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Drift Observations and Mitigation in LCLS-II RF

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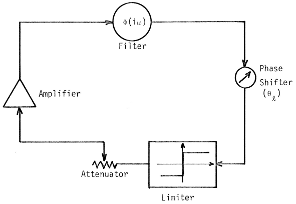
LLRF'23 Workshop, Gyeongju, South Korea

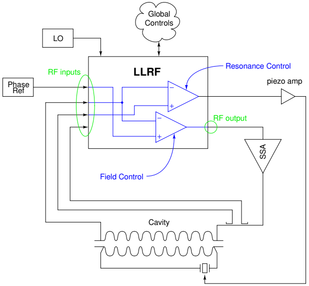
Outline

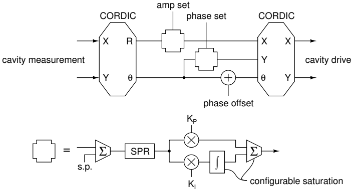
- Introduction
- Phase Reference System
- RF hardware design
- Capture of PRL signal
- SEL phase offset
- Detuning computations
- Beam energy noise
- Discussion and Conclusions

Introduction

- LCLS-II SRF cavity field control is performed with a digital Delayen-style self-excited-loop (SEL)
- Cavity phase is measured relative to a phase reference line (PRL)
- Resonance control is effected by piezo actuators (and stepper motors) based on state-space interpretation of forward and cavity waveforms







Introduction - Feedback

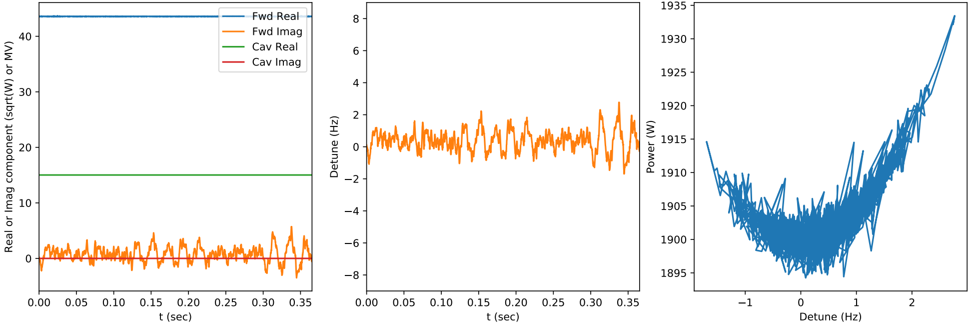
- Topic is SRF cavity control with feedback loops "at scale"
  - 280 $\times$ 1.3 GHz SRF cavities
  - 16 $\times$ 3.9 GHz SRF cavities
  - not considered here: gun and bunchers (those use copper cavities)

qty.	Type	actuator	bandwidth
2	PRL drive phase	physical RF phase	300 Hz
74	PRL recovery	all-digital	10 kHz
(2$\times$) 296	**Field control loop**	physical RF amp & phase	10 kHz
296	**Resonance control loop**	piezo	1 Hz
296	SEL phase offset drift correction	all-digital	0.001 Hz
296	Resonance measurement $\angle b$ drift correction	all-digital	0.001 Hz
6	Beam-based linac adjustment	all-digital	0.1 Hz
1562	total (but some are disabled IRL)		

- each feedback loop needs classic design considerations of bandwidth, stability, measurement noise, and plant noise

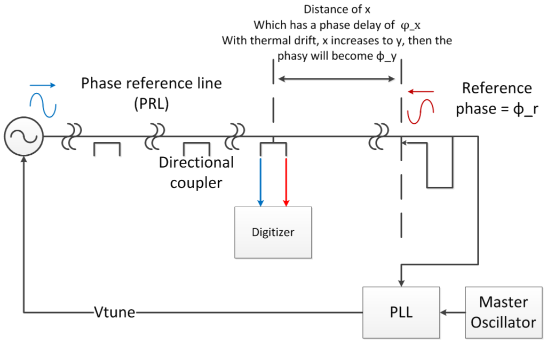
Introduction - Microphonics

- Microphonics (time-varying cavity resonance frequency) is both a problem and a solution
  - Problem: increases the RF power required to hold steady field
  - Solution: injects a (non-LTI) plant perturbation that disambiguates cable-electrical-length variations from cavity resonance frequency shifts
- This “signal” gets used operationally to find and correct drifts in proper SEL phase offset and state-space *b* coefficient



