EFFECT OF THE TUNER ON THE FIELD FLATNESS OF SNS SUPERCONDUCTING RF CAVITIES

An Sun, Oak Ridge National Laboratory, Oak Ridge, TN 37830*
Haipeng Wang, Genfa Wu, Jefferson Lab, Newport News, VA 23606#

Abstract

The field flatness (FF) in a multi-cell superconducting cavity affects not only net accelerating voltage, but also peak surface field [1] and Lorentz detuning coefficient [2]. Our measurements indicate that the tuner's motion changes not only the cavity frequency but also its FF. This field amplitude change is a linear tilt and proportional to the distance between each cell center and the cavity's geometric center. This tilt also changes the coupling of the Fundamental Power Coupler (FPC) and Field Probe (FP) on either side of the cavity. The tilt has been measured and simulated, and is ~20%/MHz on the Spallation Neutron Source (SNS) medium β cavities. The FF change is not only due to the uneven volume change within the cell, but also due to the cell-to-cell coupling.

INTRODUCTION

The FF in a multi-cell cavity can be derived from its original definition [2].

$$\eta_{ff} = \frac{E_{c\max} - E_{c\min}}{\frac{1}{N}\sum_{i=1}^{N} E_{ci}} \times 100\% \qquad (1)$$

Here E_{ci} is the peak axial electric field in the *i*th cell.

The FF specification for SNS production cavities is less than 8%. The FF was tuned after manufacture at ACCEL and qualified at JLab by the bead-pulling measurement during the cavity tuning. After final cavity etching and rinsing, there is no way to check or correct the FF.

The SNS cavity tuner uses a stepper motor to drive a tuner frame. The frame is seated on the one end of the helium tank to compress the cavity end dish [3]. The resulting frequency tuning range is ~±245kHz for an axial spring distance of 1.8mm.

From our cold (2K) cryomodule measurement, we found that when the tuner changes the cavity's frequency, it also changes the external Q of both fundamental power coupler (FPC) and field probe (FP). After excluding other causes, we concluded that it relates to the relative RF field change at each end cell or the FF has been altered. A later warm bead-pulling measurement and numerical simulations confirmed this speculation.

MEASUREMENT IN CRYOMODULE

The measurements were done on a medium β cryomodule in the Cryomodule Test Facility at JLab. The power transfer function from FPC to FP can be measured by the S21 parameter on a network analyzer. With a stable cryogenic system and a well matched circuit, a -3dB bandwidth of the |S21| resonance peak can lead to a relatively accurate measurement of the external Q of the FPC, (Q_{eFPC}) which is the lowest Q for the coupled superconducting cavity.

Only a relative measurement on S21 is needed [2] to get the external Q of FP Q_{eFP} in order to get the relative FF information.

$$\frac{Q_{eFP}}{Q_{eFP0}} = \frac{Q_{eFPC}}{Q_{eFPC0}} \cdot 10^{\frac{S21-S21_0}{10}} \qquad (2)$$

Here subscript 0 corresponds to the values at the operation frequency of f_0=805MHz. Figure 1 shows this measurement data. It indicates that the field amplitude decreases at the FPC-end cell and increases at the FP-end cell, when the cavity frequency is increased by the tuner stretching the cavity. Supposing the cavity FF (η_{ff}) is perfect at f_0=805MHz (η_{ff}=0), and the electric field tilt is a linear function of frequency as the fits illustrate in Figure 1, then the FF can be expressed as:

$$\eta_{ff} = \frac{\left|\sqrt{Q_{eFPC0}/Q_{eFPC}} - \sqrt{Q_{eFP0}/Q_{eFP}}\right|}{\sqrt{Q_{eFPC0}/Q_{eFPC}} + \sqrt{Q_{eFP0}/Q_{eFP}}} \times 200\% \qquad (3)$$

Figure 2 shows this calculation from Figure 1's data. The FF change can be estimated as ~20%/MHz.

