RESONANCE CONTROL FOR FUTURE ACCELERATORS[*]

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Abstract

Many of the next generation of particle accelerators (LCLS II, PIP II) are designed for relatively low beam loading. Low beam loading requirement means the cavities can operate with narrow bandwidths, minimizing capital and base operational costs of the RF power system. With such narrow bandwidths, however, cavity detuning from microphonics or dynamic Lorentz Force Detuning becomes a significant factor, and in some cases can significantly increase both the acquisition cost and the operational cost of the machine. In addition to the efforts to passive environmental detuning reduction (microphonics) active resonance control for the SRF cavities for next generation linear machine will be required. State of the art in the field of the SRF Cavity active resonance control and the results from the recent efforts at FNAL will be presented in this talk.

CAVITY DETUNING

SRF cavities are manufactured from thin sheets of niobium to allow them to be cooled to superconducting temperatures. The thin walls make cavities susceptible to mechanical distortions from:

- Pressure variations in the surrounding helium bath
- Radiation pressure from the RF field (Lorentz Force Detuning)
- External vibration sources (microphonics)

As the walls distort, the resonant frequency of the cavity shifts from the design frequency according to the Slater rule.

Detuned cavities are more expensive to operate. If sufficient RF power is not available to maintain a constant gradient during the expected peak cavity detuning, the beam will be lost. Providing sufficient power to overcome detuning increases both the capital and the operating costs of the machine.Figure 1 shows the capital cost of the LCLS-II RF plant as a function of RMS detuning. The cost increases rapidly once the RMS detuning exceeds a few Hz.

Table 1 lists a number of SRF accelerators being planned or currently under construction [1]. Each machine can be assigned to one of four broad classes depending on the operating mode and cavity bandwidth:

- Wideband CW;
- Wideband Pulsed;
- Narrowband CW; and
- Narrowband Pulsed.

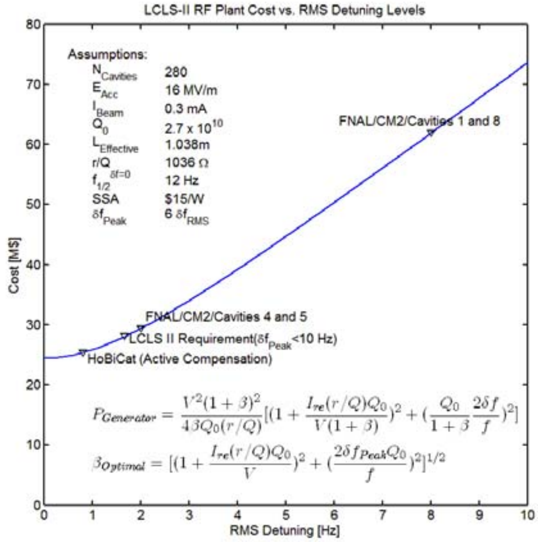

Figure 1: LCLS-II RF Plant Cost as a Function of RMS Detuning.

Minimizing cavity detuning is critical for narrowband machines, both CW and pulsed. Detuning can be one of the major cost drivers for such machines. Narrowband pulsed machines such as PIP-II present a unique challenge because of radiation pressure from the RF pulse can itself drive significant levels of cavity vibration. If such vibrations cannot be suppressed, the cost of operating such a machine may become prohibitive.

ACTIVE COMPENSATION

Active compensation of cavity detuning has been used successfully to stabilize cavity resonant frequencies in the presence of vibration sources. A fast mechanical actuator, often a piezo stack, applies pressure to cavity in an attempt to cancel all or part of the cavity wall distortions induced by external sources. The use of piezo actuators for active detuning compensation of Lorentz force detuning was pioneered at DESY [2] but is now in wide use at SRF accelerators around the world.

Measuring Cavity Detuning

In order to successfully compensate for detuning, the frequency shift of the cavity must be accurately determined. This can be done using the complex baseband forward, reflected, and probe RF signals. The complex differential

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Table 1: List of Selected Future Accelerators

