Model / Algorithm / Field Control

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PIP-II LLRF Final Design Review

July 17, 2024

A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

Theory Underpinning Control of PIP-II SRF Cavities

- Introduction
- Conclusions
- Calibration, units, and beam physics
- Decay curve and role in calibration
- State-space physics and detuning
- Complex cavity models
- Field Control loop
- Non-ideal SSA
- Pulse mode
- Summary

I've been at LBNL since 1999, and at Jefferson Lab before that.

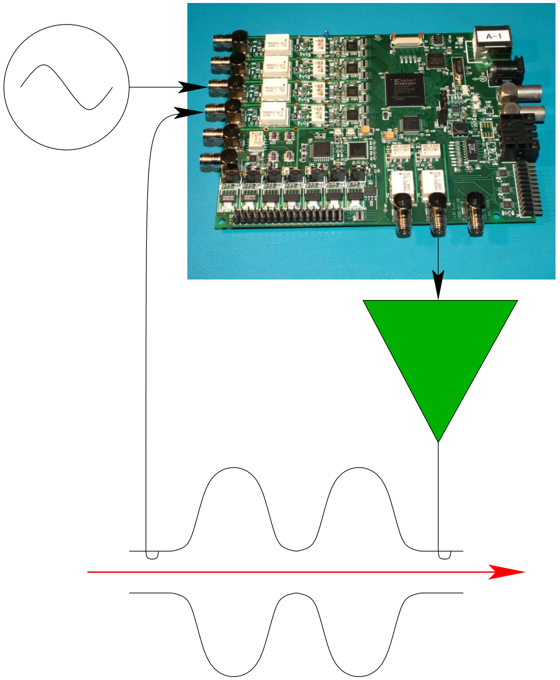
Mostly focused on LLRF and FPGAs since about 2002, but also involved in more general cavity and accelerator design.

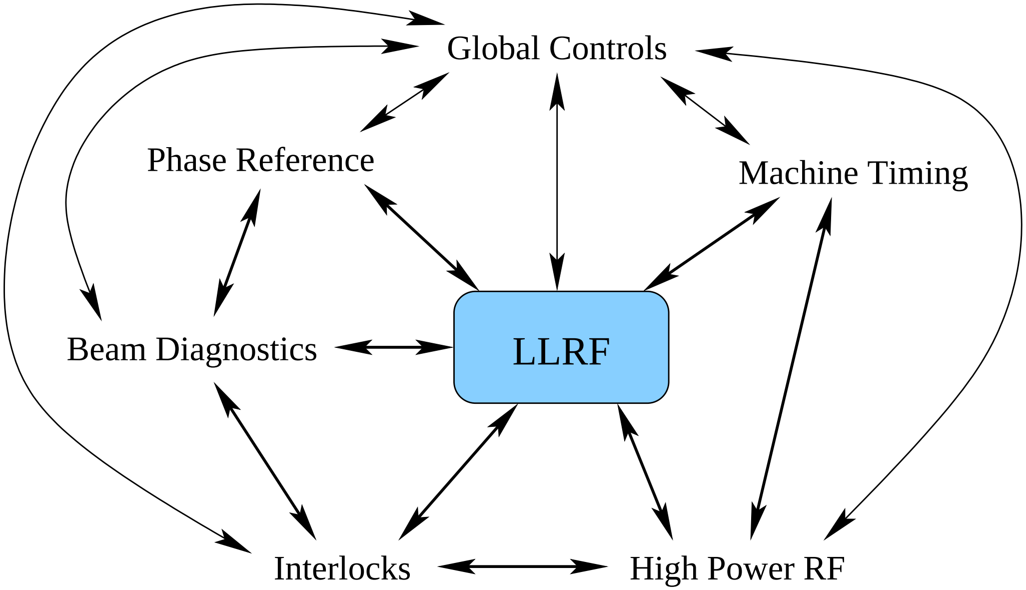
I'm actually a hardware person, even if it looks like software: "Write Verilog, visualize gates."

Conclusions first

- LBNL and the LCLS-II collaboration have (now) a history of understanding and controlling high-Q_L SRF cavities, dealing with microphonics, Lorentz forces, calibration, turn-on process
- PIP-II is nothing special here, except increased interest in exploring pulsed operation
- Cavity models are available to develop and regression-test control algorithms, including pulsed
- Acquisition of calibrated forward and reverse waveforms (complex-number $\sqrt{\mathrm{watt}}$) are key for quantifying cavity behavior; results include *in-situ* calibration of cavity field and Q_{loaded}
- As always, the hardware/software/operator system needs *a priori* knowledge of carrier frequency, length, and shunt impedance.