Phase-averaging PRL design

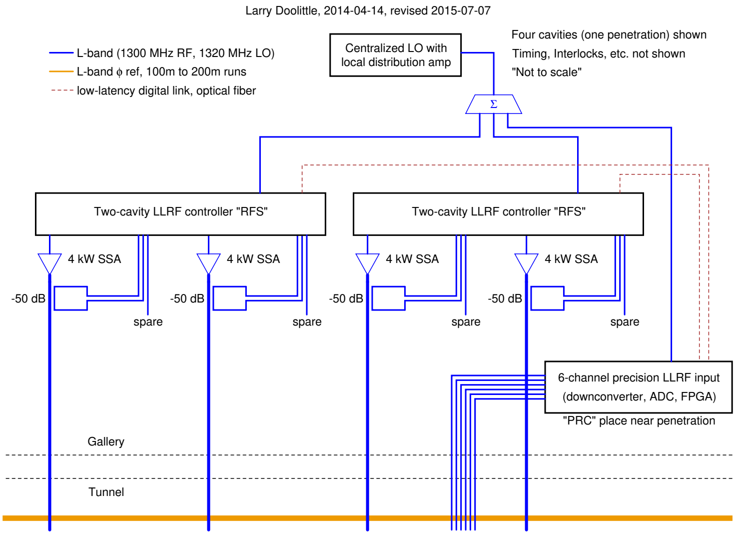
- LCLS-II MO subsystem generates LO (1320 MHz) and PRL (1300 MHz)
- PRL directional couplers provide fwd and rev reference signals to LLRF system
- Phase-averaging tracking loop in firmware corrects phase drifts caused by changes in the PRL cable length



C. Xu et al., "*LCLS-II Phase Reference System*," LLRF'17 Barcelona

S.D. Murthy et al., "*Installation, Commissioning and Performance of Phase Reference Line for LCLS-II*," LLRF'22 Switzerland

RF Station Hardware Design - (figures from 2017 FDR)



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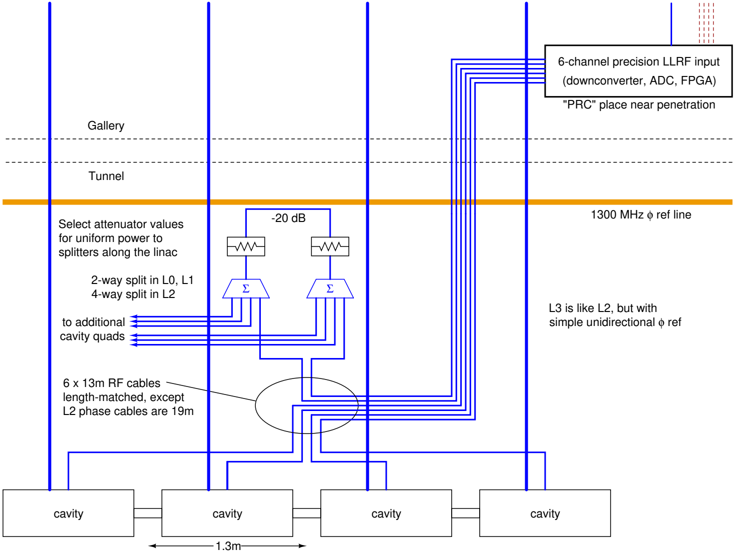


