LORENTZ FORCE COMPENSATION FOR LONG PULSES IN SRF CAVITIES

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Abstract

The Project X pulsed linac is based on SRF technology developed for ILC and XFEL projects with only difference that low beam current used in Project X drives to use high Q_L~10^7 and longer RF pulses ~8.3ms for operational gradient in cavity ~25 MV/m. It requires the compensation of the cavity detuning at the level of 20-30 Hz. Experimental studies of Lorentz force detuning compensation of Tesla style superconducting cavities during pulses of up to 9ms in duration, at operating gradients of up to 25 MV/m, and with loaded Q_L between $3*10^6$ and 10^7 has been performed for two cavities in the TESLA type II cryostat at the Fermilab Advanced Superconducting Test Accelerator (ASTA) Facility. As a result we demonstrated that detuning of the cavity was successfully limited to 30 Hz or better using active LFD compensation algorithm developed at Fermilab.

INTRODUCTION

One of the options currently under consideration for the second stage of the proposed Project X at Fermilab is a 1mA pulsed linac with an accelerating gradient of 25 MV/m. Efficient operation of the linac requires cavities operate at higher loaded Q_L and be driven by longer pulses, (4ms fill and 4.3ms flattop) than has typically been used with Tesla style cavities until now. The period of the dominant mechanical modes of the cavities is typically several milliseconds and if left uncompensated, the Lorentz force at the planned gradient of 25MV/m can drive the cavities several bandwidths off resonance during the pulse. The RF power required to drive a detuned cavity is proportional to the fourth power of the detuning so it is critical that Lorentz force detuning must be actively compensated to 30 Hz or better if such a linac to be a viable option.

The feasibility of actively compensating Lorentz force during long pulses to the levels required for efficient operation of the linac under consideration for Project X was assessed during recent studies using two cavities from CM1 at the Fermilab SRF Test Facility.

DESCRIPTION OF EXPERIMENTAL SETUP

CM1 is a DESY Type II cryomodule containing eight 9-cell elliptical superconducting Tesla style cavities operating at a frequency of 1.3 GHz [1]. Following the successful commissioning of the cryomodule, the RF distribution system and modulator were reconfigured to drive only the two highest gradient cavities, C5 and C6, with 9 ms pulses from a 120 kW klystron at repetition rates of up to 1 Hz. These two cavities can operate at accelerating gradients, E_{acc}, of 25MV/m and 27MV/m respectively. The vector sum of the two cavities was controlled using an Esecon digital controller and the LFD compensation system developed for CM1 was adapted to handle the modified cavity configuration.

The loaded Q_L of both cavities can be varied between 10^6 ($f_{1/2}$=650 Hz) and to 10^7 ($f_{1/2}$=65 Hz) by adjusting the ratios of the power couplers.

Cavity baseband waveforms were recorded for the following matrix of operating conditions:

- Q_L: $3*10^6$; $6*10^6$; $1*10^7$;
- E_{acc}: 15MV/m; 20 MV/m; 25 MV/m;
- RF power per cavity: 40 kW; 50 kW, 60 kW.

Current plans for the candidate Project X linac call for the cavities to operate with Q_L=10^7 at a gradient of 25 MV/m while driven by 50 kW of RF, power required for RF distribution losses, control overhead and compensation of residual frequency detuning from LFD and microphonics.

ADAPTIVE COMPENSATION OF THE LORENTZ FORCE DETUNING

The CM1 LFD control system employs an adaptive feed-forward algorithm developed at FNAL to tailor the piezo drive waveform for each individual cavity [2]. This algorithm has been used successfully at FNAL [3] and KEK [4] to control LFD in a variety of SRF cavity designs and operating conditions.

In contrast to the approach commonly used, driving the piezo with a simple half-cycle sinusoid impulse, the FNAL algorithm measures the detuning response of the cavity to a series of piezo impulses timed to arrive between 10ms and 0ms in advance of the RF pulse. A least squares fit is then employed to determine the linear combination of impulses need cancel the detuning of the cavity by the Lorentz force.

The bias, impulse width, amplitude, and timing with respect to the RF pulse of a half sine piezo drive pulse can be adjusted to compensate for the constant, linear and quadratic detuning components during the flattop of a short RF pulse. As the length of the RF pulse becomes comparable to the period of dominant mechanical mode of the cavities a more complex piezo waveform such as that produced by the FNAL algorithm is required to damp out mechanical oscillations.

Figure 1 shows a sample screenshot of the LFD controller online display. Compensation is applied over the window set by the two blue lines in Panel B. The piezo drive pulse begins 30ms prior to the arrival of the RF pulse and continues for the duration of the 9ms RF pulse.

