Precision Amplitude and Phase Control of High Q_L SRF Cavities

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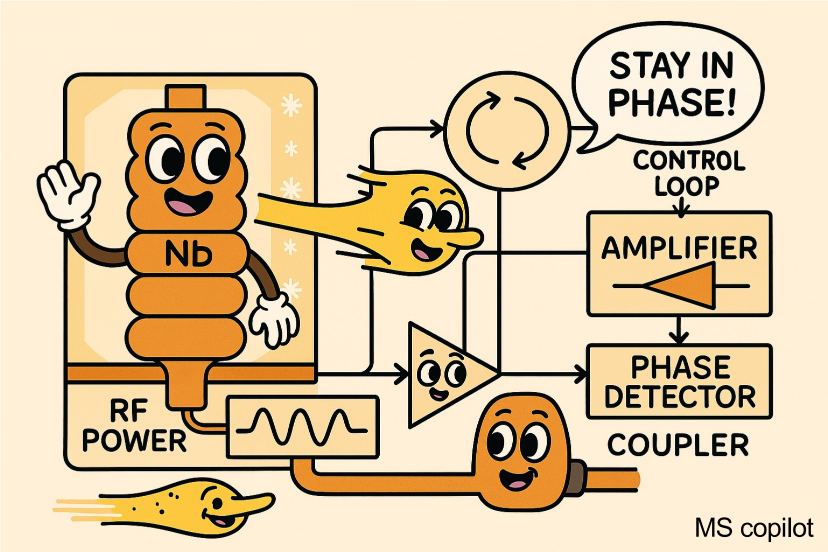
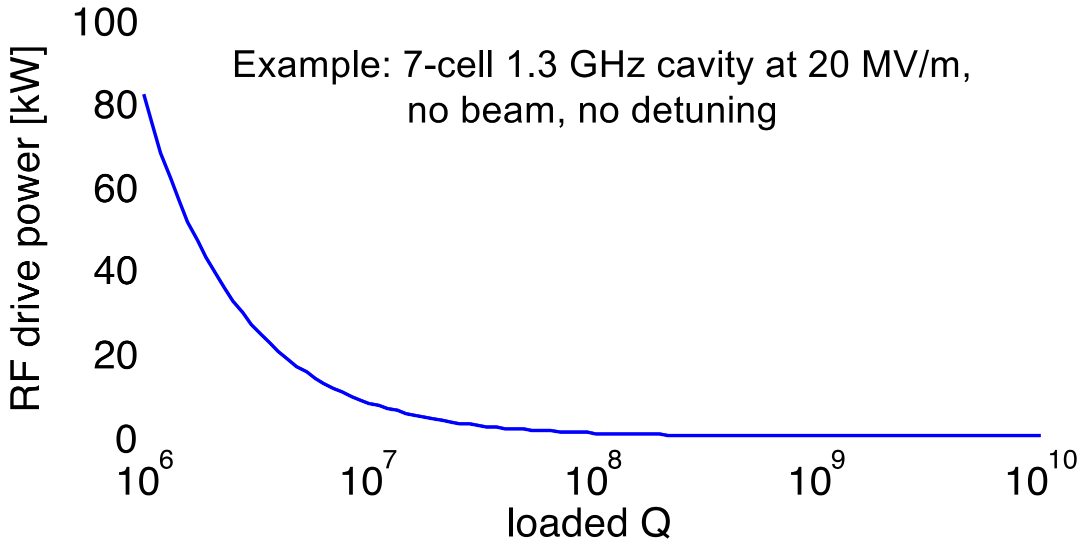


Outline

- Why high loaded Q?
- Challenges
- LLRF Control for high Q_L

Motivation: Why would one want to run at high Q_L?

- Low beam current machines:
  - Little RF power needed in principle (wall dissipation, power transferred to beam)
  - High matched external loaded Q: **10^7 to 10^9 range**

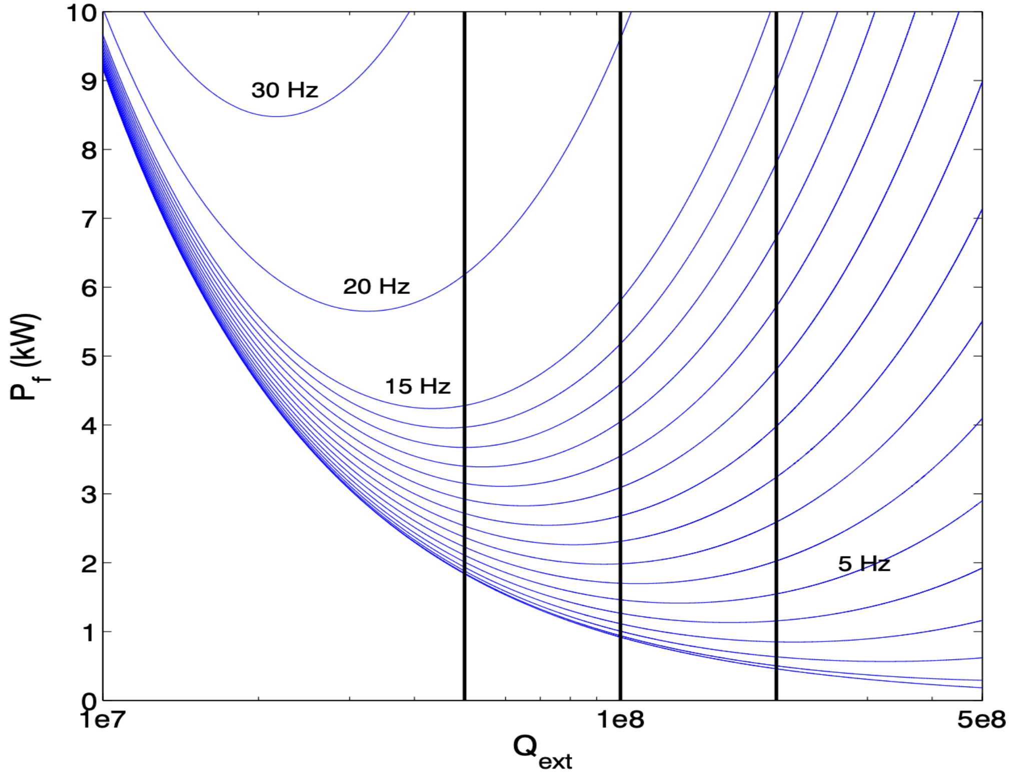


No beam, no detuning case:

