A prototype microwave cavity control circuit for use in next generation free electron laser

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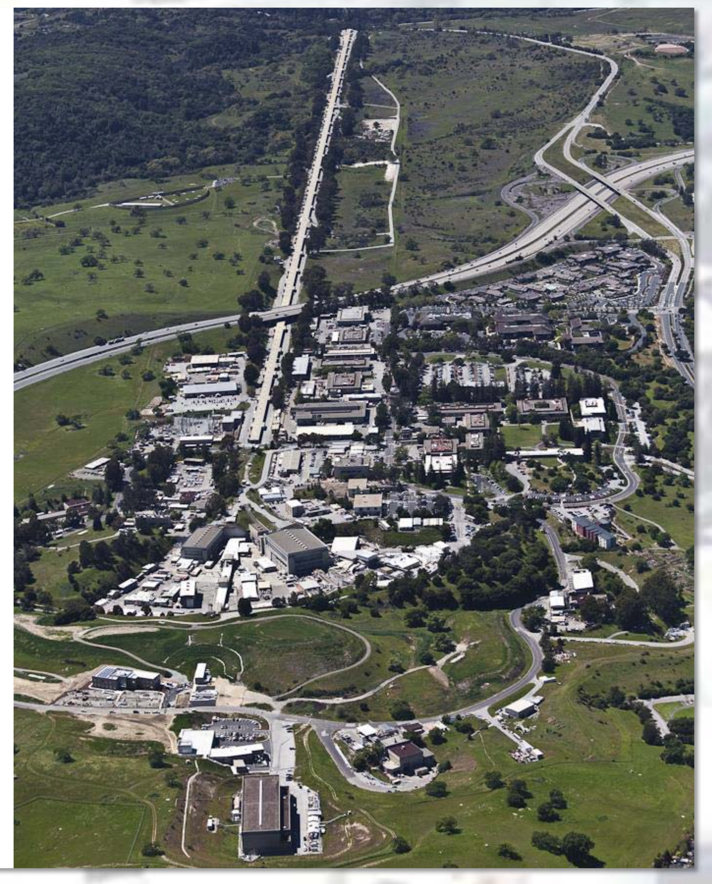
Abstract

Plans for the LCLS-II upgrade at SLAC require a control circuit to monitor and control the inherent instabilities of the new superconducting materials needed for the linear accelerator's replacement cavities. To prove that such a system can even function with the high performance and low latency requirements, an electronic cavity model is built and characterized with similar properties to test the feasibility of such a control system.

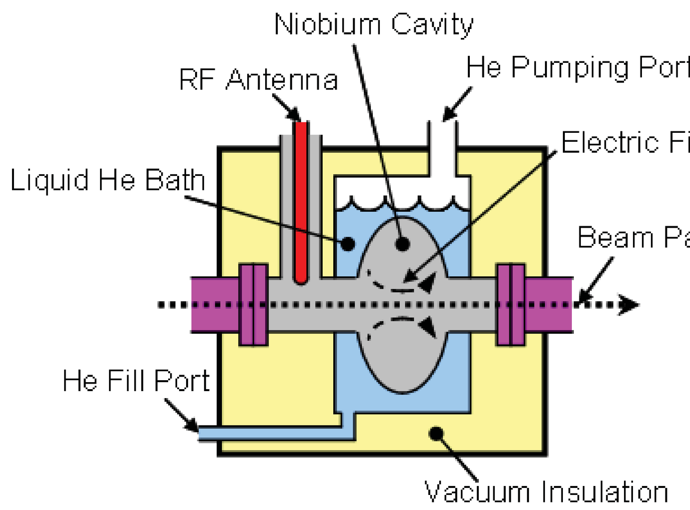
What is SLAC and LCLS?

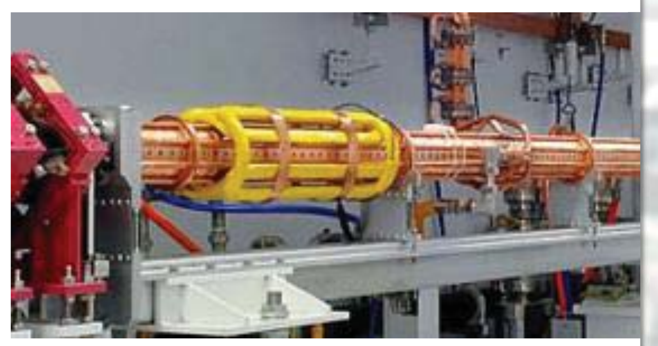
- SLAC was built in 1962 to examine high energy physics with the largest linear accelerator ("linac") in the world.
- While the whole linac is not dedicated for high energy physics anymore, portions of its 3-kilometer length are now used for other branches of science.
- One program, the Linac Coherent Light Source (LCLS) uses a Free Electron Laser (FEL) to emit the most intense, coherent X-rays possible to examine structures and processes at the ultrafast molecular scale.



