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Measurements of the PXIE RFQ: LLRF system and resonant frequency transients

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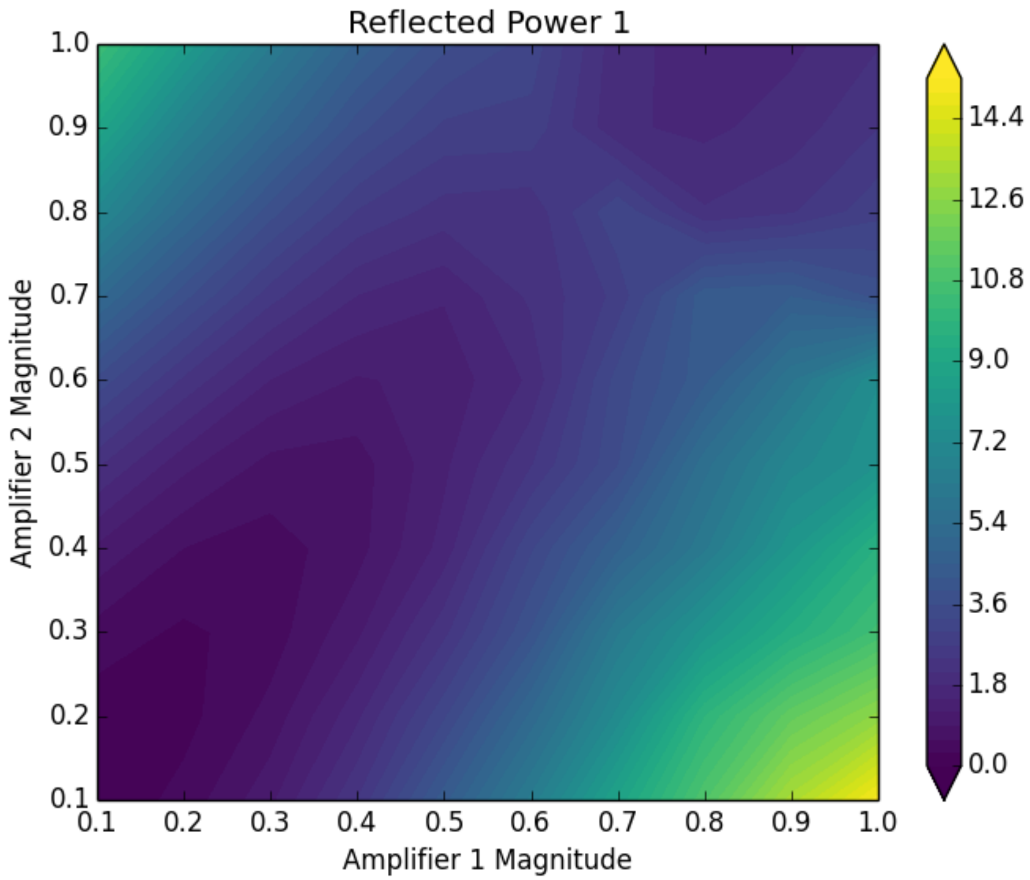
Things to note…

- Data presented in this talk are only a small subset of the total effort
- We collected data on both the LLRF system and the water cooling system over about a month of testing consisting of upwards of 15 shifts with help from many people
  - Brian, Jim, Daniel, Philip, Ed, Auralee, Sunny, Lionel, Bruce, Ralph, Dave, and I am probably missing someone
- These data allowed us to answer some key questions about the machine but there is still much more work to be done

