Adaptive Compensation of Lorentz Force Detuning in Superconducting RF Cavities

Yuriy Pischalnikov and Warren Schappert
Fermilab, Batavia, IL 60510

Email: warren@fnal.gov
Web site: www.fnal.gov

The Lorentz force can dynamically detune pulsed Superconducting RF cavities and considerable additional RF power can be required to maintain the accelerating gradient if no effort is made to compensate. Fermilab has developed an adaptive compensation system for cavities in the Horizontal Test Stand, in the SRF Accelerator Test Facility, and for the proposed Project X.

Superconducting RF cavities are in common use at accelerators around the world and cryomodules incorporating high-gradient (>30 MV/m) pulsed Tesla style 9-cell cavities are currently being constructed for the SCRF Test Area in NML at Fermilab as a part of the ILC Global Design Effort.

The walls of SCRF cavities are deliberately kept thin (<= several mm) to allow the cavities to be kept cool but the thin walls make the cavities susceptible to mechanical deformations induced by:

- The force of the accelerating electromagnetic field on the cavity walls (the Lorentz force);
- Fluctuations in the pressure of the surrounding helium bath;
- Mechanical vibrations induced by external mechanical noise sources (e.g. pumps, cranes, etc.).

These mechanical deformations can change the resonant frequency of the cavity. For high-gradient, pulsed cavities operating in super-fluid helium, the Lorentz force is the dominant source of cavity detuning. If no efforts are made to compensate for LFD, cavities can dynamically detune by several bandwidths. Maintaining the accelerating gradient under these conditions would require considerable excess RF power.

I. THE STANDARD APPROACH TO LFD COMPENSATION

The use of piezo actuators to compensate for LFD was pioneered at DESY but has since been adopted widely [1]. Actuators connected to the beam flange are driven by a short unipolar drive signal prior to the arrival of the RF pulse. The timing, amplitude, width and bias level of the piezo drive signal are chosen such that the detuning of the cavity by the resulting acoustic impulse cancels the detuning of the cavity induced by the Lorentz force. This technique can successfully reduce the detuning of the cavity during the RF pulse from several hundreds of Hz to several tens of Hz.

While the standard approach can provide acceptable compensation for LFD, the mechanical response of individual cavities to the Lorentz force and to the piezo actuator can differ. Changes in cavity operating conditions, for example the changes in the gradient or bath pressure can require corresponding changes in the compensating waveform. In the standard approach compensation parameters are selected manually. Operating multiple cavities for extended periods will require control systems that can automatically determine the best parameters for each cavity and adapt to changing operating conditions. Because the cavity detuning does not respond linearly to the changes in some parameters of the standard unipolar pulse, the adaptive capability that can be incorporated in LFD systems based on this approach may be limited. Furthermore while a single unipolar pulse can compensate cavities driven by short RF pulses, it may not be suitable for cavities where the length of the RF pulse is comparable to or greater than the period of the dominant mechanical resonance.

II. OPTIMAL LFD COMPENSATION

The electromagnetic and mechanical behaviour of the cavity can be described well [2] by the following set of coupled differential equations relating the complex envelopes of the forward, F, and probe, P signals to the detuning, δ, the frequencies of the mechanical modes of the cavity, Ω_k, and the piezo drive voltage, V^{Piezo}.

$$\frac{dP}{dt} = -\left(\omega_{1/2} - i\delta\right)P + 2\omega_{1/2}F;$$

$$\frac{d^2\delta_k}{dt^2} + \frac{\Omega_k}{2Q_k}\frac{d\delta_k}{dt} + \Omega_k^2\delta_k = \Omega_k^2 K_k^{LFD}|P(t)|^2 + \Omega_k^2 K_k^{Piezo}\, V^{Piezo}(t);$$

$$\delta = \sum_{k=0}^{N_{Modes}-1} \delta_k\ .$$

In closed loop operation, the the stored energy in the cavity,$|P(t)|^2$, does not depend on the detuning and, if the couplings of the mechanical modes to the Lorentz force, K_k^{LFD}, and to the piezo, K_k^{Piezo}, are known, a closed form solution for the actuator drive waveform that minimizes the RMS detuning of the cavity can be constructed:

