FIRST FERMILAB RESULTS OF SRF CAVITY LORENTZ FORCE DETUNING COMPENSATION USING A PIEZO TUNER*

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Abstract

Lorentz force detuning compensation of TESLA type cavities using commercially available piezo electric actuators was first demonstrated at DESY [1]. Compensating for Lorentz force detuning to avoid excessive RF power requirements is critical for high gradient cavities such as the ones proposed for the ILC. For this reason, Fermilab is working on issues related to range, reliability, and automation of SRF cavity fast tuners. A mechanical resonance excitation method is used to increase the piezo tuner range. In order to study the long-term reliability of the design a strain-gauge based sensor was developed, which monitors the piezo tuner preload continuously. A feed forward Lorentz force detuning compensation algorithm using the forward power signal, the field probe signal, and the phase difference between them has been developed. This algorithm is being implemented in a hybrid PC/FPGA based control system providing automated signal acquisition, system identification, and waveform playback. In parallel, an FPGA based real-time cavity simulator has been developed to validate the performance of the system prior to its deployment and to provide a test-bed for further detuning and microphonics algorithm development. The control system will be used to compensate for cavity detuning in the first cryomodule installed in the ILC Test Area at Fermilab. In tests of the algorithm using CCII at a gradient of 26 MV/m, compensation with a fast piezo tuner reduced the Lorentz Force detuning from 275 Hz to 20 Hz. This compensation resulted in a corresponding decrease of the peak klystron power requirement from 120% to 105% of the nominal power on resonance.

INTRODUCTION

Over the last several years, Fermilab has become actively involved in the development and testing of superconducting radio frequency cavities (SRF) for the proposed International Linear Collider (ILC).

In the context of the ILC SRF research and development program issues related to the operation, reliability, and automation of SRF cavity fast tuners are currently being examined.

A major issue affecting the operation of SRF cavities is the Lorentz force detuning. Since SRF cavities are designed with thin walls to maximize heat transfer, the shape of a cavity can be distorted by electromagnetic forces (Lorentz force) when a high gradient RF pulse is applied. This distortion can change the tune of the cavity during the pulse. For instance, the detuning of an ILC baseline cavity at 35 MV/m is expected to be more than twice the cavity bandwidth during the flattop, resulting in an excessive RF power requirement. Fast tuners based on piezo actuators have been used to dynamically compensate for Lorentz force detuning. Progress has also been made using these tuners to actively damp cavity vibrations induced by external sources (microphonics).

Most of the work with fast tuners at Fermilab to date has been performed using a piezo tuner installed in Capture Cavity II (CCII) [2], a 1.3 GHz Tesla type cavity that is slated to become part of the photo-injector for the ILC Test Area (ILCTA) currently under development. Successful compensation of Lorentz force detuning in CCII using a piezo actuator in conjunction with a resonance excitation technique [3] has been demonstrated.

More recently, Fermilab has successfully commissioned the Horizontal Test Stand (HTS), a cryostat designed to allow rapid testing of “dressed” superconducting cavities. The HTS will provide yet another test-bed at Fermilab for fast tuner design, development, and testing. During the commissioning of the HTS, we have acquired data using geophone vibration sensors in order to better characterize the effects of the Lorentz force and microphonics.

Fermilab has also developed an FPGA-based real-time cavity simulator to allow the rapid evaluation, development, testing, and integration of control algorithms, electronics and data acquisition systems.

LORENTZ FORCE DETUNING COMPENSATION IN CCII

The fast tuner installed in CCII, as shown in Fig.1, is a modified version of a DESY single piezo tuner assembly with additional diagnostic instrumentation such as strain gauges mounted on a solid stainless steel bullet shaped device. The strain gauges monitor the forces on the piezo fast tuner assembly during cavity thermal cycles as well as the interaction between the piezo assembly and the slow tuner. This information is important for specifying an adequate piezo preload during assembly to prevent the actuators from becoming inoperable due to excessive or insufficient preload or damaged by excessive shear forces. Additional details and results can be found in [4].

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Figure 1: CCII fast piezo tuner.

