INNOVATIVE TUNING TECHNIQUES FOR LOW-BETA SRF CAVITIES *

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Abstract

Superconducting low- β cavities enable and often operate with high loaded Q's and small loaded bandwidths, making them extremely sensitive to RF frequency errors which are large relative to the loaded cavity bandwidth.   Mechanical vibrations which couple to the cavity field drive RF frequency errors which require a combination of tuners and extra RF power to compensate. This paper presents an overview of innovate techniques for low- β (0.05 < β < 0.6) superconducting cavity design and tuning to maximize RF field stability.

INTRODUCTION

The radio-frequency (RF) field in accelerator cavities must be operated with stable amplitude and phase-locked to the particle-beam bunches. The accuracy and precision to which the cavity accelerating field's amplitude and phase are controlled determines:

1) The reliability and availability of beam for experiments
2) The beam quality
3) Beam losses (activation of the accelerator)

Mechanical vibrations, helium pressure fluctuations, and Lorentz detuning all combine to drive dynamic RF frequency errors, detuning. Extra RF power is required to prevent detuning which is a large fraction of the loaded cavity bandwidth from disrupting the amplitude and phase stability of the cavity accelerating field. This requires higher power amplifiers, increasing both the capital and operating expenses of an accelerator.

There are two schemes available to help reduce cavity detuning: design the cavities to decouple the accelerating field from the dominant mechanical vibrations and to employ tuners which introduce a controllable RF frequency perturbation which is used to destructively interfere with the cavity detuning. The first part of this paper reviews electro-mechanical design techniques which decouple the accelerating field from the mechanical vibrations in low- β cavities. The second part of this paper discusses several tuning techniques, both in use and proposed, for low- β cavities.

CAVITY DESIGN

The majority of frequency detuning effects can be minimized or even eliminated by design, whereas neglect can lead to an unusable system. This is accomplished by decoupling the cavity electromagnetic field from common mechanical vibrations, e.g. helium pressure fluctuations in cw operation, dynamic Lorentz detuning in pulsed operation, and resonant mechanical vibrations in both.

The relationship between changes in RF frequency and mechanical deformations is given by the Slater Perturbation Theorem [1], which for a deformation in a cavity's wall is given in equation 1 where E_0 and H_0 are the unperturbed electric and magnetic fields respectively, U_0 is the stored energy, μ_0 is the permeability of free space, ε_0 is the permittivity of free space, f_0 is the unperturbed cavity frequency, and Δf is the difference between the perturbed and unperturbed cavity frequencies. The Slater Perturbation Theorem and how it relates to cavity design is the focus of the next two subsections.

$$\frac{\Delta f}{f_0} = \frac{\int_{\Delta V}\left(\mu_0\left|\vec{H}_0(\vec{x})\right|^2 - \varepsilon_0\left|\vec{E}_0(\vec{x})\right|^2\right)d^3x}{4\cdot U_0} \quad (1)$$

CW Operation

In cw operation above the lambda point helium pressure fluctuations are the dominant driver of cavity RF frequency errors. Low-β cavities may be designed to minimize the total RF frequency shift due to changes in the helium pressure (df/dP) by balancing deflections of the cavity walls in areas with high magnetic fields (increasing frequency) with deflections in areas with high electric fields (decreasing frequency).

Figure 1 shows an example of this technique. The ANL β = 0.5 345MHz triple spoke cavity was designed to minimize df/dP, the frequencies sensitivity to changes in external pressure, by adding support ribs to the end walls and the cylindrical wall of the cavity [2]. These ribs stiffen the cavity walls but are not intended to reduce df/dP simply by stiffening; rather they balance the opposing electromagnetic field contributions. In actual construction, some of the ribs were made slightly oversize to allow for post-construction fine-tuning by cutting away part of each rib. After fine-tuning df/dP = -0.7 Hz/torr. However, after welding the helium jacket the sensitivity increased to -2.9 Hz/torr.