$$P_g = \frac{V_{acc}^2}{\frac{R}{Q} Q_0} \frac{(1+\beta)^2}{4\beta}$$

A more complete picture: Impact of Cavity Detuning

Example: 7-cell 1.3 GHz cavity at 20 MV/m, no beam



$$Q_{opt} \approx \frac{1}{2}\frac{f_0}{\Delta f}$$

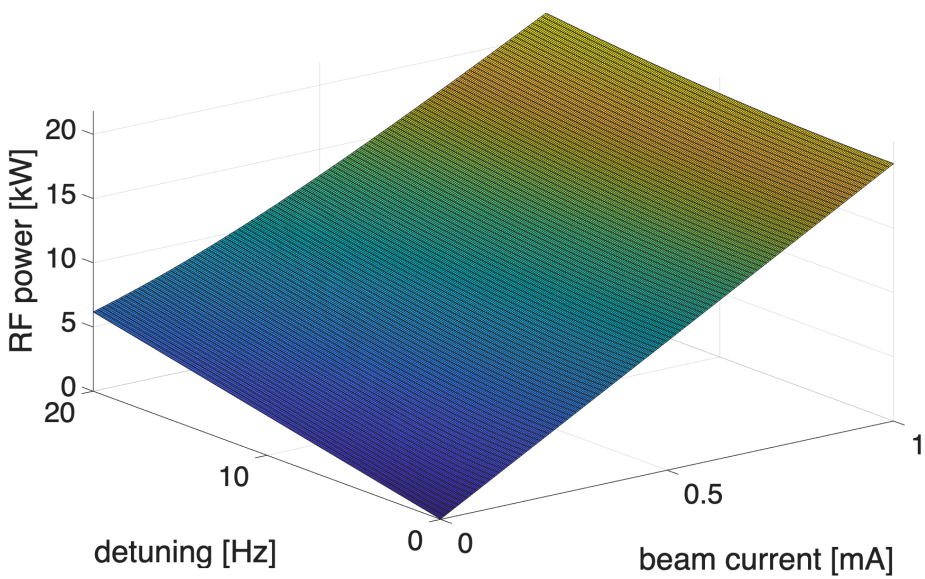
Δf = detuning

$$P_{g,\min} \approx \frac{V_{acc}^2}{2r/Q}\frac{\Delta f}{f}$$

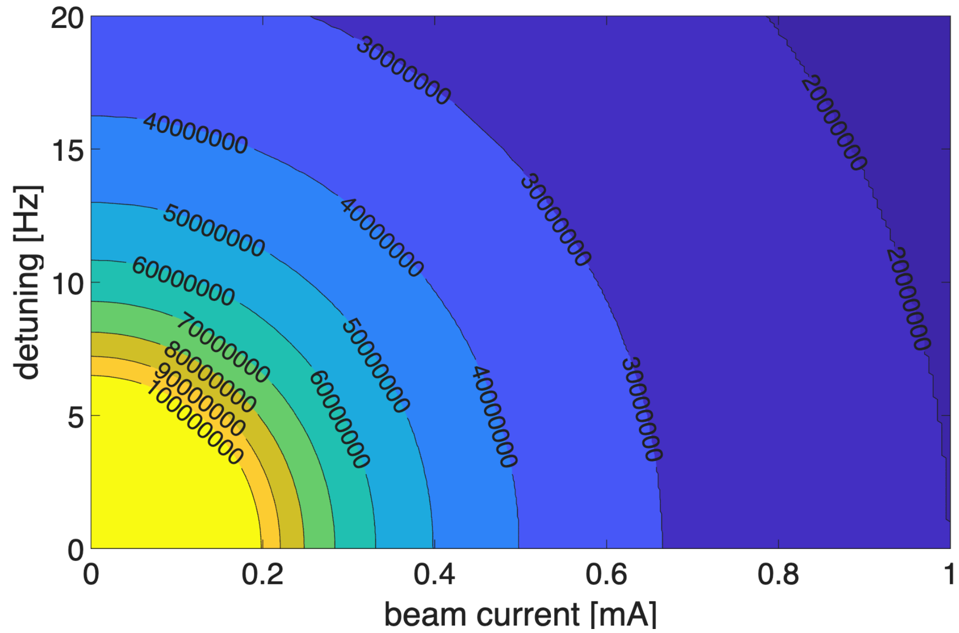
(for $Q_{ext} << Q_0$)

A more complete picture: Add Non-Zero Beam Current

Example: 9-cell 1.3 GHz cavity at 20 MV/m

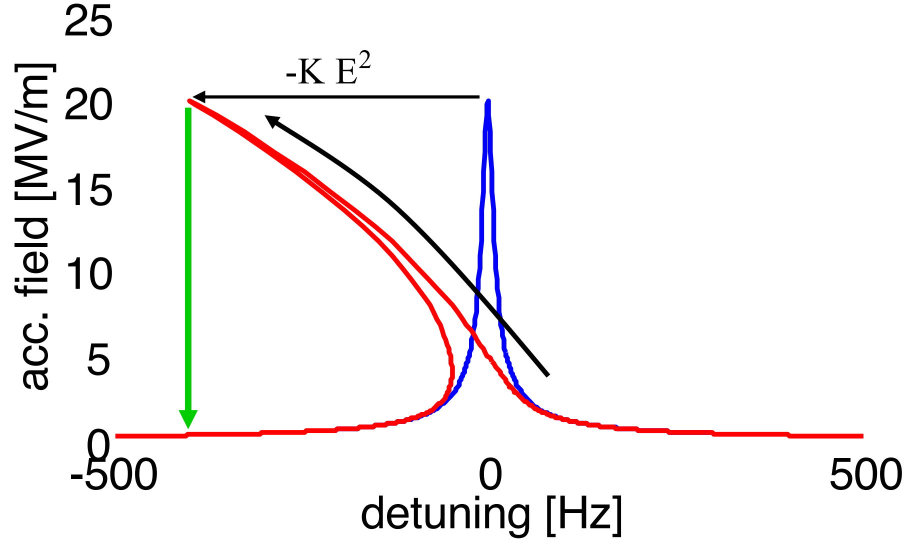


Optimal external Q: 10^7 to $>10^8$ range



High Q_L Challenges

- **The higher Q_L, the smaller the resonance bandwidth, and the more the field gets perturbed by cavity detuning**
- **Runing at high Q_L only useful if small (few Hz) cavity detuning can be maintained over long durations**
- **Also need to deal with Lorentz-force detuning during field ramp-up**

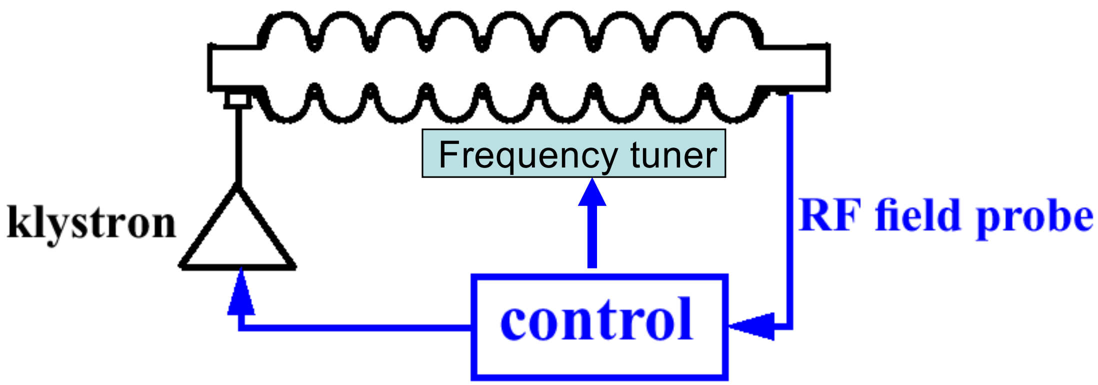


What's needed?

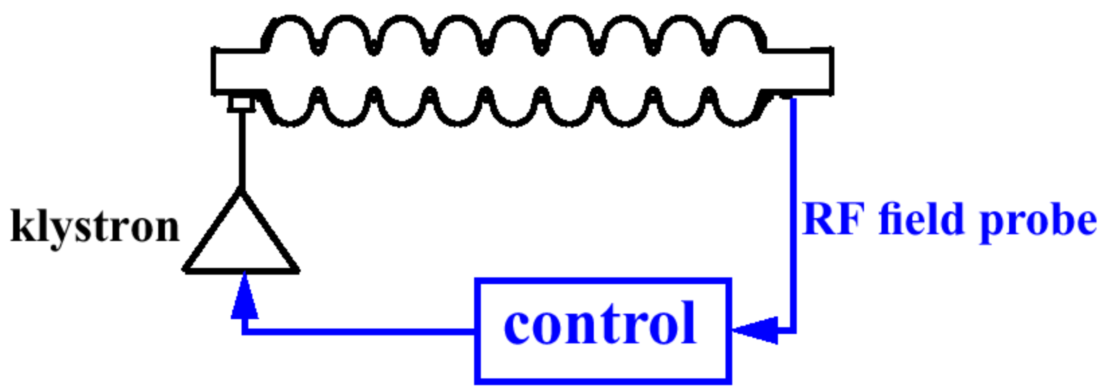
A. **RF control system which can deal with large amplitude and phase field perturbations**