General LLRF





Global Controls

Phase Reference

Machine Timing

Beam Diagnostics

LLRF

Interlocks

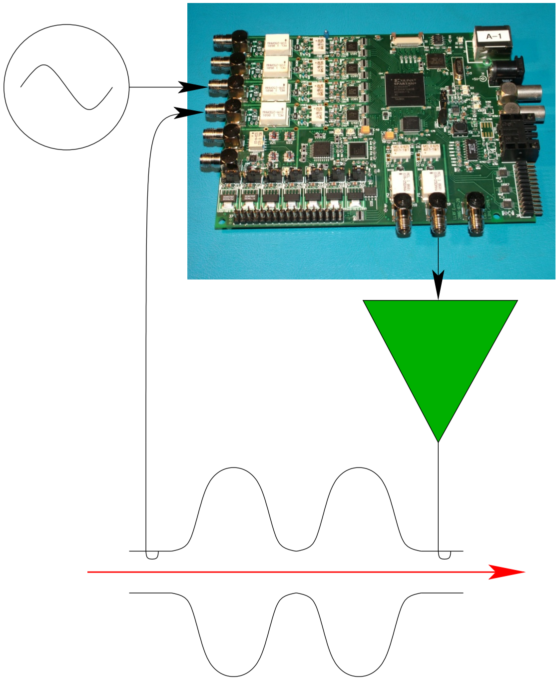
High Power RF

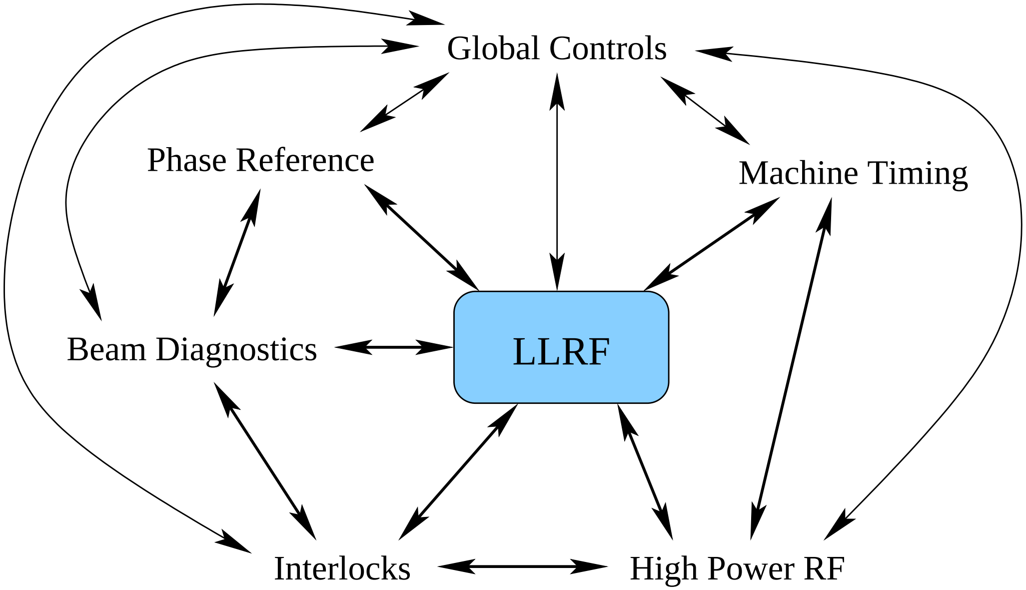
as presented at APAC 2007

What's the difference between hardware and software?

- Rick Cochran, U.S. system analyst, as told to me in 1982

General LLRF





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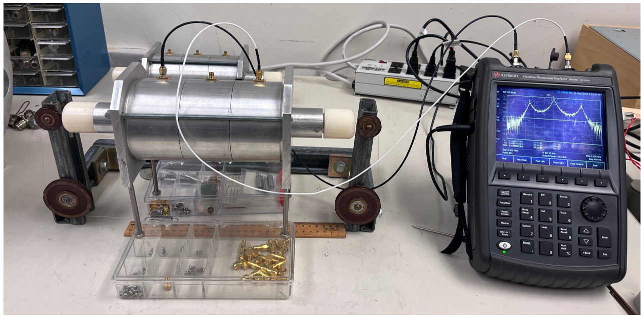
What's the difference between hardware and software?
Hardware keeps getting cheaper, faster, and smaller.
- Rick Cochran, U.S. system analyst, as told to me in 1982

