MODE SENSITIVITY ANALYSIS OF 704.4 MHZ SUPERCONDUCTING RF CAVITIES*

K. Papke †[1,2], S. Papadopoulos[1], S. Horvath-Mikulas[1], E. Pilicer[1], F. Pillon[1], F. Gerigk[1]
and U. van Rienen[2]
[1]CERN, Geneva, Switzerland
[2]University of Rostock, Rostock, Germany

Abstract

Due to the large variety of beam patterns considered for the superconducting proton linac (SPL) at CERN it is likely that the frequencies of some higher order modes (HOM) are close to machine lines during operation. Hence, in the interest of developing a method to shift HOM frequencies away from machine lines, we study the influence of cavity detuning and retuning (e.g. by field flatness tuning and frequency tuning during operation) on HOMs. The sensitivity of HOMs with respect to the fundamental mode was studied for a mono-cell and for five-cell high-beta SPL cavities operating at 704.4 MHz. First, the variation of the HOMs during the flat-field tuning was measured. In this process, several detuning and retuning cycles were made to estimate the range of residual HOM frequency shifts. Secondly, the effect of the frequency tuner on the HOMs is presented and finally the frequency shifts of all modes due to the cool-down.

INTRODUCTION

The SPL linac [1] is composed of two types of five-cell cavities (geometrical beta = 0.65/1.00) operating at 704.4 MHz in pulsed mode. As the linac allows a large variety of beam patterns, HOMs may easily drive instabilities. Thus, they have to be damped or shifted away from machine lines in order to avoid a resonant build-up. This paper focuses on the latter option and discusses its possibilities and limits for the high beta SPL cavities [2]. We study the influence of cavity detuning and retuning on HOMs as well as their sensitivity with respect to the fundamental mode using the tuning bench shown in Figure 1.

For the sake of simplicity, only the modes with the highest R/Q (Table 1) are shown. The tuning bench allows to compress and to lengthen the SPL mono-cell [2] and each cell of the five-cell cavity individually. In order to lengthen the mono-cell or the end cells of the multi-cell cavity, the setup shown in Figure 1 needs to be changed. One or both tuning wall(s) have to be connected to the beam pipe flanges, which leads to a traction not only of the cell but also of the beam pipe. Thus, the measurements of deformation between compression and traction are not comparable in these cases as we measure deformations always via the cavity length (see displacement sensors in Fig. 1). A direct measurement of the cell deformation using displacement sensors at the cell irises was not possible.

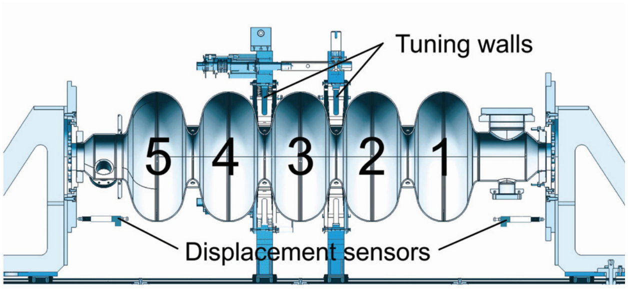


Figure 1: Setup of the tuning bench for a 5-cell SPL cavity.

In the following we present the detuning and retuning tests carried out with a mono-cell made of niobium and a five-cell cavity made of copper. Afterwards the frequency shift of HOMs during a tuner test is discussed and finally the effect of cool-down on the mode spectrum.

Table 1: Modes with High R over Q Values for the High-beta SPL Cavity [3, 4]

Monopole modes			Dipole modes		
Type	f [MHz]	R/Q [Ω]	Type	f [MHz]	$R/Q_\perp$ [Ω]
$\mathrm{TM}_{010}\pi$	704.4	566	$\mathrm{TE}_{111}3/5\pi$	915	57
$\mathrm{TM}_{011}4/5\pi$	1322	39	$\mathrm{TE}_{111}4/5\pi$	950	60
$\mathrm{TM}_{011}\pi$	1331	140	$\mathrm{TM}_{110}3/5\pi$	1014	36
TM_{021}	2087	10	$\mathrm{TM}_{110}4/5\pi$	1020	25
TM_{021}	2090	21	Hybrid	1409	20
$\mathrm{TM}_{022}\pi$	2449	9			

