LORENTZ FORCE DETUNING COMPENSATION STUDIES FOR LONG PULSES IN ILC TYPE SRF CAVITIES

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Abstract

Project-X 3-8 GeV pulsed linac is based on ILC type 1.3 GHz elliptical cavities. The cavity will operate at 25 MV/m accelerating gradient, but in contrast with XFEL and ILC projects the required loaded Q is much higher ($Q\sim10^7$) and RF pulse is much longer (~8ms or even 26ms). For these parameters Lorence force detuning (LFD) and microphonics should be controlled at the level <30 Hz to minimize power overhead from the klystron. A new algorithm of LFD compensation, developed at Fermilab for ILC cavities was applied for Lorentz force compensation studies for 8ms pulses. In these studies two cavities inside TESLA-type cryomodule at Fermilab NML facility have been powered by one klystron. Studies done for different cavity gradients and different values of loaded Q demonstrated that required level of LFD frequency compensation is achievable. Detuning measurements and compensation results are presented.

INTRODUCTION

For the proposed second stage of Project X at Fermilab a 1mA H^- beam will be accelerated from 3 to 8 GeV in pulsed linac, based on XFEL/ILC technology. Each of 28 cryomodules with 8 cavities and one quadrupole will be powered by one RF power source. Efficient operation of the linac requires cavities operating at 25 MV/m with a higher loaded Q_L 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 for different values of Q_L is shown in Figure 1. Since detuned cavity requires extra power, it is critical to have LFD compensated to 30 Hz or better to keep RF power below 50 kW, enough to cover cavity detuning, RF distribution losses and provide overhead for LLRF control. The chosen value $Q_L=10^7$ is a compromise between cavity bandwidth and required power.

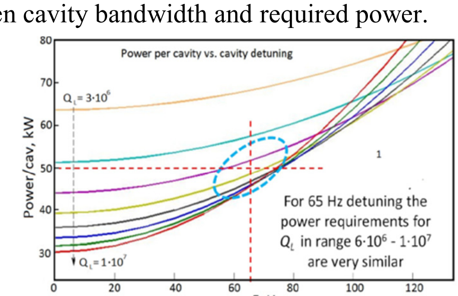

Figure1: Required power per cavity vs. cavity detuning

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.

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] , see Fig.2.

Figure 2: Cryomodule in NML at Fermilab

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: $3\cdot10^6$; $6\cdot10^6$; $1\cdot10^7$;
- 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-sine impulse with bias, width, amplitude, and timing adjusted to compensate detuning during the flattop of a short RF pulse, 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 needed to cancel the detuning of the cavity by the Lorentz force. 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.

An earlier test of adaptive algorithm for 8 ms pulse for dressed ILC-type cavity with blade-tuner in Horizontal Test Cryostat (HTS) at 22 MV/m the demonstrated LFD compensation at the level below 100 Hz peak-to peak [4]. This short test was performed at the end of routine testing of the cavity for short 1.3 ms pulses without optimizing of algorithm and cavity parameters. In current studies with two cavities at CM1, the main focus has been optimization of algorithm for long pulse operation.

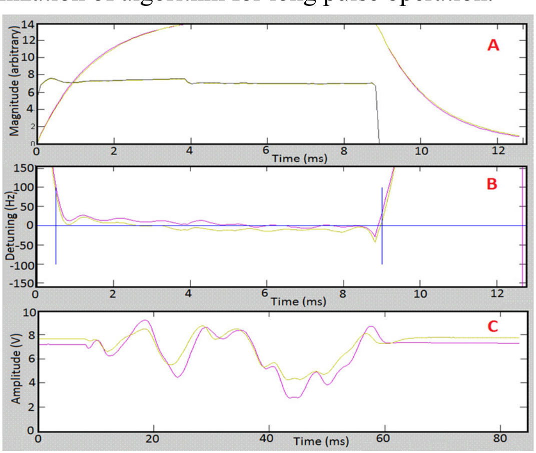

Figure 3: LFD compensation in C5 and C6 during a 9ms RF pulse at E_{acc}=25 MV/m. (A): Baseband envelopes of the forward and cavity field probe signals. (B): Residual detuning using following compensation by adaptive LFD algorithm. (C): Piezo drive waveforms.

Figure 3 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 30msec prior to the arrival of the RF pulse and continues for the duration of the 9ms RF pulse. The LFD compensation algorithm was first tested and tuned for the modest set of cavity parameters Q_L~$3\cdot10^6$ (typical value for ILC cavity) and cavity gradient 18 MV/m. Large bandwidth provides robust operation in this regime.

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.

With an available RF power of 120 kW (~60 kW per cavity) the gradient was limited by 18 MV/m for $Q_L=3.10^6$. For higher values $Q_L=6.10^6$ and $Q_L=10^7$ the gradient ~25 MV/m was achieved.

Figure 4(left) shows the superposition of C6 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 shows the std deviation of the sample at each point in time. The peak detuning during the flattop is 10Hz. Figure 4(right) 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 and 2.27Hz RMS. For all other operating conditions standard deviation of detuning was in range 2-4 Hz.