Accelerator	Location	Description	Particle	Gradient	Current	Frequency	Half Bandwidth	LFD	Peak Detuning
				MV/m	mA	MHz	Hz	Hz	Hz
Wideband CW									
ARIEL	TRIUMF		e-	10	10	1300	220		
SPIRAL-II		30 MeV, 5 mA protons -> Heavy Ions	Ion	11	0.15-5	88	176		
Wideband Pulsed									
XFEL	DESY	18 GeV electrons – for Xray Free Electron Laser – Pulsed)	e-	23.6	5	1300	185	550	
ESS	Sweden	1 – 2 GeV, 5 MW Neutron Source ESS - pulsed	p	21	62.5	704	500	400	
Narrowband CW									
CEBAF Upgrade	JLAB	Upgrade 6.5 GeV => 12 GeV electrons	e-	20	0.47	1497	25		10
LCLS-II	SLAC	4 GeV electrons –CW XFEL (Xray Free Electron Laser)	e-	16	0.06	1300	16		10
FRIB	MSU	500 kW, heavy ion beams for nuclear astrophysics	Ion	7.9	0.7	322	15		20
Wideband Pulsed									
PIP-II	Fermilab	High Intensity Proton Linac for Neutrino Beams	p	17.8	2	650	30	300	20

equation that related the baseband envelopes of the forward and probe signals can be separated into two real equations, one involving the only real components of the waveforms and the second involving only the imaginary components.

$$\frac{dP}{dt} = -(\omega_{1/2} + i\delta)P + 2\omega_{1/2}F$$

$$\omega_{1/2} = -\frac{\left\langle \mathrm{Re}\left(P^{*}\left(\frac{dP}{dt}\right)\right)\right\rangle}{\left\langle \mathrm{Re}\left(P^{*}(P-2F)\right)\right\rangle}$$

$$\delta = -\frac{\mathrm{Im}\left(P^{*}\left(\frac{dP}{dt} - 2\omega_{1/2}F\right)\right)}{P^{*}P}$$

Accurate determination of the detuning from the baseband signals requires:

- Accurate calibration of the signals; and
- Understanding and correcting for systematic effects

Baseband Signal Calibration

The ratios of the forward/probe and reflected/probe complex I/Q baseband signals are linear functions of detuning. The cavity half-bandwidth can be extracted from the equation for the real equation while the detuning can be extracted from the equation for the imaginary equation.

$$\frac{Z_T I_{Forward}}{V_{Cavity}} = \frac{1 + \beta^{-1} + i\frac{\omega' - \delta}{\omega_T}}{2}$$

$$\frac{Z_T I_{Reflected}}{V_{Cavity}} = \frac{1 - \beta^{-1} - i\frac{\omega' - \delta}{\omega_T}}{2}$$

$$\omega_T = \frac{\omega_T}{1 + \beta^{-1}}$$

Self-consistency constraints can be used to determine the relative gains and phases of the three cavity baseband signals from the signals themselves.

- The slopes of the forward/probe and reflected/probe inverse transfer functions must be are purely imaginary and must be of equal magnitude with opposite sign.
- The sum of the two inverse transfer functions must add to unity.

Detuning measurements require only relative calibration of the signals. Absolute calibration of the signals, for example to determine the cavity gradient, requires comparison of one or more of the signals to an independent external reference level.

Systematic Effects

Reflections from ferromagnetic circulators can re-reflect energy from the cavity reverse wave back into the forward wave as additional true forward power. Re-reflected energy can systematically shift the resonant frequency and bandwidth measured using the combined waveguide/cavity system from the intrinsic frequency and bandwidth of the cavity needed to determine cavity detuning. Figure 2 shows how the measured half-bandwidth of a cavity/waveguide system varies as the length of the wave guide changes. The effects of such reflections cancel out if ratios of the complex baseband signals are employed rather than the baseband signals themselves.

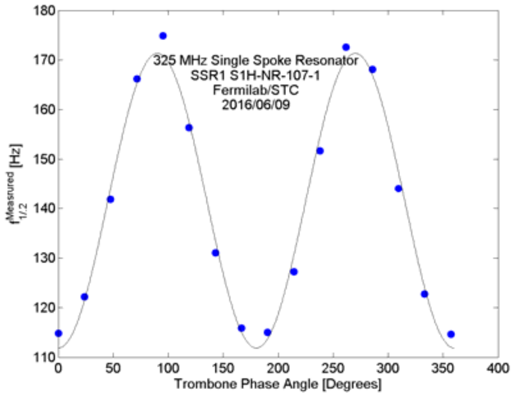

Figure 2: Measured Half-Bandwidth vs Waveguide Length

Finite directivity of directional coupler used to separate the forward and reverse waves can lead to cross-contamination of the two signals. The forward and reflected voltage signals measured using a 20dB directivity coupler may be cross-contaminated by up to 10%. This can lead to a 20% bias in the measured detuning. Directional couplers with directivity of 40dB or more should be employed if detuning measurements with percent accuracies or better are required.