MONO-CELL CAVITY

The cavity was first compressed plastically by 0.23 mm using the setup in Figure 1 (tuning walls at the irises of the cell). The value of 0.23 mm corresponds to the pressure limit of the tuning bench at that time. Afterwards, the cell was lengthened plastically (tuning walls fixed at the beam pipe flanges) until the original frequency was restored. The results of the complete compression and traction cycle are depicted in Figure 2. Due to the different setup, the deformation is not equal to the cell deformation in the traction

---

* Work supported by the Wolfgang-Gentner-Programme of the Bundesministerium für Bildung und Forschung (BMBF)

† kai.papke@cern.ch

range because the beam pipe underlies stresses, too. Therefore we have chosen the frequency shift of the fundamental mode (TM_{010}) for the x-axis instead of the deformation. After retuning, the fundamental mode had a residual frequency difference of only 20 kHz whereas the interesting HOMs were still shifted by several hundreds of kHz and even up to 1.6 MHz for the TM_{021} mode. Only the TM_{110} dipole mode was less sensitive to deformations.

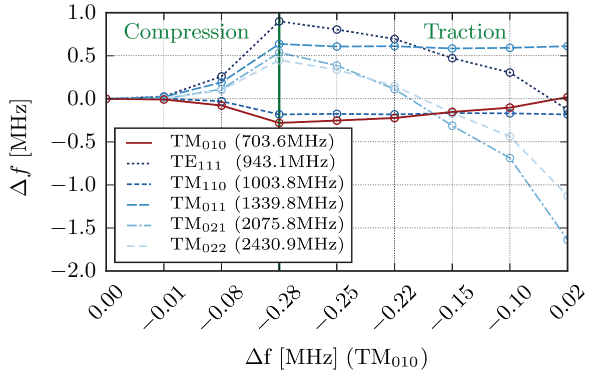


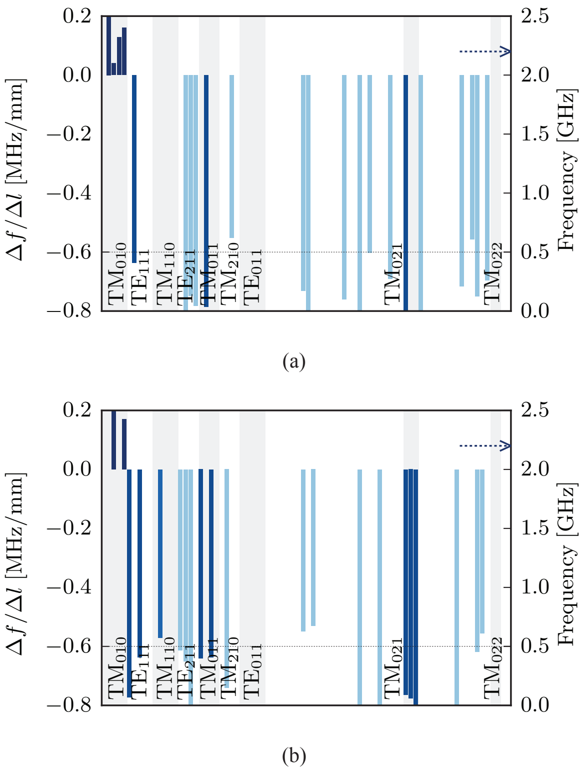
Figure 2: Frequency shift of HOMs for the SPL mono-cell during detuning (compression) and retuning (traction) in comparison to the frequency shift of the TM_{010} mode.

FIVE-CELL CAVITY

The following tests were carried out on a SPL five-cell cavity made of copper [2] with an initial field flatness of 1.3 %. The tests were performed only for the three middle cells to avoid any change of the setup between compression and traction in contrast to the mono-cell test. Each cell was detuned and retuned several times, increasing the detuning step-wise up to a maximum of 1.5 mm plastic deformation. The tuning bench is equipped with a bead pull system to measure field flatness and to determine the required change in resonance frequency for each cell in order to tune the fundamental mode [5]. It turned out that the field flatness recovers well inside a range of 2 % to 3 % after detuning and retuning the same cell even for deformations up to 1.5 mm. The mode spectrum was measured at all detuned and retuned states, allowing conclusions about mode sensitivities and frequency shifts due to deformations as discussed in the following.