Calibration, units, and beam physics

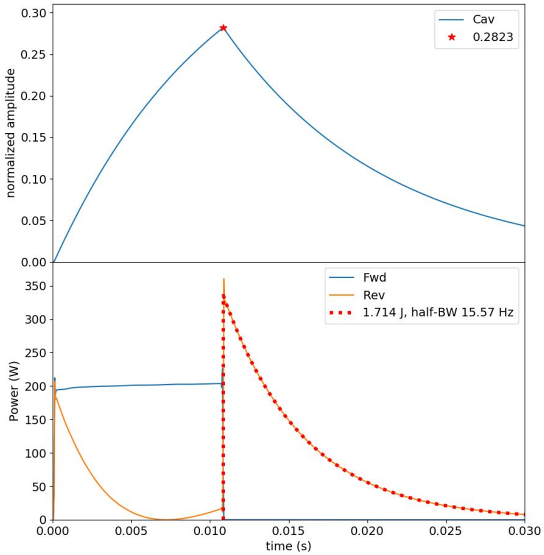
subtle clarification of traditional calibration - unconventional and can be ignored in this review

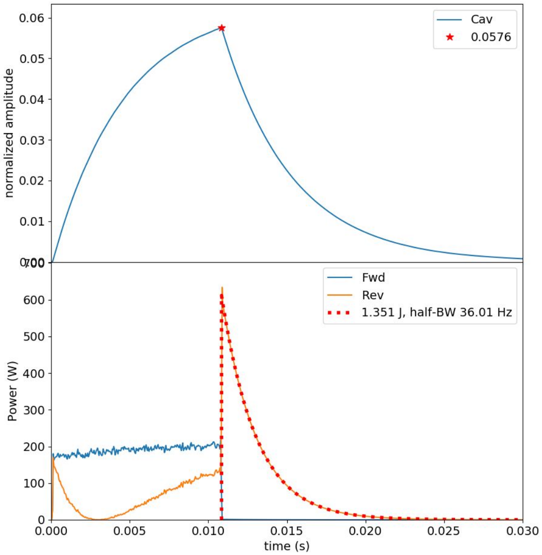
- Refactoring usual calibration process to use $\sqrt{\mathrm{J}}$ as the cavity amplitude unit, and communicating half-bandwidth instead of Q_{loaded}, allows calibrated operation of a cavity station without any *a priori* assumptions/configuration (besides correct calibration of fwd & rev measurements).
- Instead, a "user unit" conversion from $\sqrt{\mathrm{J}}$ to *e.g.*, MV can be dialed in depending on the audience, much like converting absolute times from UTC to a local time zone.
  Specifically, $V_{\mathrm{cav}} = \sqrt{U} \cdot \sqrt{(R/Q)\omega}$.
- Note that this conversion depends on particle-beam velocity β.
- Example: for PIP-II SSR1 with $R/Q = 242\,\Omega$ (at $\beta = 0.222$) and $\omega = 2\pi \cdot 325\,\mathrm{MHz}$,
  $V_{\mathrm{cav}} = \sqrt{U} \cdot 0.703$ MV/$\sqrt{\mathrm{J}}$.
- Further digression: as I explained (and students executed) in the 2020 and 2023 USPAS microwave measurements course, this conversion can be measured on a low-power model with a bead pull setup. The final path integral is calculated based on an assumed particle velocity, well within the capabilities of even a spreadsheet. Thus no essential dependence on fancy 3-D electromagnetic solvers.



Decay curve and role in calibration

- Area under reverse decay curve gives stored energy
- Easiest interpretation and most accurate in typical SRF case where wall losses are approximately zero
- Should include corrections for circulator S_{22}
- Ideally can distinguish intrinsic cavity Q_{loaded} vs. system effective Q_{loaded}
- Digital LLRF makes this much more practical to deploy than old-school analog implementations
- Field probe calibration directly computed from probe waveforms and (calibrated) reverse waveforms


