MICROPHONICS STUDIES OF THE CBETA LINAC CRYOMODULES*

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Abstract

The Cornell BNL ERL Test Accelerator (CBETA) incorporates two SRF linacs; one for its injector and another for the energy recovery loop. Microphonics in both the cryomodules play a crucial role in determining the energy stability of the electron beam in high current operation. We have measured vibrations and frequency detuning of the SRF cavities and determined that the cryogenic system is the major source of microphonics in both cryomodules. In this paper we discuss these measurements and demonstrate an Active Microphonics Compensation system implemented using fast piezo-electric tuners which we incorporated in our Low Level RF control system to be used in routine operation.

INTRODUCTION

The Cornell-BNL ERL Test Accelerator (CBETA) [1] [2] is a multi-turn Energy Recovery Linac (ERL), currently under construction at Cornell University. It will be the first ERL to use Superconducting Radio Frequency (SRF) cavities for acceleration. The Injector Cryomodule (ICM) which is a part of the Cornell high-current photo-injector [3] will be responsible for accelerating high beam currents for injection into the ERL loop and the Main Linac Cryomodule (MLC) will execute energy recovery in the machine. CBETA will also be the first ERL to have multiple return loops in one beampipe. This will be achieved with Non-Scaling Fixed Field Alternating Gradient (NS FFAG) optics employing permanent magnets for it's return arc. Being a high-current medium energy electron accelerator, it will be an unique platform for research into nuclear physics and materials science. Initially the project is set to prototype components and illustrate beam physics essential for the construction of eRHIC at BNL.

ERL operation is similar to electron time of flight spectrometers [4], consequently stability of electric fields in the SRF cavities is an important issue. The major factor affecting stability is vibrations of the SRF cavities also called microphonics which we investigate in this paper. Firstly, we discuss the theoretical considerations related to mechanical detuning of the SRF cavities, then we report on vibration measurements undertaken recently and finally we discuss some results of using a microphonics compensation system.

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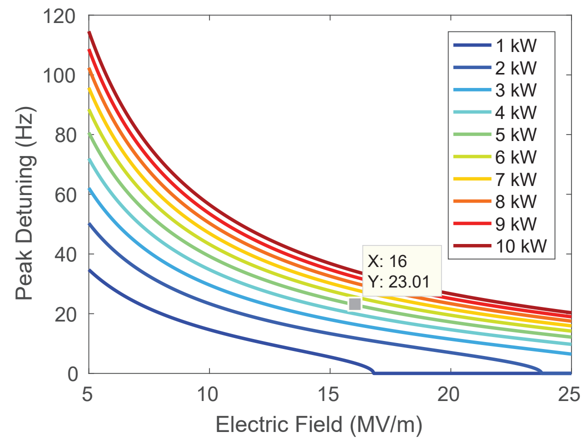

Figure 1: Peak detuning which can be tolerated by the RF system as a function of sustained electric field for some values of maximum forward power. The 7-cell cavity is designed to sustain a maximum field of 16 MV/m which can be reached using a 5 kW power source if the peak detuning is less than 23 Hz.

CAVITY DETUNING

The RF power required to maintain constant accelerating voltage V_{acc} inside a cavity is given by

$$P_f = \frac{V_{acc}^2}{8\frac{R}{Q}Q_0}\frac{(1+\beta)^2}{\beta}\left[\left(1+\frac{2Q_0}{(1+\beta)}\frac{R}{Q}\frac{I_b\cos\phi_b}{V_{acc}}\right)^2 + \frac{Q_0^2}{(1+\beta)^2}\left(\frac{f_c}{f_{\text{drive}}}-\frac{f_{\text{drive}}}{f_c}+\frac{R}{Q}\frac{2I_b\sin\phi_b}{V_{acc}}\right)^2\right] \quad (1)$$

where $\beta = Q_0/Q_{ext}$ is the coupling strength of the input coupler, R/Q is given by the circuit definition, f_c is the resonant frequency of the cavity, $f_{\text{drive}} = 1.3$ GHz is the RF drive frequency; I_b and ϕ_b are the beam current and the bunch phase respectively. The injector cavities operate with large beam loading and have $Q_{ext} \approx 5.4\times10^4$ which results in large bandwidth and relatively less sensitivity to detuning[5]. In contrast, the main linac cavities which execute energy recovery operate at zero beam loading and have $Q_{ext} \approx 6\times10^7$. Solid state power amplifiers capable of delivering 5 kW were chosen to power these cavities and having a strict RF power budget is a crucial part of operations. Figure 1 shows steady state power requirements of the 7-cell main linac cavities in the presence of detuning.