Lorentz Detuning

The dynamic Lorentz detuning, which dominates pulsed operation, is fundamentally different from the pressure fluctuations discussed above. Here regions of high magnetic field exert an outward force, while regions of high electric field exert an inward force on the cavity walls. These deflections conspire to decrease the cavity frequency under all conditions. To decrease the coupling strength of the cavity RF field to Lorentz detuning the rigidity of the walls must be increased, see for example [3]. Combining the cavity stiffening plan with a
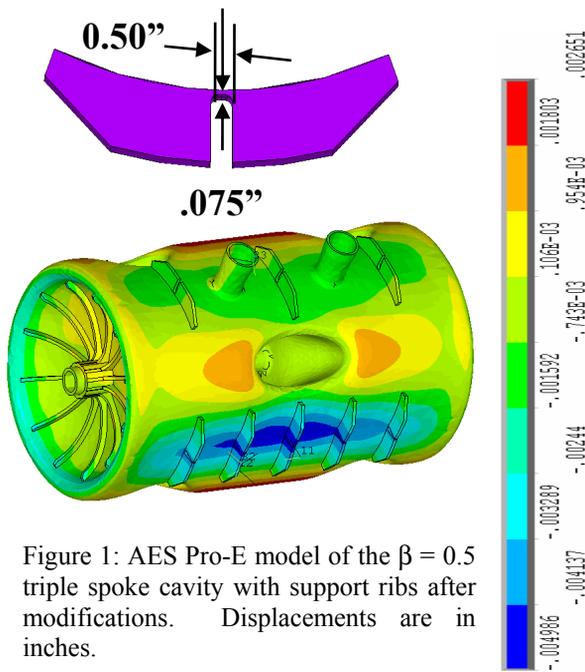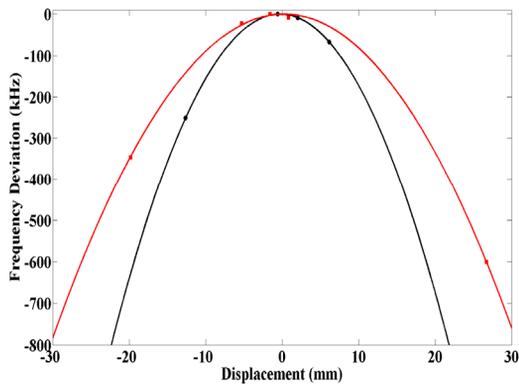
0.50" →

.075"

Figure 1: AES Pro-E model of the β = 0.5 triple spoke cavity with support ribs after modifications. Displacements are in inches.

Figure 2: Quarter wave cavity resonator frequency's dependence on center conductor displacement (Top). The black data is for displacements along the beam line, the red data is for displacements perpendicular to the beam line. The table gives the expected peak-to-peak detuning amplitude for several displacements of the center conductor along the beam axis (Bottom).

Displacement (mm)	0	0.25	0.5	1
$\Delta f_{\text{p-p}}$ (Hz)	0.2	16	33	66

scheme to reduce df/dP may also prove beneficial, see for instance [4] where additional feedback for helium pressure fluctuations reduced the total cavity detuning.

Resonant Vibrations

It is not possible to eliminate vibrations in cavities. It is possible, through careful design, to increase the lowest mode frequencies, decreasing their relative contribution to cavity phase errors [5] or to decouple them completely from the cavity RF field.

Structures with quarter wavelength loading elements are subject to strong detuning driven by resonant pendulum motion of the loading elements. By electrically centering the loading elements the pendulum-motion driven detuning may be eliminated [5].

An example of this is shown in figure 2 for a 72.75 MHz β = 0.077 quarter-wave cavity being fabricated for the ANL ATLAS intensity upgrade [6]. The graph shows the cavity RF frequency's dependence on displacements from the electrical center of the cavity. The table gives the expected peak-to-peak (p-p) cavity detuning for a 20 $\mu m_{\text{p-p}}$ pendulum vibration amplitude for several displacement of the center conductor along the beam axis. Notice that when centered the detuning is negligible. Further tests are planned once the cavity fabrication is complete to verify this result.

CAVITY TUNERS

To operate a cavity RF field with a stable amplitude and phase a combination of techniques and devices are used. Typical schemes proposed today combine slow tuners with combinations of forward power modulation and fast mechanical tuning to achieve the accelerator design goals while minimizing the required RF power.

ANL

The ANL intensity upgrade 72.75 MHz β = 0.077 quarter-wave cavities will operate at 12.5 MV/m with a loaded bandwidth of 25 Hz providing 2.5 MV of voltage per cavity. Separate slow and fast mechanical tuners are being developed to support operation at this level. The ANL method separates the action of the fast tuner from the slow tuner. Separation allows for the implementation of a mechanically compliant slow tuner, reducing its mass and cost. Whereas, the fast tuner is made rigid, by design, to increase the mechanical resonant frequencies excited during operation.

The ANL slow tuner is a pneumatic tuner which squeezes the cavity beam ports, see figure 3. The system is composed of bellows which are actuated with 0 to 60 psig helium gas. As the bellows expands it pushes outward on the wire ropes which pull in on bars bolted to the cavity beam port flanges, squeezing the cavity. This design was first developed in 1978 and variations of it have reliably operated for over 25 years [7].