Mode Sensitivity

The frequency of modes up to 2.5 GHz as a function of plastic cell deformation in the considered detuning range (±1.5 mm) consistently showed a linear behavior. Thus, the mode sensitivity can be expressed by the gradient $\Delta f/\Delta l$. In Figure 3, the sensitivities are depicted for cell number two and three. The important HOM bands as well as the fundamental band are highlighted. As expected the sensitivity differs from cell to cell dependent on the mode of a band. For example the TE_{111} $4/5\pi$ mode is resistant against deformations of cell three as the field is mainly concentrated in all other cells whereas the corresponding π mode changes twice as much as the fundamental mode.



(a)

(b)

Figure 3: Mode sensitivity of the five-cell SPL cavity made of copper for plastic deformations a) on cell number 2 and b) on cell number 3. The important bands are highlighted in dark blue.

Cycles of Detuning and Retuning

Figures 4 and 5 show the residual frequency shift of selected modes after retuning as a function of the prior cell

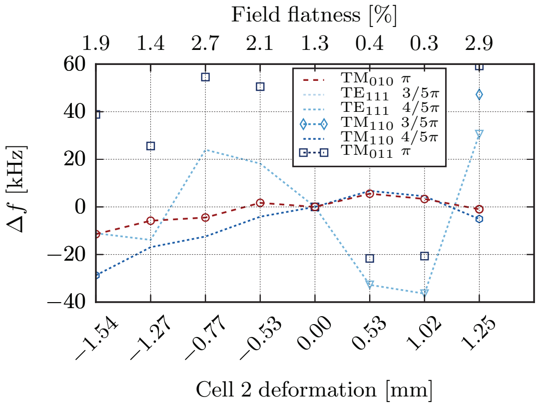
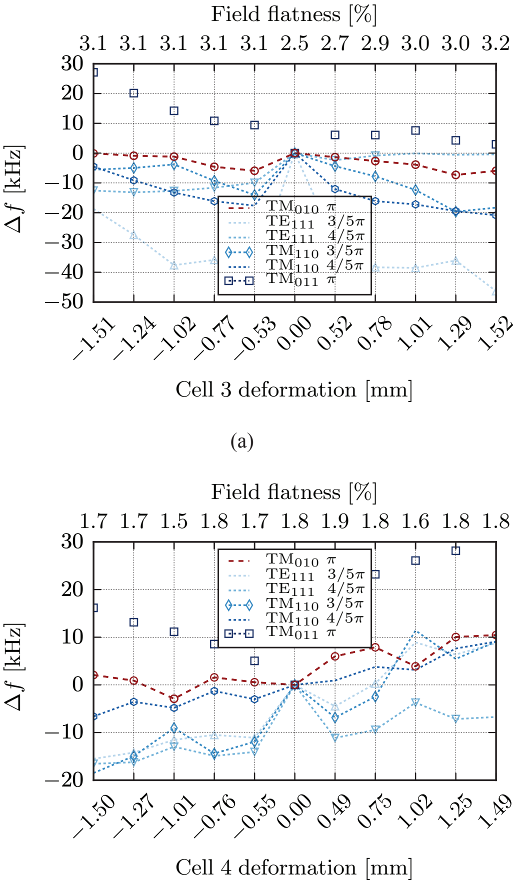


Figure 4: Residual frequency shift of HOMs for the SPL five-cell cavity after retuning cell 2 as a function of its prior detuning. The fundamental mode is highlighted in red.



(b)

Figure 5: Residual frequency shift of HOMs for the SPL five-cell cavity after retuning cell 3 (a) and cell 4 (b) as a function of their prior detuning. The fundamental mode is highlighted in red. The deformation was measured via the cavity length.

deformation. Hence, one data point corresponds to a complete detuning-retuning cycle. Initially the field flatness of the tuned cavity was 1.3 %. Due to the detuning and retuning of the single cells, this value changed throughout the test series (0.3 % − 3.1 %), which explains the different starting values for the field flatness in the following three tests.

