Machine Learning-Based Tuning of Control Parameters for LLRF System of Superconducting Cavities

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Content

Linac Coherent Light Source II (LCLS-II)

- Continuous wave (CW). Nominal bunch output frequency of 0.929 MHz.
- 4GeV Superconducting LINAC.
- 35 1.3GHz Cryomodules.
- 280 1.3GHz SRF cavities.

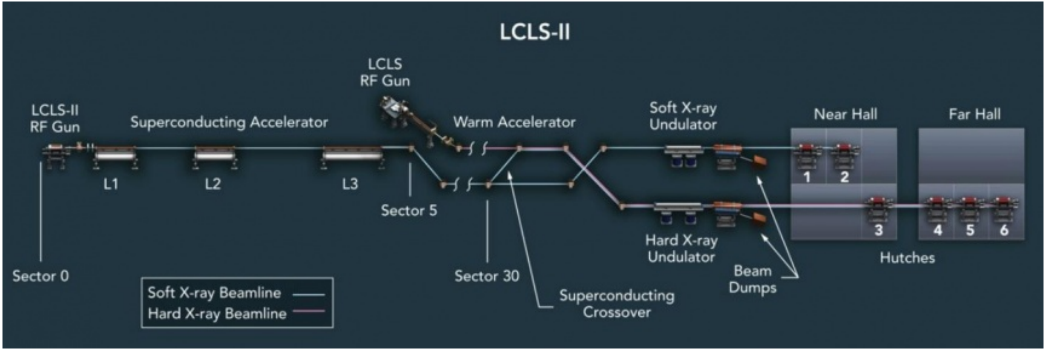
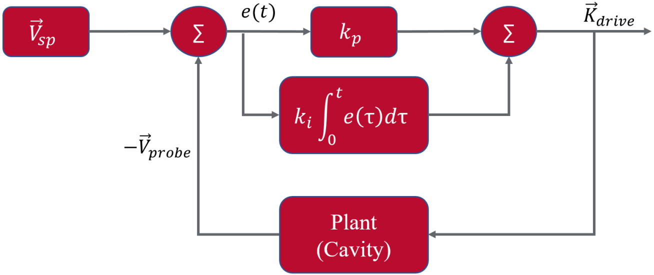


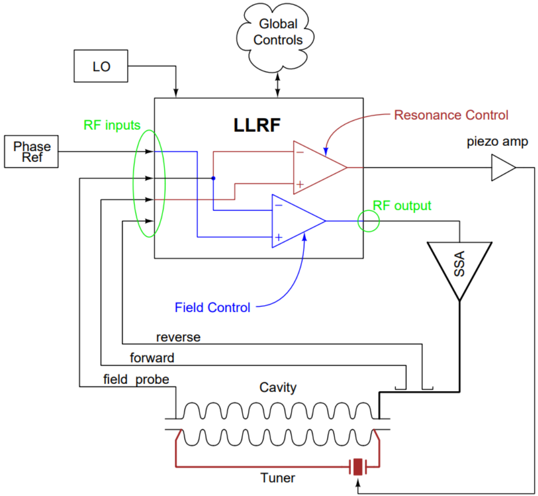
Image taken from https://lcls.slac.stanford.edu/lcls-ii

Low Level RF (LLRF) Control System idea



- Proportional-Integral (PI) Control loop.
- RF Field Control for amplitude and phase.

LLRF Control System Simplified Implementation



- Power Source: Solid State Amplifier (**SSA**)
- Local Oscillator (**LO**) for up- and down-conversion and to generate clocks for digital boards.
- Phase reference line to all cavities. Phase averaging between forward and reflected signals to account for drift.
- Global Controls: Experimental Physics and Industrial Control System **EPICS**.
- Tuners: Stepper motor and piezo tuner for resonance control.