$$V^{Piezo} = -\frac{1}{\sqrt{2\pi}}\int d\omega e^{-i\omega t}\, \frac{H^{Piezo}(\omega)^*\Delta^{LFD}(\omega)}{\left|H^{Piezo}(\omega)\right|^2+\sigma^2(\omega)};\ \text{where}$$

$$\Delta^{LFD}(\omega) = \frac{1}{\sqrt{2\pi}}\int dt e^{i\omega t}\delta^{LFD}\,(t);\ \text{and}$$

$$H^{Piezo}(\omega) = \frac{1}{\sqrt{2\pi}}\sum_{k=0}^{N_{Modes}-1} \frac{\Omega_k^2 K_k^{Piezo}}{\omega^2+\frac{i\omega\Omega_k}{2Q_k}+\Omega_k^2}.$$

If $\left|H^{Piezo}(\omega)\right|^2$ has no zeros, the regulatory term, $\sigma^2(\omega)$, in the denominator of the expression for the optimal drive waveform can be set to zero.

The half-bandwidth, $\omega_{1/2}$, and detuning, δ, during the pulse can be extracted from the cavity probe and forward RF waveforms by rearranging the terms of the equation for the complex envelope of the cavity field:

$$\omega_{1/2} = \frac{Re(P^*\frac{dP}{dt})}{Re(2P^*F - P^*P)};$$

$$\delta = \frac{Im(P^*\frac{dP}{dt} - 2\omega_{1/2}P^*F)}{P^*P}.$$

Accurately determining the half-bandwidth and the detuning requires accurate measurements of the complex cavity forward and probe RF waveforms.

The envelope of each RF waveform is usually measured only up to some arbitrary gain and phase. At a minimum the relative gains and phases of these signal must be determined if the detuning it to be calculated.

The relative gain and phase of the probe and reflected signals can be established by comparing these waveforms as the energy in the cavity decays.

Determining the relative gain and phase of the forward and probe signals is more involved. The real parts of the probe waveform, the probe rate of change, the forward envelope and the half-width are related by the second of the three equations above. The forward/probe relative gain, G, and phase, φ, along with the cavity half-bandwidth can be estimated by to minimize the following quadratic form with respect to $\omega_{1/2}$, α, and β.

$$\left| Re\left(P^* \frac{dP}{dt}\right) + \omega_{\frac{1}{2}} P^*P - 2\alpha Re(P^*F) - 2\beta Re(iP^*F) \right|^2 .$$

The relative gain and phase are related to α and β by the following equations:

$$G = \frac{\sqrt{\alpha^2+\beta^2}}{\omega_{1/2}}; \text{ and}$$

$$\varphi = \tan^{-1}\frac{\beta}{\alpha}.$$

Once the relative gain and phase of the forward and probe signals have been established the detuning can be compares cavity detuning throughout the course of the RF pulse at two gradients as the piezo drive voltage is varied. In both cases, the frequency of the cavity closely tracks the piezo bias. While the cavity frequency changes very little during the RF pulse at the lower gradient, at the higher gradient the effects of the Lorentz force are clearly visible.

A. Correcting For Cross-Contamination

The cavity field is measured by a dedicated antenna installed in the cavity and the complex envelope of the probe signal is known well up to an overall gain and phase. In contrast the forward and reflected signals are measured by a common pickup in the waveguide near the cavity and are susceptible to cross-contamination. Prior to calculating the detuning as described above an ad-hoc procedure is applied to estimate and correct for the level of contamination in the forward signal.

The signal from the forward pickup often shows a non-zero tail after the end of the klystron drive pulse. This tail is assumed to be due entirely to contamination from the wave reflected by the cavity. A contamination coefficient can be extracted by comparing the magnitude and phase of the tail to the reflected waveform. This coefficient can then be used to subtract the contaminated component of the forward signal. Figure 1 shows the forward signal as the piezo bias is varied. before and after correction Varying the bias changes the frequency of the cavity which in turn changes the power reflected by the cavity but should not affect the forward power. Both the magnitude and phase of the forward signal are more stable following correction.