LCLS2 9-Cell 2021-02-09

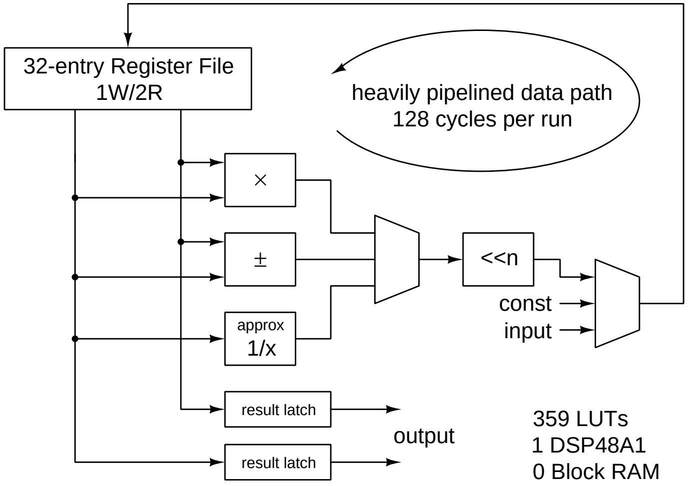

PIP2IT SSR1-1 2021-04-02

State-space physics and detuning

- Cavity voltage complex-number state-space model (LTI):

$$dV/dt = aV + bK + cI$$

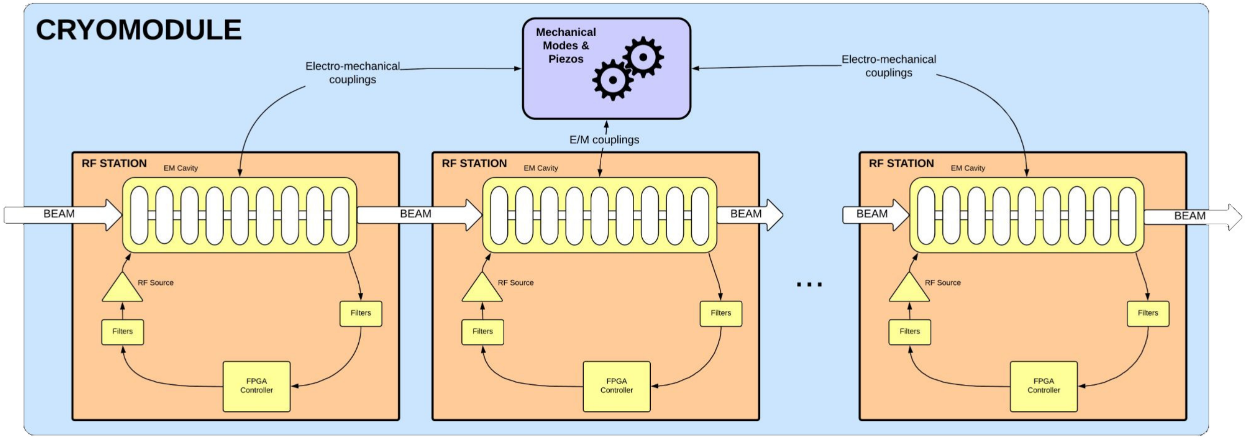
- Solve this equation for a, then simple arithmetic (including dV/dt) directly yields values of a (imaginary part is detuning, including microphonics) millisecond-by-millisecond in the FPGA.
- Requires *in-situ* calibration of b (easily found by analyzing waveforms from an RF pulse)
- To include time-varying (pulsed) beam loading, real-time connection to the machine timing system is required, as well as *in-situ* calibration of c. Such a feature is planned, but not yet implemented.



359 LUTs
1 DSP48A1
0 Block RAM

Complex cavity models

- Deconstruct electrical and mechanical cavity behavior from continuous physics (Hilbert space) to normal modes.
- Each of resulting finite-dimensional (lumped) electrical and mechanical systems are approximated as LTI (linear time-invariant), but the coupling between them is nonlinear.
- Physics summarized in 4-page handout
- FPGA implementation† available and tested for use in connection with actual controller
- Difficulty is usually measuring the parameters of the real system (attempts to calculate mechanical modes from CAD models historically have come up short)



