ELECTRO-MECHANICAL PROPERTIES OF SPOKE-LOADED SUPERCONDUCTING CAVITIES

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Abstract

This paper presents experimental data characterizing the electro-mechanical properties of superconducting spoke-loaded cavities developed for high-intensity ion-linac applications, such as the cw ANL Advanced Exotic Beams Laboratory (AEBL) driver linac and the pulsed FNAL High Intensity Neutrino Source (HINS, now project X) proton driver linac. High-gradient cw operation at 4.2 K can produce violent boiling in the liquid helium coolant causing microphonic frequency noise. A spoke cavity designed to minimize the effects of helium pressure on RF eigenfrequency, the total microphonic induced RF frequency variations, were found to be on the level of the phase noise in the reference oscillator. To determine the pulsed cavity RF performance, the Lorentz transfer function was measured and used to predict the dynamic detuning in pulsed operation. There is good agreement between the predicted fit and the measured data, demonstrating the utility of the Lorentz transfer function, which can completely characterize the dynamics of the coupling between the mechanical cavity structure and the cavity RF field due to the Lorentz force.

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 RF field amplitude and phase can be controlled determine:

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

The accelerating mode RF frequency variations of a $\beta = 0.4$ double-spoke-loaded (DSR) cavity and of a $\beta = 0.5$ triple-spoke-loaded (TSR) cavity have been measured and will be presented. An analysis of the microphonic-noise data presented here led to the development of fast tuning systems presented in references [1, 2].

LORENTZ DETUNING

This section will present experimental results which characterize the coupling between the electromagnetic eigenmode used to accelerate particles, f_0 = 345 MHz, and the mechanical eigenmodes when the interactions are driven by the Lorentz force. This is relevant to the pulsed operation of spoke cavities where the time-dependent Lorentz force can drive large variations in the cavity resonant frequency by exciting mechanical modes.

To characterize the coupling between the cavity RF field Lorentz force and the mechanical eigenmodes, the Lorentz transfer function is experimentally measured. The Lorentz transfer function is a mathematical expression which expresses the relationship between the time-dependent cavity RF Field amplitude and the cavity RF frequency. It is important to point out that the transfer function contains all of the information required to determine how a linear time-invariant system will respond to an arbitrary time-dependent stimulus. The physics of the interaction was reviewed by Delayen [3].

Two methods were employed to experimentally measure the Lorentz transfer function in the frequency domain [4]. The first experimental method employs a function generator and an oscilloscope [5]. The function generator generates the signal used to amplitude modulate the forward power, which results in an amplitude modulation of the cavity field. Then both the frequency modulation signal and the RF field pick-up signal are input into an oscilloscope allowing for the RF field amplitude modulation, the corresponding RF frequency modulation, and their relative phase shift to be measured as a function of the amplitude modulation frequency. This method is use to measure the Lorentz transfer function at amplitude modulation frequencies within a few hertz of mechanical mode eigenfrequencies which couple to the cavity RF field, e.g. 220 Hz and 320 Hz. Another experimental method, which is more efficient, employs a lock-in amplifier. The lock-in amplifier measures the signal amplitudes and relative phase shift directly and can be programmed to sweep the forward power modulation frequency to automate the measurement. The $\beta = 0.5$ TSR Lorentz transfer function amplitude and phase are graphed in figure 1.

The horizontal axis is the amplitude modulation

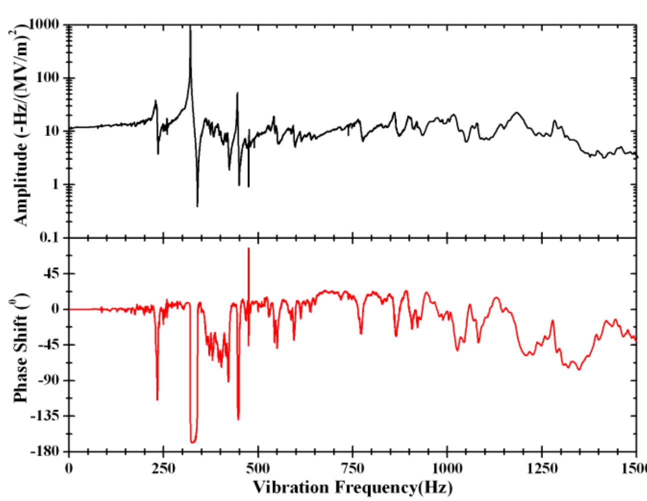

Figure 1: The $\beta = 0.5$ TSR Lorentz transfer function.

frequency, referred to as the vibration frequency. The top half of the plot is the ratio of the amplitude of the sinusoidal cavity RF frequency modulation where the factor $(MV/m)^2$ comes from:

$$\Delta E^2 = E^2_{acc,\max} - E^2_{acc,\min}$$

and $E^2_{acc,max}$ and $E^2_{acc,min}$ are the maximum and the minimum of the accelerating gradient sinusoidal amplitude modulation. The lower half of the graph is the relative phase difference between the cavity RF field amplitude modulation and the cavity RF frequency modulation.