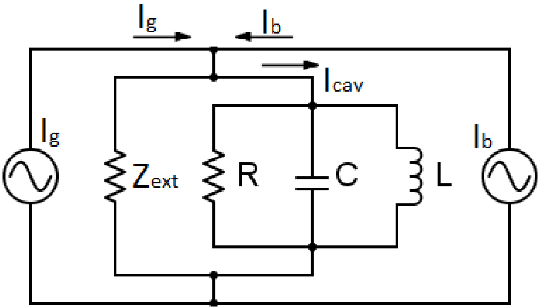
Image taken from Larry Doolittle's talks.

Motivation

- Proportional and Integral gains are set manually. Or, in the best case, following some basic rules from control theory.
- Proportional and Integral gains of the control loop can be automatically optimized using Neural Networks to minimize amplitude and stability errors.
- Very useful for facilities with hundreds of cavities. LCLS-II has 280 cavities, 1120 controller gains.
- Goal: Machine Learning-based tuning of proportional and integral gains for the LLRF system.

Cavity Model

- Cavity's eigenmode circuit model is a RLC parallel circuit.
- Taking inspiration in the Cryomodule-on-Chip engine developed by LBNL [1], we developed our own simplified `Python` code to simulate a RF station (cavity, SSA, PI controller, perturbations).



$$\boldsymbol{V} = \boldsymbol{S}e^{j\theta}$$

$$\frac{d\theta}{dt} = w_d$$

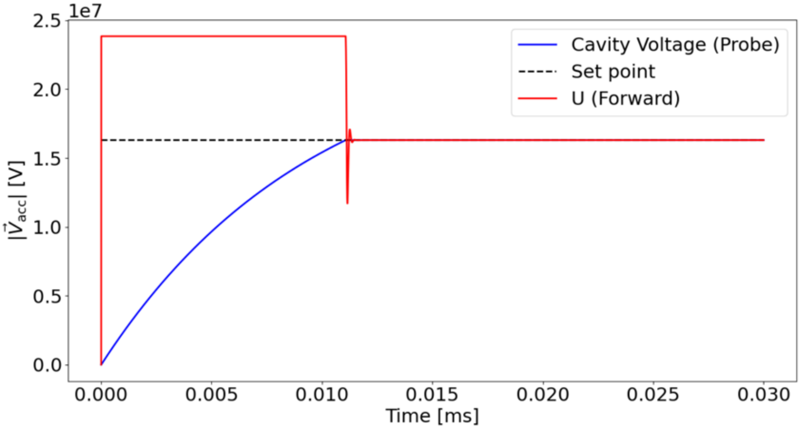
$$\frac{d\boldsymbol{S}}{dt} = -w_f\boldsymbol{S} + w_f e^{-j\theta}(2\boldsymbol{K_g}\sqrt{R_g} - R_b\boldsymbol{I})$$

Perturbations:

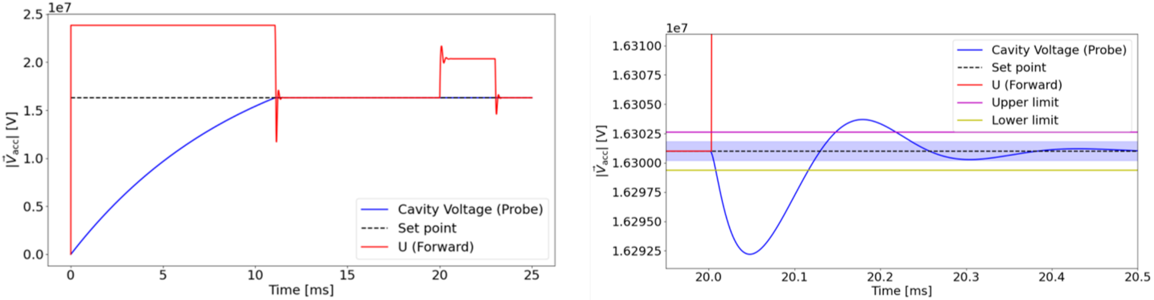
- Beam Loading
- Cavity Detuning
- Measurement Noise

Ideal Cavity Response

- Cavity fill-time about 12 ms.
- Power source saturates while cavity reaches set point.