LLRF system

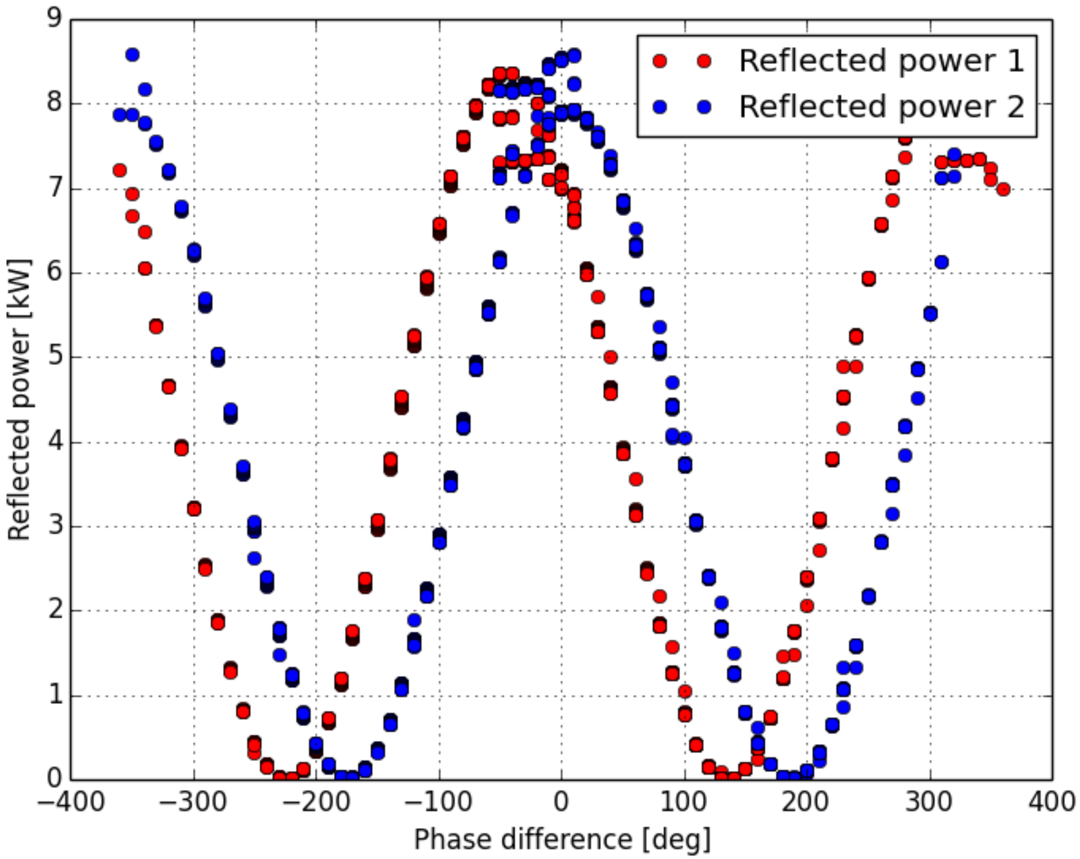
- Amplifier amplitude scans
- Amplifier phase scans
- Temperature effects in the amplifiers
- Forward power trips
- Optimization for a short pulse with a clean turn on
- Initial beam compensation performance

RF Amplifier studies (amplitude scans)



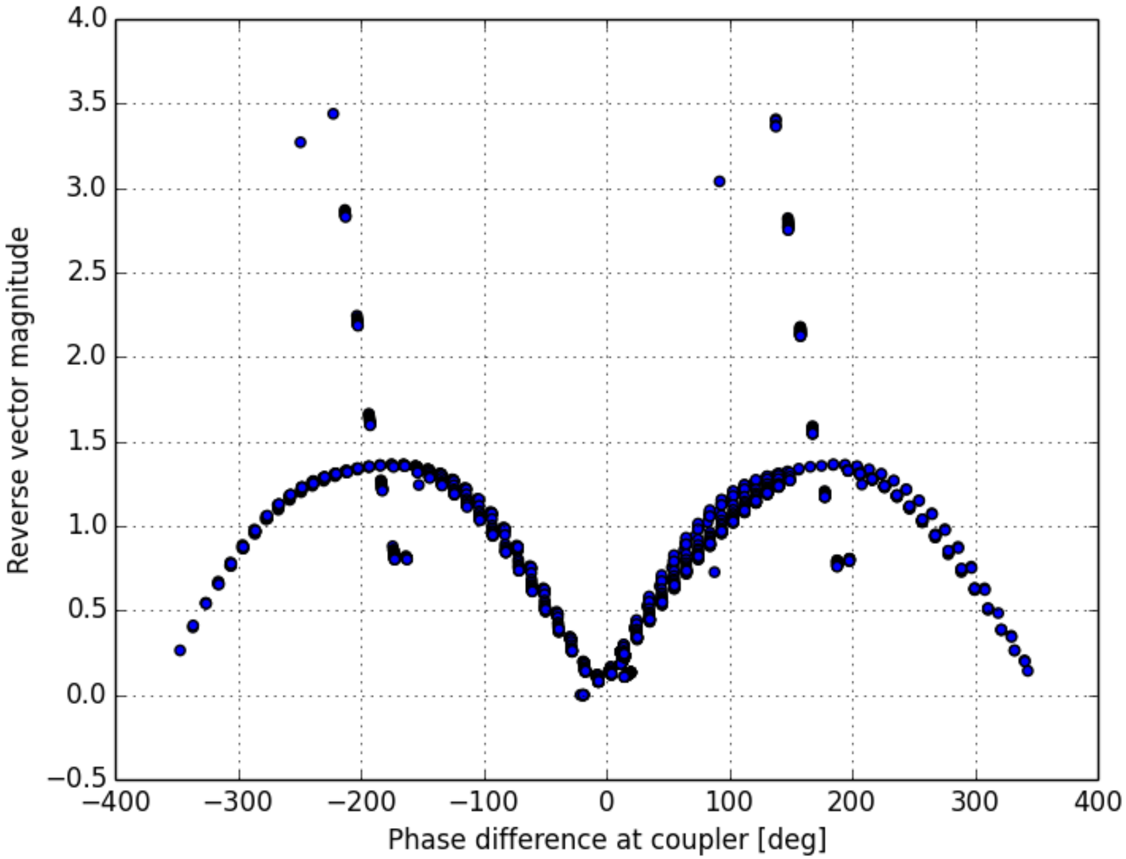
- Reflected power [kW] in the right amplifier as a function of the two amplifier up-converter gain adjustments
- Matched gains would make this plot symmetric