The Lorentz transfer function (LTF) can be used to predict the response of the cavity RF frequency to any time-dependent RF field amplitude, E^2_{acc}., according to:

$$f(t) = \int_{-\infty}^{\infty} LTF(\Omega) \cdot E^2_{acc}(\Omega) \cdot e^{-i\Omega t}\, d\Omega$$

The predicted and the measured response of the β = 0.5 TSR to a pulsed cavity field for two different pulse durations and amplitudes are graphed in figure 2. The pulsed cavity measurements were limited by the available RF power (5 kW). The predicted response of the β = 0.5 TSR to a 1.5 ms 10 Hz 10.5 MV/m pulse, operating conditions in the proposed FNAL 8 GeV proton driver linac, is graphed in figure 3. In figures 2 and 3 the horizontal axis is time in milliseconds. The upper plot is the cavity RF frequency deviation from an external oscillator. The lower plot is the squared field pulse driving the cavity detuning.

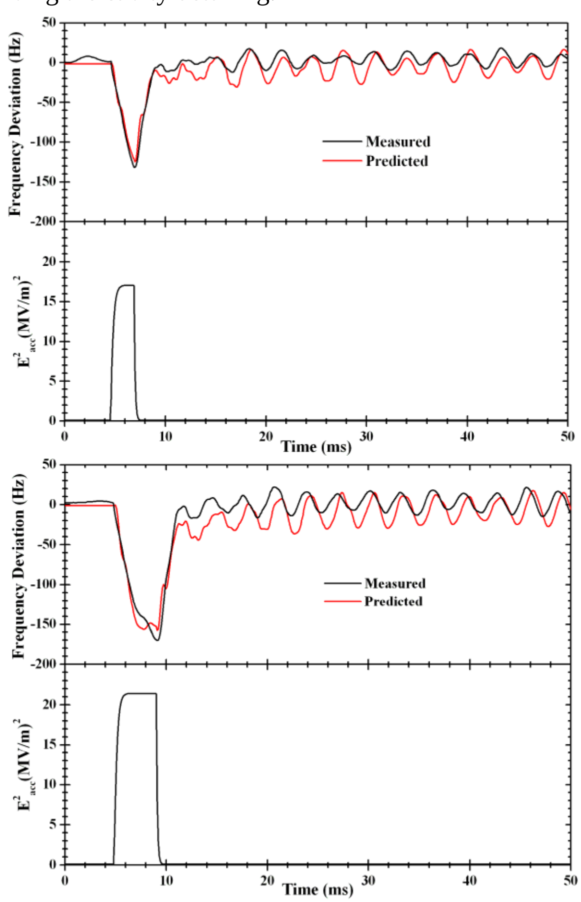

Figure 2: Measured and predicted cavity detuning.

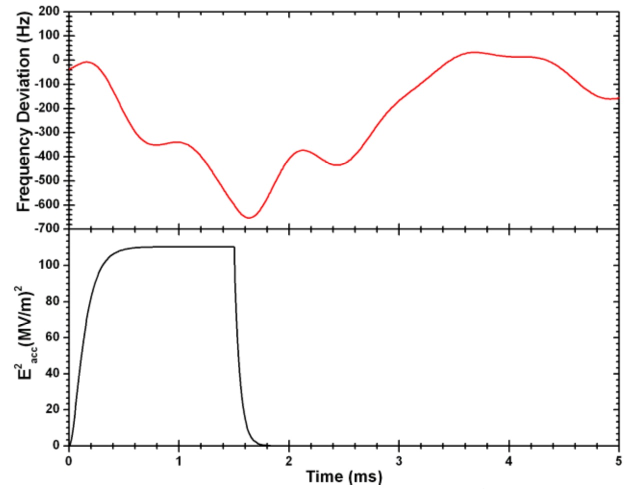

Figure 3: The predicted detuning of the β = 0.5 TSR operated under realistic conditions.

MICROPHONIC-NOISE

Liquid Helium Coolant-Boiling

This section presents the experimental results used to characterize the microphonic-noise of multi-spoke loaded cavities. The microphonic-noise of the β = 0.4 DSR was reported earlier [6]. A series of measurements were performed to determine if this microphonic-noise was due to variations in the helium vapor pressure.

The β = 0.4 DSR microphonic-noise and helium vapor pressure were measured at input powers of 5 W, 14 W, and 22 W. Figure 4 graphs the time-domain data and figure 5 graphs the cross-correlation between the β = 0.4 DSR RF frequency variation and the helium vapor pressure at each of the three input power levels.

This data shows that:

- The β = 0.4 DSR RF frequency deviations are highly correlated with changes in the helium vapor pressure.
- The RF power dissipated in the cavity appears to be driving both the variations in the β = 0.4 RF frequency and the helium vapor pressure.