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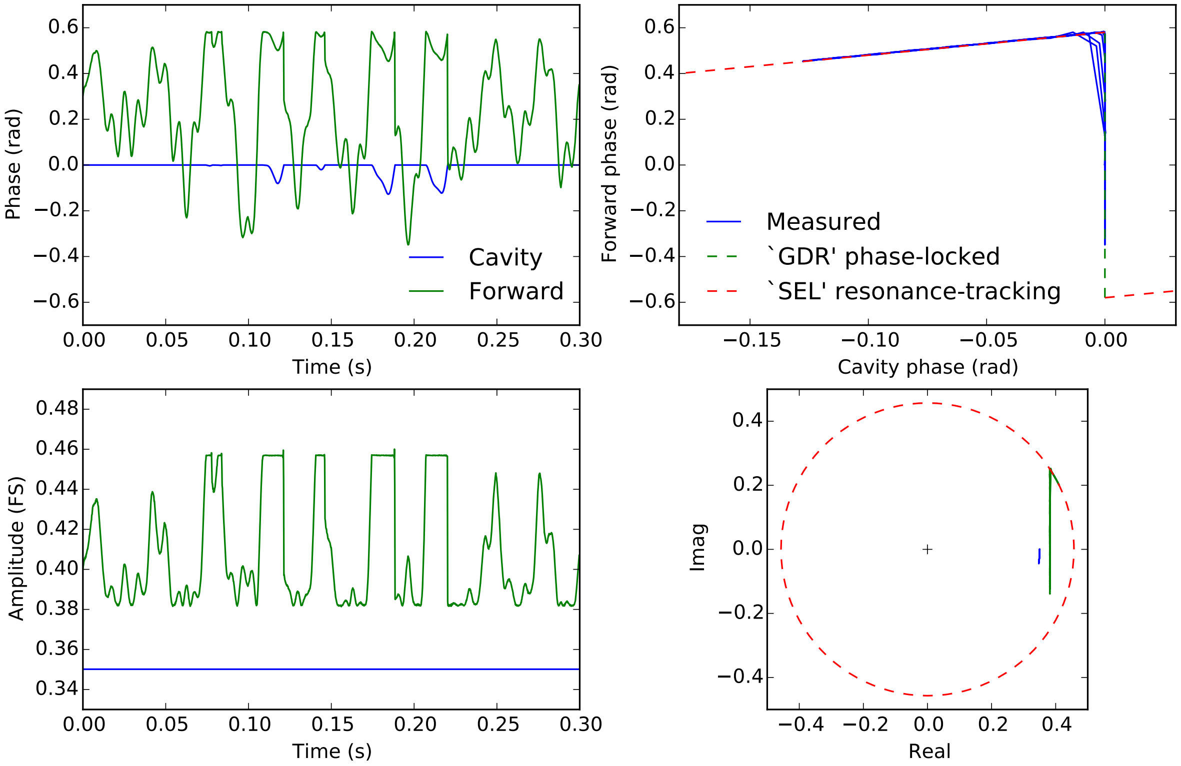
† See Cryomodule-On-Chip Simulation Engine, C. Serrano et al., ICALEPCS2017, Barcelona