Observation

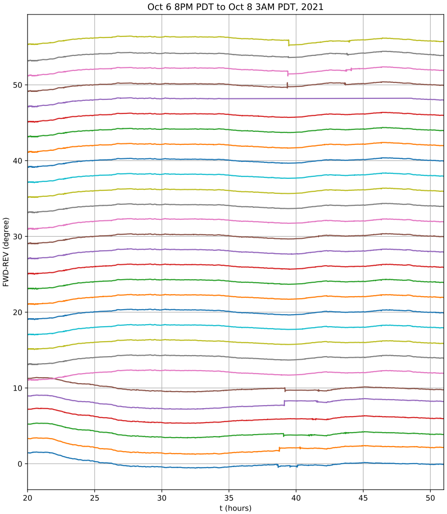
A cavity control rack can run mostly OK without input from PRL

- Right frequency, unknown absolute phase (or even relative to its neighbor)
- Perfectly useful for cavity commissioning and testing
- Much of the firmware and software was developed and tested in this context
- Clearly not useful for running beam

Using the PRL eliminates sensitivity to LO distribution phase drifts and chassis-level divider state

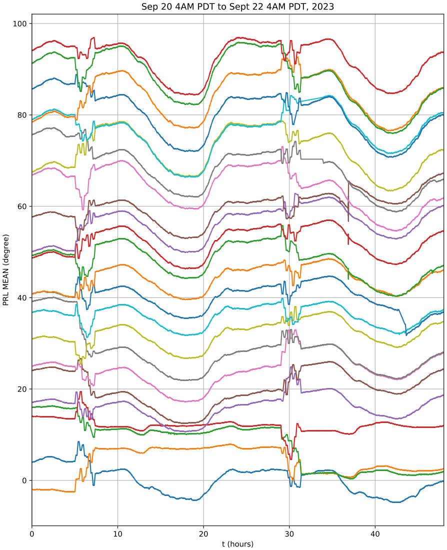
Capture of and use of PRL waves in PRC

- local all-digital PLL, sets digital LO used for downconverting all six RF channels in the PRC ($2 \times$ PRL, $4 \times$ cavity probe)
- Fwd-Rev represents PRL changing length
- Physical 150 m (in L2) PRL is mostly in the tunnel - thermally stable
- Median span is 1.3°



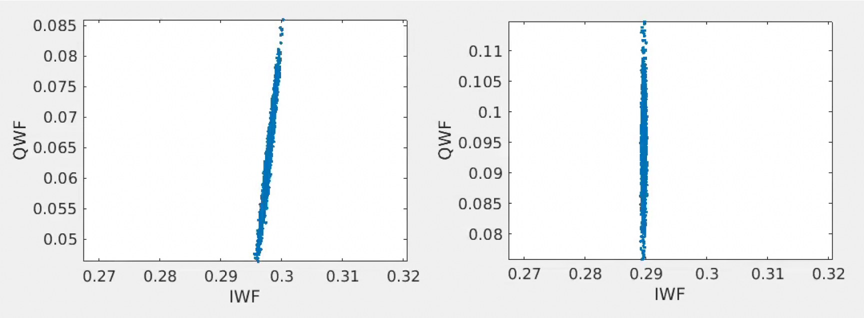
Capture of and use of PRL waves in PRC

- Mean represents LO distribution cable changing length
- Physical 150 m (in L2) LO cable is in the gallery - uncontrolled temperature
- Median span is 14.8°



SEL phase offset

Complex-number DSP output of a Delayen-style SEL controller should have almost constant real part. If the "Cheeto" is tilted, you need to adjust the phase offset. Human operators can't do that for 296 cavities! Obvious candidate for automation. Figure shows the complex control locus for an example cavity before and after adjusting `SEL_POFF` by 7°. Operators call this their "Cheetos straightener," and it now runs in the background. It can only work when a cavity's field control loops are **not** clipping.



