LOW-LEVEL RF CONTROL OF MICROPHONICS IN SUPERCONDUCTING SPOKE-LOADED CAVITIES

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Abstract

This paper presents the results of cw RF frequency control and RF phase-stabilization experiments performed with a piezoelectric fast tuner mechanically coupled to a superconducting, 345 MHz, β = 0.5 triple-spoke-loaded cavity operating at 4.2K. The piezoelectric fast tuner damped low-frequency microphonic-noise by an order of magnitude. Two methods of RF phase-stabilization were characterized: overcoupling with negative phase feedback, and also fast mechanical tuner feedback. The β = 0.5 triple-spoke-loaded cavity RF field amplitude and phase errors were controlled to ±0.5% and $\pm 3^0$ respectively.

INTRODUCTION

The Advanced Exotic Beams Laboratory (AEBL) proposed at Argonne National Laboratory utilizes 206 TEM-class superconducting cavities to provide 833 MV of cw voltage gain, of which 587 MV is provided by 94 345 MHz superconducting spoke-loaded cavities [1]. The RF field of each and every resonant cavity must be phase-locked to the heavy-ion beam bunches. This is accomplished by locking the resonant cavities to a stable external oscillator, and at the same time synchronizing the beam bunches with the oscillator. When the cavity RF frequency deviates from the stable external oscillator, the phase relationship between the cavity RF field and a particle bunch is altered, introducing time and energy errors in the beam. Three techniques have been developed to control the RF phase of superconducting cavities.

- Overcouple to the cavity and use negative phase feedback to control the cavity RF field. This damps the loaded-cavity *Q*, increasing the bandwidth and permitting operation in the presence of eigenfrequency fluctuations [2].
- Couple the cavity RF field to a variable reactance circuit, reactive tuning [3]. An ideal reactive tuner does not load the cavity. In practice there are RF losses in reactive tuners and the loaded-cavity *Q* is reduced. Reactive fast tuners have not been developed for frequencies much larger than 100 MHz or for cavities operating at stored energies greater than a few joules. As a result, they are currently not an option for 345 MHz spoke-loaded cavities.
- Employ a mechanical fast tuner to introduce a controllable RF frequency variation to maintain the phase relationship between the cavity RF field and the beam. This technique does not damp the loaded-cavity quality factor and requires no additional RF power. These tuners were successfully developed for elliptical-cell cavities operated in the pulsed mode of operation [4-6].

This work discusses the first application of fast mechanical tuners to the continuous-wave operation of superconducting spoke-loaded cavities

MECHANICAL FAST TUNING

The fast mechanical tuner consisted of an APC International, Ltd., PSt 1000/25/100 piezoelectric actuator mounted in a homemade guide assembly. The homemade guide assembly was discussed in reference [7]. This paper presents experiments which characterize the performance of this piezoelectric fast tuner and demonstrate its utility as a frequency and phase controller for a β = 0.5 triple-spoke-loaded resonator (TSR) operated in the continuous-wave mode. First, the general operating performance of the piezoelectric fast tuner is presented (the piezoelectric fast tuner transfer function). Second, the piezoelectric fast tuner is used to damp the ambient microphonic-noise. Finally, the piezoelectric fast tuner is used as part of a phase control system.

Piezoelectric Fast Tuner Transfer Function

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 is measured [6, 8]. The measurement was performed by sweeping the frequency of the sinusoidal signal driving the fast tuner and simultaneously recording the relative phase and amplitude of the resulting cavity RF frequency modulation. The amplitude of the correlation measurement and relative phase between the cavity RF frequency modulation and piezoelectric fast tuner drive signal is graphed in figure 1 and is referred to as the piezoelectric fast tuner transfer function. Similar results were reported in 2005 with a Physik Instrumente P-239.90 piezoelectric actuator [7].

The horizontal axis of the piezoelectric fast tuner transfer function is the amplitude modulation frequency of the electrical signal used to drive the piezoelectric fast tuner; called the vibration frequency. The top graph is the amplitude, defined as the ratio between the amplitude of the sinusoidal cavity RF frequency modulation to the amplitude of the sinusoidal amplitude modulation on the piezoelectric drive signal. The lower graph is the relative phase between the cavity RF frequency modulation and the piezoelectric drive signal amplitude modulation. The piezoelectric fast tuner transfer function can be used to