A simplified schematic of the CCII fast tuner instrumentation is shown in Fig. 2. A piezo drive signal was generated by an NI PXI7831 R FPGA card. The amplitude, delay and frequency of the piezo driver signal were controlled manually via a LabView GUI. A phase detector, based on an AD8302 evaluation board, was used to measure the phase difference between the forward power and the field probe signals. These three signals, shown in Fig. 3, were recorded using a PXI/NI-6281 multifunction I/O card.

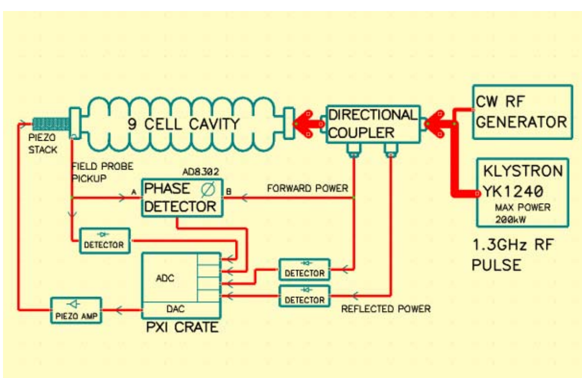

Figure 2: Experimental setup of CCII Lorentz force detuning compensation study.

During the studies described here, the cavity was operated under closed loop control of the RF. A strong mechanical resonance at 165Hz was identified by exciting the cavity using two different methods:

1. Driving the piezo tuner with a swept sine wave between 10Hz and 500Hz while exciting the cavity in CW mode. Changes in the response of the phase detector were monitored.
2. Measuring the voltage induced on the piezo as the cavity was driven by an RF pulse.

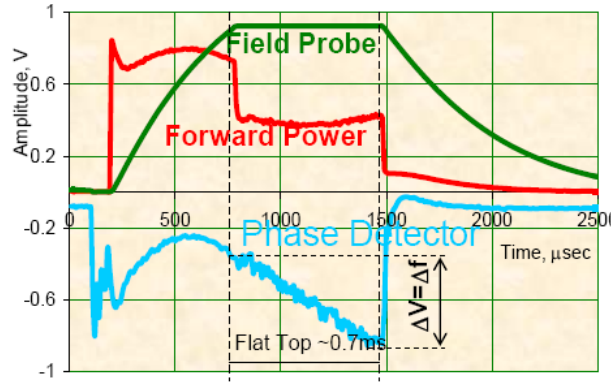

Figure 3: The forward power, field probe and phase detector signals from CCII, at a gradient of 26MV/m.

The 165Hz resonance was deliberately excited by driving the piezo using the waveform shown in Fig. 4. This was done in order to excite a large oscillation in the cavity using the limited stroke of the piezo. Cavity detuning is minimized by adjusting the peak voltage lead time of the piezo pulse.

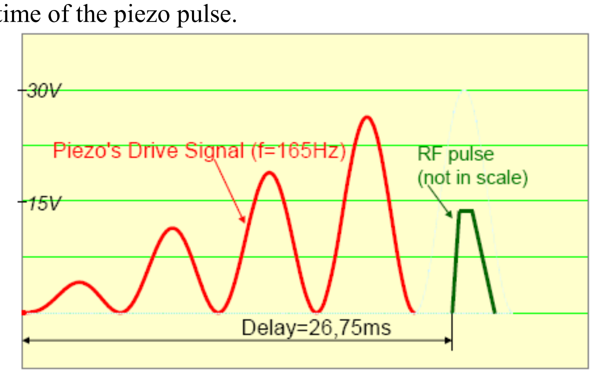

Figure 4: Piezo drive waveform used to compensate for Lorentz force detuning.

As shown in Fig. 5, the optimal pulse peak drive voltage (25.5 Volts) was determined by measuring detuning as the drive voltage was varied. Note that the variation in the pulse-to-pulse detuning at each drive voltage was due to cavity microphonics.

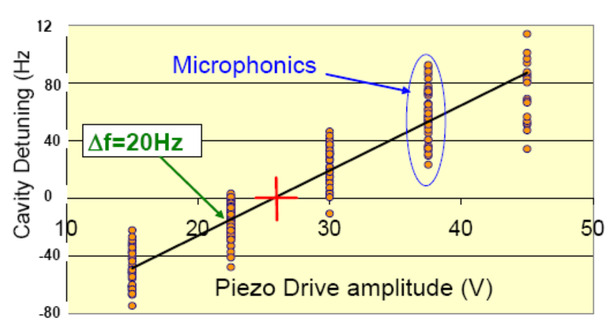

Figure 5: CCII Lorentz Force detuning compensation as a function of the peak piezo drive voltage at E_{Acc}=26MV/m.