For the first test with cell 2 (Fig. 4) a jump in field flatness from 0.3 % to 2.9 % correlates with a significant shift of HOM frequencies. The measurements on cell number three showed a per se worse but overall more stable field flatness in a range of 2.5 % to 3.2 % (Fig. 5a). In most cases the largest HOM frequency shifts took place already after the very first detuning and tuning cycle with a plastic cell deformation of ±0.5 mm. As expected, higher mode sensitivity yields higher residual frequency shifts (e.g. the TE$_{111}$ $3/5\pi$ mode at 917.3 MHz which concentrates most of its energy in cell number three shifts the most in Figure 5a). Similar results were also obtained from cell number four but with a better field flatness within a range of 1.5 % to 1.9 %. For cells three and four a possible residual HOM frequency shift of up to 30 kHz was measured. For cell number two shifts of up to 60 kHz were recorded. Furthermore one can derive a preference which cell to choose in order to shift the frequency of a distinct HOM as summarized in Table 2.

Table 2: Cell Preferences for De- and Retuning Cycle

Monopole modes			Dipole modes		
Type	f [MHz]	Cell(s)	Type	f [MHz]	Cell(s)
TM$_{011}$$4/5\pi$	1322	2,4	TE$_{111}$$3/5\pi$	915	3
TM$_{011}$$\pi$	1331	2,3,4	TE$_{111}$$4/5\pi$	950	2,4
TM$_{021}$	2087	2,4	TM$_{110}$$3/5\pi$	1014	2,4
TM$_{022}$$\pi$	2449	2,4	TM$_{110}$$4/5\pi$	1020	2,3

Finally, the procedure was extended to a coupled deformation of cells two and three. In this case the detuning was only done by compression as the hydraulic cylinders connected to the tuning walls reached almost their maximum elongation in the default position. During the test the field flatness was less controllable and ranged between 2.4 % and 3.6 %. Nevertheless, the results shown in Figure 6 depict a certain drift of the HOMs while maintaining the fundamental mode frequency in the same order as for the single cell deformations when considering a corresponding amount of prior detuning.

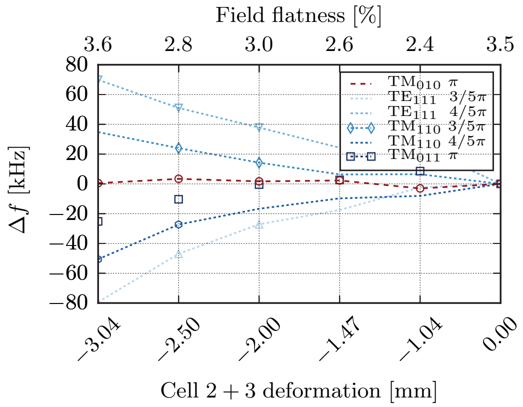


Figure 6: Residual frequency shift of HOMs for the SPL five-cell cavity after retuning cell 2 and 3 together as a function of their prior detuning. The fundamental mode is highlighted in red. The deformation was measured via the cavity length.

COLD TUNER TEST

The frequency shift during cold tuner operation was tested at warm. The cold tuner shown in Figure 7 has been developed by CEA Saclay [6] and is supposed to correct frequency drifts of the fundamental mode by elastic deformations. During the test, the cold tuner operated only in the compression mode as it is foreseen later inside the cryostat. The measurements were carried out on a multi-

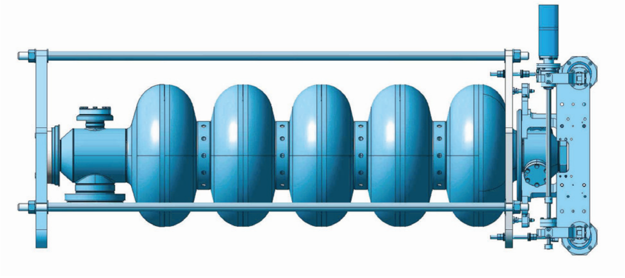


Figure 7: Tuner setup with a five-cell SPL cavity installed on a frame which replaced the helium tank for the test.