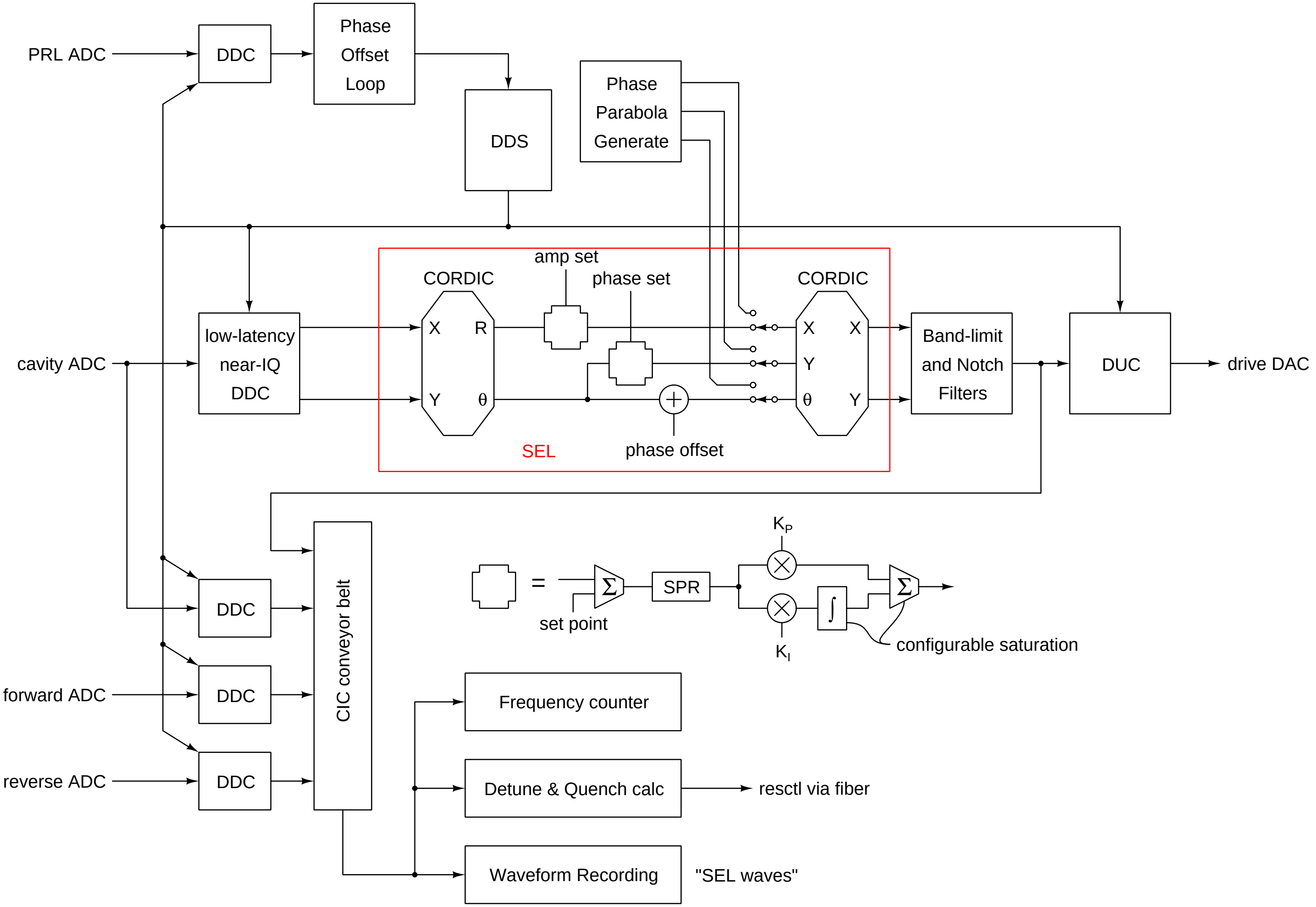
Field Control Loop

- All the usual topologies (Amplitude + Phase, I + Q, SEL) can be adjusted to have the same limiting small-signal behavior.
- A Self-Excited Loop (SEL) has advantages when dealing with large excursions of cavity resonant frequency. Keeping the amplitude locked prevents instabilities involving Lorentz forces.