The optimal delay between the piezo and RF pulses was determined by adjusting the timing delay until the zero crossing of the first mechanical oscillation coincided with the center of the RF flat-top as shown in Fig.6.

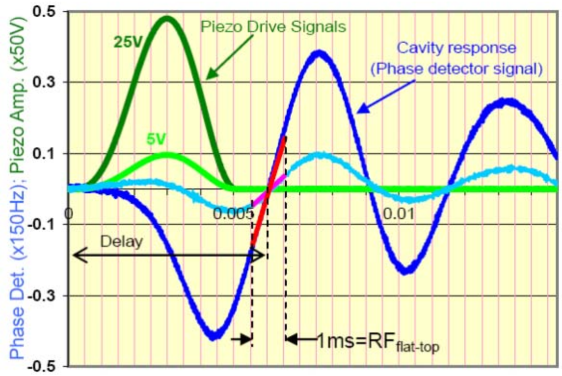

Figure 6: Relative timing of the piezo drive and RF pulses.

The results of CCII Lorentz force compensation using the pulse parameters determined in this way are shown in Fig. 7. Using the peak amplitude of 22.5V reduced the detuning (averaged over 20 consecutive RF pulses) from 275 Hz to 20Hz.

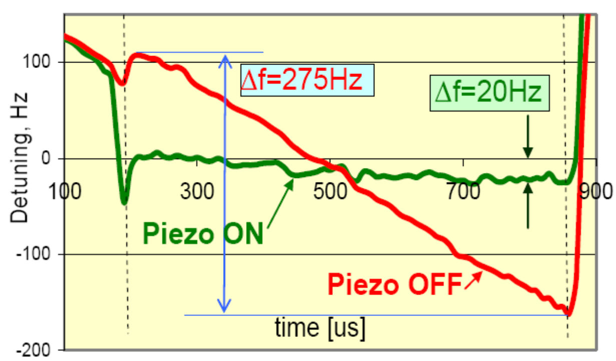

Figure 7: CCII average Lorentz force detuning at EAcc=26MV/m with and without compensation

At the same time, as shown in Fig. 8, the peak forward power requirement (averaged over 20 consecutive RF pulses) was reduced from 120% to 105% of the nominal forward power at resonance with a cavity loaded $Q_L=1.8\times10^6$.

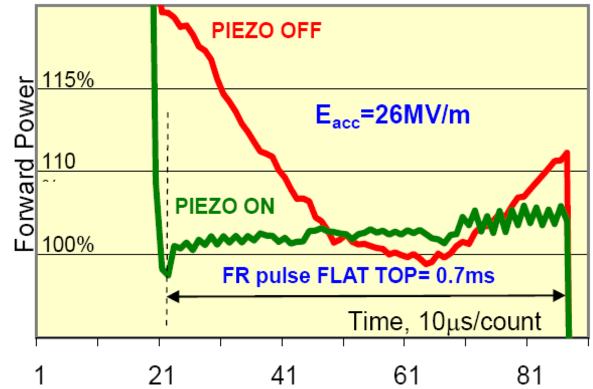

Figure 8: CCII average forward power during "Flat Top" at EAcc=26MV/m.

Mechanical oscillations of the cavity induced by the Lorentz force and by external vibration sources (microphonics) result in significant pulse-to-pulse variations of the cavity resonance frequency, as shown by the variations in the phase detector signals in Fig. 9. The standard deviation of the pulse-to-pulse detuning in CCII can be up to 40 Hz. No attempt has yet been made to compensate for microphonics in CCII, and methods such as [5] can be further developed for this purpose.

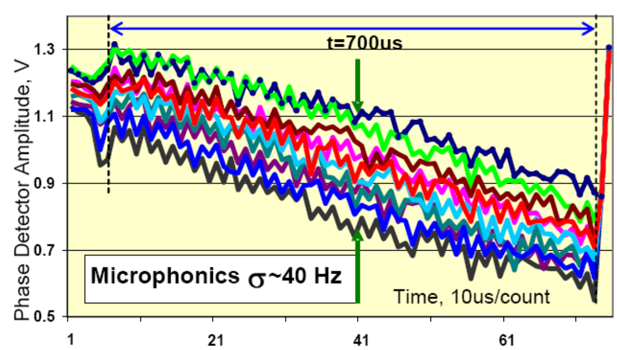

Figure 9: Pulse-to-pulse variations in the CCII phase detector signal due to microphonics.