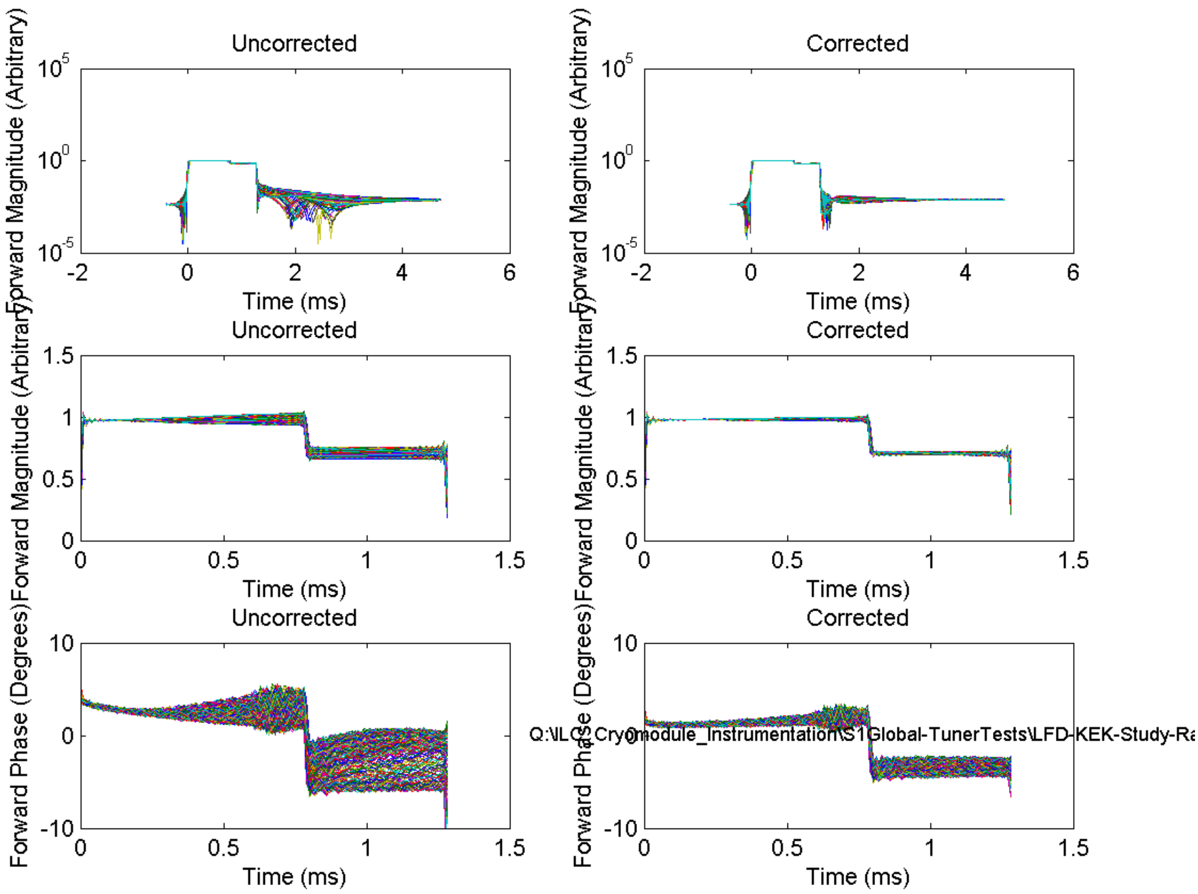

Figure 1: A comparison before and after correction as the piezo bias is varied. The top row shows the magnitude of the entire forward pulse. The next two rows show the magnitude and phase of during only the fill and flat-top respectively.

During operations in the Fermilab HTS contamination of the forward signal by up to 20 percent has been observed. On the flattop where

$$\frac{dP}{dt} = 0,$$

the sensitivity of the detuning , $\Delta\delta$, to contamination of the forward power,ΔF,can be estimated using the expression:

$$\frac{\Delta\delta}{\delta} = \frac{Im(P^*\Delta F)}{Im(P^*F)}.$$

At gradients of 35 MV/ the Lorentz force can detune the ILC style cavities tested in the HTS by up to 700 Hz. If contamination of the forward power were left uncorrected, this could bias the detuning measurement by up to 140 Hz.