B. **Solution for field ramp up**

C. **Microphonics mitigation and control**

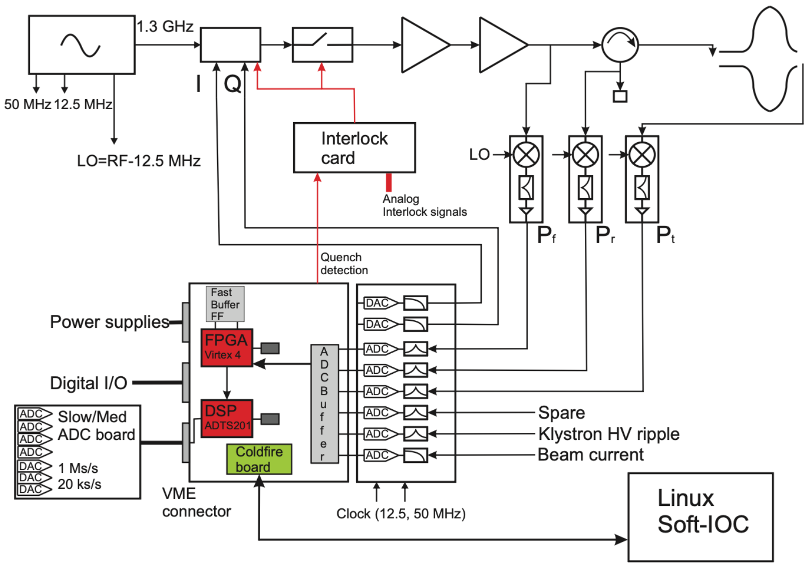


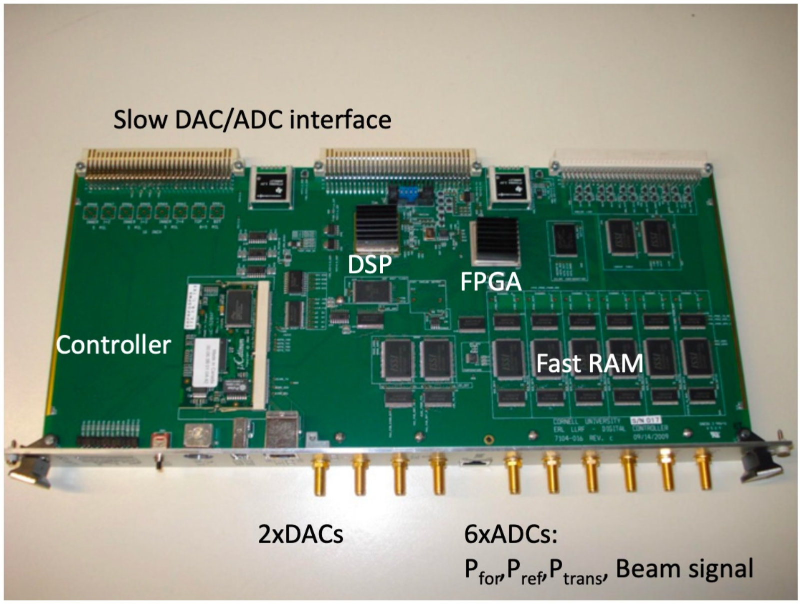
A. RF control system which can deal with large amplitude and phase field perturbations



Cornell LLRF R&D

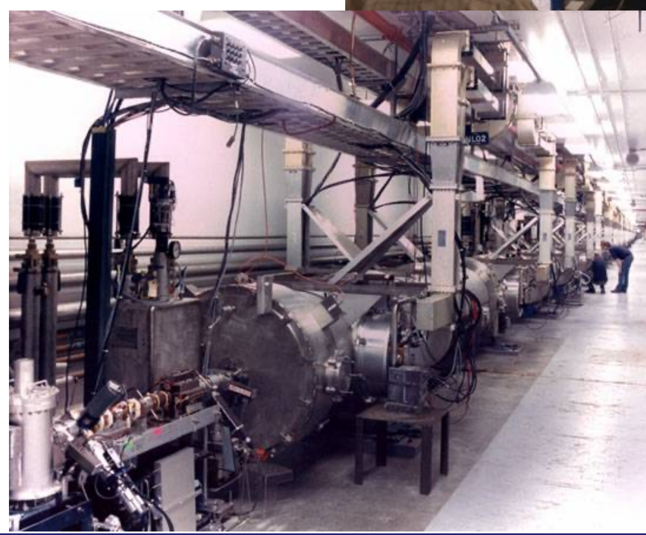
- Fast **digital** components
- Fast **I-Q proportional-integral feedback and feedforward control loops**
- Fast cavity frequency control (piezo cavity frequency tuner)
- Designed to deal with large amplitude and phase field perturbations





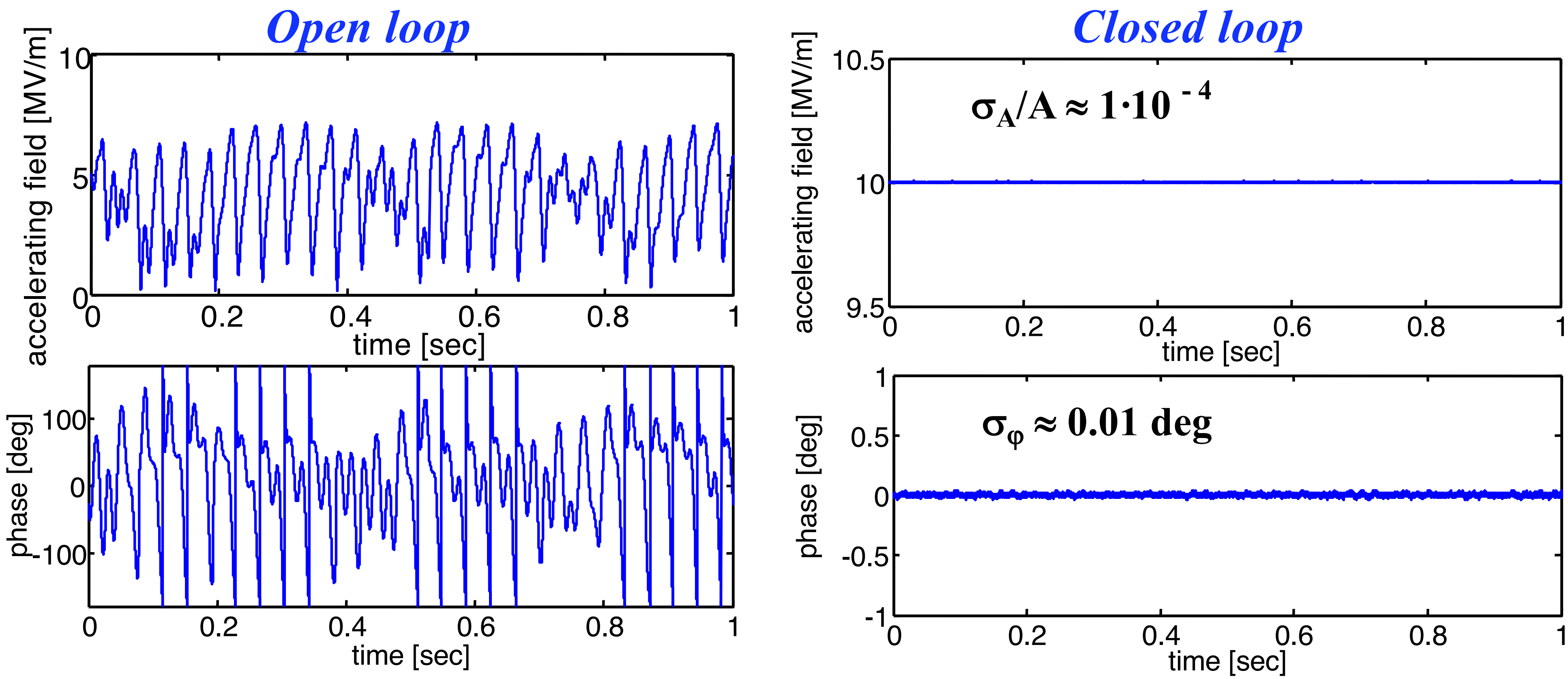
Cornell LLRF High Q_L Operation Test at CEBAF

- Connected Cornell RF control system to one of the CEBAF 5-cell cavities.
- Increased loaded Q to **$4.2 \cdot 10^7$** (36 Hz cavity bandwidth)
- Run up to 4*100 μA = 400 μA total beam current.



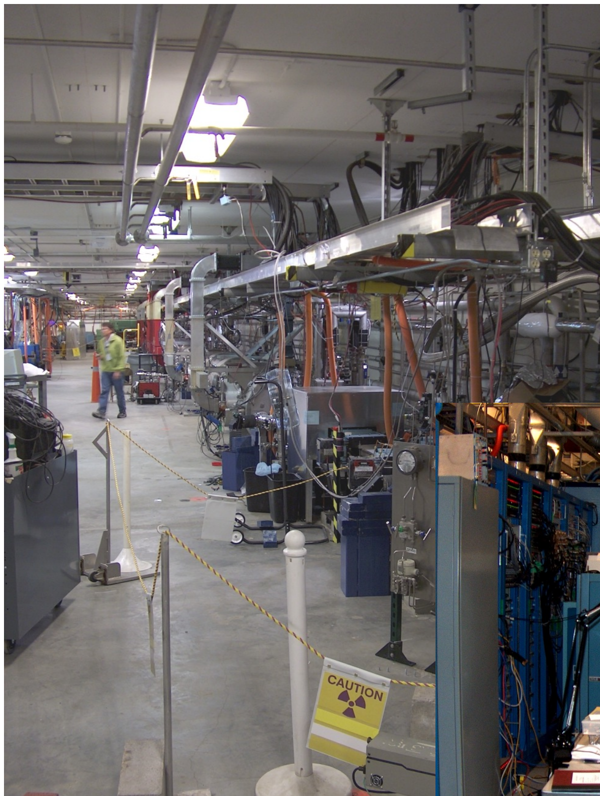
Cornell LLRF High Q_L Operation Test at CEBAF (cont.)