RF Amplifier studies (phase scans)



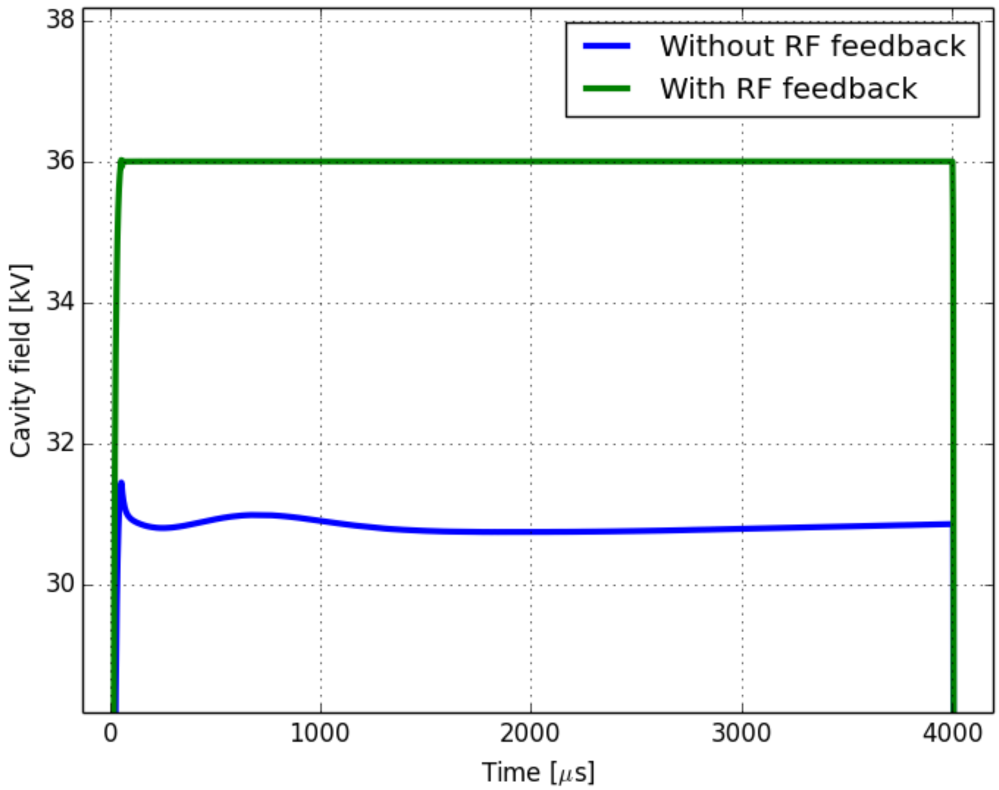
- Reflected power in the two amplifier circulators as a function of the phase difference at the up-converters
- The optimum operating point may send some reflected power to both circulators
- A phase difference at the up-converter will compensate for mismatched RF transport lines

RF Amplifier studies (phase scans)