Compensating for Detuning

Ponderomotive Compensation

If the frequency shift due to the Lorentz force exceeds several cavity bandwidths, the cavity can become unstable during CW operation[3]. At frequencies above the cavity resonance the Lorentz force will stabilize the cavity against small perturbations of the resonant frequency. As the frequency shifts higher/lower, the cavity field with decrease/increase leading to a decrease/increase of the pressure on the walls, counteracting the perturbation. For frequencies at or below the resonance however, the Lorentz force will amplify the effects of any perturbation. Even a small shift in the resonant frequency can cause the cavity gradient to suddenly crash to zero.

Cavities can be successful stabilized against ponderomotive forces by driving the piezo with a voltage proportional to the magnitude squared of the cavity gradient as was first demonstrated at Cornell [4]. Figure 3 shows the cavity lineshape as the feedforward coefficient is varied. With no compensation the cavity is unstable below the resonance. With optimal compensation the line shape is stable in both directions. With higher than optimal compensation the cavity can be made unstable above the resonance.

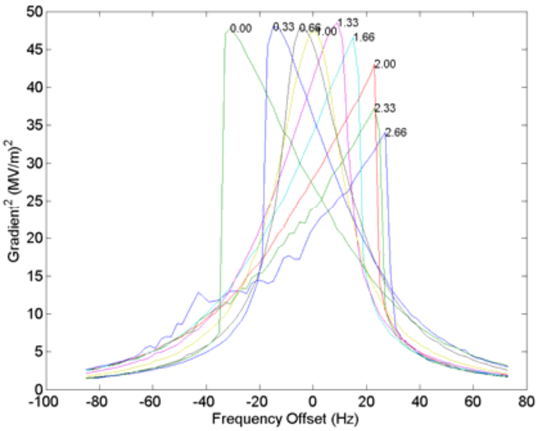

Figure 3: Feed-forward Compensation for Ponderomotive Shifts in the Cavity Resonant Frequency for different coefficients scaled to ideal compensation.

Feedback

Feedback has be used to successfully compensate for detuning from non-deterministic sources such as helium pressure fluctuations external vibrations. Initial studies at Fermilab were able to suppress resonance lines by up to 20 dB using an LMS adaptive filter [4].

Extensive studies in the HoBiCaT test stand at BESSY[6] using 1.3 GHz nine-cell cavities showed feedback could reduce RMS detuning levels to a fraction of a Hz as shown in Figure 4

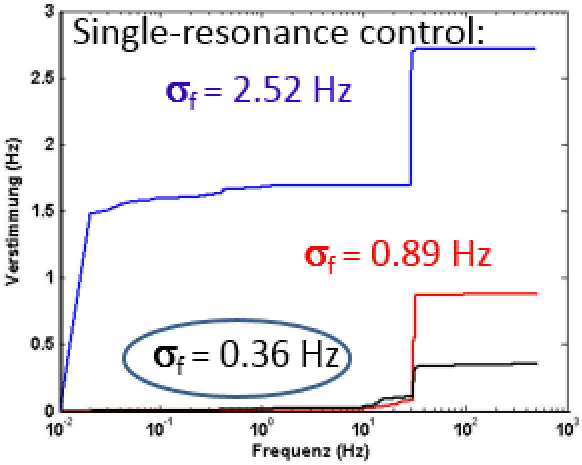

Figure 4; Feedback Compensation for Microphonics Resonance (Courtesy A. Neumann, HZB).

LFD Compensation

In pulsed cavities, the Lorentz force from the RF pulse can be a significant source of vibration. The FLASH XFEL at DESY successfully used a single sine-wave cycle waveform to drive the piezo tuner. The amplitude, period, and

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timing of the pulse were adjusted to minimize detuning during 700 us flattop [2].

An adaptive feedforward algorithm developed at Fermilab has successfully compensated for detuning over wider range of pulse length. The cavity is first characterized by exciting the piezo with series of positive and negative impulses at different delays with respect to the RF pulse. The sum and difference of detuning from positive and negative impulses at each delay allow the impulse response to be separated from background detuning. This process is the time domain equivalent of a frequency domain transfer function measurement.

Any arbitrary detuning waveform can decomposed into an appropriately weighted sum of the piezo impulse responses. If the sign of the weighted sum is reversed, the piezo waveform should cancel the detuning. Figure 5 shows the detuning of a 325 MHz Spoke Resonator with and without feedforward compensation. The dotted black lines in the figure show the peak detuning specification for the PIP-II machine.