B. Measuring The Piezo-Detuning Impulse Response

The response of the cavity frequency to the piezo can be easily measured by driving the piezo with an impulse while the cavity is excited by a CW drive signal. Since it is often not convenient to connect a pulsed cavity to a CW source and alternative technique to measure this response was developed.

A procedure very similar to that used to optimize the pulse delay in the standard approach is employed. A low amplitude short unipolar drive pulse is sent to the actuator some 10 ms prior to the arrival of the RF pulse. For 20 successive RF pulses, the delay between the piezo drive and the RF pulse is reduced by 0.5 ms increments until the piezo pulse follows the RF pulse by 10ms. The forward, probe and reflected RF waveforms are recorded at each delay.

Following this step the bias voltage on the piezo is stepped from pulse to pulse in small increments over the full range of the actuator and again the RF waveforms are recorded for each pulse.

Finally to measure the detuning due to the Lorentz force alone, the RF waveforms are recorded while no drive signal is sent to the piezo.

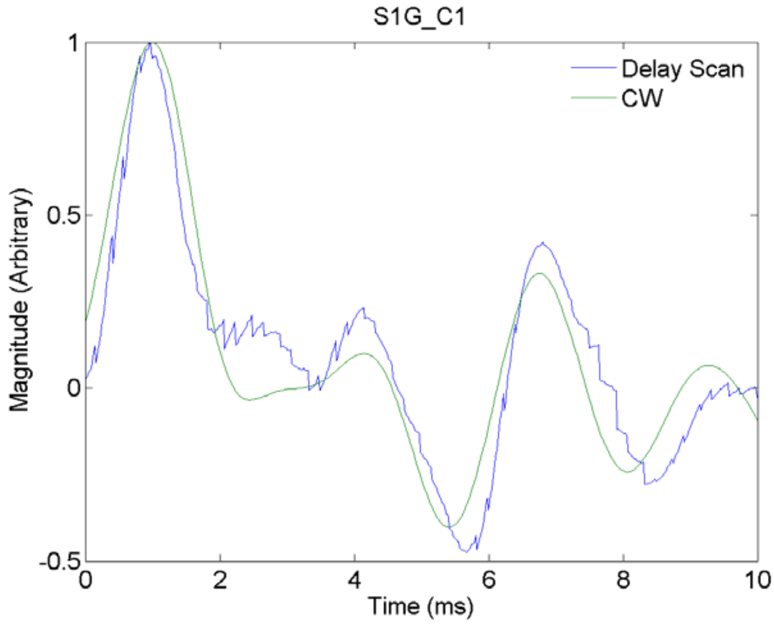

Figure 2: A comparison of the impulse response measured by the delay scan and using CW.

This procedure is usually performed at a gradient of several MV/m below the cavity maximum. This ensures the detuning due to the Lorentz force can be measured accurately while still allowing stable operation.

The procedure is equivalent to measuring the detuning impulse response during CW excitation. Figure 2 shows the detuning levels calculated from the RF waveforms for the piezo delay was varied. Each measurement has been shifted in time by the delay between the piezo impulse and the RF pulse. A CW measurement of the impulse response for the same cavity is shown for comparison. The delay-scan data reproduces the features of the CW impulse response in the +-10 ms window covered by the scan.

C. Calculating the Piezo Drive Pulse

As discussed above, the optimal compensation pulse can be determined from once the couplings between the mechanical modes and the Lorentz force and piezo are known.

While the impulse response could be calculated from the delay-scan measurements and the compensation pulse calculated in turn from the impulse response, it is more convenient to determine the waveform directly the delay-scan measurements.