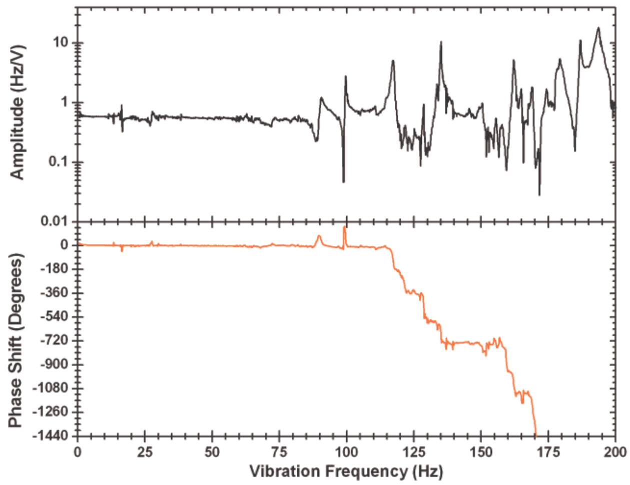

Figure 1: Piezoelectric fast tuner transfer function amplitude (top) and relative phase shift (bottom). This tuner was subsequently used as a frequency and as a phase controller on the β = 0.5 TSR.

predict the cavity response for any arbitrary voltage waveform driving the piezoelectric actuator.

Notice, that at low-frequencies no mechanical eigenmodes of the mechanically coupled cavity and fast tuner are excited. This feature allows for the compensation of low-frequency non-resonant microphonic-noise below 50Hz, the dominant contributor to continuous-wave operated spoke-loaded cavity phase-errors [9-11].

Piezoelectric Microphonic-Noise Damping

This section discusses measurements where the piezoelectric fast tuner is used to damp the microphonic-noise of the β = 0.5 TSR cavity. These measurements were performed with the β = 0.5 TSR intentionally coupled to an external vibration source to drive the microphonic vibrations; the external vibration source being the ATLAS accelerator forced flow helium refrigeration system.

First, the β = 0.5 TSR cavity was operated for five minutes without the piezoelectric fast tuner damping the cavity microphonic-noise. This measured the background microphonic-noise of the coupled cavity/cryostat/helium refrigeration system.

Immediately following the background measurement, the piezoelectric fast mechanical tuner was used in a negative feedback loop to damp the β = 0.5 TSR microphonic-noise. Data was collected for five minutes.

Figure 2 graphs the probability density of the cavity RF frequency deviations with and without the piezoelectric fast tuner damping the microphonic-noise. The horizontal axis is the RF frequency deviation of the cavity from an external source and the vertical axis is the number of counts on a logarithmic scale:

$$dB_{\#\,counts} = 20 \cdot Log\left(\frac{\#\,of\ counts\ in\ the\ bin}{total\ \#\,of\ samples}\right)$$

Figure 3 graphs the vibration spectrum of the cavity RF frequency deviations with and without piezoelectric feedback. The horizontal axis is the mechanical vibration frequency in hertz and the vertical axis is the RF frequency deviation amplitude, both axes use a logarithmic scale. For reference, the peak frequency deviation at a given vibration frequency required to drive a 0.3^0 phase precession, the AEBL design goal, is included on the graph.

To avoid exciting mechanical eigenmodes with the piezoelectric fast tuner a low pass filter is included in the tuner feedback loop. The -3dB point of the filter used was 20 Hz; consequently, the piezoelectric fast tuner would only damp RF frequency deviations which were driven by low frequency mechanical vibrations. Notice in figure 3 that the spectrum of RF frequency deviations is damped by an order of magnitude below 20 Hz.

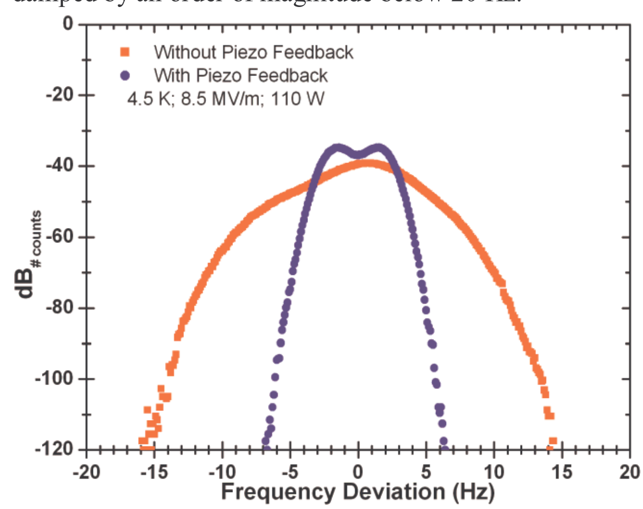

Figure 2: The β = 0.5 TSR cavity RF frequency variation spectral densities with the input power = 110 W (E_{acc} = 8.5 MV/m) at 4.5 K with and without piezoelectric damping of the RF frequency deviations.