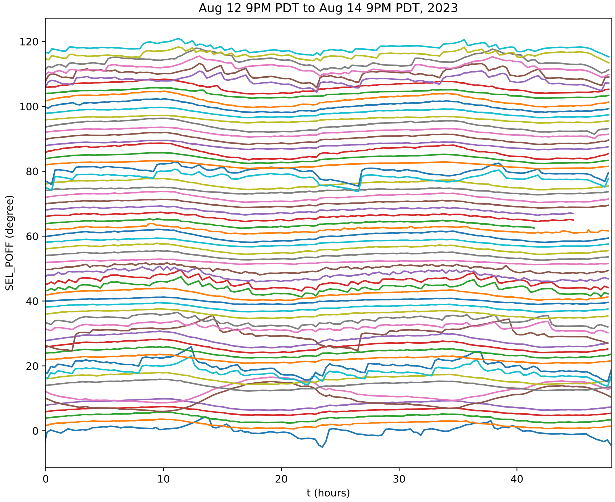
2048 points in 366 ms from cavity 35-1, 2022-10-09

SEL phase offset

Optimized SEL phase offset changes observed during normal operations.

Only a quarter of the cavities are displayed.

Median span is 3.7°.

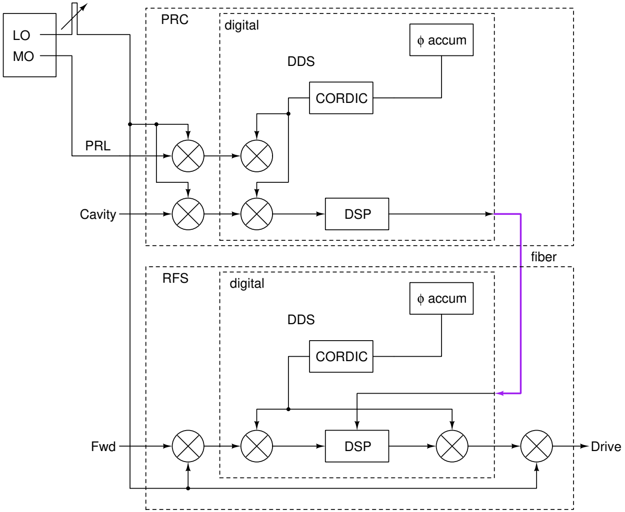


Detour - between-chassis phase shifts

Our multiple-chassis subdivision is good for keeping crosstalk low.

When phase-locking to the PRL in the PRC, it also creates unexpected phase shifts when the LO distribution drifts.

Sanity is restored by copying the DDS phase offset from PRC to RFS.



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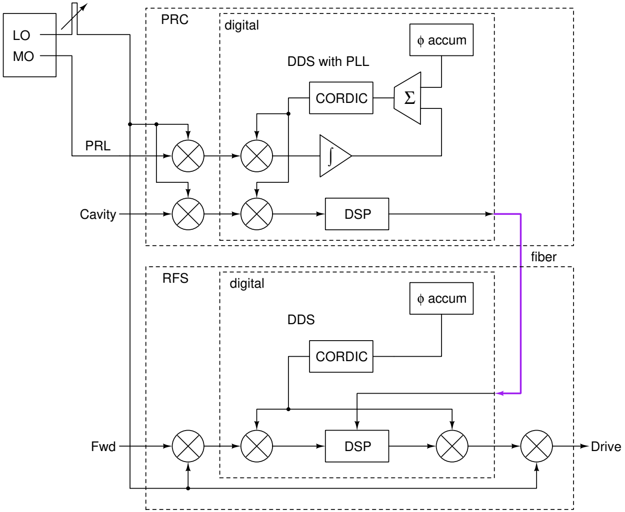