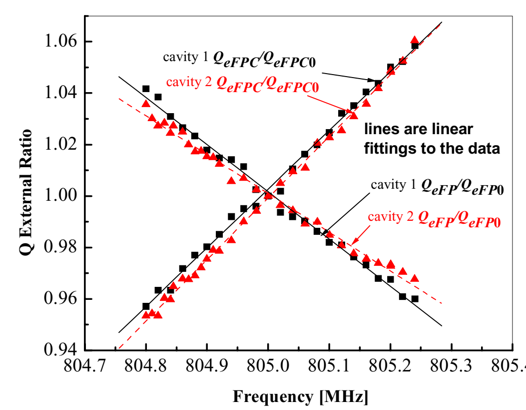

Figure 1: The relative external Q changes on FPC and FP measured on a medium beta cryomodule operated at 2K when tuner changes the cavity frequency.

BEAD-PULL MEASUREMENT

To verify the above result, we did a bead-pull experiment on cavity MB-19 with attached helium vessel to measure axial electric field profiles. To measure the helium vessel effect, we performed the bead-pull on

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cavity MB-29 without the helium vessel. Tuner frames were then installed on both of them. A 3mm needle was used as a bead in all cases.

The phase angle change of S21 (*arg(S21)*) due to the needle's perturbation in the time domain were measured using a network analyzer. The coupling of input and pickup antennas was weak enough not to perturb the end-cell fields. A ~35dB gain preamplifier was needed for a signal strong enough to maintain phase lock. When the needle is short enough, the *arg(S21)* range can be controlled within a few degrees. Figure 3 shows this bead-pulling result. Then the FF can be approximated [2] by:

$$\eta_{ff} = \frac{\sqrt{-\arg(S21)_{max}} - \sqrt{-\arg(S21)_{min}}}{\frac{1}{N}\sum_{i=1}^{N}\sqrt{-\arg(S21)_i}} \times 100\% \quad (4)$$

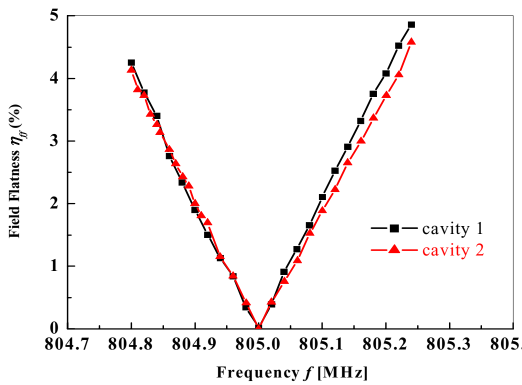

Figure 2: Measured FF changes calculated by Equation (3) from Figure 1's data.

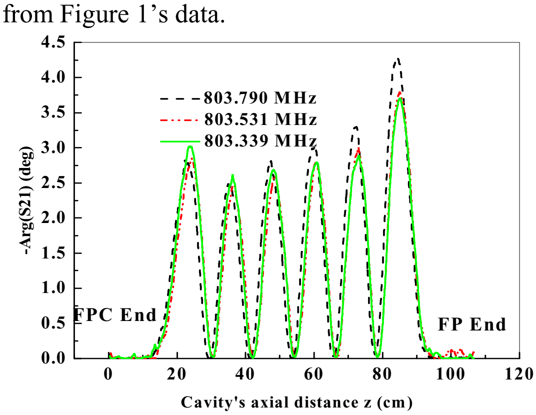

Figure 3: The bead pulling measurement on MB-19 cavity to measure the electric stored energy profile along the cavity beam axis.

As illustrated in Figure 4, the field tilt rate agrees with the cryomodule measurement The results on the MB-29 cavity were similar to those for the MB-19 cavity, but the FF change was ~17.2%/MHz.

NUMERICAL SIMULATIONS

To further understand the mechanism for the FF change, the ANSYS code was first used to calculate the cavity shape deformation when the tuner compressive force is applied. The actual displaced cavity shape and original shape were input into the SUPERFISH code. Using the option "MODT36=1" in the AUTOMESH program, SUPERFISH can calculate newly tuned cavity resonance frequency and field profile precisely.