The detuning measured during each pulse of the delay scan can be combined to form a detuning matrix D. Each column of the response matrix contains the detuning history for a single RF pulse. The rows contain samples of the waveforms at specific times within the RF pulse.

$$D = \overset{\textit{Pulse}}{\begin{bmatrix} \delta_{11} & \cdots & \delta_{m1} \\ \vdots & \ddots & \vdots \\ \delta_{1n} & \cdots & \delta_{mn} \end{bmatrix}} \quad \textit{RF Sample}$$

A second matrix describing the excitations applied to the cavity during each pulse of the scan can also be constructed. Each column of the excitation matrix corresponds to the excitation applied during a single RF pulse. The majority of the rows contain a single 1 or a single -1. The remainder of the entries in these rows is zero. An entry of 1 or -1 in a given row and column indicates that a positive or negative going impulse was used to drive the piezo at a specific delay prior to the corresponding RF pulse. Two auxiliary rows are used to account for excitations of the cavity by the Lorentz force and the piezo DC bias. All of the entries of the row corresponding to the Lorentz force contain 1 indicating the Lorentz force was present during each RF pulse of the scan. The entries of the row corresponding to the piezo DC bias contain a number between -1 and 1 proportional to the bias applied to the piezo during each RF pulse.

$$X = \overset{\textit{Pulse Number}}{\begin{bmatrix} 1 & 1 & \cdots & 1 & 1 \\ -1 & -0.9 & \ldots & 0.9 & 1 \\ 1 & 0 & \ldots & 0 & 0 \\ 0 & 1 & \ldots & 0 & 0 \\ \vdots & \ldots & \ddots & \ldots & \vdots \\ 0 & 0 & \ldots & 1 & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix}} \begin{matrix} \textit{LFD} \\ \textit{Bias} \\ -10\ ms\ \textit{Delay} \\ -9.5ms\ \textit{Delay} \\ \ldots \\ 9.5ms\ \textit{Delay} \\ 10\ ms\ \textit{Delay} \end{matrix}$$

For small excitations of the piezo, the detuning matrix and excitation matrices should be related by a response matrix, R, characteristic of the couplings between the applied excitations and the detuning.

$$\mathrm{D{=}R\,X.}$$

Least squares minimization leads to the following estimate for the response matrix

$$\mathrm{R{=}D\,X^T\,(XX^T)^{-1}}.$$

The first column of the response matrix contains an estimate of the Lorentz force detuning present during each pulse of the scan.

$$\mathrm{R} = [\mathrm{D_{Lorentz}} \quad \mathrm{R_{Bias}} \quad \mathrm{R_{Delay}}]$$

The remaining columns describe the response of the cavity to any arbitrary combination of the piezo drive pulses applied during the delay scan in combination arbitrary DC piezo bias. These two components can be separated and used to calculate the combination of drive pulses and bias required to cancel the Lorentz force detuning.

$$\mathrm{X_{Compensation}} = -(R^{\mathrm{T}}R)^{-1}R^{\mathrm{T}}\,\mathrm{D_{Lorentz}}.$$

The waveform determined by this procedure consists of a linear sum of the delayed impulses applied to the cavity during the delay scan. The resulting waveform be complex and the specifying the waveform requires a larger set of parameters than the standard unipolar pulse. On the other hand, because it involves a linear relationship between the set of basis waveforms used to excite detuning of the cavity and the compensation waveform those parameters be very easily determined using standard matrix operations. In particular the procedure described here lends itself well to automated measurement and compensation of Lorentz force detuning.

D. Relation to the Optimal Compensation Waveform

This procedure described here measures the detuning transfer functions over limited time windows:

$$\tilde{\Delta}^{LFD}(\omega) = \frac{1}{\sqrt{2\pi}}\int_{Flattop} dt\, e^{i\omega t}\delta^{LFD}(t);$$ and

$$\boldsymbol{\tilde{H}^{Piezo}(\omega) = \frac{1}{2\pi}\int_{t_1}^{t_2} dt\, e^{i\omega t}\, h(t)};$$ where

$$\boldsymbol{h(t)} = \frac{1}{\sqrt{2\pi}}\int d\omega e^{-i\omega t}\, H^{Piezo}(\omega).$$

As the windows are extended, the drive signal will approach the optimal compensation waveform.

E. Adaptive LFD Compensation

As mentioned previously, operation of multiple cavities for extended periods of time will require automated procedures to measure the individual response of each cavity and to compensate automatically for changes in operating conditions such as gradient and bath pressure.

