 500 MHz 5-cell superconducting RF (SRF) cavity was designed as a candidate for high-current accelerators. A copper prototype and a niobium cavity were fabricated at SINAP in 2012. To ensure these cavities achieved the desired frequency and field flatness exceeding 98%, frequency control measures were implemented throughout the manufacturing process, and pre-tuning was performed using a simple fixture based on the bead-pull method. For the copper prototype, the TM010-π mode frequency was tuned within 5 kHz of the target, and the field flatness reached 98.9%. The same procedure was then applied to the niobium cavity, yielding field flatness better than 98%, which significantly improved its performance in vertical testing.

Keywords: Superconducting RF cavity, Frequency control, Pre-tuning, Field flatness, Bead-pull method
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INTRODUCTION

II. FREQUENCY CONTROL

For multi-cell superconducting RF (SRF) cavities, machining errors during deep-drawing introduce slight shape variations among cells, causing resonant frequency deviations from design and non-uniform accelerating electric field amplitudes. This leads to several problems: the accelerating field E_{acc} cannot be maximized, and the peak surface electromagnetic fields E_{peak} and B_{peak} cannot be minimized. These issues can be addressed through comprehensive frequency control during manufacturing and final pre-tuning procedures.

Frequency control is an essential aspect of SRF cavity production. Pre-tuning regulates both the resonant frequency and field strength distribution within the cavity, providing an effective means to achieve a uniform, ideal field profile and resonance at the desired frequency. The bead-pull method is widely adopted for pre-tuning various types of SRF cavities [?, ?, ?].

The 500 MHz 5-cell SRF cavity operates at a lower frequency than 700 MHz and 1.3 GHz cavities, which translates to lower BCS surface resistance at the same temperature, a larger aperture, and a longer accelerating gap. These characteristics offer advantages including reduced cryogenic heat load, lower high-order mode power, and a higher beam current threshold, making it a promising candidate for high-current, compact linear accelerators. However, fabricating and pre-tuning such a large cavity presents significant challenges.

The operating frequency of the 5-cell SRF cavity is 499.65 MHz at 4.2 K. The cavity geometry and length fundamentally determine its frequency and partially affect assembly to the cryostat. Therefore, frequency must be precisely controlled throughout the entire manufacturing process, including trimming, electron beam welding (EBW), mechanical barrel polishing, buffered chemical polishing (BCP), and other steps.

For the 500 MHz 5-cell cavity [**?**], based on experience developing a 500 MHz single-cell cavity, the TM010-π mode frequency at room temperature after EBW should be 498.8 MHz to achieve 499.65 MHz after cryostat assembly. The straight section on the equator of each single-cell could be adjusted to tune the frequency. CST simulation results showed that the TM010-0 mode frequency varied identically to the TM010-π mode (Fig. 1 [Figure 1: see original paper]). Therefore, we employed a straightforward method to control the TM010-π mode frequency by controlling the TM010-0 mode frequency. Frequency measurements were performed on two assembled half-cells rather than on an EBW dumbbell. The straight section on the end cell was modified in length to regulate field flatness. The EBW copper cavity exhibited a TM010-π mode frequency of 497.62 MHz and field flatness of $(91.7 \pm 0.6)\%$ before pre-tuning. The frequency deviation from the target value was within 1.2 MHz, which was corrected during the subsequent pre-tuning process.

III. PRE-TUNING

A. Review on Pre-tuning Theory

The first step in pre-tuning involves calculating the field flatness and the required frequency adjustments for each cell. When a metal bead passes through the cavity axis, the TM010-π mode electric field relates to the perturbation according to [**?**]:

$$E^2 \propto \Delta f \propto \tan(\Delta\phi)$$

where $\Delta\phi$ is the phase shift of S_{21} and Δf is the TM010-π mode frequency excursion of the cavity. By measuring Q_L and $(\Delta\phi_{max})_i$ (where $i = 1, 2, \ldots, N$ is the cell number), one obtains the maximum phase shift of Cell i, $(\Delta f_{max})_i$, and the relative $(E_{max})_i$. Substituting $(E_{max})_i$ into Eq. (2) yields the field flatness f_f:

$$f_f = \frac{\sum_{i=1}^{N} (E_{max})_i}{N} \times 100\%$$

The frequencies needed to tune each cell [**?**] can be calculated using Eq. (3):

$$(\Delta f_{tune})_i = \Delta f_\pi + (\Delta f_c)_i$$

where $\Delta f_{tune} = (f_{\pi}^{desired} - f_{\pi}^{measured})/N$, $f_{\pi}^{desired}$ and $f_{\pi}^{measured}$ are the desired and measured frequencies of the TM010-π mode, respectively, and $(\Delta f_c)_i$ is related to $f_{\pi}^{measured}$ and $(\Delta f_{max})_i$.

Pre-tuning a cell is a physical procedure involving axial squeezing or stretching of the cells to be tuned. Squeezing a cell lowers its resonant frequency, while stretching increases it. Thus, by pushing or pulling cells, the resonant frequency can be tuned to the desired value and a good field distribution can be obtained.