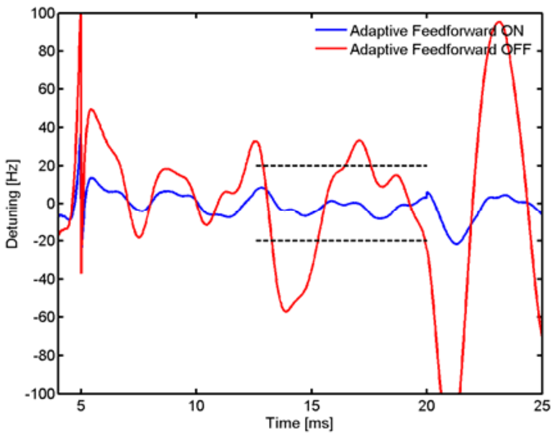

Figure 5: Detuning With and Without Adaptive Feed-forward Compensation of LFD.

Optimal Control

Optimal control techniques were pioneered by Kalman in the early 1960s. The Kalman filter and the Linear Quadratic Gaussian Controller perform a weighted, recursive, least-squares fit at each time step to extract the best possible (in the L2 sense) linear state and control signal estimates from noisy data given knowledge of the system evolution equations and the noise covariance. The implementation of time-invariant digital Kalman filters and LQGR Controllers in modern FPGA hardware is straightforward if tedious.

When combined with system identification techniques which can extract the low order transfer functions needed to construct optimal filters and controllers from stimulus-response measurements, optimal control methods offer the possibility of automatically generating the best possible combined electro-magnetic (linear) controller for each individual cavity.

Figure 6 shows the improvement in measured vibration levels using an optimal controller to damp a single vibration mode of a 1.3GHz, nine-cell, elliptical cavity at BESSY. Up to 9 eigenmodes could be processed by the pipelined controller implemented in a Xilinx Artix-7. Current plans call for the full controller to be first tested in the SRF gun.

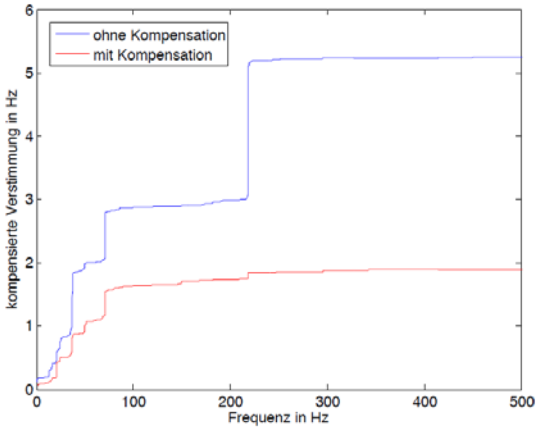

Figure 6: Cavity Detuning With and Without Optimal Compensation of a Single Resonance (Courtesy A. Neumann, HZB).

LIMITS OF ACTIVE COMPENSATION

Active compensation by itself is unlikely to be sufficient if no other measures to minimize detuning are taken. A much larger program incorporating both active and passive measures is required. A coordinated effort across multiple disciplines and trade-offs between specifications for all machine subsystems is required. Each element of the machine must be carefully designed to minimize transmission of vibration to the cavities and to minimize the response of cavities to vibration. As one example, helium pressure stability specifications (cryogenic engineering) must be traded off against cavity pressure sensitivity specifications (cavity design) and active compensation performance specifications (RF control Engineering).

Experience at a variety of laboratories has shown that seemingly minor design changes can lead to large changes in vibration levels. Ensuring adequate implementation of passive control measures requires a program of:

- Outreach
- Education, and
- Enforcement

The organizational challenges associated with implementing such a program may be far more daunting than the technical challenges of active compensation.

CONCLUSION

Cavity detuning can be a major cost driver for future narrow-band SRF accelerators. Great strides have been made in active detuning compensation over the last several years:

- Ponderomotive effects can be suppressed using feed-forward proportional to the gradient
- Deterministic sources (e.g. LFD) can be suppressed using adaptive-feedforward

- Non-deterministic sources (e.g. microphonics) can be suppressed using feedback

Active compensation alone is unlikely to be sufficient if no other measures are taken. Suppressing cavity detuning a coordinated effort across multiple disciplines and tradeoffs between specifications for all machine subsystems. The organizational challenges of such an effort may be far more daunting than the technical challenges.

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