A fast mechanical tuner is being developed to ensure reliability of operation and, if able to reduce cavity detuning, to increase the operating voltage of the cavities. The mechanical and thermal design is described in detail in reference [8]. In order to characterize the fast tuner performance, the correlation between the amplitude and frequency of the piezoelectric fast tuner drive signal and the amplitude and relative phase of the cavity RF frequency modulation was measured with the tuner mounted on a 169 MHz halfwave cavity. The measurement was performed by sweeping the frequency of the sinusoidal signal driving the fast tuner and simultaneously measuring the relative phase and
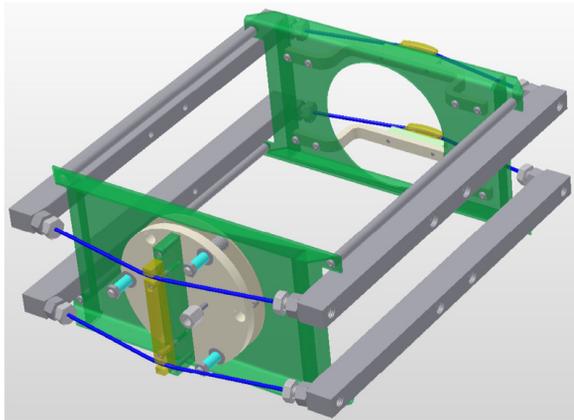
Figure 3: The ANL Intensity Upgrade pneumatic slow tuner: bellows (light gray), wire rope (blue), and bars which bolt to beam ports (dark gray).
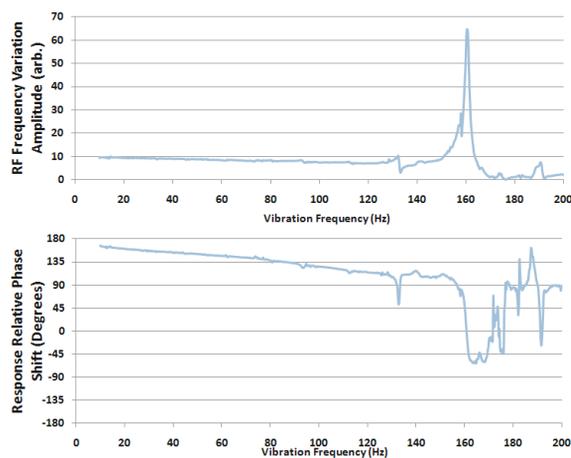

Figure 4: Piezoelectric fast tuner transfer function with a 169 MHz halfwave cavity.

amplitude of the resulting cavity frequency modulation. The results of this measurement are shown in figure 4 and are encouraging for compensation of low frequency microphonics driven by helium bath pressure fluctuations.

TRIUMF

TRIUMF developed a quarter wave cavity tuner which deforms a flexible plate on the bottom of the cavity [9]. The plate deformation is controlled by a level arm which is fixed on one end, attached to the tuning plate in the center, and connected to a long rod which extends from the bottom of the cavity, through the cryomodule lid, and is actuated with a linear servo motor. The tuner resolution is 0.04Hz/step which correspond to a 5nm/step displacement on 141 MHz quarter wave cavities with response time which may be useful for compensating microphonics. A variation of this tuner is being used as part of the FRIB project at MSU [10].

INFN-Legnaro

INFN-Legnaro has developed a tuner for 352 MHz β = 0.09 and 0.16 halfwave cavities for the EURISOL driver linac. The tuner uses a large slotted plate located 90 degrees from the beam ports which can be moved by

~10mm. Their design is reported on in reference [11] and provides a tuning range of 100 to 150 kHz for the 352 MHz halfwave cavities.

IPN-Orsay

For slow tuning in Spiral-2, IPN developed a high RRR niobium plunger which is inserted into the high magnetic field region of their quarter wave cavities. The plunger is hollow and is directly cooled with liquid helium. Initially, the plunger tuners were found to increase the RF losses of the cavities they were mounted on, and have been redesigned. Currently, they can provide up to 90 kHz of tuning without loading the cavity. Both variable and fixed geometries have been successfully tested [12]. This is a powerful method of tuning which only requires a port on the cavity through which the plunger can be inserted.

CONCLUSIONS

Low-β cavities are used in a variety of accelerator applications and should be designed to minimize the coupling between the cavity RF field and common sources of detuning. The coupled electromagnetic and mechanical design should start early to avoid or eliminate unnecessary interactions between the cavity mechanical and RF modes. Many tuner designs and methodologies exist and should be tailored to specific applications.

ACKNOWLEDGEMENTS

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