β = 0.5 TSR Microphonic-Noise

The next multi-spoke-loaded cavity designed and fabricated was the β = 0.5 TSR [1, 7]. The β = 0.5 TSR was designed to minimize the coupling between the cavity RF frequency and adiabatic changes in the external pressure. This was accomplished by balancing the RF frequency shift due to deformations in regions with predominantly magnetic surface fields with those due to the regions of predominantly electric surface fields. The β = 0.5 TSR was constructed with mechanical support ribs on both the end-walls and the cylindrical wall of the cavity. The support ribs stiffen the cavity, reducing the deformation of the walls due to changes in the helium bath pressure, and balance magnetic and electric field contributions to the frequency shift of the cavity. Several of the reinforcing ribs were intentionally oversized, leaving a residual Δf/Δp of -12.4 Hz/torr. The residual

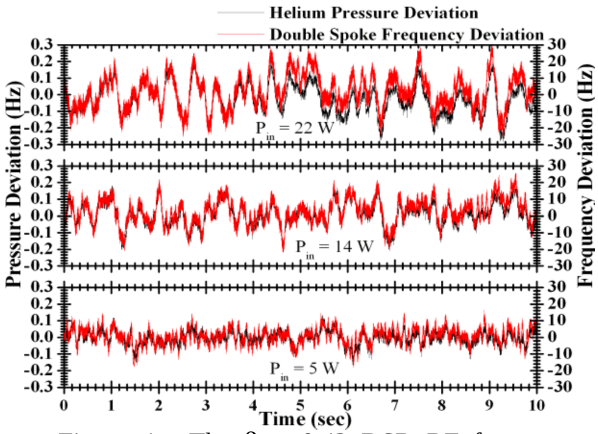

Figure 4: The β = 0.42 DSR RF frequency variations with the variations of the helium coolant vapor pressure superimposed.

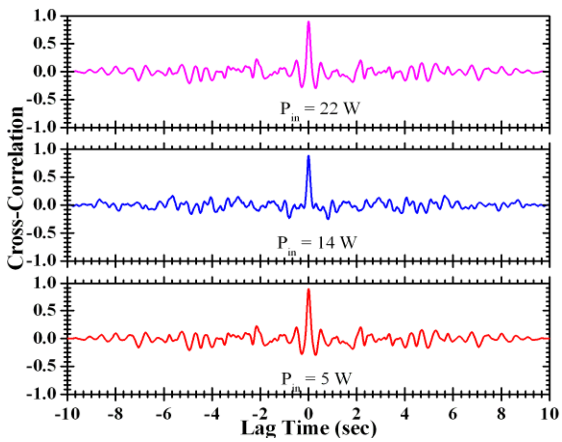

Figure 5: The cross-correlation functions between the RF frequency variation and the helium vapor pressure variation of the β = 0.42 DSR.

Δf/Δp was kept to allow for a fine tuning of Δf/Δp by cutting away sections of the oversized support ribs after characterizing the cavity microphonic induced RF frequency variations at 4 K. The microphonic-noise before the final reduction in Δf/Δp was published previously [7]. After modifying the support ribs, Δf/Δp decreased to -0.5 Hz/torr and the β = 0.5 TSR microphonic-noise was experimentally characterized.

Figure 6 graphs the probability density of the microphonic noise at input power levels of 20 W and 100 W, and the RF phase noise of the reference oscillator. Notice that the probability density does not change as the input power is increased and is Gaussian to > 4 orders of magnitude with an rms RF frequency deviation < 0.5 Hz. Also, the rms frequency deviation is approximately equal to the noise on the reference oscillator used in the measurement, an HP8644B.

SUMMARY

First, this paper presented a powerful method for studying and analyzing Lorentz detuning in superconducting cavities, the Lorentz transfer function. Second, the microphonic induced RF frequency variations of a β = 0.4 DSR and a β = 0.5 TSR were presented. It was shown that the microphonic-noise was due to boiling

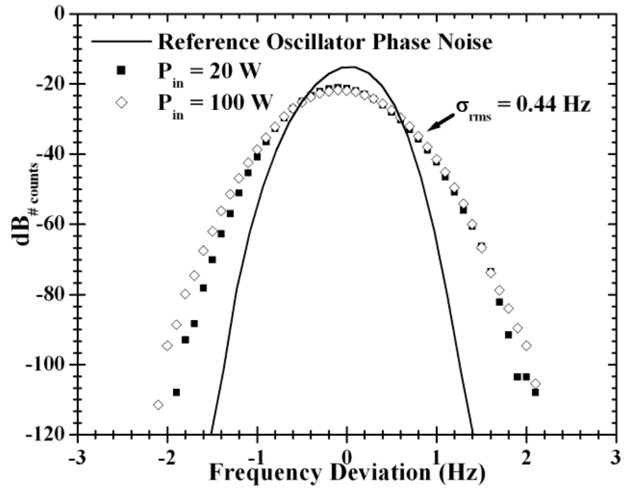

Figure 6: Probability density of the β = 0.5 TSR microphonics induced RF frequency variations and the reference oscillator phase-noise.

in the liquid helium bath. The β = 0.5 TSR was designed to decouple the cavity from adiabatic changes in the external helium pressure to reduce the bandwidth of microphonic-noise. The β = 0.5 TSR microphonic-noise was found to be very small with σ_{rms} = 0.44 Hz and barely above the level of the phase noise on the output of the external oscillator used for the measurement.

ACKNOWLEDGEMENTS

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