The cavity frequency is a linear function of the cavity longitudinal deformation. The coefficient is 296 kHz/mm. The bead-pulling result is ~276 kHz/mm. Figure 5 shows the field profile from these simulations.

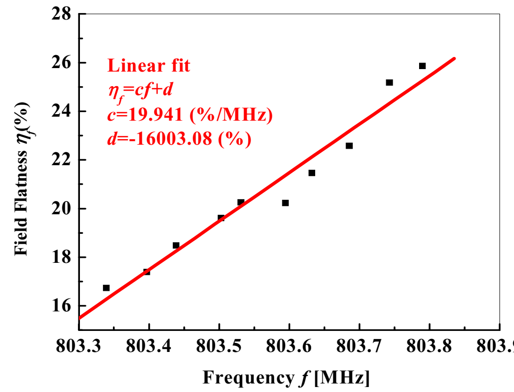

Figure 4: The MB-19 cavity's FF measured by the bead pull. The initial FF was 26% before the tuner compressed the cavity.

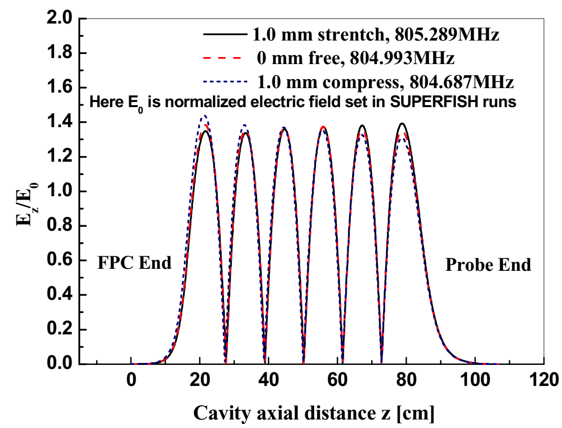

Figure 5: The cavity axial electric field profiles using ANSYS and SUPERFISH simulations.

To study the relative field amplitude change within each individual cell and the cell-to-cell coupling effect, we use the ratio of perturbed field amplitude E_c to its original value E_{c0} at a given frequency. Figure 6 shows the result. It can be seen that the end cells have a relatively larger change rates than the center cells. The E_{ci}/E_{ci0} ratio is nearly prefect (1.0) at f_0=805MHz.

From Figure 6, we can conclude and rewrite the E_{ci}/E_{ci0} as a linear function of frequency. The coefficient $\xi(i)$ is linear with cell number (i) as well. It is also the FF change rate.

$$E_{ci}/E_{ci0} = \xi(i)f + \eta_i , \quad (5)$$

As depicted in Figure 7, the line pivot is at the structure center (including the beam pipe lengths) but not at any cell center. Interesting enough in the simulation is that Figure 8 would not be a symmetric "V" shape if the bottom of "V" was higher than 2% [2].

To study the cell-to-cell coupling effect on the FF, we used the ANSYS APDL (and Excel) to calculate the cavity volume deformation as a function of cavity axial distance z (Figure 9). We found that the larger deformation in the iris area is the major cause to the frequency change. We integrated the cavity volume change with the energy densities on the wall from SUPERFISH (before compression). The relative stored energy changes in each cell can be obtained (Figure 10). Comparing the relative electric field amplitudes indicates that if we treat a multi-cell cavity as the individual uncoupled cavity cells, the relative stored energy changes by the volume deformation, both electric and magnetic, are not mainly responsible for the FF change of the cavity field. Instead the cell-to-cell coupling plays a major role.