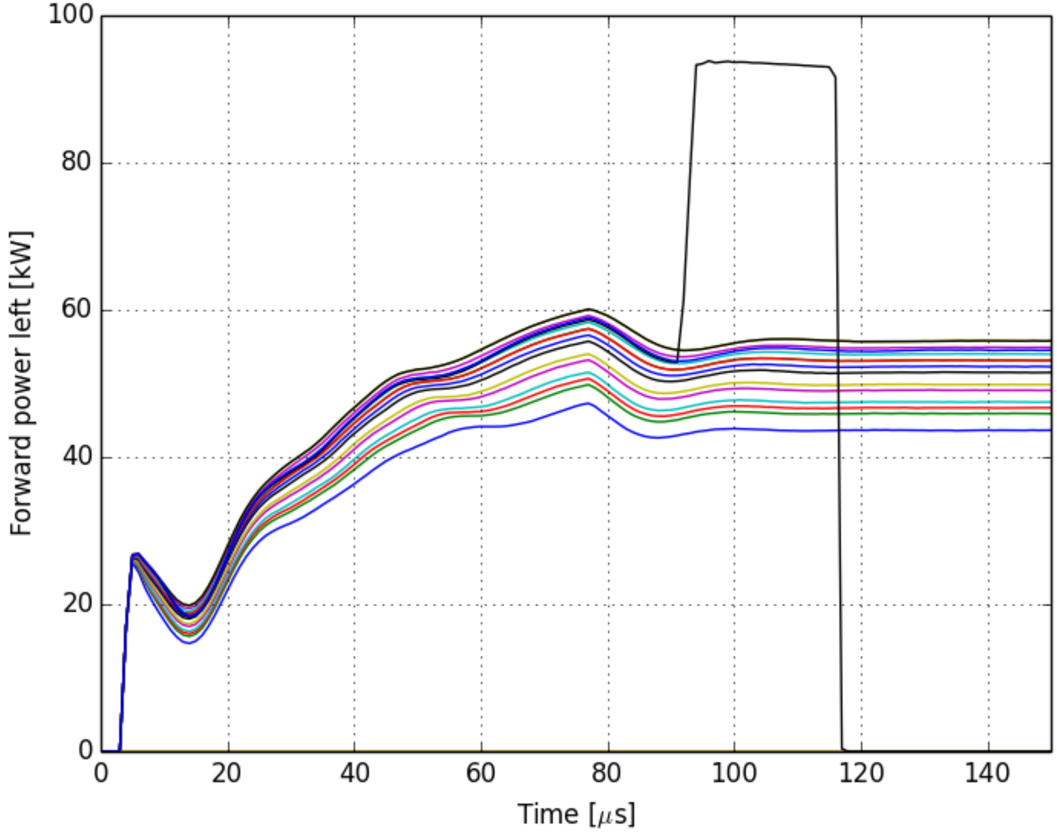
- Reverse vector magnitude as a function of the amplifier phase difference at the coupler.
- This verifies sum mode for maximum coupling into the RFQ

Amplifier characterization



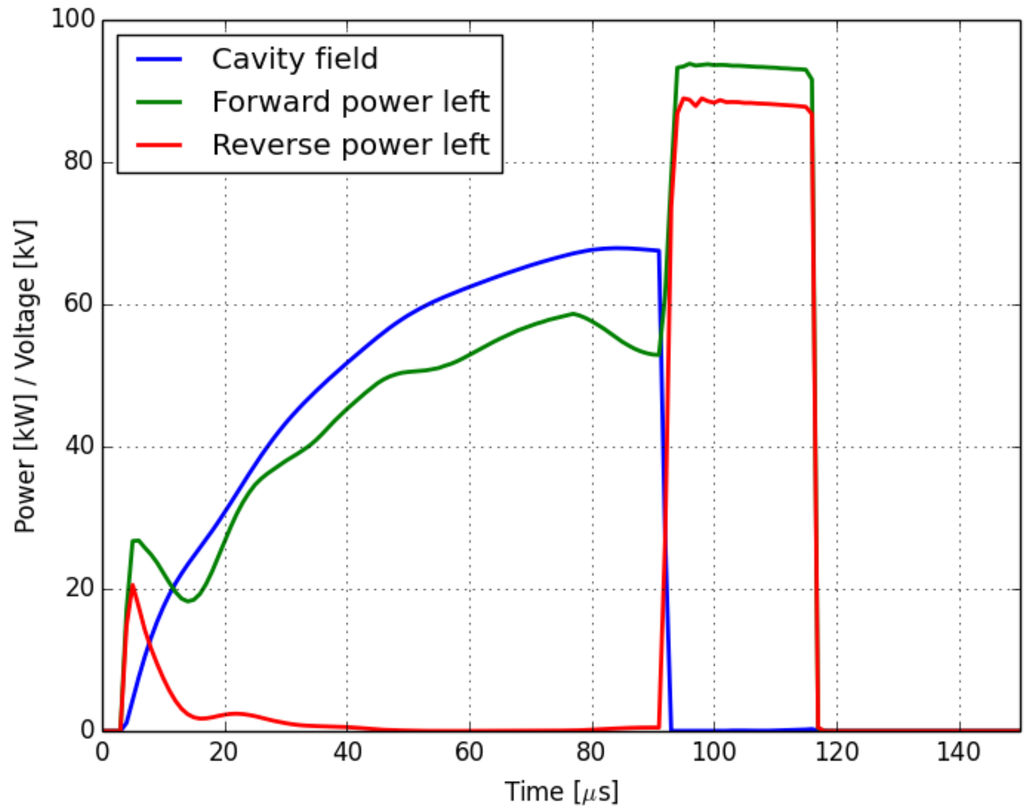
- Representative picture of the amplifier response in open loop