As operating conditions vary, the RF waveforms can be used to measure any residual detuning. The response matrix can then be used to calculate the incremental waveform required to cancel that residual detuning.

$$\Delta X_k = -R - 1\, \Delta D_k;$$
$$X_{k+1} = X_k + \Delta X_k.$$

III. COMPENSATION SYSTEM HARDWARE

A single-cavity system based on the procedure described here has been deployed in the Fermilab Horizontal Test Stand. The system down-converts 13 MHz IF signals from the HTS LLRF system to baseband using AD 8333-EVAL I/Q demodulator boards. The baseband signals are digitized by an NI-4472B DSA card. A Matlab implementation of the adaptive procedure described above is used to update the compensation waveform with each RF pulse. The compensation waveform is played through an arbitrary waveform generator implemented in VHDL driving one 16-bit 100kS/s DAC of an NI-7833R board. The output of the DAC drives a 10x10x40 mm Noliac SCMAP9 stack actuator installed in fast tuner through a 200V PiezoMaster™ driver [3]. A similar single-cavity systems have been deployed at the 325MHz Spoke Cavity Test Facility (SCTF) in Fermilab Meson Detector Building [5] and at the SRF Accelerator Test Facility in Fermilab NML [6] for used during the commissioning of the first cryomodule installed there.

An integrated LLRF/Detuning Control system is being developed for the SCRF Test Facility. Digital RF waveforms captured by the LLRF system will be processed by a resonance control task running in the MVME5500 LLRF controller. The bulk of the C language source for the detuning control task will be translated automatically from code developed for the single cavity system using the Embedded Matlab Compiler.

IV. EXPERIMENTAL RESULTS

Figure 3 shows the detuning with and without compensation of a nine-cell elliptical cavity equipped with a blade tuner operating in the Fermilab HTS at a gradient of 35 MV/m. Compensation reduces the detuning from 750 Hz to less than 20 Hz. Figure 4 shows the piezo drive waveform used to compensate this cavity.

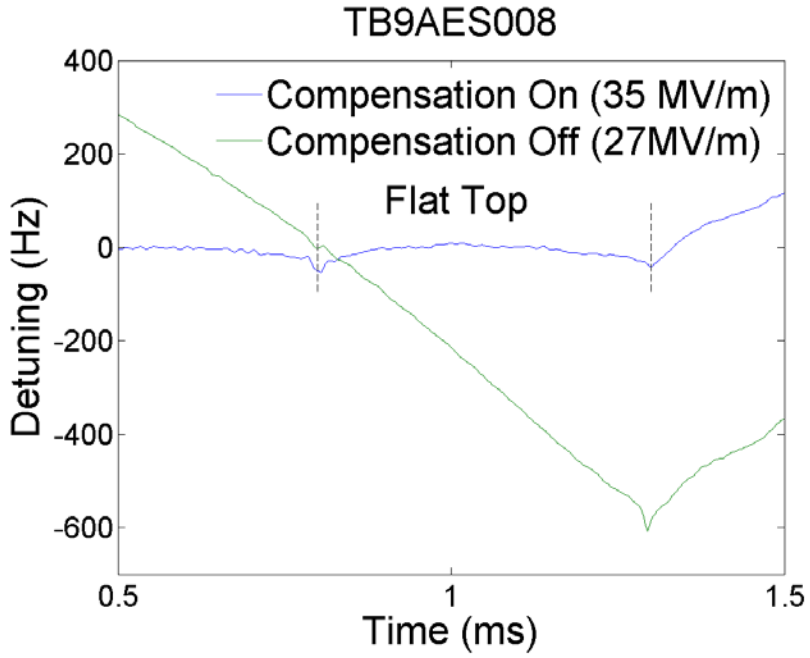

Figure 3: Lorentz force compensation in a nine-cell elliptical cavity at 35 MV/m.