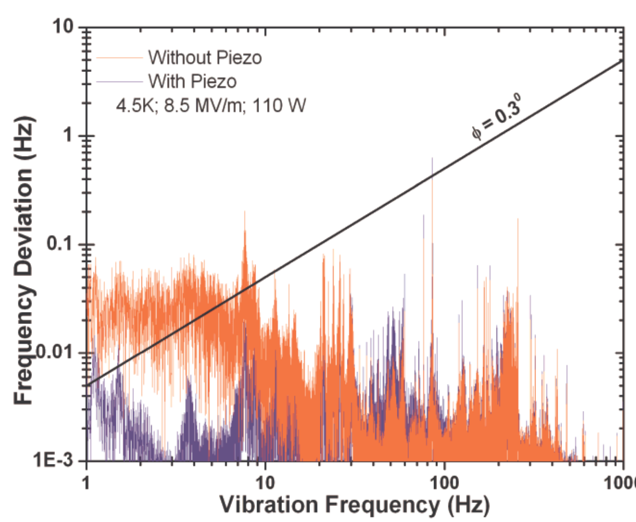

Figure 3: The β = 0.5 TSR cavity RF frequency deviation spectrums with the input power = 110 W (E_{acc} = 8.5 MV/m) at 4.5 K with and without piezoelectric damping of the cavity RF frequency deviations.

Piezoelectric Fast Tuner Phase Control

This section discusses measurements made with a phase-control system which is comprised of a voltage controlled 345 MHz RF phase shifter and the piezoelectric fast tuner.

First, the RF power source used for these experiments was limited to 3 kW at 345 MHz. At Q_L = 1.3 x 10^7, the AEBL design goal, the operating field level of 2.5 MV/m was determined to be the maximum accelerating gradient at which the cavity RF field could be phase-locked to an external oscillator with the available 3 kW and with a microphonic-noise background of ±50 Hz. Higher fields could have been reached if more RF power was available.

Second, the cavity was phase locked to an external oscillator with the 345 MHz phase controller. The controller was able to limit the cavity RF phase error to $\pm 3^0$ and the amplitude error to 0.5% with 700 W of RF power instead of the 3 kW required without the piezoelectric fast tuner.

The piezoelectric fast tuner performance as a phase controller is characterized in figure 4. Figure 4 graphs the measured cavity RF phase error and RF frequency deviation from an external oscillator over 250 seconds. The horizontal axis is time in seconds. The top graph vertical axis is the phase deviation of the cavity from the reference oscillator in degrees. The lower graph vertical axis is the RF frequency deviation in hertz.

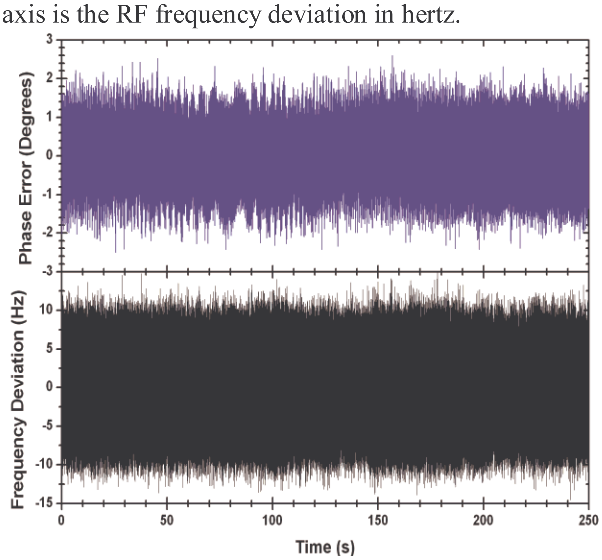

Figure 4: The measured cavity RF phase-error (top) and RF frequency deviation (bottom).

SUMMARY

It was demonstrated that the piezoelectric fast tuner developed here is useful for the compensation of the low-frequency non-resonant microphonic-noise characterized in [10, 11]. The cavity tests were performed with a helium refrigeration system similar to what is found around present superconducting accelerators.

The piezoelectric fast tuner damping of the low frequency microphonic-noise of a β = 0.5 TSR was demonstrated. The piezoelectric fast tuner decreased the amplitude of the cavity RF frequency deviations by an order of magnitude at low vibration frequencies.

Using the piezoelectric fast tuner the RF power required to phase lock the β = 0.5 TSR to an external oscillator was reduced from 3 kW to 700 W.

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