Very strong microphonics (peak detuning > 1.5 cavity bandwidth)



M. Liepe et al., Proceedings of PAC'05, Knoxville, Tennessee

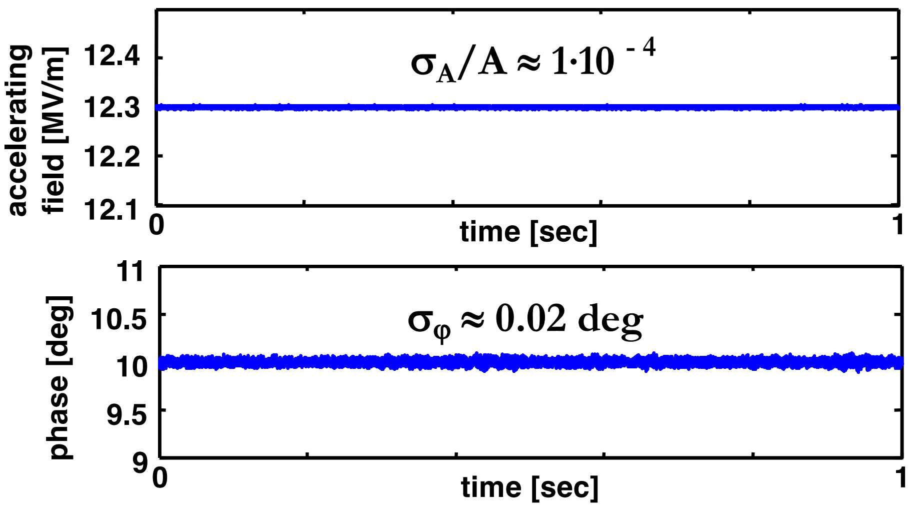
Cornell LLRF High Q_L Operation Test at JLAB FEL

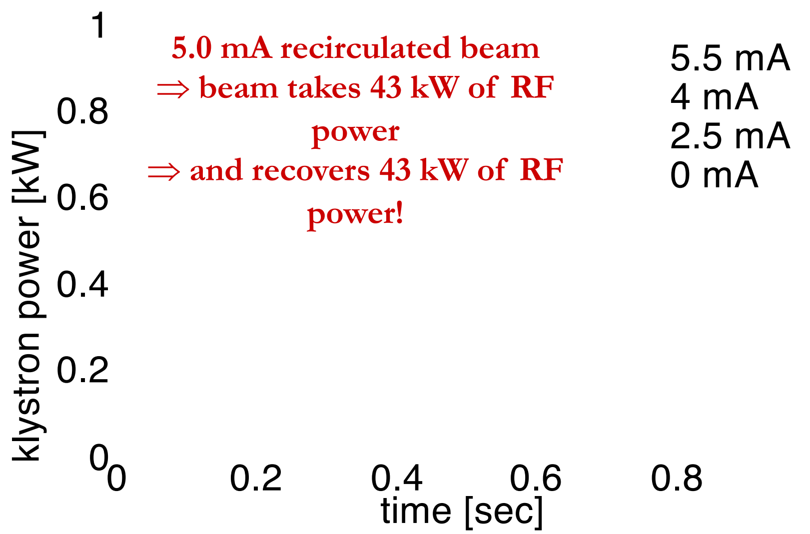


- **Operated cavity at Q_L=1.2·10^8 with 5 mA energy recovered beam.**
- **Active control loops :**
  - **PI loops for cavity field (I and Q component)**
  - **Stepping motor feedback for frequency control**
  - **Piezo tuner feedback for frequency control**

Cornell LLRF High Q_L Operation Test at JLAB FEL (cont.)

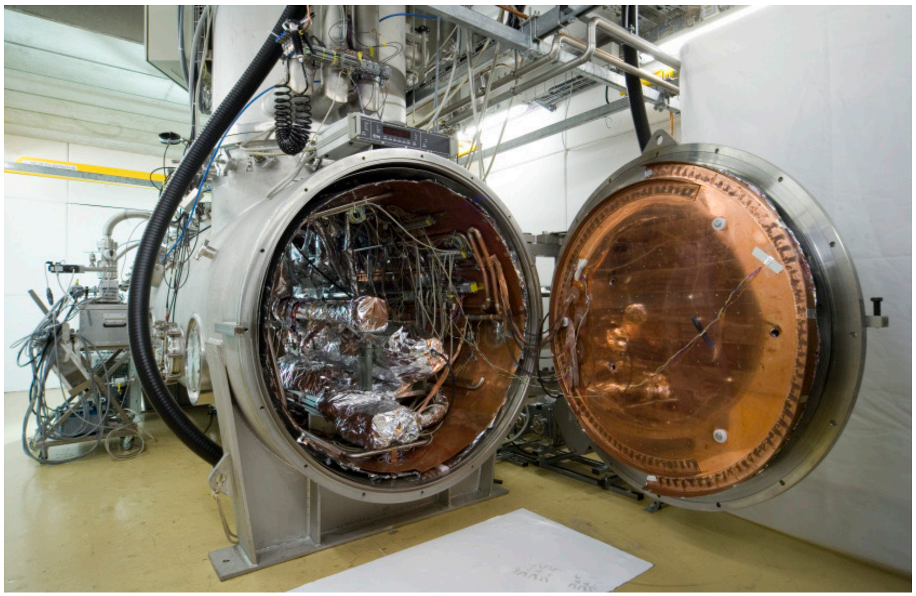
- Proof-of-principle experiment with high- Q_L ERL cavity
  - Loaded Q of **$1.2 \cdot 10^8$** (12 Hz cavity bandwidth)
- Excellent field stability
- Very efficient cavity operation (some 100 W instead of kWs)





M. Liepe et al., Proceedings of PAC'05, Knoxville, Tennessee

Cornell LLRF High Q_L Test at HZB Test Stand



- Connected Cornell RF control system to a nine-cell TESLA cavity in the HZB horizontal test stand (HoBiCaT).
- Increased loaded Q up to **$2 \cdot 10^8$** (6.5 Hz cavity bandwidth).
- RMS microphonics cavity detuning of 4 Hz with 15 Hz peak detuning.
- No beam.

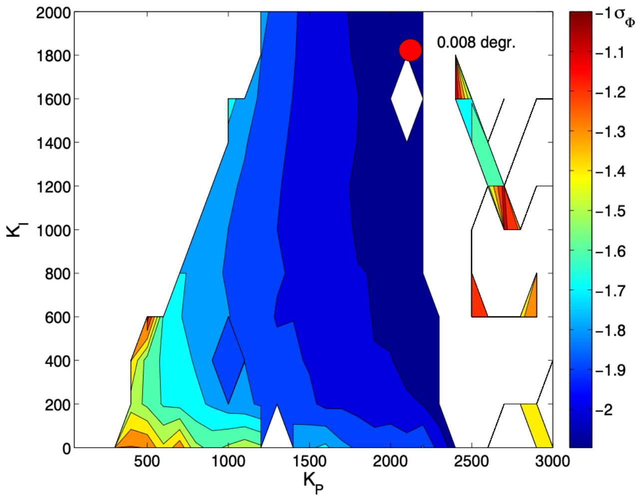
Cornell LLRF High Q_L Test at HZB Test Stand (cont.)