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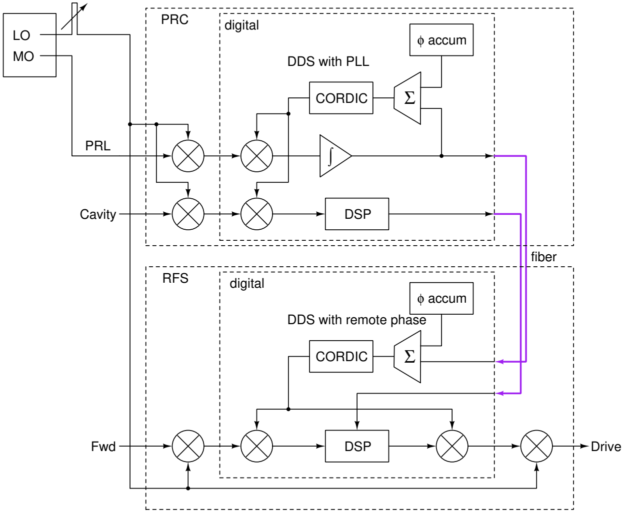
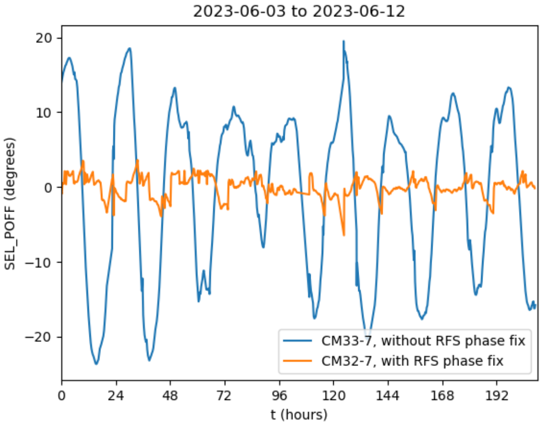


SEL phase offset

After copying the DDS phase offset from PRC to RFS, all 18 RF channels (in three chassis) stay phase-stable in the presence of LO phase drift.

Testing with adjacent cryomodules shows daily span of `SEL_POFF` reduced from 43° to 10°.



Detuning state-space equation

Forward and cavity signals are analyzed in terms of the (complex number) state-space equation

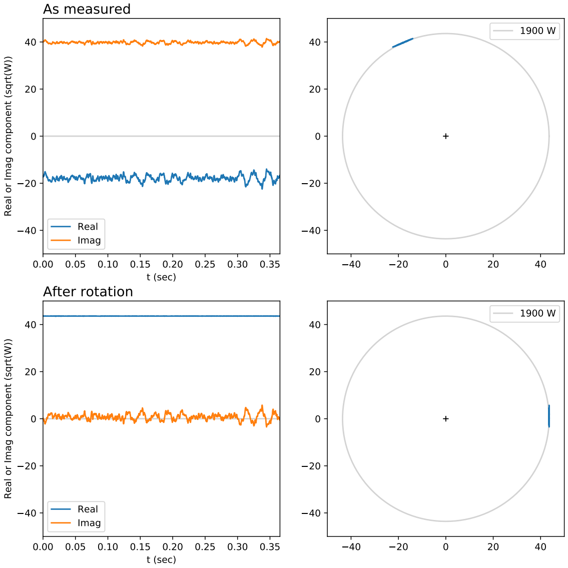
$$\frac{dV}{dt} = aV + bK$$

- Given b, and live measurements of V and K, solve for a every $11.2\,\mu$s
  - a represents bandwidth (real part) and detuning (imaginary part)
  - that detuning is then used by resonance control loop
- The b coefficient is characterized in the cavity turn-on process, but will drift with cable electrical length
- Self-tuning of $\angle b$ has key similarities to `SEL_POFF` process
  - uses detune modulation from microphonics as a probe of system physics
  - same requirement that cavity is locked in amplitude and phase
  - software analyzes waveforms and periodically adjusts DSP hardware
- Self-tuning of $\angle b$ has key differences from `SEL_POFF` process
  - excellent linear-fit properties, since the SSA is not part of the model
  - linear-fit analysis doesn't need an initial guess for $\angle b$

Detuning state-space equation

Standard 2-D statistics can find the axes of strong and weak variation in the (closed-loop) measured forward wave signal (in $\sqrt{\mathrm{W}}$). Specifically covariance (`np.cov`) and eigenvalues (`np.linalg.eig`).