cell SPL cavity made of niobium (No. 3 [2]) which was compressed by up to 1.8 mm. The HOM spectrum up to 2.1 GHz was measured at several deformation states. The frequency shift of all investigated modes increased or decreased (dependent on the mode) always linear and allows to compare the modes by the gradient $\Delta f/\Delta l$ (Fig. 8). The frequency of most of the HOMs decreases for increasing compression in contrast to the fundamental band. The first and third dipole band are more than twice as sensitive as the TM_{010} modes whereas the sensitivity of the TM_{011} band at 1.3 GHz is only 10 % higher than the sensitivity of the TM_{010} band. In pulsed machines, where cavities are subject to Lorentz force detuning and its active compensation (either by RF power or by fast piezo tuners), also the HOMs will change their frequencies during each RF pulse. This effect will certainly reduce the resonant build-up of HOM power in cavities and may make the use of HOM couplers obsolete.

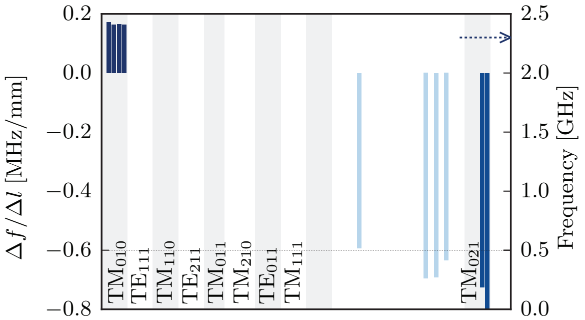


Figure 8: Mode sensitivity of a five-cell SPL cavity made of niobium (No. 3) obtained from the tuner test. The cavity was deformed several times in a range of 0 mm to −1.8 mm. The important bands are highlighted in dark blue.

MODE SHIFT DURING COOL-DOWN

Several vertical cold tests have been performed for two SPL five-cell cavities in 2015 [7]. During the tests the HOM spectrum was measured at 2 K and 4 K as well as during the warm-up phase starting from 40 K (Fig. 9). However the measurements between 40 K and 80 K were very noisy, most likely due to a very inhomogeneous temperature distribution over the cavity surface. Starting from 80 K the mode drift versus temperature rise is reproducible. Figure 10 summarizes the frequency shifts due to the warm-up from 2 K to 293 K which is proportional to the mode frequency. For example, the frequencies of modes in the TM_{010} band are lowered by almost 1 MHz during cool-down whereas the frequencies of dipole modes in the TE_{111} band drop by up to 1.6 MHz.

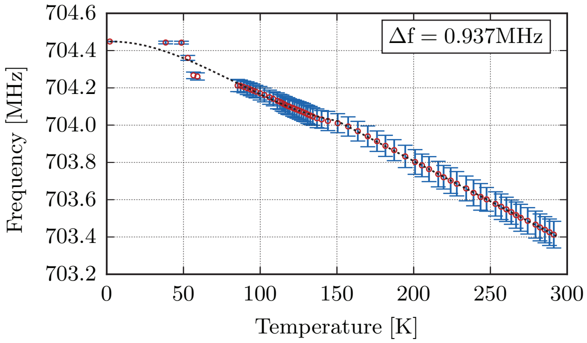


Figure 9: Frequency drop of the fundamental mode during warm-up which reflects the behavior of all modes. The first measurement is at 2 K. The bars correspond to the 3 dB bandwidth of the mode at the different temperatures.

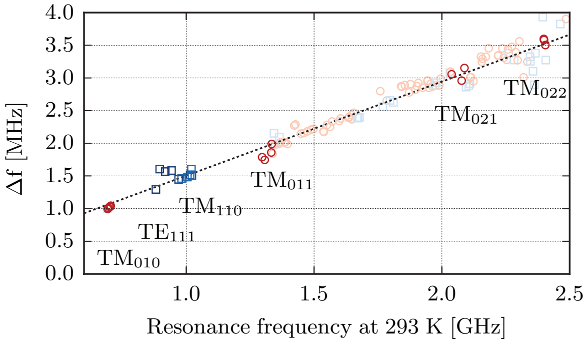


Figure 10: Frequency shift due to thermal contraction for modes up to 2.5 GHz during cool-down, or respectively warm-up.