HORIZONTAL TEST STAND

Fermilab has recently commissioned the Horizontal Test Stand using 1.3 GHz Tesla type cavity. The cavity was equipped with a single piezo fast tuner identical to the fast tuner installed in CCII.

Since the cavity used in HTS was capable of maintaining only limited gradients, there has not yet been an opportunity to study Lorentz force detuning there in any detail. As higher gradient cavities become available for testing, the development program, begun at CCII, will continue.

During the commissioning, however, we were able to acquire vibration data. The cavity used to commission the HTS was equipped with two geophones (Model GS-14-L9) mounted on the flange at the tuner end in order to directly measure the longitudinal and vertical vibrations of the cavity and the coupling between them. Both geophones were magnetically shielded to limit the magnetic flux at the cavity to less that 1 μTesla. Two additional geophones (Model GS-11D) were mounted on support structure below the cavity inside the cryostat in order to measure vibrations induced by external sources.

Fig. 10 shows the spectrogram of the response of the longitudinal geophone as the piezo actuator is driven with a stepped sinusoid. Each line of the spectrogram represents the frequency spectrum of one second of data from the geophone. The intensity of the spectrogram is proportional the log of the absolute value of the Fourier transform. The bright diagonal narrow band across the spectrogram is the response of the geophone to the piezo drive. Fainter narrow diagonal bands corresponding to higher harmonics of the drive frequency are also clearly visible. These are likely due to non-linearities in the response of the piezo actuator. The vertical bands at lower frequencies correspond to microphonic vibrations. Since the microphonic bands are relatively narrow and stable over time, it should be possible to actively damp them with the fast tuner.

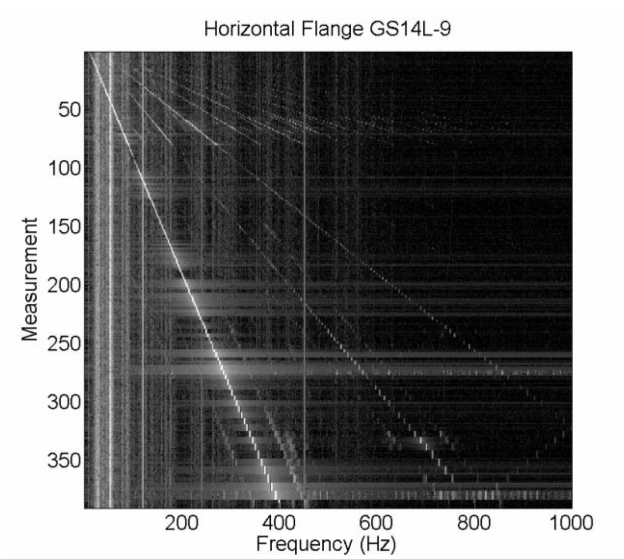

Figure 10: Spectrogram of cavity vibrations in the HTS.

One of the primary objectives of the tuner program for the HTS is to fully characterize the vibrational characteristics of the cavity by accurately measuring the transfer functions for the following sensors and actuators.

1. Cavity detuning response to the piezo.
2. Geophone response to the piezo.
3. Geophone response to the Lorentz Force.

Accurate measurements of these transfer functions can be used to improve the fidelity of the offline and real-time cavity simulations.

REAL-TIME CAVITY SIMULATOR

To allow for the rapid evaluation, development, testing, and integration of tuner and microphonics control algorithms, electronics and data acquisition, we have developed a real-time cavity simulator. The simulator accepts 13 MHz IF signals for the forward power and generates IF signals for the reflected and transmitted power. The simulation includes:

- A complete electrical model of the cavity.
- A three mode mechanical model.
- Simplified models of the piezo actuator and longitudinal geophone response.
- A simplified model of closed loop LLRF control.
- Waveform capture and playback.

The simulator is implemented on a Lyrtech VHS-V4-ADC-DAC CompactPCI board, which includes the following components:

- A Xilinx Virtex 4 FPGA.
- 8 Channels of 14-bit, 105 MHz ADC.
- 8 Channels of 14-bit, 105 MHz DAC.