Beam Loading

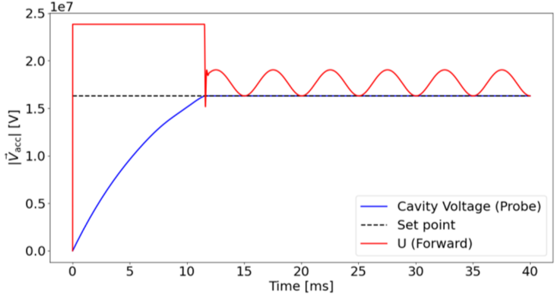


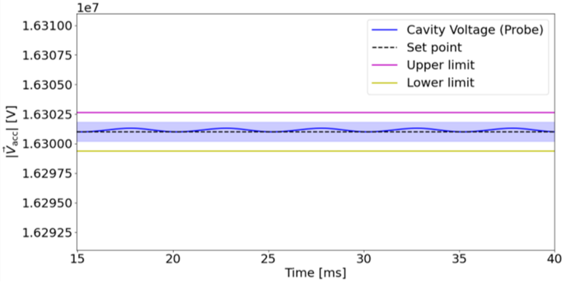
$$\frac{d\theta}{dt} = w_d$$

$$\frac{d\boldsymbol{S}}{dt} = -w_f\boldsymbol{S} + w_f e^{-j\theta}(2\boldsymbol{K_g}\sqrt{R_g} - R_b\boldsymbol{I})$$

- Beam current is 100 μA.
- Cavity requires more power to compensate for beam loading.
- Transient effect at the beginning and end of beam.

Detuning



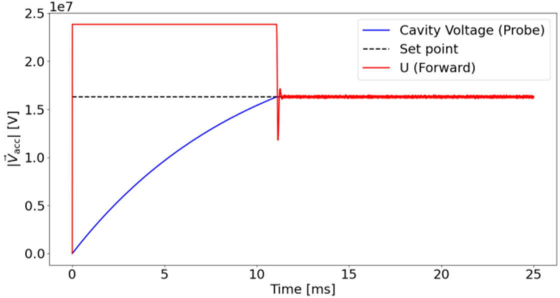


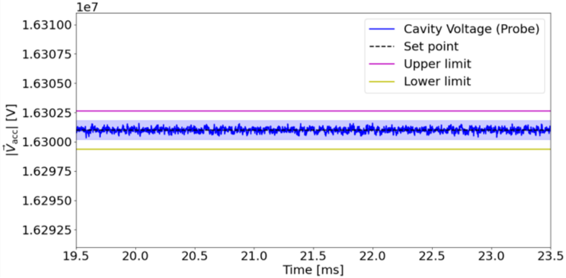
$$\frac{d\theta}{dt} = w_d$$

$$\frac{d\boldsymbol{S}}{dt} = -w_f\boldsymbol{S} + w_f e^{-j\theta}\left(2\boldsymbol{K_g}\sqrt{R_g} - R_b\boldsymbol{I}\right)$$

- $\Delta f_c = 10\sin(2\pi 100 t)$ Hz
- Cavity requires more power to compensate for detuning.
- 10Hz detuning limit is usual for TESLA-type cavities.