Right: Aerial view of SLAC looking west toward linac and Highway 280. LCLS-I & II will use the ending (in this picture, closest) 2/3 of the linac.

Transitioning to LCLS-II: Superconductor Microwave Cavities

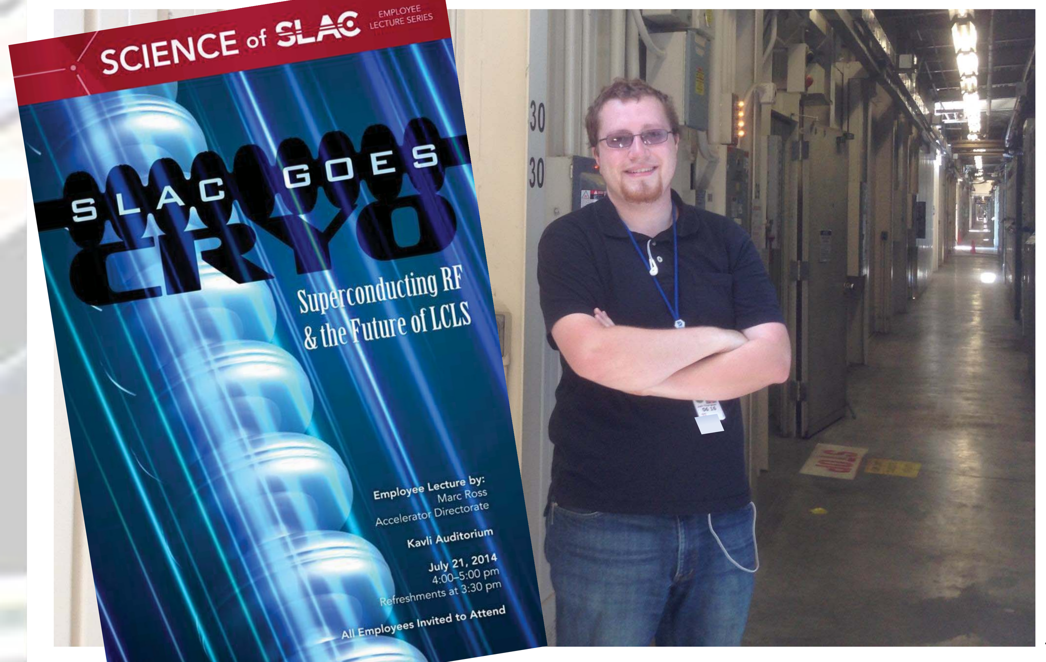




Left: A schematic of how a superconducting cavity works. Notice the demand for liquid-He to maintain superconducting state. Center: An example of several of these cavities made as a tube of 9. Right: Current Cu cavity design used at SLAC, which are limited by their resonant properties. This makes for slow pulse rates and are expensive to run.

To gain higher pulse rate & general performance, a linac upgrade (LCLS-II) plans to replace current Copper cavities with superconducting Niobium . While Nb is superior to Cu, Nb has many challenges, including cryogenic needs and slim, erratic bandwidths. This summer, we try to answer if we can control these instabilities (see control circuit at right).

Results of Proof of Concept



While the FPGA algorithm was incomplete at the end of the summer, all other steps functioned as required for accurate sims.

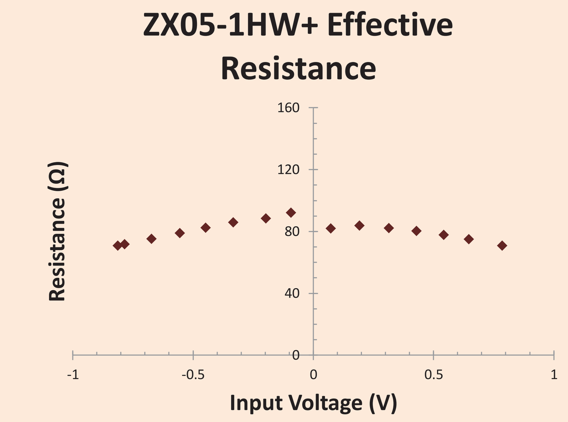
For future research, more variables can be added to our pseudo-cavity model (namely non-linear resonance) once the FPGA is ready. After this, our design can be used as a proof of concept for future LCLS-II designs.