B. Establishing Pre-tuning Frame

A pre-tuning fixture based on the bead-pull method was applied to the 500 MHz 5-cell cavity. Fig. 2 [Figure 2: see original paper] shows the schematic diagram, which includes field distribution data acquisition and cavity frequency tuning. The hardware (Fig. 3 [Figure 3: see original paper]) consists of a perturbation bead, computer, vector network analyzer (VNA), step motor and controller, etc. The software comprises hybrid LabVIEW and MATLAB codes. The LabVIEW code handles data acquisition between the VNA and computer, as well as step motor control, while the MATLAB code performs calculations. In this pre-tuning fixture, the VNA is set to continuous wave mode [**?**] at the unperturbed TM010-π mode frequency, and the step motor moves at constant speed so the perturbation bead passes through each cell uniformly at fixed frequency. The phase shift as the bead passes through each cell is obtained from the S_{21} curve.

C. Pre-tuning of the Copper Prototype Cavity

Before fabricating the niobium cavity, a copper prototype was built to explore fabrication procedures and develop measurement techniques. The pre-tuning process on the Cu cavity revealed that $f_{\pi}^{measured}$ was 497.618 MHz, with the resonant frequencies of Cells 1, 2, 3, 4, and 5 being lower than the target by 0.181 MHz, 0.271 MHz, 0.256 MHz, 0.297 MHz, and 0.163 MHz, respectively. With frequency control, the copper cavity achieved field flatness of $(91.7 \pm 0.6)\%$ and a frequency deviation of 1.2 MHz from target. The strong cell-to-cell coupling ($k_{cc} = 3.18\%$) due to the cavity's large aperture and the deep-drawing technology employed also played important roles.

Cell-by-cell regulation is a straightforward pre-tuning approach [**?**, **?**]. For the 500 MHz 5-cell copper cavity, Cells 2, 3, and 4 had similar Δf_{tune} values with differences of only 0.041 MHz, while Cells 1 and 5 were over 0.1 MHz lower in Δf_{tune} than the other cells. We attempted two tuning methods. The first involved squeezing Cells 1 and 5 to increase their Δf_{tune} to 0.27 MHz to achieve field flatness better than 98%, followed by stretching the entire cavity to raise the TM010-π mode frequency to 498.8 MHz. However, after 600 °C annealing, the copper cavity became very soft. When stretching the whole cavity, deformation occurred in Cells 1 and 5, and the field flatness decreased to about 92%.

The second method involved pulling the entire cavity from 2221 mm to 2229 mm to reach 499.1 MHz, slightly above the desired frequency (Fig. 4 [Figure 4:

see original paper]), followed by pushing Cells 1 and 5 to tune the frequency to 498.8 MHz and achieve field flatness better than 98%. This approach yielded field flatness of 98.9% and a TM010-π mode frequency of 498.798 MHz, just 2 kHz below the desired frequency. The electric field distribution profile in Fig. 5 [Figure 5: see original paper] was uniform, showing excellent agreement with simulation results [**?**]. After pre-tuning, the total length of the copper cavity returned to 2224 µm. The five TM010 mode frequencies measured by VNA after pre-tuning are given in Table 1 .

D. Pre-tuning of the Niobium Cavity

The pre-tuning results from the copper cavity provided a solid foundation for the niobium cavity. For the 500 MHz 5-cell niobium cavity before pre-tuning, $f_{\pi}^{measured}$ was 497.754 MHz, with the resonant frequencies of Cells 1, 2, 3, 4, and 5 being lower than the target by 0.131 MHz, 0.241 MHz, 0.223 MHz, 0.221 MHz, and 0.225 MHz, respectively, and the field flatness was only 78.6%. It was pre-tuned similarly to the copper cavity. However, after 680 °C annealing, the niobium cavity remained quite hard, making plastic deformation difficult to achieve through manual squeezing or expanding. Therefore, we decided to squeeze only Cell 1 to improve field flatness and forego frequency adjustment. The tuning process is shown in Fig. 6 [Figure 6: see original paper]. Eventually, the field flatness was tuned to 98.5%, and the TM010-π mode frequency was 497.728 MHz, i.e., 1.1 MHz lower than the desired frequency.

After pre-tuning, vertical testing of the niobium cavity was performed on December 17, 2012. A good result of $V_{acc} = 7.5$ MV at $Q_0 = 1 \times 10^9$ was achieved. The TM010-π mode frequency was approximately 498.3 MHz at 4.2 K.

IV. CONCLUSION

A large-aperture 500 MHz 5-cell SRF cavity was designed and fabricated at SINAP. Frequency control was considered from the outset, ensuring the EBW cavity had a frequency deviation of less than 1.2 MHz. Both the copper prototype and niobium cavity were pre-tuned using the established apparatus, achieving field flatness better than 98%, compared to only 78% before pre-tuning the niobium cavity. The frequency control and pre-tuning procedures helped ensure excellent performance in the cavity's final vertical testing.

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