CONCLUSIONS

We presented several tests to analyze the dynamic mode spectrum of different 704.4 MHz SPL cavities. Frequency shifts due to elastic and plastic cell deformation have been analyzed and compared between the modes. Most HOMs appear to be more sensitive than the fundamental mode though this behavior cannot be generalized. For example during the tuner operation the TM_{110} modes appear to be less sensitive than the fundamental mode (Fig. 8) while some seem to be more sensitive during the plastic deformation of single cells (Fig. 3). Thus, it is not possible to compare directly single-cell with multi-cell deformations. It depends how much field is concentrated in the deformed area.

The detuning-tuning cycles of inner cells resulted in residual frequency shifts for the HOMs up to 30 kHz after retuning from a prior cell deformation of ± 1.5 mm. From the tests with the single-cell cavity one can conclude that detuning-tuning cycles on the end-cells yield larger residual frequency shifts. In general, higher sensitivities result in higher residual frequency shifts after retuning.

The cold tuner is able to shift the HOM frequencies by hundreds of kHz. Using the results in Figure 8 one can estimate and predict the frequency shifts during the cold tuner operation. We also note that in pulsed machines, HOM frequencies will move during the RF pulses due to Lorentz force detuning and its compensation measures. This should reduce the build-up of HOM power in the cavities.

The frequency shift during cool-down to 2 K depends linearly on the mode frequency and starts with 1 MHz for the fundamental band.

OUTLOOK

Since single-cell detuning and retuning can only be done on undressed cavities, it is important to measure the HOM shifts which are introduced by the welding of the helium tank. This assessment together with a mode sensitivity analysis of cold-tuning a dressed cavity are foreseen soon after the welding of the tanks. At that point a plastic deformation of a dressed cavity and subsequent retuning would be a valuable exercise to assess whether HOM frequencies can still be shifted.

ACKNOWLEDGMENT

The authors would like to thank Kurt Artoos for the useful discussions about the tuner operation. Specific recognition should go to Oscar De Frutos for his advice and support for the tuning bench. Also, we gratefully acknowledge the patience and support of Karim Hernandez and Alick Macpherson for the measurements during the cold tests.

REFERENCES

[1] F. Gerigk, S. Atieh, I. Aviles Santillana, W. Bartmann, et al., Conceptual Design of the Low-Power and High-Power SPL: A Superconducting H$^-$ Linac at CERN, CERN, July 2014.

[2] O. Capatina, S. Atieh, I. A. Santillana, G. A. Izquierdo, et al., “CERN Developments for 704 MHz Superconducting Cavities,” FRIOB04, Proc. SRF2013 (2013).

[3] M. Schuh, F. Gerigk, J. Tückmantel, and C. P. Welsch, “Influence of Higher Order Modes on the Beam Stability in the High Power Superconducting Proton Linac,” Phys. Rev. ST Accel. Beams **14**, 051001 (2011).

[4] C. Liu, W. F. O. Müller, W. Ackermann, and T. Weiland, “Various Approaches to Electromagnetic Field Simulations for RF Cavities,” tech. rep., CERN, Sep 2012.

[5] H. Padamsee, T. Hays, and J. Knobloch, *RF Superconductivity for Accelerators*, Wiley series in beam physics and accelerator technology, (New York, NY : Wiley, 1998), pp. 129–144.

[6] G. Devanz, “Tuner Design and Performance.” presentation at the 3rd SPL collaboration meeting, https://indico.cern.ch/event/63935/, CERN, November 2009.

[7] A. Macpherson et al., “CERN’s Bulk Niobium High Gradient SRF Programme: Developments and Recent Cold Test Results,” *these proceedings* MOPB074, Proc. SRF2015, Whistler, Canada (2015).