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MICROPHONICS SUPPRESSION IN THE CBETA LINAC CRYOMODULES*

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Abstract

The Cornell-BNL ERL Test Accelerator (CBETA) is a new multi-turn energy recovery linac currently under construction at Cornell University. It uses two superconducting linacs, both of which are susceptible to microphonics detuning. The high-current injector accelerates electrons to 6 MeV and the main linac accelerates and decelerates electrons by 36 MeV. In this paper, we discuss various measures taken to reduce vibrations caused by instabilities and flow transients in the cryogenic system of the main linac cryomodule. We further describe the use of a Least Mean Square algorithm in establishing a stable Active Microphonics Compensation system for operation of the main linac cavities.

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 multi-turn 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. The Main Linac Cryomodule (MLC) [4] will execute energy recovery in the machine. CBETA will also be the first ERL to have multiple energy return loops in one beampipe. This will be achieved with Non-Scaling Fixed Field Alternating Gradient (NS FAG) [5] optics employing permanent magnets for it's return arc. Operating this machine presents unique challenges and one of them will be maintaining the energy stability of multiple beams with different energies simultaneously using a single main linac. CBETA will be the first high current electron accelerator to use active microphonics compensation to help achieve this goal.

ERL operation is similar to electron time of flight spectrometers [6], consequently stability of electric fields in the SRF cavities is an important issue. Microphonics detuning arising out of transient deformation of the SRF cavities due to mechanical vibrations in the cryomodule is a major source of perturbations. In this paper, we report on the microphonics measurements done on the injector and the main linac and identify the sources. Then we discuss modifications of the cryogenic valves to reduce the majority of microphonics. Finally, we discuss our implementation of an active microphonics compensation system and present the results of our experiments.

MICROPHONICS MEASUREMENTS

The change in resonant frequency (detuning) of a SRF cavity increases the RF power consumed by the system to maintain field [7] and has a detrimental effect on accelerating field stability. The injector cavities operate with large beam loading and have $Q_L \sim 5 \times 10^4$ which results in large bandwidth and relatively less sensitivity to detuning. Previous measurements indicate a comparatively high peak detuning (~300 Hz) which is however much smaller than the RF bandwidth and hence is sufficient to permit high current operation. In contrast, the main linac cavities of CBETA are designed to be operated at about $Q_L \sim 6 \times 10^7$ using solid state amplifiers capable of delivering a maximum forward power of 5 kW. Particular care has been taken in the design of the MLC cavities to reduce the effect of transient mechanical forces. 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 has been 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 [8]. Further, all SRF cavities used in the CBETA project are equipped with fast tuners to compensate for transient detuning [9, 10].

The microphonics measurements of the main linac cryomodule are shown in Fig. 1. Cavities 2, 4 and 6 are fitted with stiffening rings and exhibit peak microphonics detuning well below the 54 Hz limit [11] posed by the limited forward power capability of the solid state power amplifiers whereas the other cavities suffer from very high peak detuning. The raw microphonics data shows sudden bursts of peak detuning occurring intermittently almost every 10 minutes, as much as 280 Hz in cavity 3. This severely limits the maximum field which can be maintained by the RF system. Apart form the transient bursts, steady vibrations of 8 Hz, 40 Hz and 80 Hz can be seen in the spectrum of detuning. These observations motivated the use of 10kW amplifiers to drive the un-stiffened cavities along with the inclusion of 3-stub tuners to ease the constraints on the accelerating field. In the interest of suppressing microphonics as much as possible we identified the major sources and discuss them in the next section.

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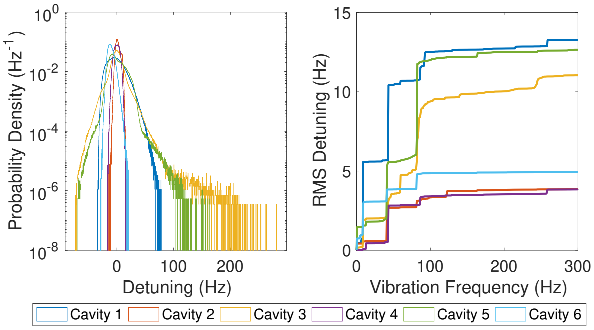

Figure 1: Microphonics measurement on all main linac cavities. The left panel shows the histogram of microphonics detuning. The right panel shows RMS detuning as a function of vibration frequency.