Table 1: Cavity field stability results at E_{acc}=10 MV/m

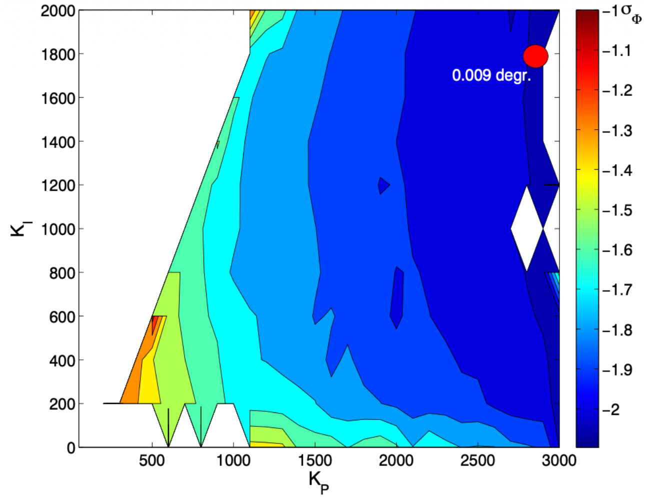
Q_L	σ_f (Hz)	σ_Φ (deg)	σ_A/A	P_f (kW)
$5.0 \cdot 10^7$	9.5	0.008	$1 \cdot 10^{-4}$	1.106
$1.0 \cdot 10^8$	7.9	0.0093	$2 \cdot 10^{-4}$	0.595
$2.0 \cdot 10^8$	4.2	0.024	$3 \cdot 10^{-4}$	0.324

- Very good field stability even at $Q_L = 2.0 \cdot 10^8$ with strong microphonics (peak detuning >2.5 full bandwidths)

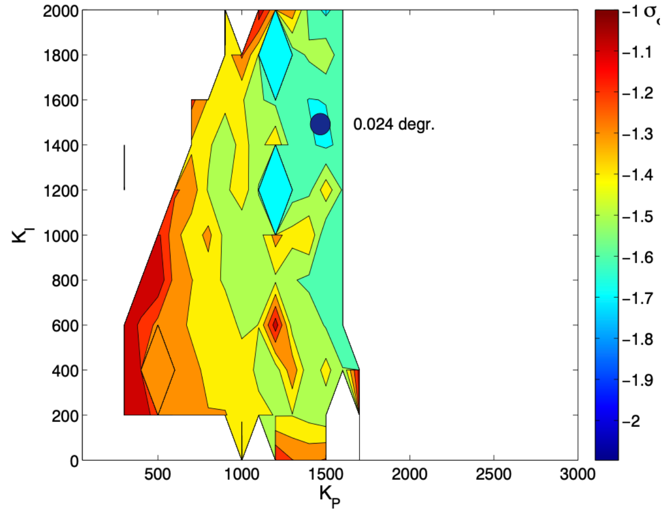
$Q_L = 5.0 \cdot 10^7$



$Q_L = 1.0 \cdot 10^8$

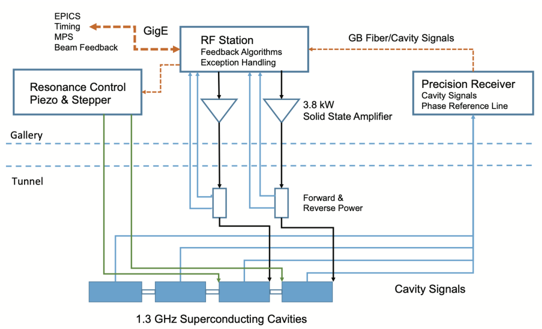


$Q_L = 2.0 \cdot 10^8$



A. Neumann et al., Proceedings of SRF2011, Chicago, IL USA

LCLS-II LLRF Developments for high Q_L Cavities



- Control algorithm is based on **digital Delayen-style Self Excited Loop concept, extended by an amplitude and phase lock feature**.
- Resonance controls system is fully integrated with the LCLS-II LLRF system.
- Excellent field stability, meeting the requirements of up to 0.01% in amplitude and 0.01° in phase (**Q_L of 4 ×10^7**).

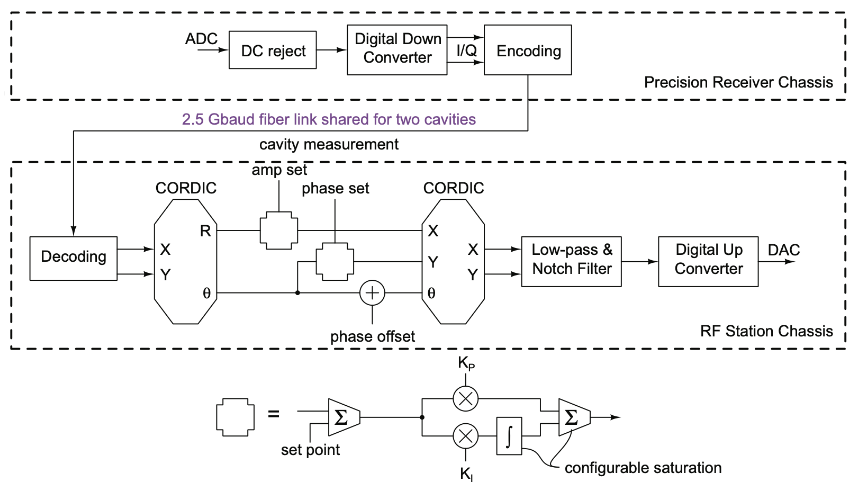


Figure 4: Simplified block diagram of DSP path for field control loop.

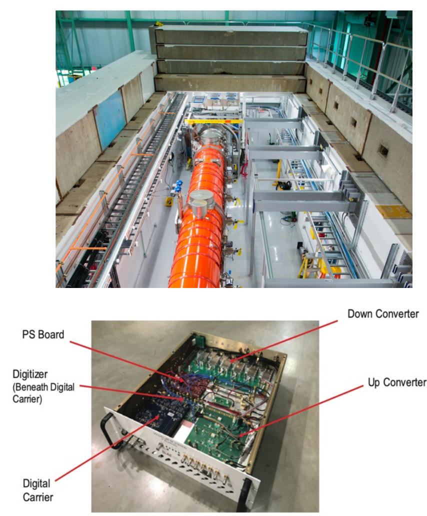
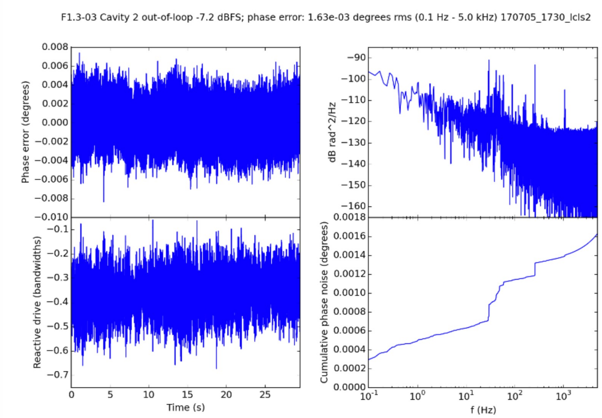
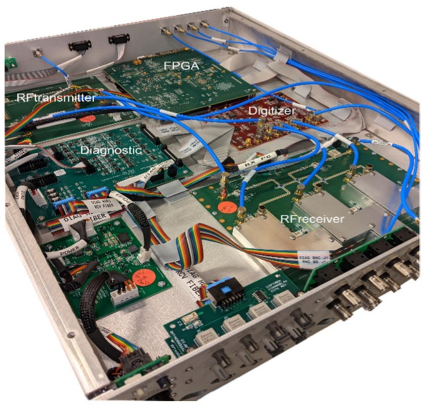


Figure 7: LCLS-II LLRF RF station.

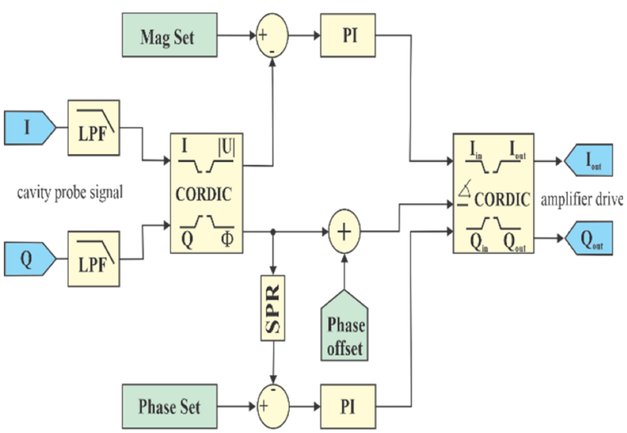


L. Doolittle et al., SRF2017, Lanzhou, China
G. Huang, NAPAC2016, Chicago, IL, USA
C. Serrano, IPAC2018, Vancouver, Canada

JLAB LLRF Development for high Q_L CEBAF Cavities



- Control algorithm is based on **digital Self Excited Loop concept, extended by an amplitude and phase lock feature (SELAP).**
- Tested results shown below are with a 7-cell SC cavity with external Q of **$9 \cdot 10^6$**.
- Good field stability: better than 0.15° in phase and 0.01% in amplitude.
- SELAP mode enables very quick trip recovery.



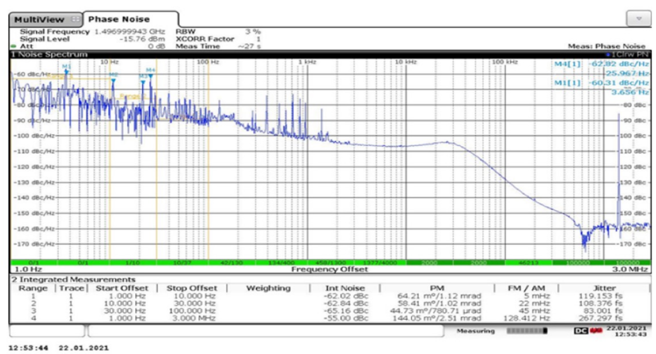


Figure 5: Cavity field phase noise [SELAP].

