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~10^7) and RF pulse is much longer (~8ms or even 26ms). For these parameters Lorentz 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.

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.

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.

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-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.

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 $Q_L = 3 \times 10^6$. For higher values $Q_L = 6 \times 10^6$ and $Q_L = 10^7$ the gradient $\sim 25$ 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 $\pm 10$ Hz peak-to-peak and 2.27Hz RMS. For all other operating conditions standard deviation of detuning was in range 2-4 Hz.

Figure 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.

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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.

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 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.](image)

![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).](image)

**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.

**REFERENCES**