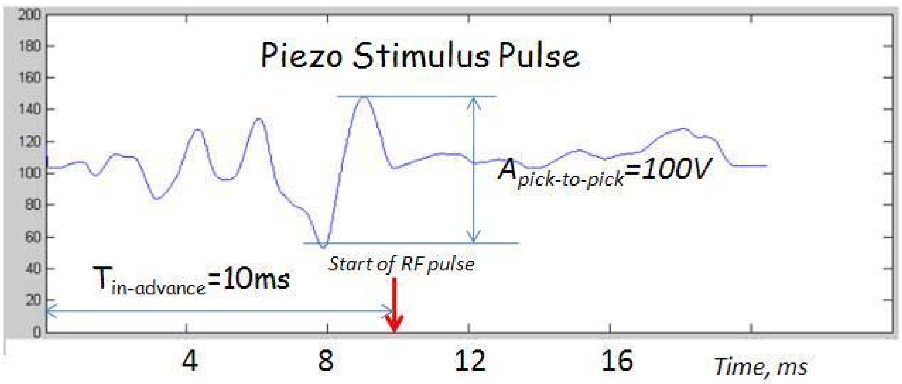

Figure 4: Compensation Piezo Wave Form for the Elliptical Cavity

Figure 5 shows the detuning of a 325 MHz spoke resonator at a gradient of 30 MV/m with and without compensation for multiple RF pulses.

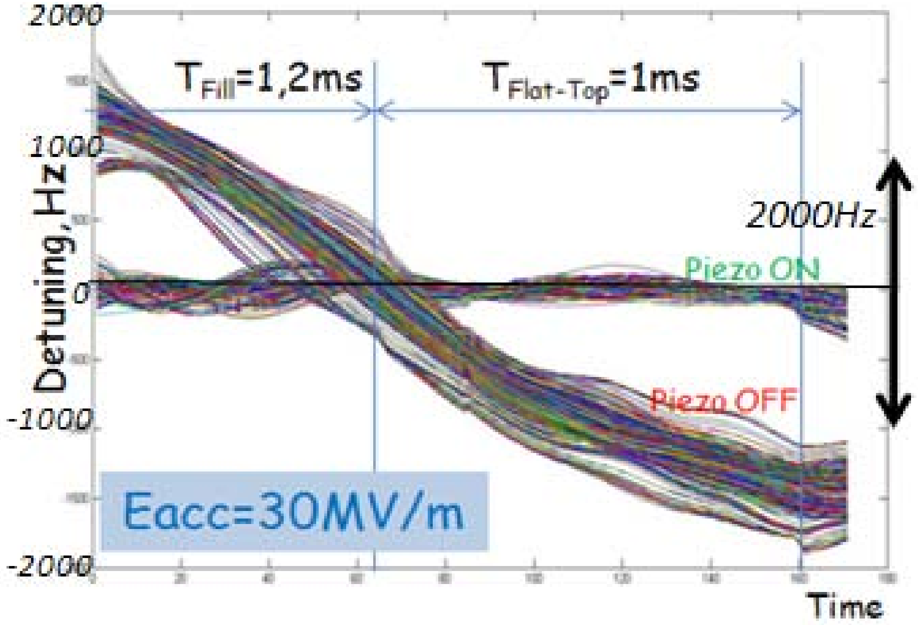

Figure 5: Detuning of a 325 MHz Spoke Resonator with and Without Compensation

Figure 6 shows the piezo waveforms used to compensate detuning in the spoke resonator. While the shape of the pulse changed little from pulse to pulse the bias adapted to compensate for pressure variations in the 4.5 K He bath. [4].

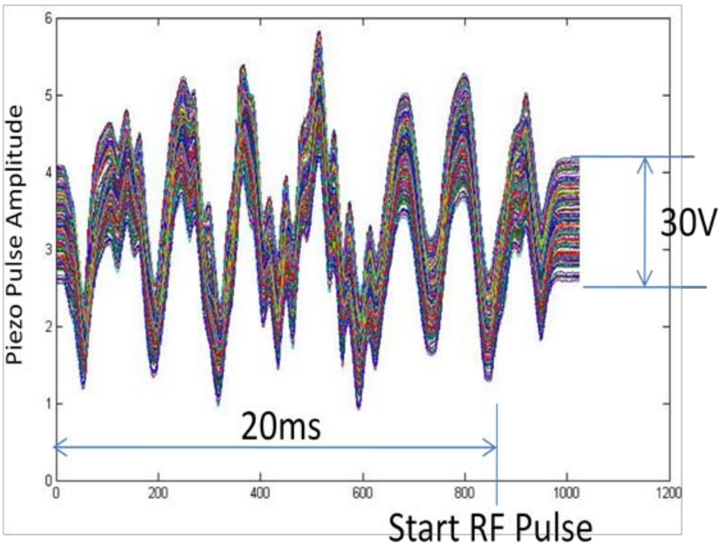

Figure 6: Compensation waveforms for the Spoke resonator.