Phase-locking SEL with clip limits on Q component works as intended

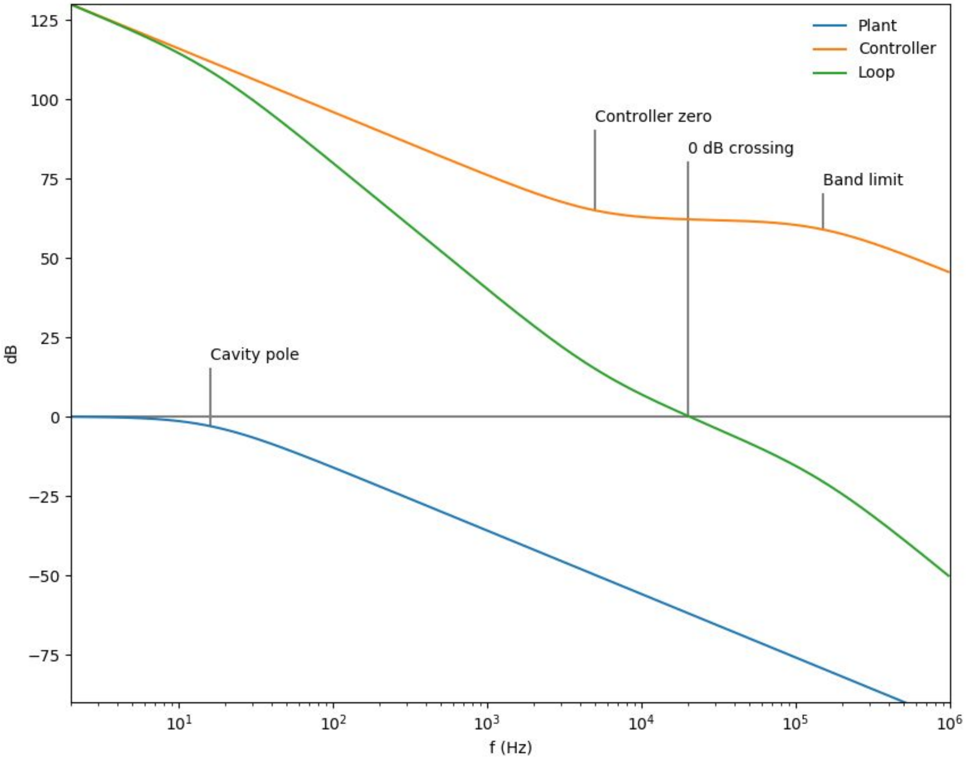


Field Control Loop Datapath



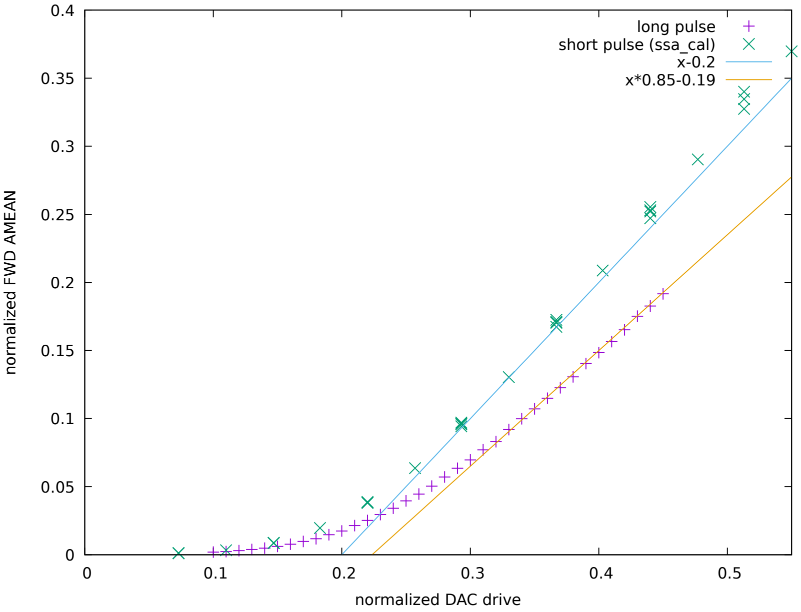
Field Control Loop

- Abstract Bode plot for stiff control of SRF cavity field
- Not new: clearly related to JLab 1987 analog controller, and indeed to textbook PLL design
- Loop stability requires microsecond-level system latency



Non-ideal SSA

Always wish for an amplifier (Klystron, SSA) that is LTI, at least approximately. Feedback can handle small, slow deviations.



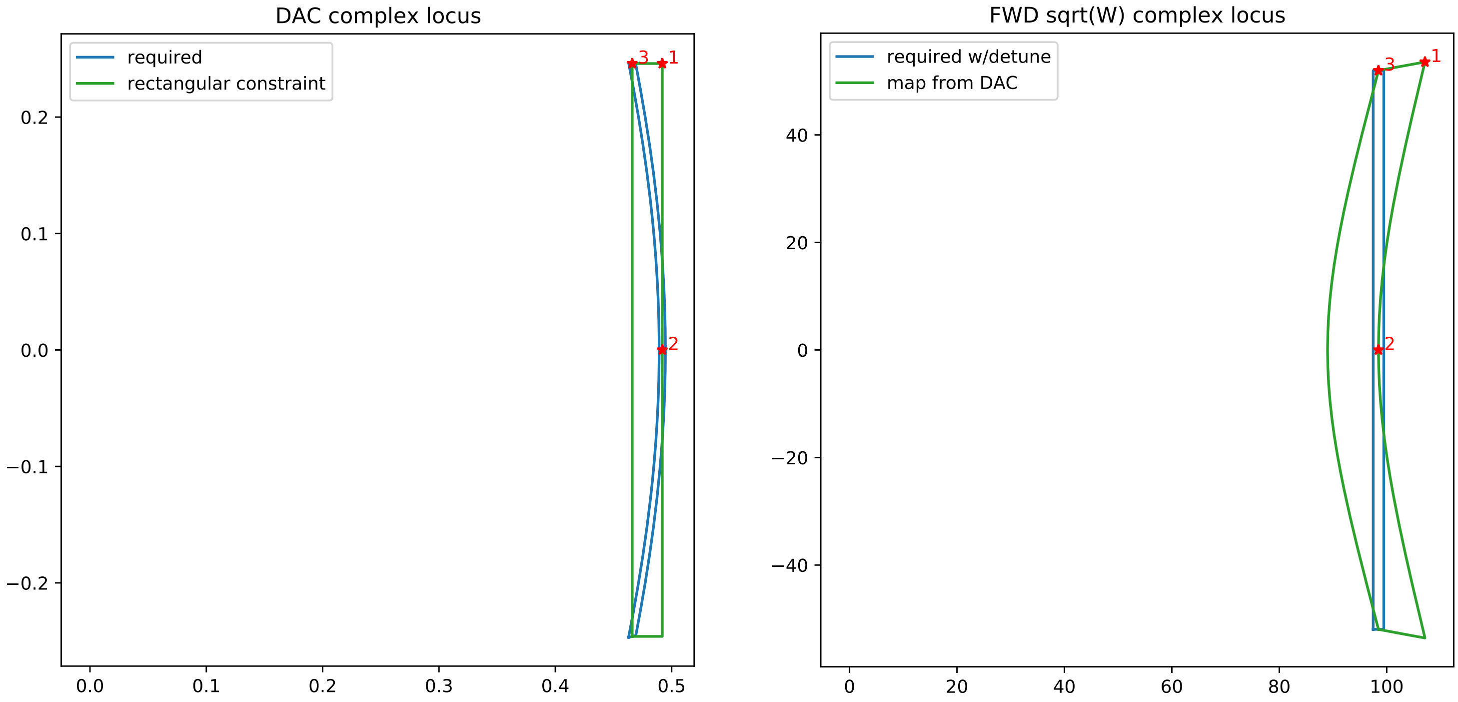
Straight line does not mean linear!
For the “L” in LTI to be satisfied, that straight line must go through zero.
The mathematician in me categorizes the measured relationship as approximately affine.