SRF cavities are deformed by radiation pressure of the field contained inside it or by the force from external vibrations called *microphonics*. The former, Lorentz Force Detuning (LFD) is only relevant while turning on field inside the cavity and remains as a constant offset to the resonant frequency of the cavity under continuous mode of operation. On the other hand, vibrations result in transient detuning of the cavity. Microphonics detuning may get particularly strong if the external vibration excites one of the many mechanical eigen-modes the cavity-tuner-cryomodule structure may have. Since mechanical energy of eigen-modes increase quadratically with frequency, the cavity structure is designed to have higher frequency vibrational modes which are harder to excite. To this effect, three of the six SRF cavities in the MLC have been mechanically optimized by using stiffening rings [6]. Nonetheless, all cavities used in the CBETA project are equipped with fast tuners to compensate for transient detuning [7] [8].

MICROPHONICS MEASUREMENTS

Microphonics measurements have been carried out for both cryomodules to look for sources of vibration and assess power requirements for the MLC. The measurement setup uses the Low Level Radio Frequency (LLRF) control system [9] to measure the tuning angle ϕ_t which is the phase difference between forward power and the field probe signal. The microphonics detuning δf is calculated using

$$\delta f = \frac{f_{\text{drive}}}{2Q_L} \tan \phi_t \qquad (2)$$

where $Q_L = 1/(Q_0^{-1} + Q_{ext}^{-1})$. Piezo-electric sensors attached to the fast tuners pick up vibrations in the the cavity walls; their output along with the detuning signals available from the LLRF are saved using a National Instruments data acquisition system. The contribution from different vibration sources have been identified by calculating the integrated detuning spectrum,

$$\delta f_{\text{int}}(f_{\text{mech,n}}) = \frac{1}{N}\sqrt{2\sum_{i=0}^{n}|\delta \tilde{f}_i|^2} \qquad (3)$$

where, $\delta f_{\text{int}}(f_{\text{mech,n}})$ is the root mean square detuning with contributions ranging from vibrations of 0 Hz up to $f_{\text{mech,n}}$, $\delta \tilde{f}_i$ is the ith element in the Discrete Fourier Transform (DFT) of the raw signal and N is the total number of data points. Each vibration source shows up as a step in the integrated detuning function and the step size indicates it's relative importance.

The integrated detuning spectra for all five 2-cell cavities used in the injector are shown in Fig. 2. The vibrations measured in this cryomodule exhibit strong intermittent pulses which account for a significant portion of microphonics. These pulses were first observed in the ICM in 2009 and it was determined that they were caused by the cryogenic system [7]. The liquid helium vessel enclosing the cavity has chimneys on the top feeding into the Helium Gas Return Pipe (HGRP)and inlets at the bottom connecting to a pre-cool line used during during warm up and cool down. The pre-cool line is normally shut-off during routine operation and Helium gas trapped in this pipe escape every few seconds into the Helium vessel, the resulting pressure wave leads to ringing in the cavities. On opening the valve which connects the pre-cool line directly to the HGRP, the build-up of gas is prevented and the impulses stop. However this state is not stable and after a few hours some other form of oscillation takes over leading to higher RMS microphonics detuning compared to when the valve is closed. In the current configuration, the maximum detuning does not exceed 300 Hz which is sufficient for the injector to drive beam currents of 40 mA required for high-current operation of CBETA [2].

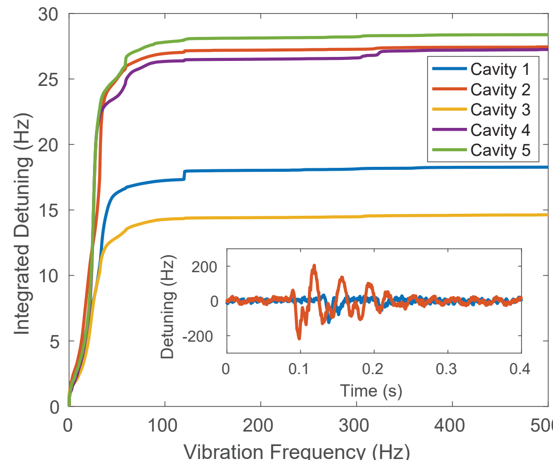

Figure 2: Integrated detuning f_{int} as a function of vibration frequency f_{mech} for all cavities in the Injector Cryomodule from a measurement taken for 800 sec. The largest contribution ranging from f_{mech} of a few Hz up to 40 Hz arises from intermittent mechanical impulses such as the one shown in the inset. These contribute most to the microphonics, with instantaneous microphonics detuning reaching 300 Hz.

The main linac cavities will be operated with $Q_{ext} \sim 6 \times 10^7$ at $V_{acc} = 6$MV [2] and hence be particularly sensitive to detuning. The maximum forward power available to each cavity is limited to 5 kW and from Eq. 1 the maximum detuning which the RF system would tolerate is 53.9 Hz. This necessitates having microphonics measurements over long periods of time. Results from microphonics data taken from an un-stiffened cavity are shown in Fig. 3. Microphonics detuning for this cavity typically ranges from -50Hz to 50Hz, which is within the acceptable range. The low frequency contributions shown in the inset are from pressure variations in the liquid helium bath. While there are no instabilities in the 1.8 K liquid Helium system, there appears to be an occasional impulse which results in high instantaneous detuning (163 Hz in this data set). These impulses coincide with actuation of a particular Joule-Thomson valve on a 5 K Helium pre-cool line. We are conducting further tests to quantify microphonics on other cavities and looking at ways to fix the valve position so as to remove these impulses. Once removed, the un-stiffened cavity will be able to operate at 6 MV without any further intervention.