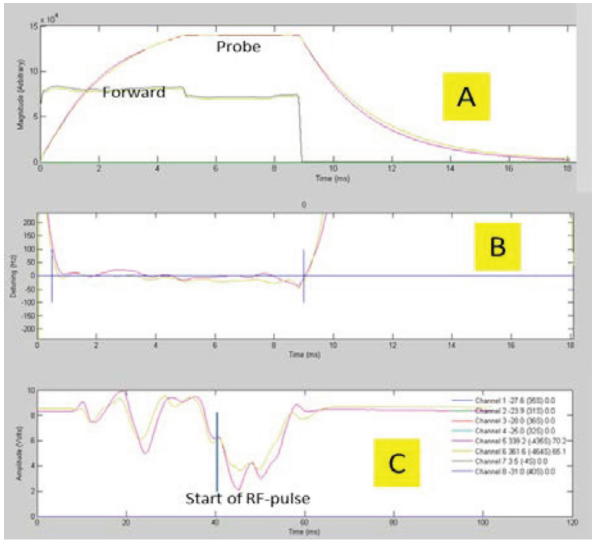

Figure 1: LFD Compensation in C5 and C6 during a 9ms RF pulse at E_{acc}=25MV/m and $Q_L = 6*10^6$. (A): Baseband envelopes of the forward and cavity field probe signals. (B): Residual detuning using following compensation. Adaptive LFD algorithm. (C): Piezo drive waveforms.

The LFD compensation algorithm was first tested and tuned for the modest set of cavity parameters $Q_L \sim 3 \cdot 10^6$ (typical value for ILC cavity) and cavity gradient 18 MV/m. Figure 2 shows the result of LFD compensation for long pulse operation. Large bandwidth provides robust operation in this regime.

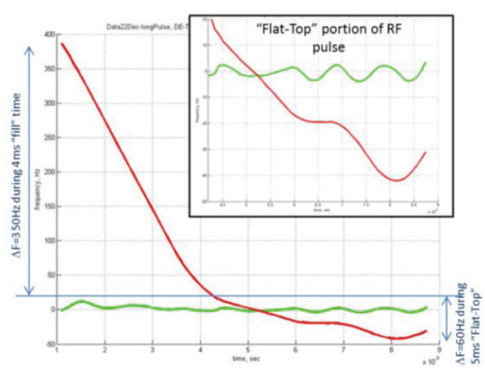

Figure 2: Detuning of the cavity ($Q_L=3*10^6$ and Eacc=18MV/m) by Lorentz forces during a 9ms pulse. Red curve is cavity's LFD when piezo compensation is OFF. Green curve is the cavity's detuning when cavity resonance control with piezo tuner and adaptive compensation algorithm is active. Insert: zoomed window shows LFD detuning during 5ms "Flat-Top" portion of RF pulse (red-piezo OFF; green- piezo ON).

RESULTS

The recorded baseband waveforms were analysed offline to determine the peak detuning during the flattop, pulse-to-pulse variation of detuning, and the phase and amplitude stability of both the vector sum and of the two individual cavities.

Figure 3A shows the superposition of C5 detuning of 1800 pulses collected over a period of 30 minutes during operation at $Q_L=10^7$ and E_{acc} =24.5 MV/m. The red curve shows the detuning averaged over all the pulses while the white curve show the std deviation of the sample at each point in time. The peak detuning during the flattop is 10Hz. Figure 3B shows a histogram of the average detuning for the same sample of pulses. The peak pulse-to-pulse variation during the flattop under these operating conditions is better than ±10 Hz peak-to-peak.

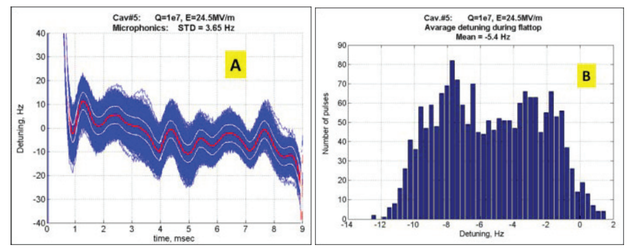

Figure 3: Residual Detuning over 30 minutes during operation at $Q_L=10^7$ and E_{acc} =24.5 MV/m. (A) shows the detuning waveforms of 1800 pulses collected over a 30 minute period while (B) shows a histogram of the average detuning for the same sample.

Figure 4 shows the closed loop amplitude and phase stability of the C5 and of the vector sum of the two cavities during operation at $Q_L=10^7$ and E_{acc} =24.5 MV/m.

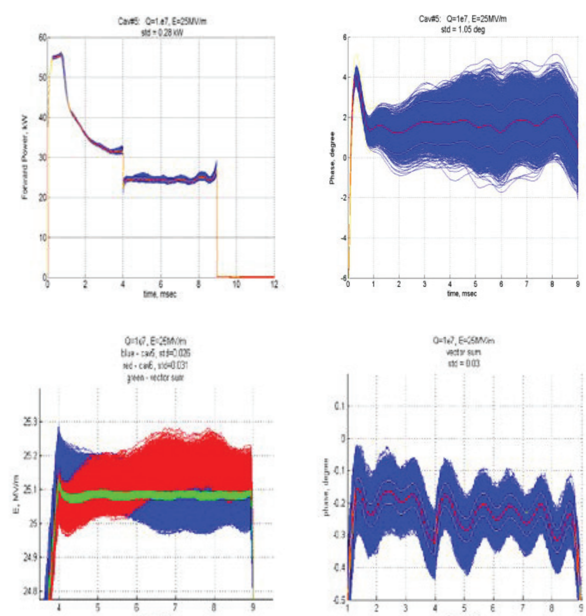

Figure 4. Top Plots: Forward Power and Phase signals of C5 and (bottom plots): Amplitude (C5, C6, Vector sum) and Phase Stability (Vector Sum) over 30 minutes during operation at $Q_L=10^7$ and E_{acc} =24.5 MV/m.