Forward power trips



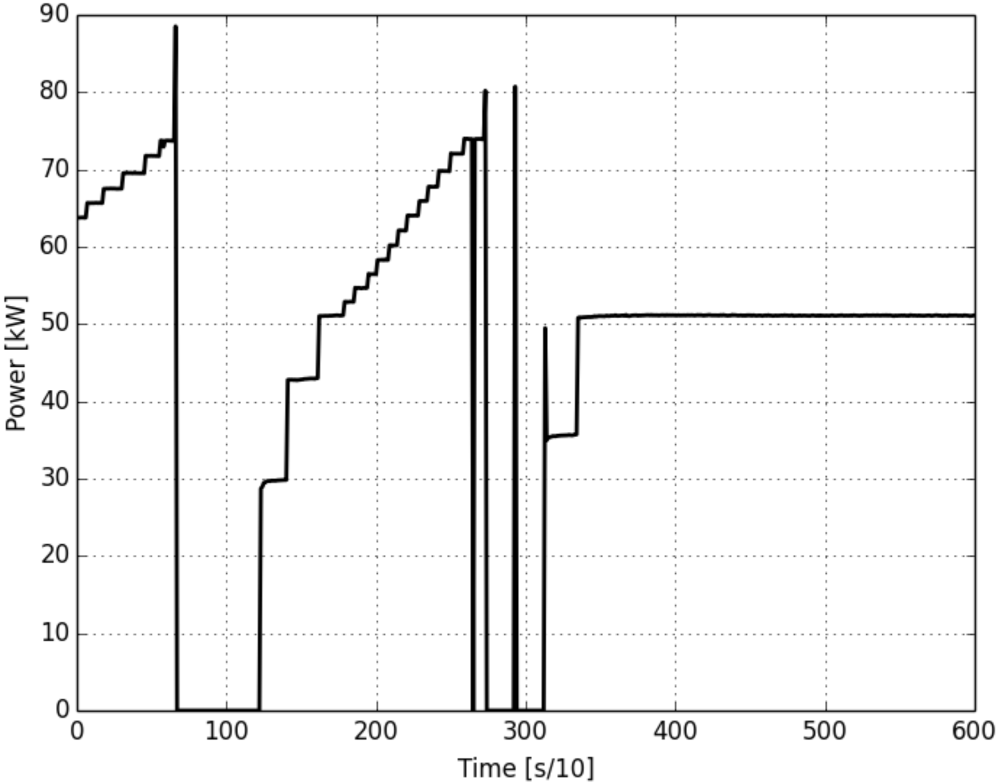
- Forward power as a function of time as we ramped up the set-point
- Here we see a spike in forward power that caused a trip
- See next slide

Forward power trips



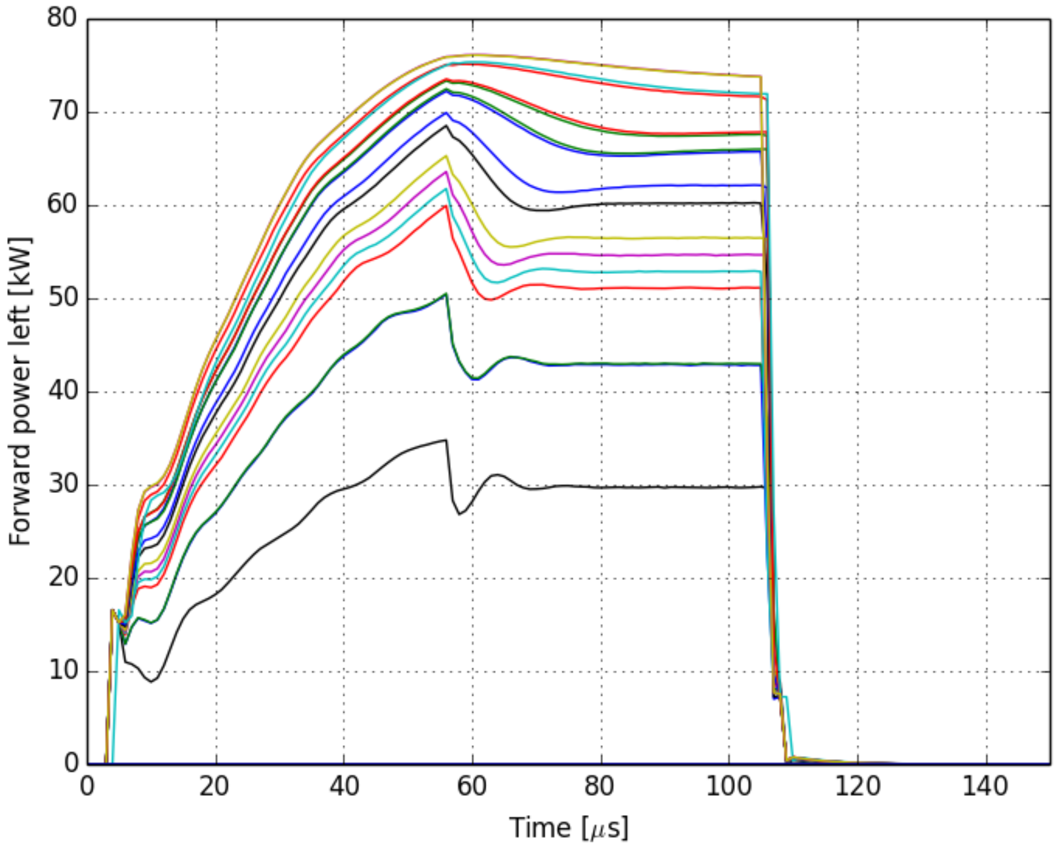
- The spike in forward power is brought on by a drop in the cavity field
- This particular spike triggered the fast interlock but it is clear that feedback is over driving the amplifier
- Plan to adjust our maximum forward power so we cannot trip the amplifiers