Figure 7 shows the detuning of a nine-cell elliptical cavity driven by an 8 ms pulse with gradient E_{acc}=22MV/m. Cavity detuning without piezo compensation was several KHz. This was sufficient to drive the cavity completely off resonance.

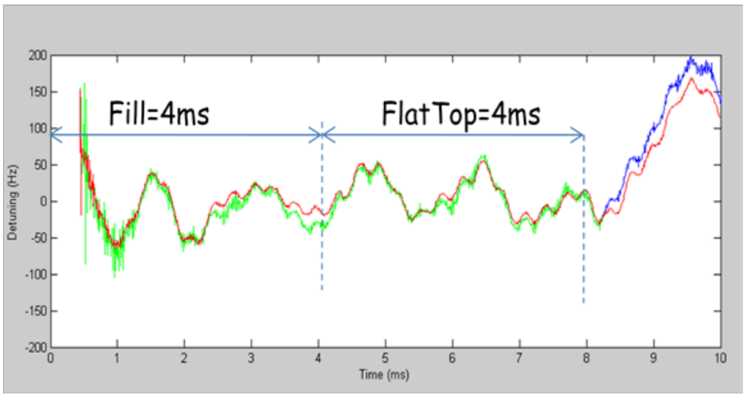

Figure 7: Detuning in a Nine-Cell Elliptical Cavity Driven by an 8 ms RF Pulse.

Figure 8 shows the detuning compensation for of a nine-cell elliptical equipped with a blade tuner at a gradient of E_{acc}=27MV/m. Detuning prior to compensation was ~300Hz. This cavity was built at Fermilab and sent to KEK for installation in the S1-G

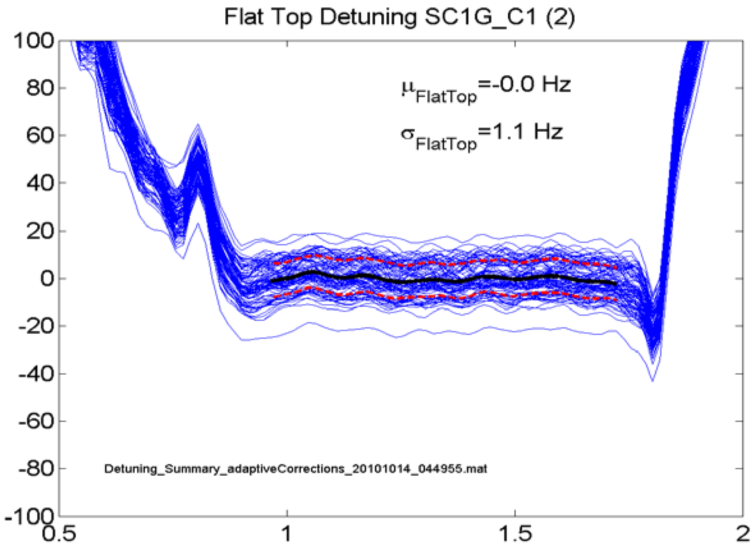

Figure 8: Detuning a Blade Tuner Equipped Cavity Installed in the S1-G Cryomodule at KEK

cryomodule. As part of the S1-G effort a single-cavity detuning control system was also deployed at KEK for several weeks. During that interval the system was able to successfully limit LFD detuning in of cavities of built to several different designs to better than 20 Hz.

V. CONCLUSION

An adaptive procedure has been developed at Fermilab to compensate for Lorentz force detuning in SRF cavities. The procedure can automatically characterize the response of individual cavities to the Lorentz force and to the compensation actuator. The measured response is used to automatically calculate an appropriate compensation waveform and adapt that waveform to changing cavity operating conditions. The procedure has been successfully used to compensate a variety of cavities at Fermilab and elsewhere. Single cavity compensations system based on this procedure are routinely used to limit Lorentz force detuning during operations in the Fermilab Horizontal Test Stand. A multi-cavity system is being developed for the Fermilab SCRF Test Facility in NML.

References

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