The simulator firmware has been generated using Simulink and SysGen. A high level block diagram of the simulator components is shown in Fig. 11.

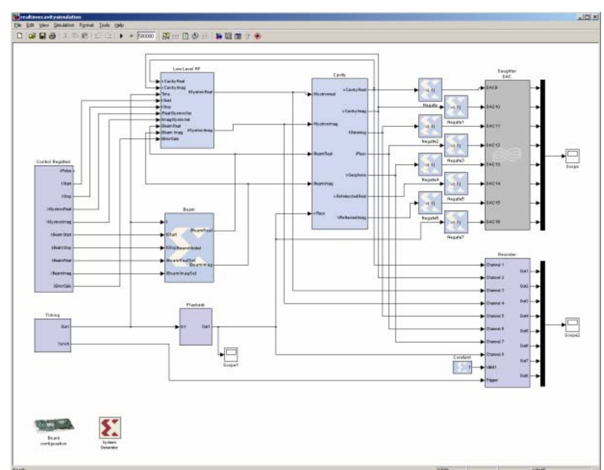

Figure 11: Simulator block diagram.

The simulator has been used to study the cavity response to the shape of the piezo pulse. Under closed-loop control, the detuning of the cavity is given by the following expression in the frequency domain:

$$\Delta f(\omega) = H_{Lorentz}(\omega) \cdot \left|V_{Cavity}^2\right|(\omega) + H_{Piezo}(\omega) \cdot V_{Piezo}(\omega)$$

$H_{Lorentz}$, and H_{Piezo} are the detuning transfer functions for the Lorentz force and the piezo actuator respectively, and V_{Cavity}, and V_{Piezo} are the voltages applied to the cavity and the piezo. Because the detuning is proportional to the square of the voltage applied to the cavity but linearly proportional to the voltage applied to the piezo, $H_{Lorentz}$, and H_{Piezo} have units of Hz/V^2 and Hz/V respectively.

To the extent that non-linearities such as those due to the response of the piezo actuator can be ignored, a pulse of the form

$$V_{Piezo}(\omega) = -\left(H_{Piezo}(\omega)\right)^{-1} H_{Lorentz}(\omega) \cdot \left|V_{Cavity}^2\right|(\omega)$$

will exactly cancel the effects of the Lorentz force. This has been demonstrated using the simulator using the simplified mechanical and sensor models that have been available to date. As more precise resonance data becomes available from measurements in the HTS, this algorithm will be explored further in both simulations and with a real cavity in the HTS.

ILCTA

The ILCTA is scheduled to come online next year at Fermilab. Initially the ILCTA will consist of a single 8-cavity cryomodule fabricated at DESY and assembled at Fermilab, but over the next several years, the facility will be expanded to include additional cryomodules built at Fermilab. The commissioning and operation of the ILCTA will provide Fermilab with experience controlling and automating a system containing multiple fast tuners.

The first cryomodule installed in the ILC Test Area will contain eight 1.3 GHz Tesla type cavities. Each cavity will be equipped with a double piezo fast tuner built at DESY. One piezo will be used as an actuator while the other will be used as a vibration sensor.

The tuner control system for ILCTA is currently under development. The system will use an 8 Channel digital phase detector implemented on a Lyrtech digitizer card. An NI FPGA card will be used to playback waveforms to the piezo actuator for Lorentz Force compensation and for active damping of microphonics. A standard PC running Windows XP, LabView, and Epics will automatically acquire the cavity transfer functions, control the tuners, and interface to the ILCTA control system.

SUMMARY

Fermilab is actively working on improving the control of Lorentz force detuning of SRF cavities. As part of this effort we have:

- Successfully demonstrated control of Lorentz force detuning in CCII, a 1.3 GHz Tesla type cavity at an accelerating gradient of 26 MV/m using a fast piezo tuner;
- Measured the vibration characteristics of a 1.3 GHz Tesla type cavity during the commissioning of Horizontal Test Stand;
- Implemented a real-time cavity simulator on a fast digital signal processing board and used it to study the effects of the piezo waveform on Lorentz force detuning;
- Begun development of the tuner control system for the first cryomodule to be installed in the ILCTA.

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