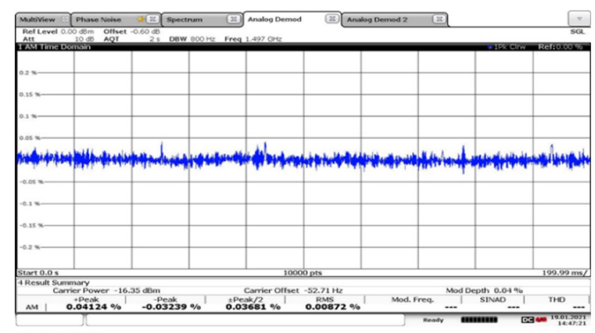
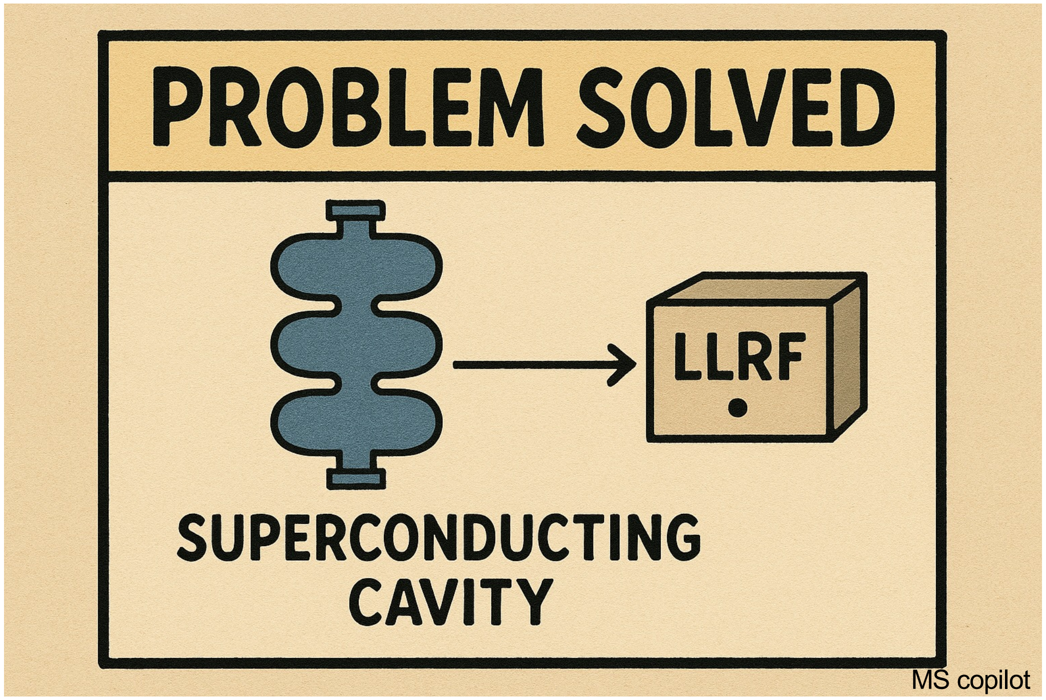


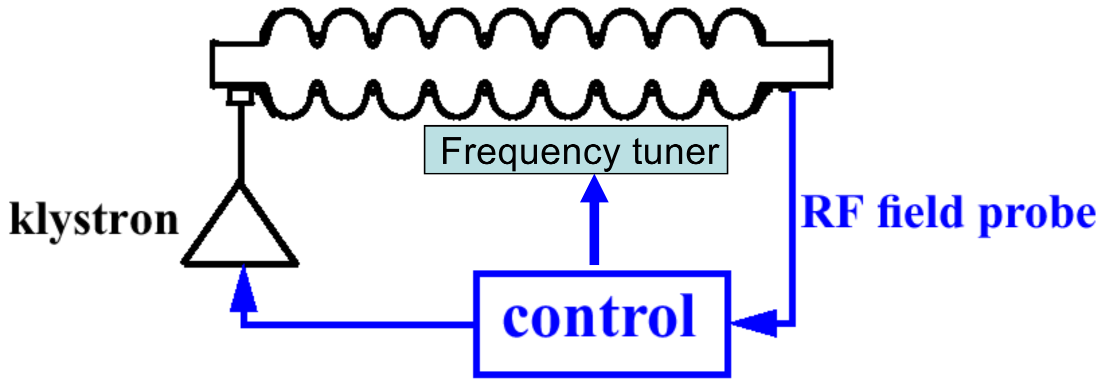
Figure 6: Cavity amplitude [SELAP].