Measurement Noise



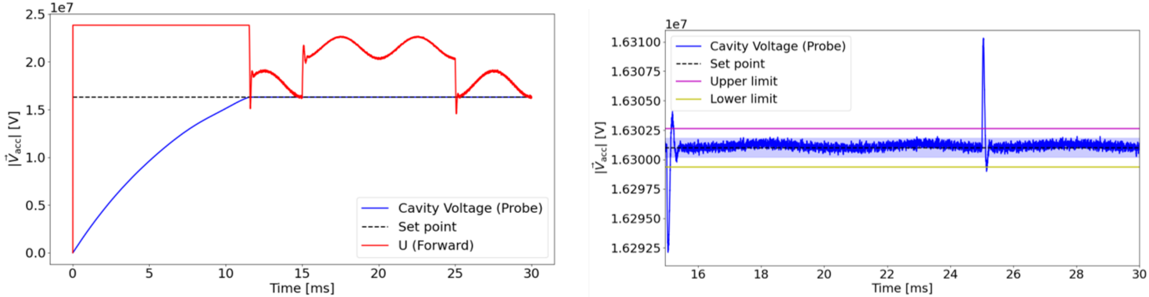


$$\frac{d\theta}{dt} = w_d$$

$$\frac{d\boldsymbol{S}}{dt} = -w_f\boldsymbol{S} + w_f e^{-j\theta}\left(2\boldsymbol{K_g}\sqrt{R_g} - R_b\boldsymbol{I}\right)$$

- -138 dBc/Hz.
- LLRF hardware design minimizes noise.

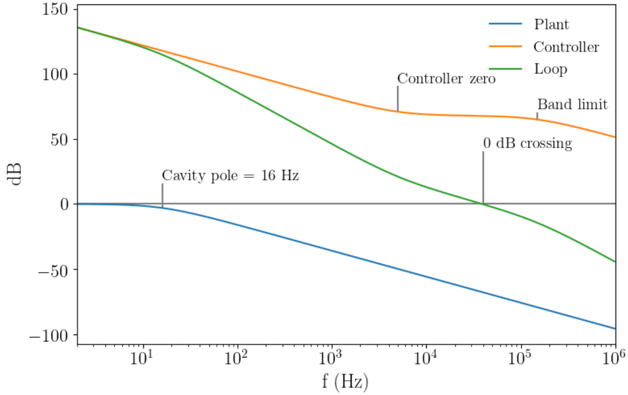
Cavity Response with All Disturbances



$$\frac{d\theta}{dt} = w_d$$

$$\frac{d\boldsymbol{S}}{dt} = -w_f\boldsymbol{S} + w_f e^{-j\theta}(2\boldsymbol{K_g}\sqrt{R_g} - R_b\boldsymbol{I})$$

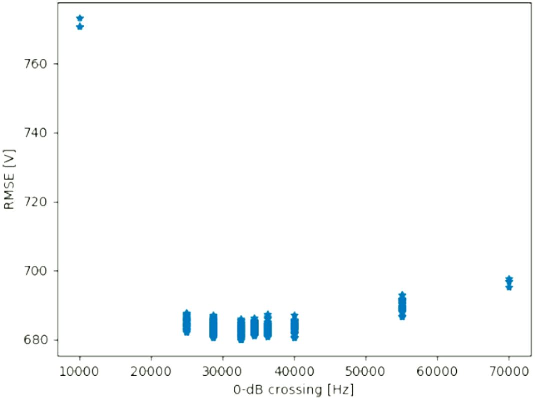
Closed loop analysis



Adapted from *The Hows and Whys of SEL feedback for LLRF* by Larry Doolittle

- Negative feedback extends the cavity bandwidth from $\sim$ 16 Hz to $\sim$ 40 KHz. This implies a proportional gain of 2500.
- Low-pass filter to limit noise amplification wit cutoff frequency of 150 KHz.
- Controller zero at 5 KHz. Integral term reduces steady state error at low frequencies to keep system stability.
- System delay $\sim 1\mu s$.

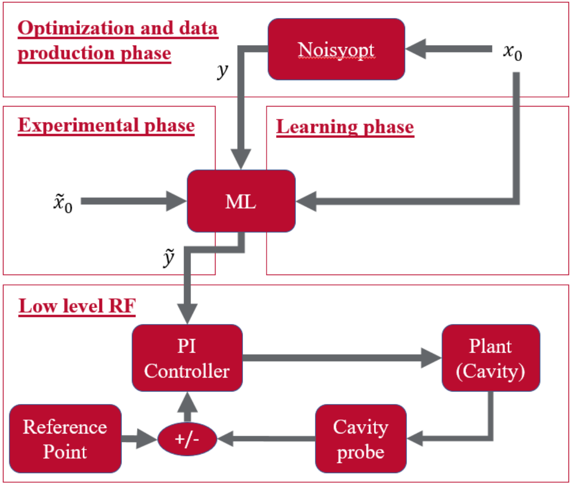
Control Parameter Optimization



- Cavity detuning perturbation inversely proportional to PI gains.
- Noise is amplified by PI gains.
- Beam loading transient effect less important due to CW machine.
- **Find the optimal proportional gain to minimize the RMSE of the cavity voltage.**
- `Python` library Noisyopt [2].