Forward power trips



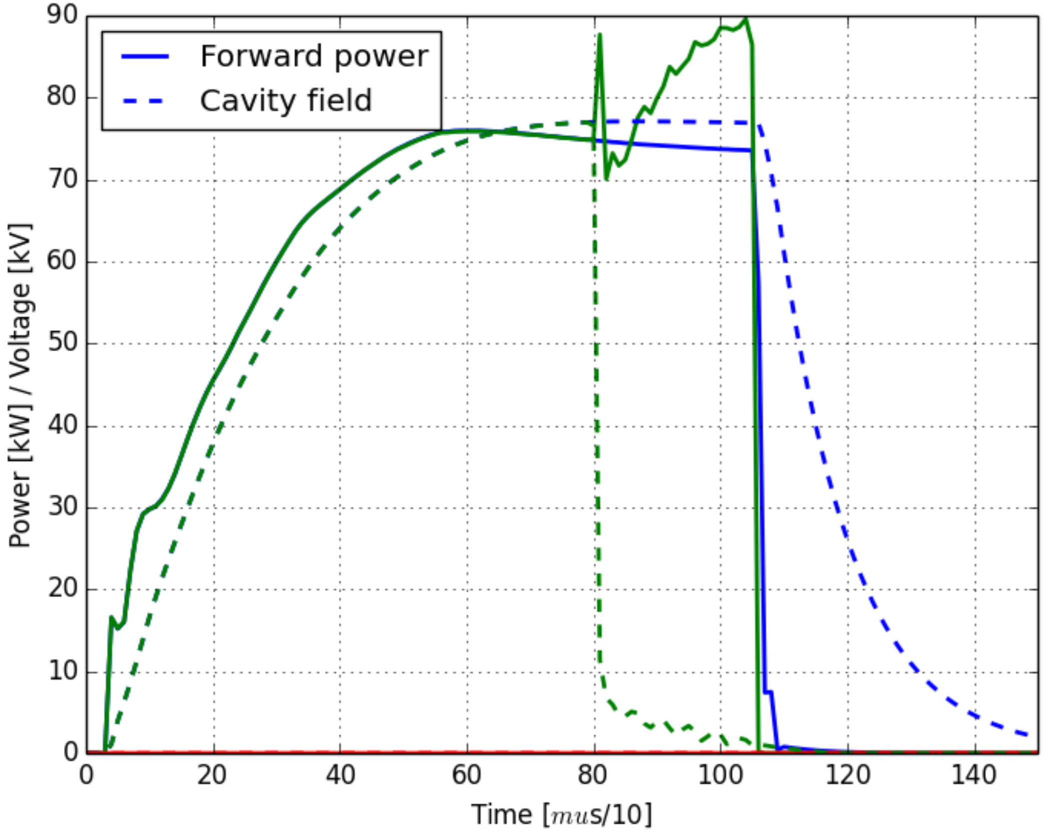
- Forward power at the end of the flat top as a function of time during a test looking for forward power trips

Forward power trips



- Forward power as a function of time as we ramped up the set-point
- Here we see the amplifiers saturate before we trip on forward power