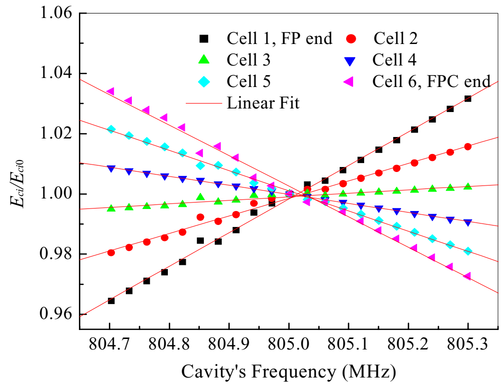

Figure 6: The relative field amplitude change within each individual cell simulated by the ANSYS and SUPERFISH.

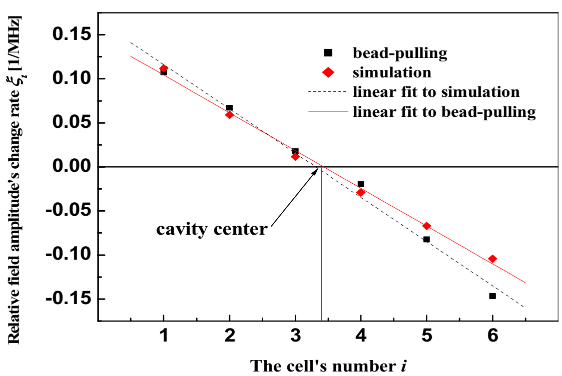

Figure 7: Linear relationship representation of Figure 6 and Equation 5.

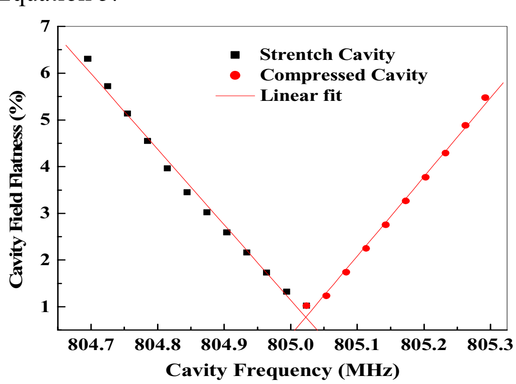

Figure 8: The simulation results of FF change with tuner-tuned frequency. The initial FF at free status is 1.32%.

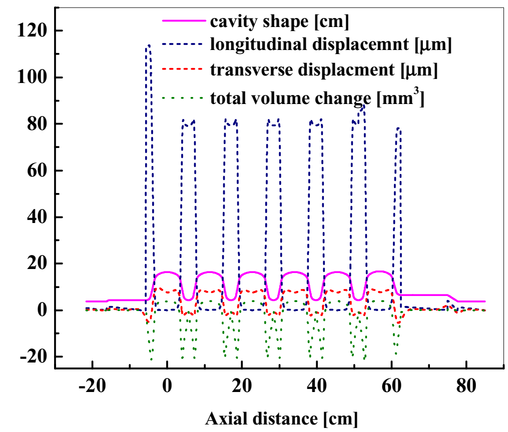

Figure 9: Cavity deformation calculated by ANSYS (and Excel) under a 1.0 mm longitudinal compression.

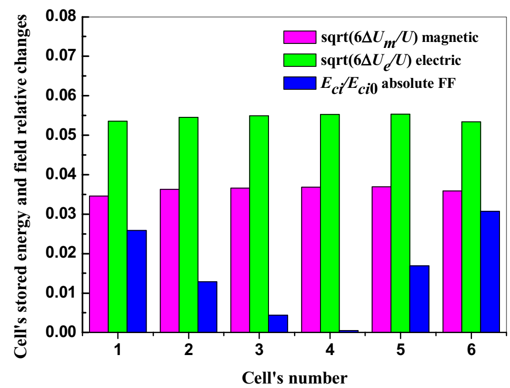

Figure 10: Cavity cell relative electric and magnetic stored energy changes by cavity deformation only after tuner compressed 1.0 mm.

GUIDE TO CAVITY TUNING PROCESS

Based on our analysis above, we can use Equation (5) to estimate the cavity FF change due to the tuner's preload and move into the operation position. We can intentionally over tune the field tilt in the cavity tuning procedure to compensate this later tuner effect.

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