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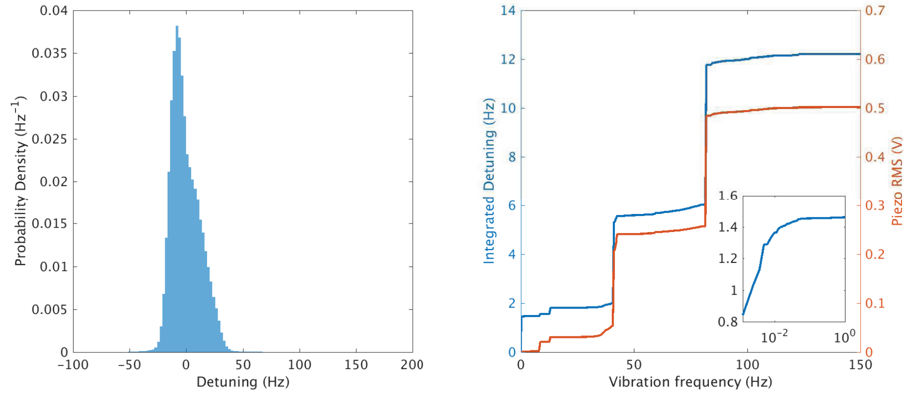

Figure 3: Microphonics measurements of an un-stiffened cavity in the Main Linac Cryomodule taken over a period of 800 sec. The left panel shows a histogram of microphonics detuning and the right panel shows the integrated spectra (Eq. 3) for detuning and piezo-electric signal measurements. There are major contributions near 40 Hz and 80 Hz along with some contribution from sub 1 Hz frequencies as shown in the inset.

ACTIVE COMPENSATION

Vibrations caused by the cryogenic system are difficult to alleviate and active compensation using fast tuners becomes necessary. In such a system, the LLRF actively controls piezo-electric actuators to tune the cavity to the drive frequency typically by monitoring the tuning angle and signals from piezo-electric sensors located in the tuner. A simple proportional integral feedback loop may be used to control the drive voltage ($u_{\rm pz}(t)$) applied to the actuator [10]. This is given by

$$u_{\rm pz}(t) = K_P \delta f(t) + K_I \int_0^t \delta f(t')\mathrm{d}t' \qquad (4)$$

where, $\delta f(t)$ is the cavity detuning, K_P and K_I are the proportional and integral gains respectively. A feedback loop based on this approach has been incorporated into the Cornell LLRF system and data taken from the un-stiffened main linac cavity after adjusting the loop gains is shown in Fig. 4. The fast tuner successfully compensates for low frequency microphonics, though it's not effective at higher frequencies. Moreover, the integral term in the feedback loop corrects for small tuning errors which can't be corrected due to the hysteresis of the slow tuner [11] or from Lorentz force detuning.

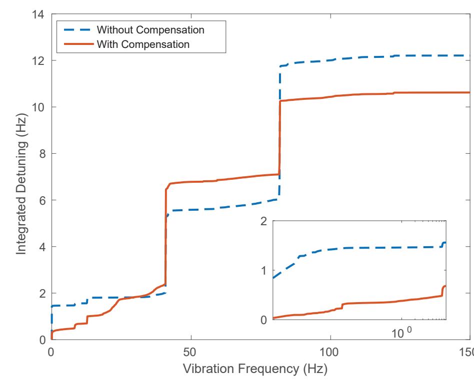

Figure 4: Integrated spectra calculated from measurements taken for 800 sec with and without active compensation on an un-stiffened cavity in the Main Linac Cryomodule. The feedback loop is clearly very effective on low frequency pressure variations as shown in the inset. However, it is not effective at frequencies more than 1 Hz.

CONCLUSION

Microphonics detuning is a crucial parameter in the operation of the SRF linacs used for the CBETA project. An instability in the cryogenic system of the injector cryomodule generates strong periodic mechanical impulses which account for a major portion of microphonics. However the injector cavities are less sensitive to detuning due to a relatively low Q_{ext} used for high-current operation and the current configuration will be capable of delivering 40 mA beams as required by CBETA. Microphonics measurements for the cavities in the main linac are underway and initial measurements on one un-stiffened cavity suggests strong contributions at 40 Hz and 80 Hz along with strong intermittent mechanical impulses which appear to be caused by the actuation of a particular valve in the 5 K Helium system. Finally, active compensation of low frequency vibrations has been successfully demonstrated. Further research will focus on compensation of microphonics at higher frequencies and of strong instantaneous impulses to ease operational constraints on the MLC.

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