Forward power trips

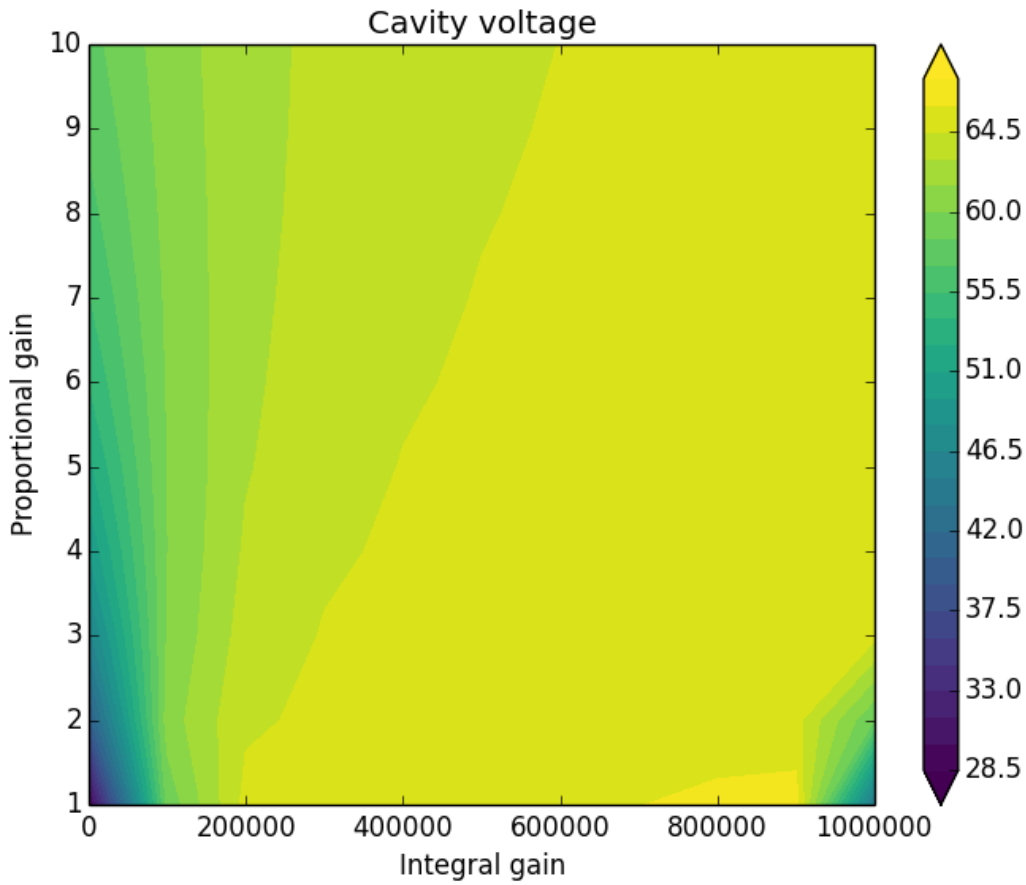


- Observation of a forward power trip
- Blue is the pulse before the trip, green is the pulse that caused the trip, and red is after the trip

Summary of amplifier control

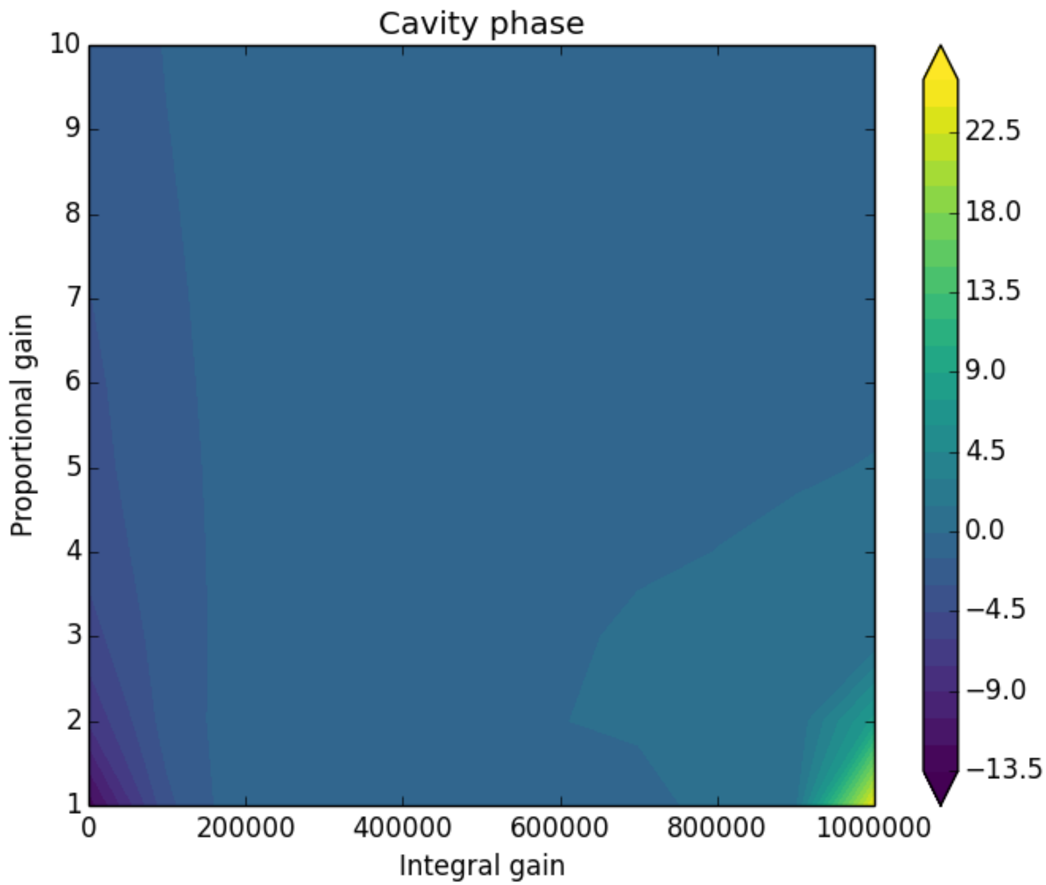
- Mismatch in the amplifier delays is compensated at the LLRF up-converters with a phase shift
- Mismatch in the amplifier gains is compensated at the LLRF up-converters with an amplitude scaling
- Phase difference at the coupler for minimum reflection is zero for sum mode as expected
- We intend to implement slow feedback on the up-converter phase and amplitude to account for temperature drift
- Forward power trips seem to be under control since firmware changes.