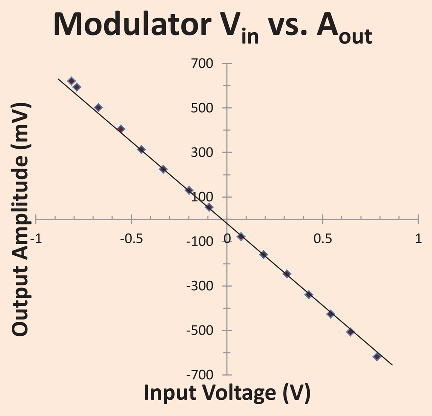
Foreground: Flyer for SLAC talk of LCLS-II upgrade. Background: Author J. Thompson in the klystron gallery of the SLAC linac.

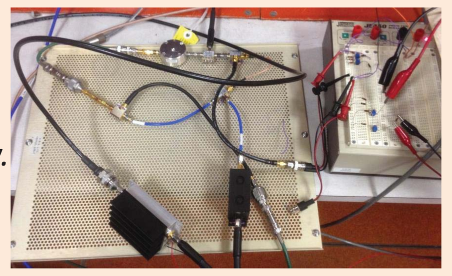
1) I/Q Modulator

The role of the I/Q (or "In-phase and Quadrature") modulator is to take a beginning signal near or at the pseudo-cavity's resonant frequency of 476 MHz and split it into two components, 90° out of phase with each other.

If a drift in frequency or power is detected in Step 4, these I and Q components can be tweaked by the modulators so the signal arriving to the cavity is always within the extremely slim bandwidth of the Nb.





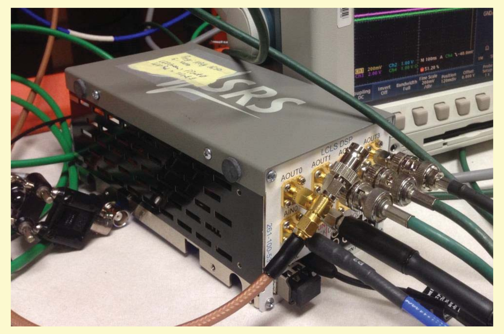


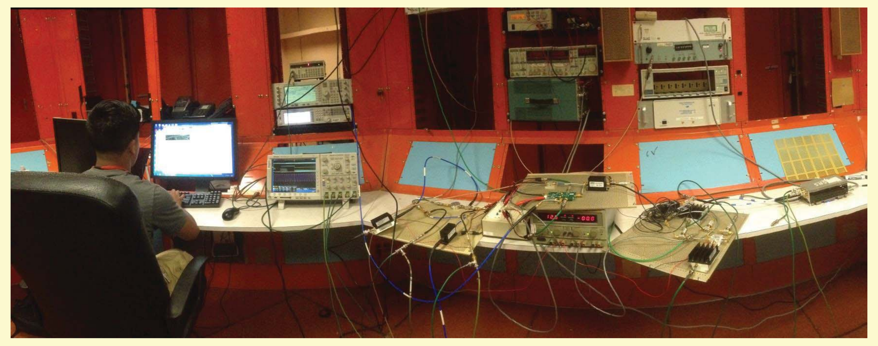
Top: Study of effective resistance generated by modulators. Center: Modulator linearity study. Bottom: Built final component.

4) FPGA Feedback Loop

The three outputs from Step 3 are then fed to a Field Programmable Gate Array (FPGA). This unit has the ability to interpret each incoming 1 MHz signal with low latency.

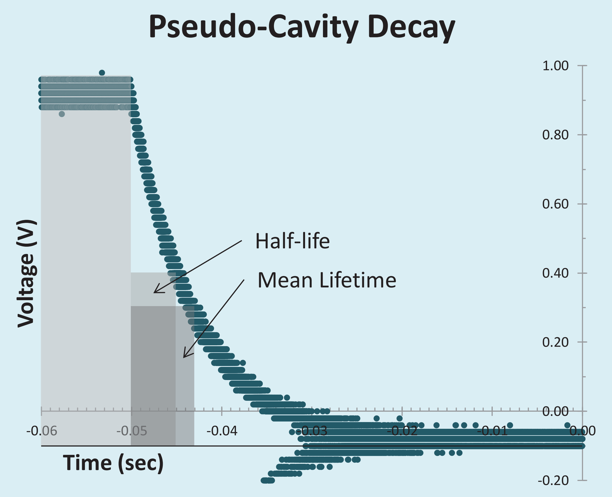
Comparing how the Step 1 and 2 differ from the reference tells the FPGA what corrections are needed for Step 1. If all components are tuned correctly, the FPGA can modulate the beginning signal into any required waveform, keeping the cavity locked at peak resonance.