While the individual cavities show pulse-to-pulse amplitude and phase variations of up to 0.2 MV/m and 4 degrees respectively, the variations of the two cavities is strongly anti-correlated and the vector sum is stable to 0.1 MV/m and 0.02°.

ISBN 978-3-95450-115-1

Some overhead in the Forward power during the filling time can be seen in the figure 4 (Top, left), because the settings for the shape of the cavity probe signal during filling time was not optimized for this value of Q_L.

The phase of vector sum consistently shows a sinusoidal modulation at a frequency close to 1 kHz. This modulation is not present when compensation is off as is apparent in Figure 1. This modulation is almost certainly an artefact induced by the compensation algorithm but there was not sufficient time during these studies to adequately investigate it. Suppressing this component might allow compensation of be further improved.

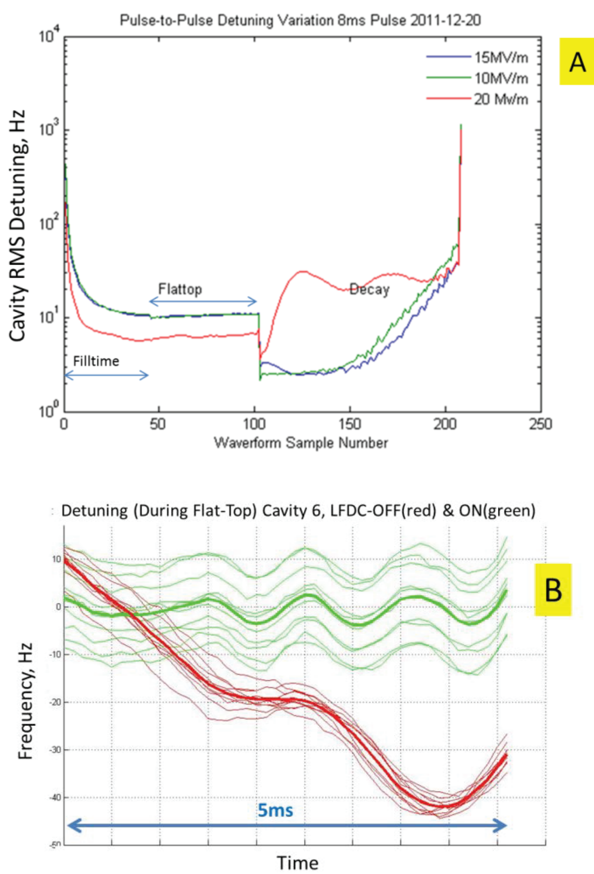

Figure 5: (A): Pulse-to-Pulse Detuning Variation (RMS Detuning) for E_{acc}=10;15;20MV/m. (B): Detuning (during 5ms Flat-Top) for the 10 RF pulses with LFDC system ON (green) and OFF (red). Thick line is average of 10 pulses.

An attempt was made to investigate the source of the pulse-to-pulse variations, although again, time for these studies was limited. Figure 5(A) shows the RMS detuning during RF pulse and following. During these measurements the adaptive portion of the compensation algorithm was turned off so that the compensation pulse did not change. The pulse to pulse variation drops dramatically when the RF feedback ends following the flattop. This may indicate that some of the pulse to pulse variation arises is due to pulse-to-pulse variations in the RF drive waveforms. Figure 5(B) compares the pulse-to-pulse detuning variation with compensation off and compensation on while the RF controller was operating with feedback turned off. Although compensation is able to reduce the average detuning, the pulse-to-pulse variation becomes somewhat larger.

CONCLUSION

The results of the studies described here can be summarized as follows:

- Active compensation is able to limit Lorentz force detuning during long pulses in cavities operation with $Q_L=10^7$ and E_{acc}=25 MV/m to ±10 Hz peak-to-peak or better. This is comparable to the pulse-to-pulse detuning variations due to non-deterministic sources.
- The residual detuning is consistent from pulse-to-pulse and is dominated by a single deterministic sinusoidal component with a frequency near 1kHz. Compensation might be improved further if this component could be suppressed.
- Microphonics levels of 2-4 Hz were observed during long pulses. This is similar to the levels measured during 1 ms pulses.
- The detuning responses of the two cavities tested were different prior to compensation, but the levels of residual detuning following compensation were similar. The compensation algorithm is able to adapt the piezo waveform to the detuning response of each individual cavity.

While further improvements may be possible these studies clearly demonstrate that a pulsed linac employing active compensation of Lorentz force detuning could already meet the phase and amplitude stability requirements for the second stage of Project X.

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