R. Bachimanchi et al., Proceedings of IPAC2021, Campinas, SP, Brazil

A. RF control system which can deal with large amplitude and phase field perturbations

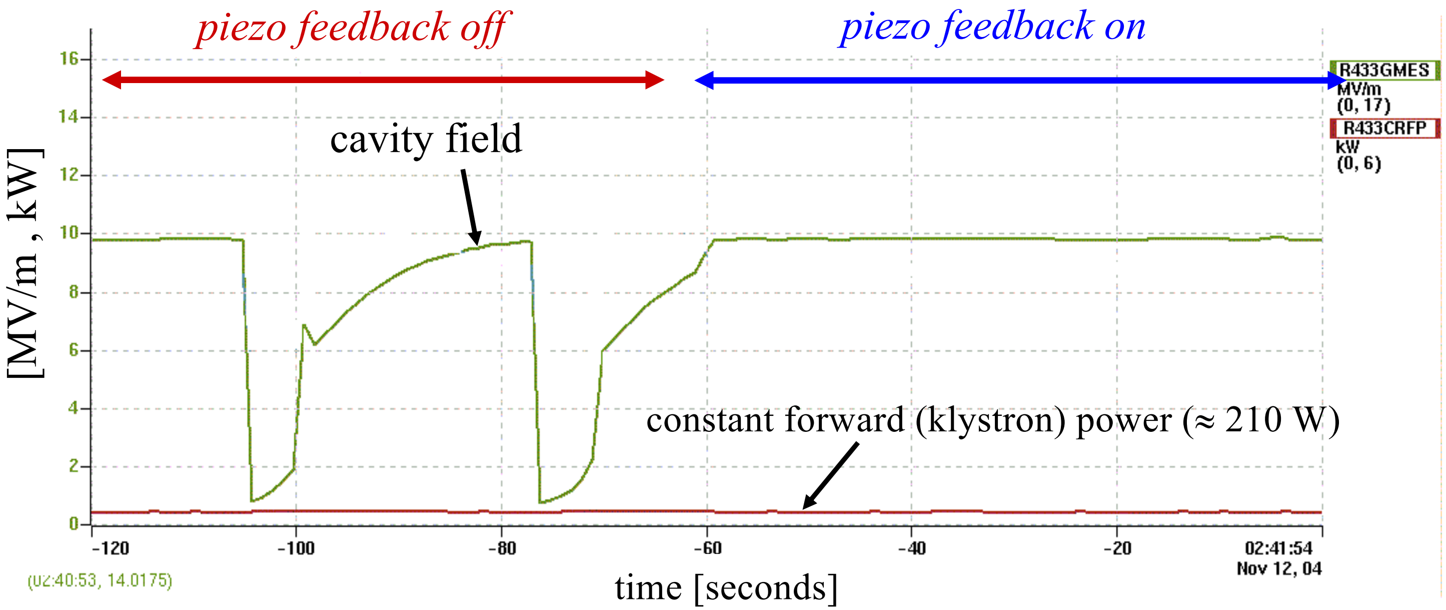


B. Solution for field ramp up (and trip recovery)



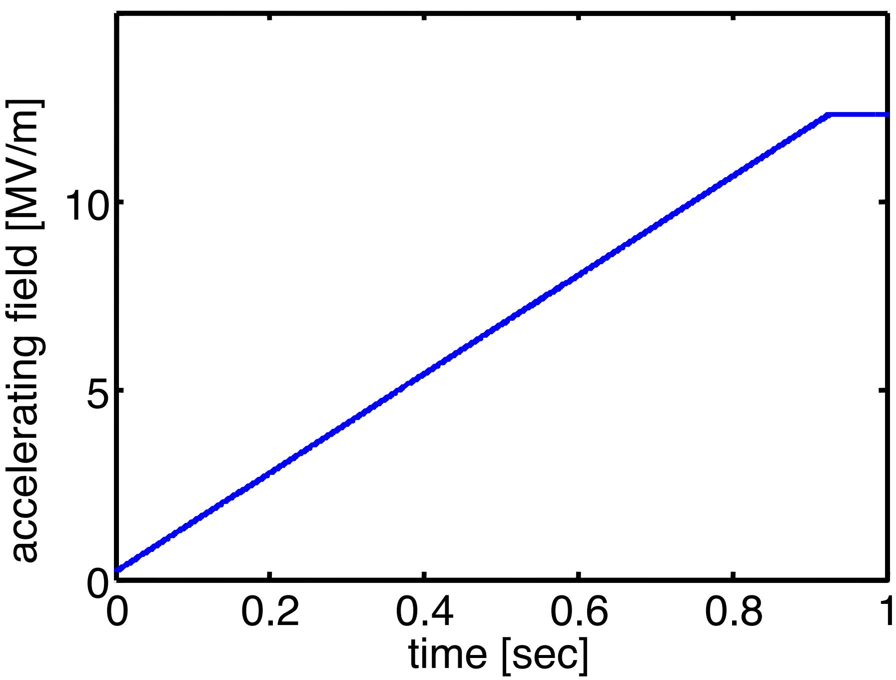
Cornell LLRF High Q_L Operation Test at JLAB FEL

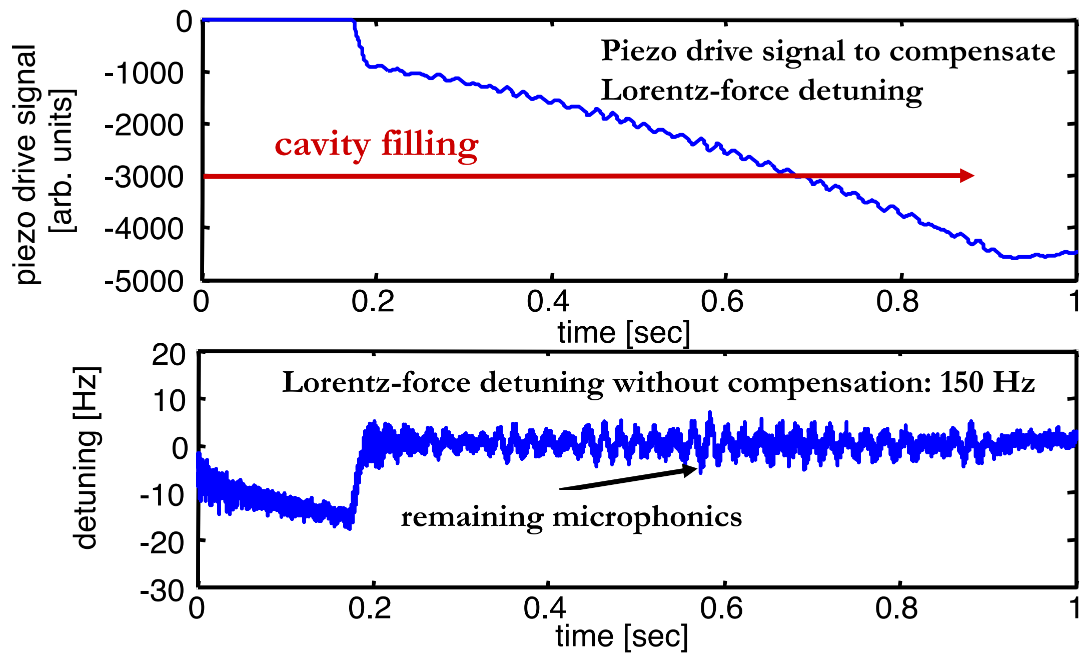
Piezo frequency tuner based fast compensation of Lorentz-force detuning



Cornell LLRF High Q_L Operation Test at JLAB FEL

Start-up: Field Ramp at $Q_L = 1.2 \cdot 10^8$





≈ 150 Hz Lorentz-force detuning compensated by piezo; cavity half bandwidth = 6 Hz.

LCLS-II LLRF Developments for high Q_L Cavities

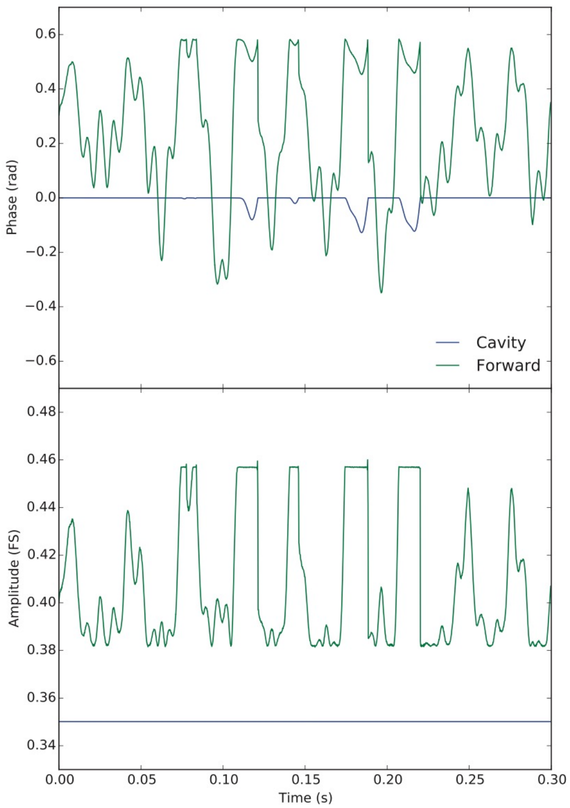
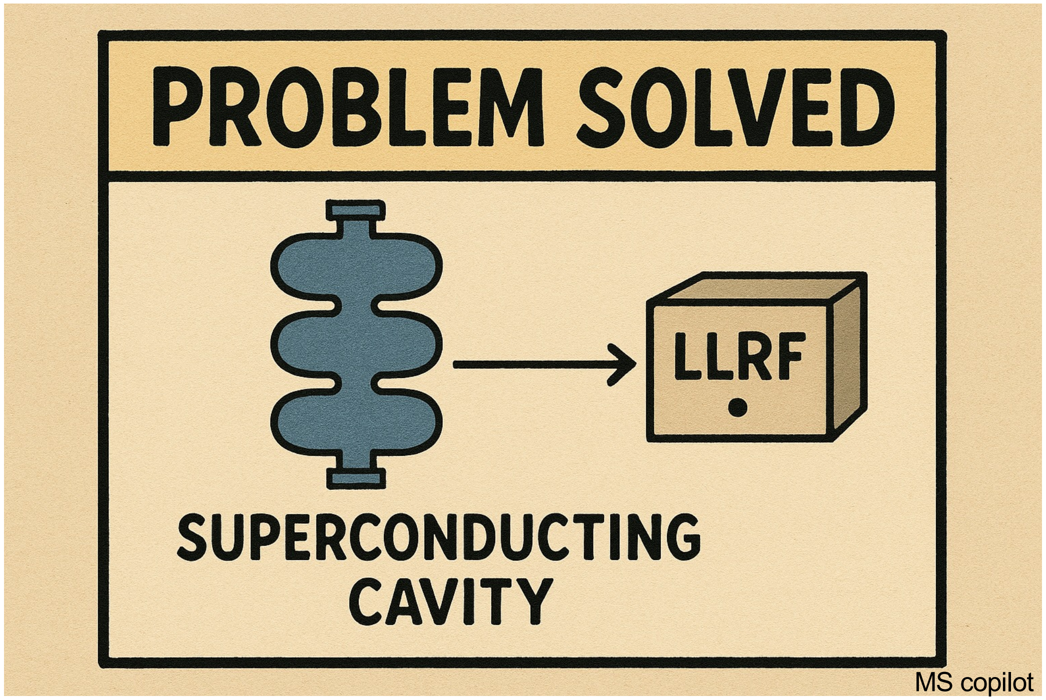


Figure 6: SEL operations with ordinary time axes.