Some projects pre-distort the SSA drive signal in the DSP to compensate. That is not (yet) deployed in the LCLS-II/PIP-II builds. Supporting such a feature will require additional calibration and testing.

Non-ideal SSA

A large-signal nonlinear SSA messes with the orthogonal axis world-view of a Self Excited Loop. Software and/or hardware need to be adjusted to compensate.

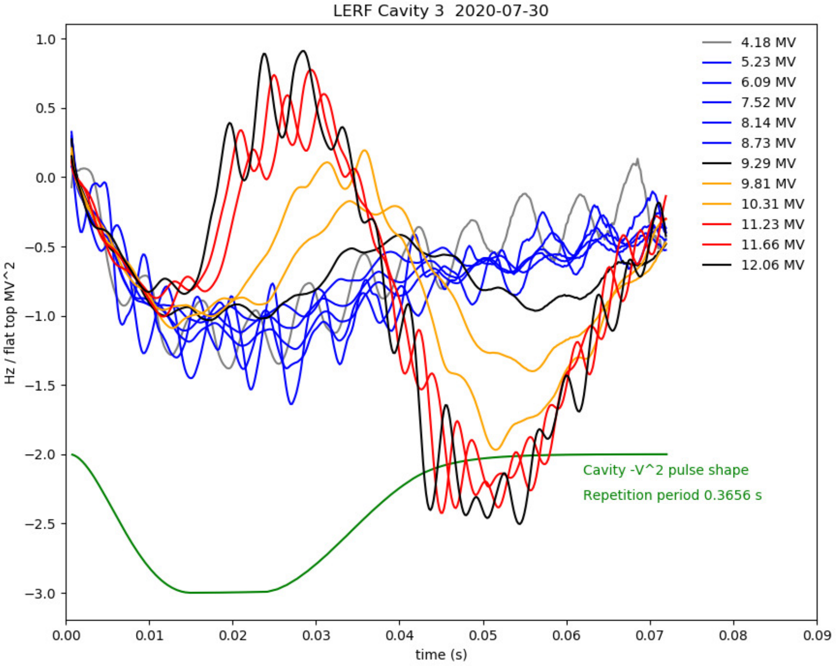
- Making changes is easy; full system testing takes facility time and effort.



Pulse mode

An aggressive pulsed-RF feature was tested at JLab LERF in 2020 for possible use with 4K cavities. The system showed limitations due to prompt helium boiling. The amplitude loop was kept closed during the ramp-up time; phase locking was not attempted.

PIP-II has ongoing interest in pulsing the RF to reduce 2K heat load. Conceptually doable, and could build on the code developed for the 2020 tests, but would require further development and testing.



Summary

- Theory and a history of experiments (including PIP2IT) have shown how SRF cavity control is supposed to work
- Existing LCLS-II experience directly applies to PIP-II, despite small (on a log scale) differences in frequency, bandwidth, shunt impedance, and Lorentz detuning coefficient
- Other talks will explain the actual work to be done, filling in gaps, porting across platforms, verifying results, etc.

"Testing leads to failure, and failure leads to understanding." – Burt Rutan

"You have testing time, you make progress;
you don't have testing time, you don't make progress." – Yuriy Pischalnikov

THANK YOU!