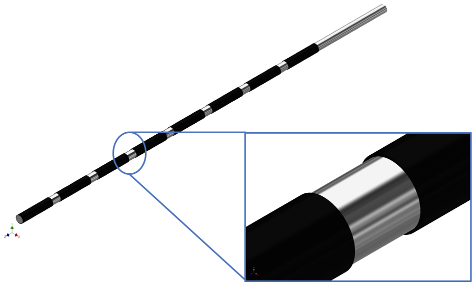

Figure 2: Planned modification of the valve stem of a cryogenic needle valve to constrict the flow of Helium gas in the space between the stem and the inner wall of the valve chamber. The black sleeves are made of PEEK plastic material suitable for cryogenic temperatures.

MICROPHONICS SOURCES AND PASSIVE SUPPRESSION

Microphonics measurements in the MLC reveal two classes of vibrations, sudden large detuning which only sustain for a few milli-seconds in the whole period of measurement (800 seconds) and steady state narrow band oscillations at 8 Hz, 40 Hz and 80 Hz. The sudden detuning have a negligible effect on the spectrum and is broadband which make active compensation complicated. On investigating various cryogenic pressures and flows it was found that sudden actuation of a cryogenic needle valve coincided with the generation of these impulses. On making this valve static, the peak detuning in cavity 3 of the main linac was reduced from 280 Hz in the default operating conditions to 50 Hz in this setting. However this valve is responsible for regulating the flow of liquid Helium into the 2K-2 phase Helium pipe in the cryomodule and the static condition leads to a slow runaway of the liquid Helium level. A feedback controlled heater was used with the valve remaining largely open to regulate the system and this led to an final peak detuning of 100 Hz which mostly consist of steady state vibrations.

Steady state narrow band oscillations can arise from rotary mechanisms such as pumps or from cryogenic instabilities. Measurements from various possible sources and microphonics detuning indicate a substantial cross-correlation with vibration of a cryogenic valve stalk. The design of the MLC includes needle valves whose stalk extend outside the cryomodule into room temperature generating a thermal gradient in the Helium gas contained in the valve chamber leading to thermo-acoustic oscillations driving 40 Hz and 80 Hz. This instability can be attenuated by filling up the space between the valve stem and the inner walls of the chamber as illustrated in Fig. 2 and is planned to be done later this month. However, the exact mechanism of excitation of the 8 Hz vibrations remains unknown but we have observed that it's intensity depends on gas flow out of the helium gas return pipe indicating that this might be a mechanical eigen-mode of the pipe-cryomodule system. In the next section we discuss a procedure to actively compensate for these vibrations.

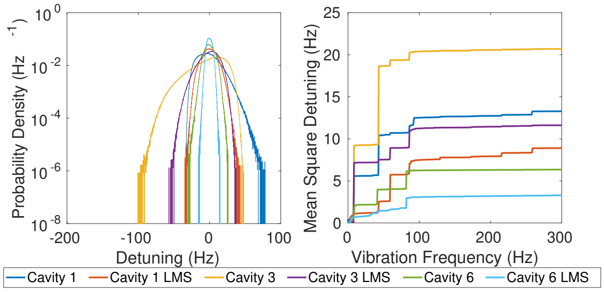

Figure 3: Performance of Least Mean Squares compensation on three cavities of the Main Linac Cryomodule in CBETA. The results from these runs are summarized in table 1.

ACTIVE COMPENSATION

Resonance control of high loaded quality factor SRF cavities is important for ERL operation to maintain good field stability using relatively modest amounts of power. In CBETA, apart from passive suppression, we use frequency tuners built with fast piezo-electric actuators to compensate for transient detuning. Depending on the frequency of vibrations, we have implemented two algorithms in the Cornell Low Level Radio Frequency (LLRF) [12] control system. A proportional-integral (PI) control loop is very effective at low frequencies (<1 Hz) and we have demonstrated it successfully in both the injector [13] and the main linac [11]. The mechanical transfer function [14] of the fast tuner system at higher frequencies exhibit complex phase structure which make it less suitable for a simple PI feedback loop and we compensate most part of microphonics detuning using a Least Mean Squares (LMS) technique.

Least Mean Square (LMS) control aims to reduce the mean square of frequency detuning $\langle(\delta f(t))^2\rangle$ in the case of cavity resonance control. A time domain version of this algorithm relies on continuously adapting a digital control filter in response to it's performance. [15] In our algorithm, we have taken advantage of the largely narrow band nature of the vibrations measured in our cryomodule as is clear from the spectrum shown in Fig. 1. The signal sent to the actuator is thus a sum of carefully controlled sinusoids:

$$u_{\mathrm{pz}}(t_n) = \sum_m I_m(t_n)\cos(\omega_m t_n) + Q_m(t_n)\sin(\omega_m t_n), \quad (1)$$

where $u_{\mathrm{pz}}(t_n)$ is the actuator signal at time t_n which is a sum of sines with frequencies ω_m whose amplitude and phase are determined by $I_m(t_n)$ and $Q_m(t_n)$. These are adjusted using a simple gradient descent optimization scheme similar to least squares fitting:

$$I_m(t_{n+1}) = I_m(t_n) - \mu_m \delta f_{\mathrm{comp}}(t_n)\cos(\omega_m t_n - \phi_m) \quad (2a)$$

$$Q_m(t_{n+1}) = Q_m(t_n) - \mu_m \delta f_{\mathrm{comp}}(t_n)\sin(\omega_m t_n - \phi_m) \quad (2b)$$

where δf_{comp} is the compensated detuning, ϕ_m is the phase difference between a sine wave of frequency ω_m applied to the piezo and the response of detuning to the perturbation (transfer function phase) and μ_m is the frequency dependent rate of gradient descent.

This algorithm works quite well for a stiffened cavity as shown in Fig. 3. The transfer function is more noisy for an un-stiffened cavity and slight changes in frequency requires large changes in ϕ_m. This phase can be updated in-situ following the same gradient descent technique:

$$\begin{aligned}\phi_m(t_{n+1}) \quad = \quad & \phi_m(t_n) - \eta_m \delta f_{\mathrm{comp}}(t_n) \times \qquad (3)\\ & \Big\{ I_m(t_n)\sin(\omega_m t_n - \phi_m(t_n)) - \\ & Q_m(t_n)\cos(\omega_m t_n - \phi_m(t_n)) \Big\},\end{aligned}$$

where we introduce η_m which is the phase change adaptation rate. We applied the modified algorithm to un-stiffened cavities 1 and 3 as shown in Fig. 3. The results from various runs are summarized in table 1 which clearly shows that the algorithm is effective in reducing detuning by more than 60% in all the cavities it was tested on. In further evidence of detuning compensation, the improved LMS algorithm reduces the power consumption appreciably (Fig. 4) and in a stable manner becoming indispensable for the operation of CBETA.

Table 1: Peak Detuning in the Main Linac Cavities

Cavity	Stiffened	Peak Detuning (Hz)		
		Initial	Static Valves	LMS on
1	No	N/A	78	45
2	Yes	18	N/A	N/A
3	No	280[1]	100	57
4	Yes	N/A	18	N/A
5	No	163	N/A	N/A
6	Yes	33	N/A	15

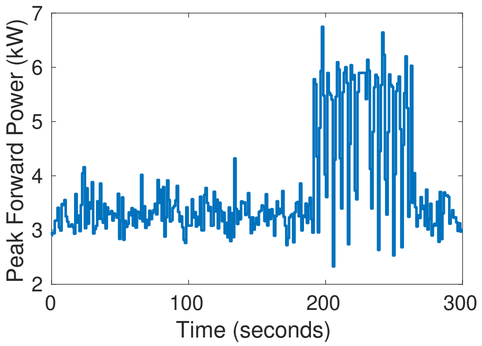

Figure 4: Peak RF power used to maintain 3 MV of accelerating voltage on cavity 3 (un-stiffened) as a function of time. LMS compensation is initially turned on and then switched off at 190 seconds, finally turning it back on at 265 seconds demonstrating that it reduces peak RF power consumption by a factor of 2.

CONCLUSION

Microphonics detuning is a crucial parameter in the operation of the SRF linacs used for the CBETA project. RF measurements on the high Q_L cavities in the main linac reveal lower microphonics in mechanically stiffened cavities while the un-stiffened cavities are subject to transient detuning much larger than their bandwidth. While thermo-acoustic instabilities in the needle valve are responsible for steady state vibrations at 40 Hz and 80 Hz, sudden mechanical bursts have been correlated to cryogenic valve actuation. By suppressing these movements and implementing an alternate route of cryogenic regulation we have shown that the peak microphonics can be greatly reduced. Further we demonstrate a resonance control system using piezo-electric tuners which is capable of attenuating both low and high frequency steady microphonics using a proportional integral and a least mean square feedback approach respectively. Active and passive suppression of microphonics together have been instrumental to reach the goal of 36 MeV total energy gain in the main linac of CBETA.

Immediate work will involve turning on all cavities simultaneously and measure the long term performance of the RF system. Future work will include research on new compensation techniques. Successful operation of the MLC for energy recovery will also involve understanding how microphonics affects field stability in high loaded quality factor SRF cavities and whether any improvements in the field control loop can help alleviate it's effects.

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[1] The very high measured value of peak detuning is due to a systematic error in phase measurement of the field. The actual value of peak detuning is probably $\gtrsim$ 100Hz.

Fermilab which prompted us to look for thermo-acoustic oscillations in our cryogenic valves. Nilanjan would like to thank the United States National Science Foundation, the Division of Physics of Beams of the American Physical Society, and TRIUMF for travel support.

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