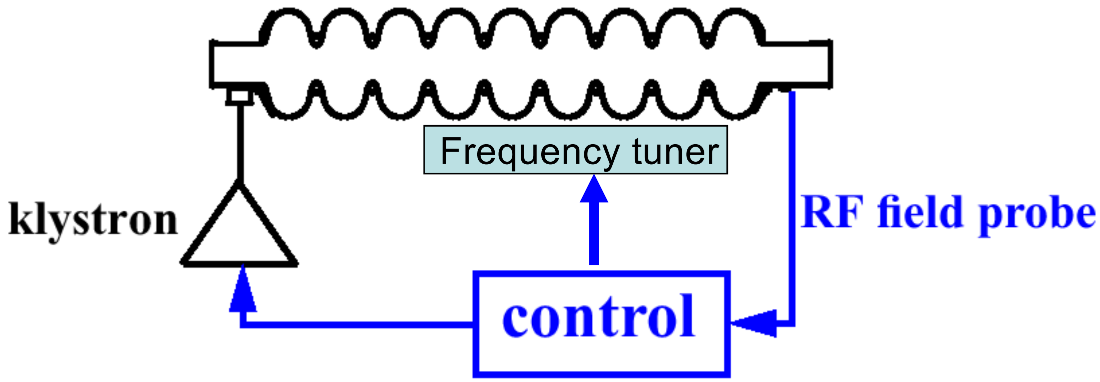
- **Control algorithm is based on digital Delayen-style Self Excited Loop concept, extended by an amplitude and phase lock feature.**
- SEL capabilities with **seamless transition between resonance-tracking mode and phase-locked mode** allow for
  - Quick field ramp up in SEL mode
  - Centering the cavity tune (at the operational gradient) as a “leisurely second step”
  - Elegant handling of RF power saturation instances: System falls back and runs in SEL with amplitude control mode. Once detuning lessens below power saturation, the system seamlessly locks back to full phase control.

L. Doolittle et al., SRF2017, Lanzhou, China
G. Huang, NAPAC2016, Chicago, IL, USA
C. Serrano, IPAC2018, Vancouver, Canada

B. Solution for field ramp up (and trip recovery)



C. Microphonics mitigation and control



Microphonics Control

- Active microphonics control challenging due to complex mechanical system.
- Some progress using advanced control algorithms, especially in suppressing narrow-band disturbances.
- Reduction of **peak detuning** most critical and most challenging.

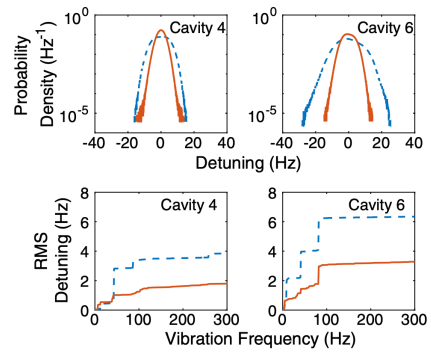
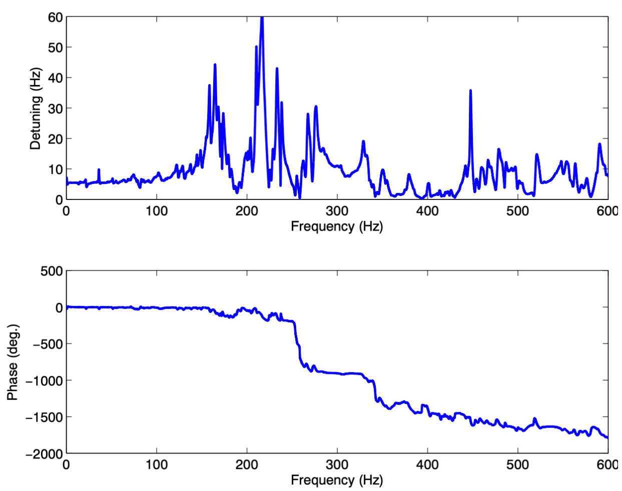
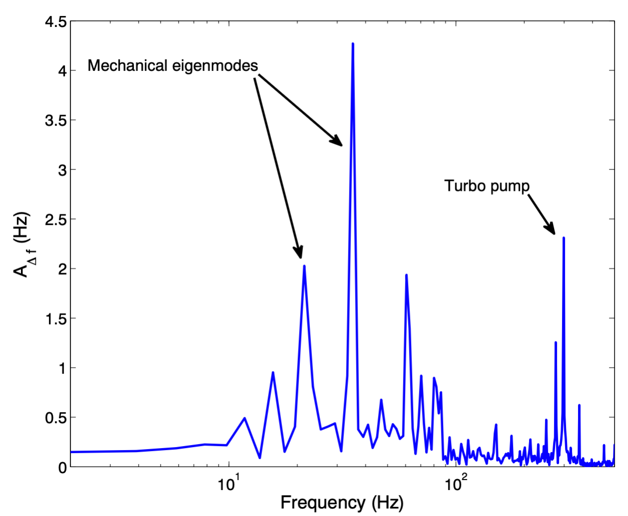
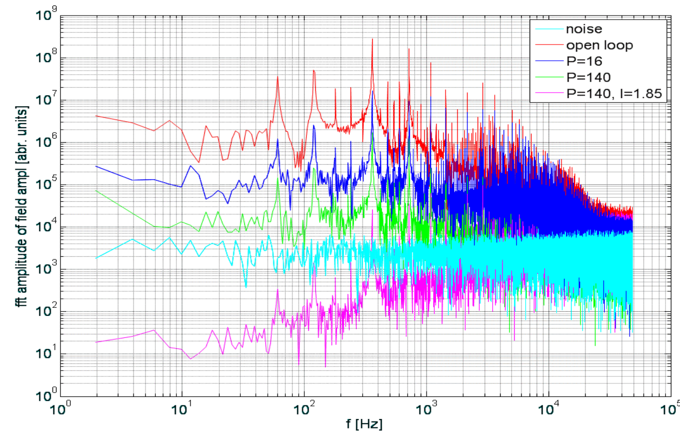


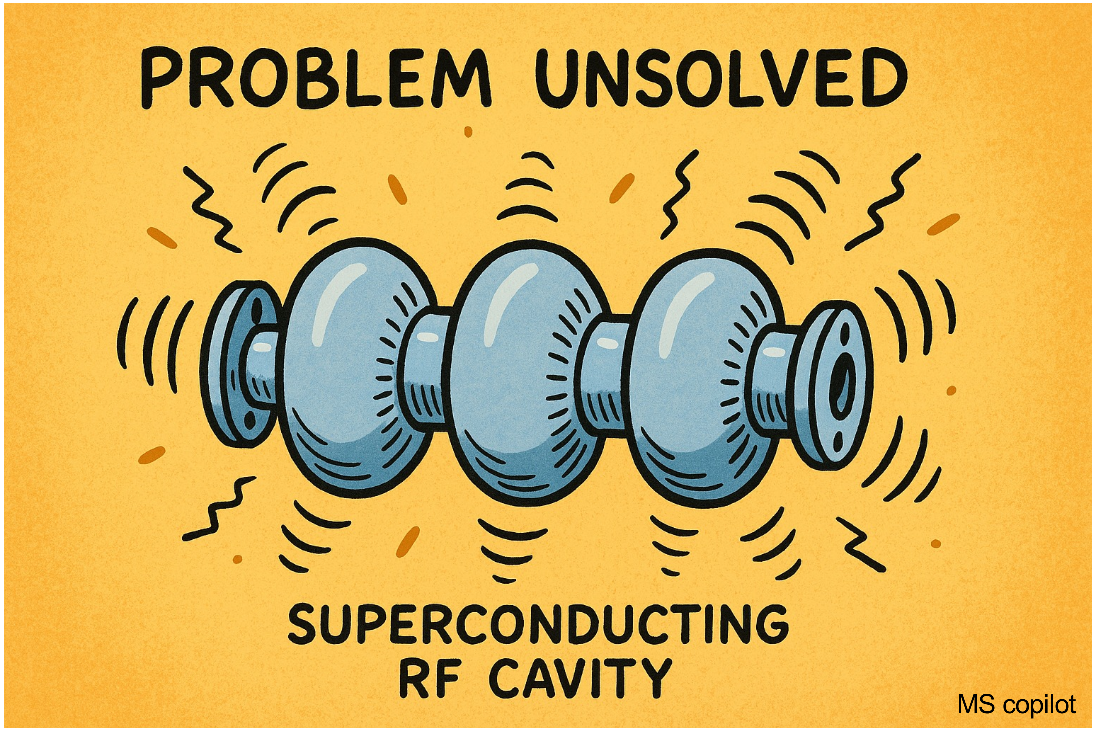
FIG. 13. Effect of active microphonics compensation on two stiffened cavities of the main linac. The dashed lines represent data without active suppression while the bold lines show the performance with ANC turned on.







C. Microphonics mitigation and control



Summary and Outlook

- **Achievable today:** SRF operation in the 10^7 loaded Q range with excellent field stability (10^{-4} amplitude, 0.01 deg phase)
- **Future:** 10^8 loaded Q range quite possible but will need significant R&D in cavity resonance control.

That’s all for now.