$$\min_{k_p} f(k_p) = \min_{x} E[F(k_p, \xi)]$$

Machine Learning Architecture

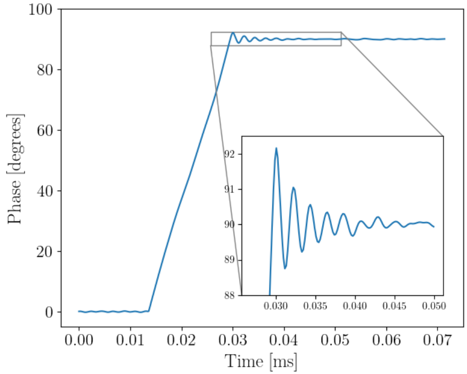


- **Optimization and data production phase**: Produce the training data. The inputs are: cavity detuning, measurement noise, beam current and cavity's set point. An optimal proportional gain is calculated with the Noisyopt library.
- **Learning phase**: Train a NN to predict the optimal PI gains. Use the THETA supercomputer at the ALCF.
- **Experimental phase**: The trained NN is used to calculate the optimal gain k_p for a real LLRF system.

Results of manual gain tuning

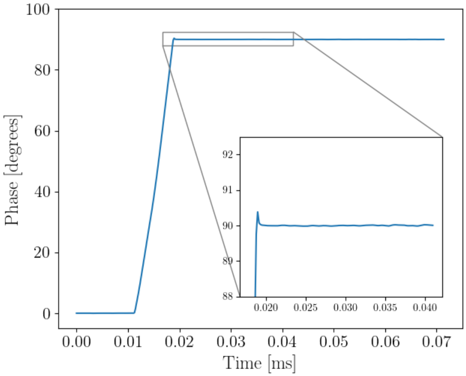
Cavity phase response to a step in the phase set point from 0 to 90 degrees before and after manual gain tuning.

- Less overshoot.
- Reduced oscillations and settling time.



Experiments performed by Janice Nelson at SLAC

- Faster settling time.
- Faster response.



Conclusions and Future Work

- A model of a LLRF system has been implemented in `Python` based on the Cryomodule-On-Chip software engine developed at LBNL, including perturbations due to cavity detuning, beam loading and measurement noise.
- An optimization algorithm has also been implemented to calculate the optimal proportional gain k_p to minimize the RMSE of the cavity's voltage. With this optimization, data for ML training can be produced by running this model and optimization algorithm in HPC.
- Manual tuning of gains using control theory has been performed for CM01 cavities of the LCLS-II project.
- With ongoing commissioning activities, we are now collecting data for ML training and we will have the opportunity to test the proposed ML architecture.

Thanks for your attention!

BACK-UP SLIDES

LCLS-II LLRF System Details

- Hardware/Firmware:
  - Precision Receiver Chassis (PRC):
    - Fiber communication for high Isolation necessary for 0.01 degree and 0.01%.
    - Exclusively for cavity signals.
  - RF Station (RFS):
    - Generates independent RF signal for 2 cavities.
    - Forward, Reverse and SSA Drive signals.
    - Detune frequency calculation, PI loop control
  - Resonance Control
    - Piezo Tuner Control.
    - Stepper Motor Control.
    - Temperature Monitoring.
    - Interlock processing.
- Software
  - Automated Scripting.
  - Cavity and SSA characterization.
  - Smooth transition between modes.
  - Channel Access.
- EPICS
  - All control displays and waveform readouts.
  - Cavity control interface.
  - Modes of Operation.
  - Hardware health .