Can only "find" angles; the coupling strength ($|b|$) is assumed to stay constant, as originally found during pulsed-mode calibration.

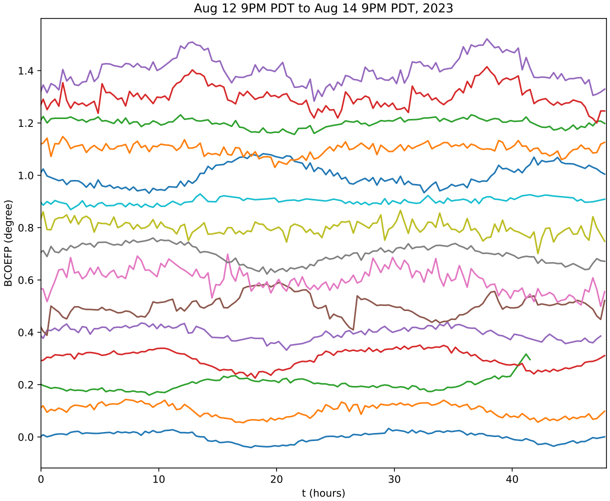


Detuning state-space equation

Observed $\angle b$ drift during demonstration run of self-tune process.

Median span is 0.14°.

That's good! It means the forward and cavity cables to the tunnel are nicely protected from day-night temperature swings.

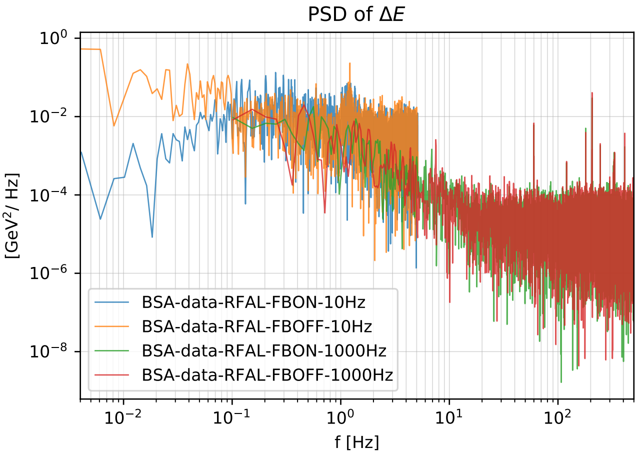


Beam energy noise

Beam energy noise spectra determined by BPM data capture, with and without the beam-based energy feedback running.

Early results - work-in-progress. First legitimate out-of-loop characterization of LCLS-II LLRF+PRL+cavity noise.

This plot shows in-loop error for the beam-energy feedback loop. That loop has its own measurement error (presumably including a $1/f$ term), which is not yet characterized.



Discussion and Conclusions

- Original (2015) hardware architecture gave enough hooks to make a usable system: most cavities take care of themselves most of the time.
- One can look at the system diagram and identify how electrical-length-drift of each cable will get self-corrected, except for the key cable-bundle from cavity and PRL to PRC.
- Python-based waveform analysis for adjusting `SEL_POFF` and `BCOEFP` every 20 minutes is “good enough,” so that there hasn’t been an urgency to develop an EPICS-IOC-based `C++` version that could refresh much faster.
- More work yet to come as beam loading is increased and firmware features are added to support that.
- Lots of software! We have pretty good CI (continuous integration testing), including hardware-in-the-loop tests, but always wish for more/better.

Conclusions

- System works well, thanks to the hard work of the team
  Andy Benwell, Daron Chabot, Jing Chen, Larry Doolittle, Bo Hong,
  Sonya Hoobler, Shree Murthy, Janice Nelson, Charlie Xu, Lisa Zacarias
- LCLS-II as a whole reached “first light” on Sept. 12, 2023
- More work ahead

Thank You