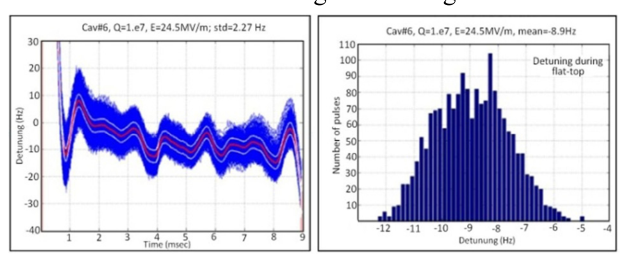

Figure 4: Residual detuning over 30 minutes during operation at $Q_L=10^7$ and E_{acc} =24.5 MV/m. (A) shows the detuning waveforms of 1800 pulses collected over (B) histogram of the average detuning for the same sample.

Figure 5 shows the closed loop amplitude and phase stability of the C5, C6 and of the vector sum of the two cavities during operation at 25 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 (right plot) and the vector sum is stable to 0.01 MV/m (0.04%) in amplitude and 0.2° in phase.

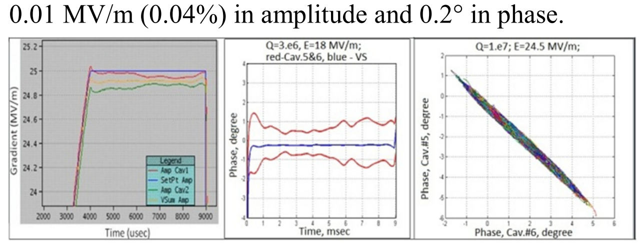

Figure 5: Amplitude (left) and phase (middle) waveforms of C5, C6 and VS. Cavity phase correlation plot (right).

The phase of the vector sum consistently shows a sinusoidal modulation at a frequency close to 1 kHz. This modulation is not present when compensation is off. 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 be further improved.

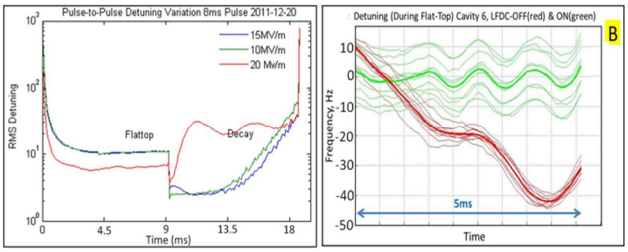

Figure 6: (A): RMS detuning for E_{acc}=10; 15; 20 MV/m. (B): Detuning (during 5ms flat-top) for the 10 RF pulses with LFDC system ON (green) and OFF (red). Thick line is average of 10 pulses**.**

An attempt was made to investigate the source of the pulse-to-pulse variations. Figure 6(A) shows the RMS detuning during and after of the RF pulse. 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 is due to pulse-to-pulse variations in the RF drive waveforms. Figure 6(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.

In these studies the settings for the shape of the cavity probe signal during filling time was optimized for $Q_L=6.10^6$. Some overhead in the forward power for $Q_L=10^7$ during the filling time can be seen in the Figure 7 (right).

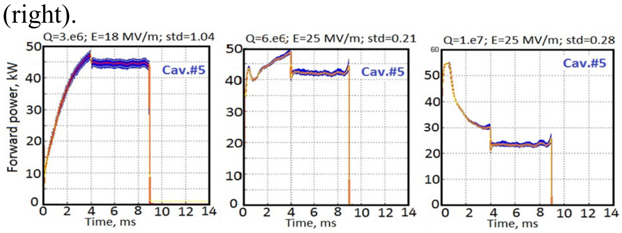

Figure 7: Forward power for $Q_L=3.10^6$ and E_{acc}=18 MV/m (left); $Q_L=6.10^6$ and E_{acc}=25 MV/m (centre); $Q_L=10^7$ and E_{acc}=24.5 MV/m (right)

DISCUSSIONS AND FUTURE PLANS

In these studies it was found that for a lower value of $Q_L< 6.10^6$ the tuning to operation regime was robust. The adaptive LFD compensation algorithm was able to react quickly enough during the period where gradient in cavity increases. Large bandwidth provides robust operation in this regime.

The tuning process for high $Q_L=1.10^7$ and E_{acc}=25 MV/m operation was more tricky in part of narrow bandwidth and because of operating gradient was close to the quench limit for C5. Also, in this regime klystron power was close to saturation (see Fig.7) complicating LLRF control. Additional difficulties for tuning of the cavity from low to high gradient arose from limitation in the drive signal applied for piezo-tuner. The later should be in range 0-200 Volts to ensure linear response. At high gradient the bias and voltage variation are increases and push required drive signal out of acceptable range. To put it back, it is required detune the cavity at intermediate gradient by using a mechanical frequency tuner, which complicates the tuning process due to hysteresis and non-linear response. As a result, after a quench it takes some time to tune cavity back to 25 MV/m again. This behavior depends on tuner design (Sacley-type tuner in these tests). The next long-pulse studies planned will involve on CM2 using two high gradient ILC cavities with blade-tuners. By that time we should have fixed known limitations of LFD compensation algorithm and LLRF system.

CONCLUSION

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

- Active compensation is able to limit LFD 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 can 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 Project X.

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