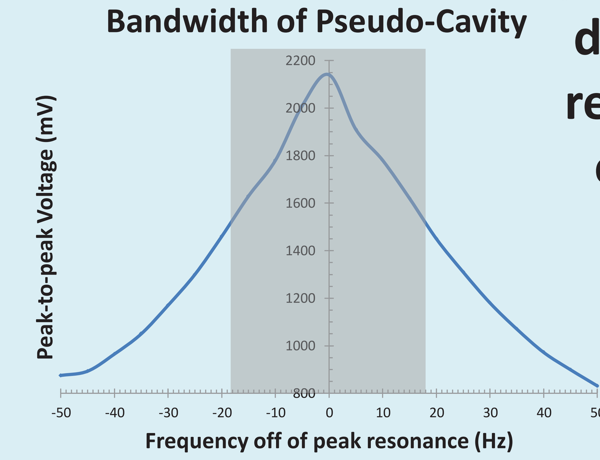




Right: Built FPGA, or "Step 4." Algorithm still in beta at end of summer. Bottom: Steps 1-4 connected together and running.

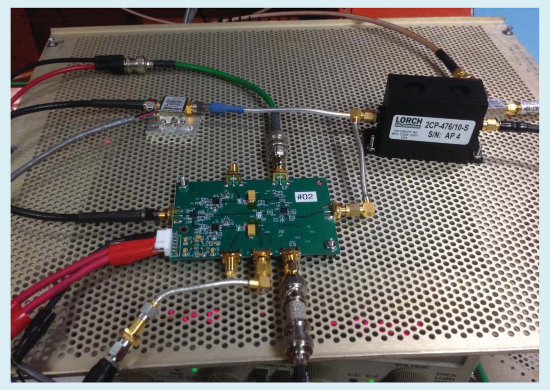
2) Pseudo-Cavity



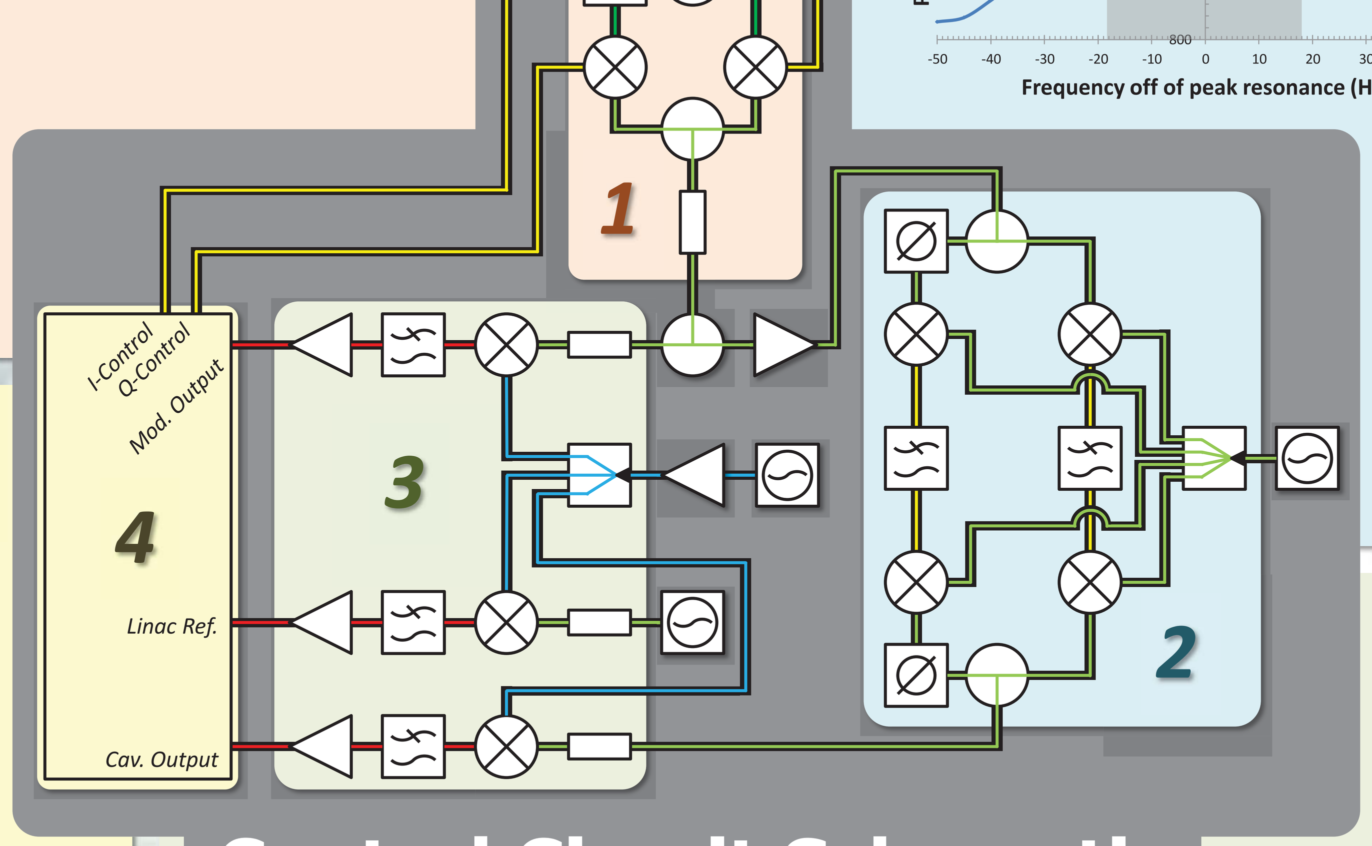


Since both the actual cavities and their control machinery are not yet made, a circuit board was built with similar electronic properties to a real superconducting cavity.

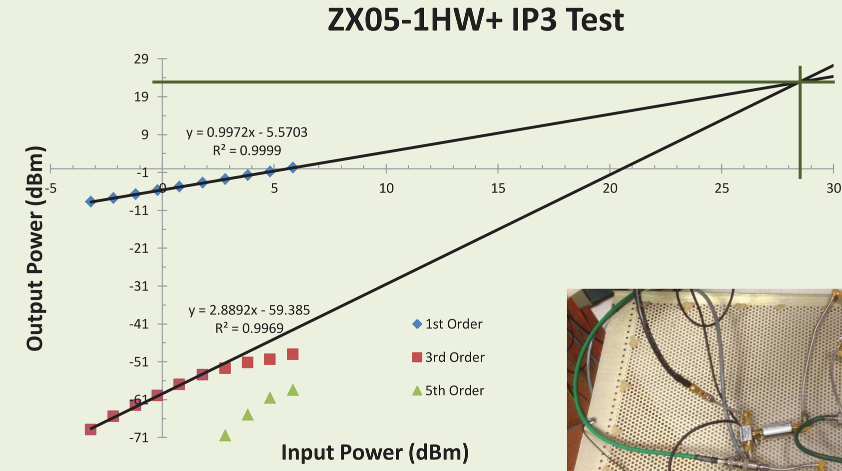
It is very important to characterize this pseudo-cavity as much as possible, since any inaccuracies or disagreement between it and the real cavity design could invalidate our tests and conclusions of our control circuit's performance.

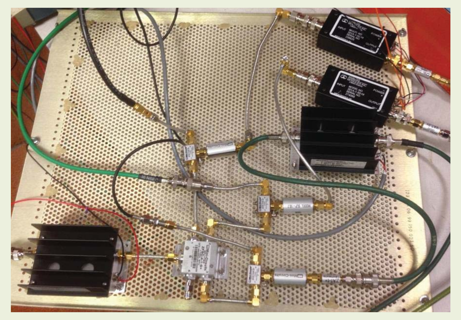


Top: Decay time of cavity, to observe "ringing." Center: Observed pseudo-cavity bandwidth, around 36 Hz . Bottom: Built final component.



Control Circuit Schematic





Top: IP3 (Third-order Intercept Point) test for used mixers. This linearity is most important for the downmixer. Right: Built final component.

3) Downmixer and Filtering

The distorted output of Step 2 is then "mixed" with a reliable 475 MHz local oscillator. This process is also done to a split Step 1 signal and a stable 476 MHz reference. This achieves two things:

1. The RF mixing and low pass filtering reduces each signal to around 1 MHz, making later analysis possible.
2. The Step 1 and 2 outputs can both be compared to the reference, monitoring how either have drifted over time.

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