Optimization for a short pulse



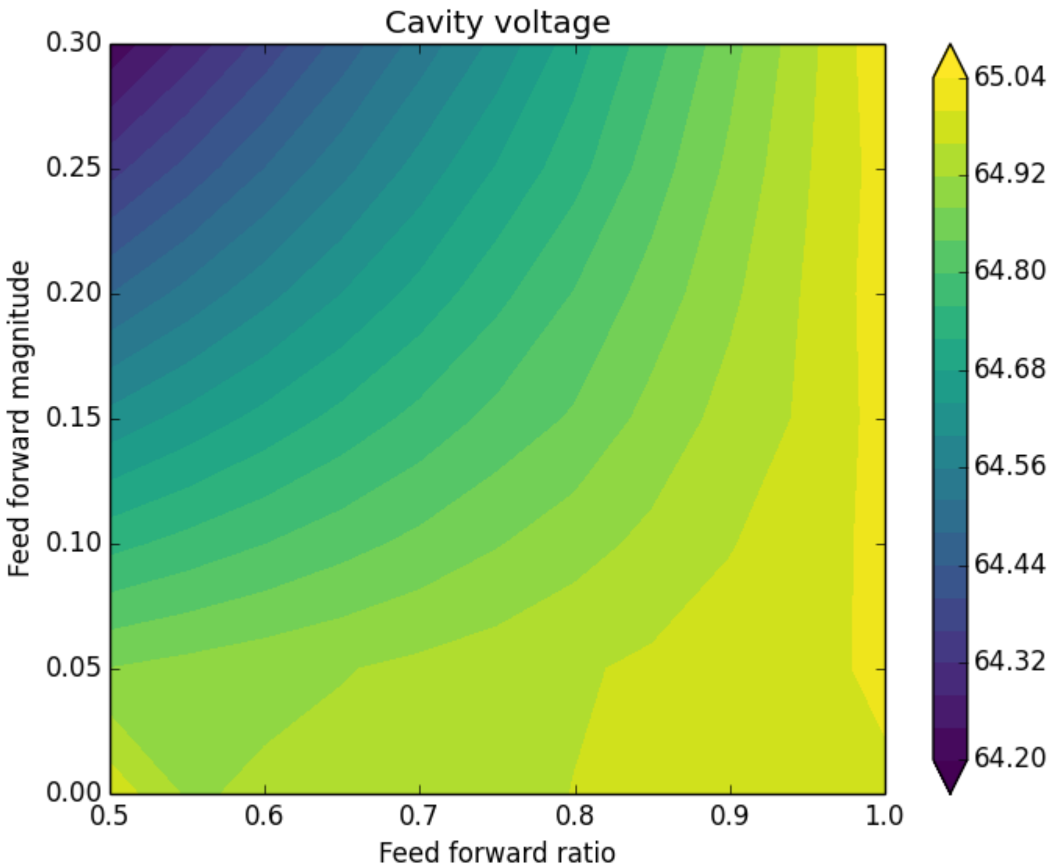
- Cavity voltage at flat top as a function of the proportional and integral gains
- Optimal gain region is shown in yellow
- Note there is no beam disturbance in this scan

Optimization for a short pulse



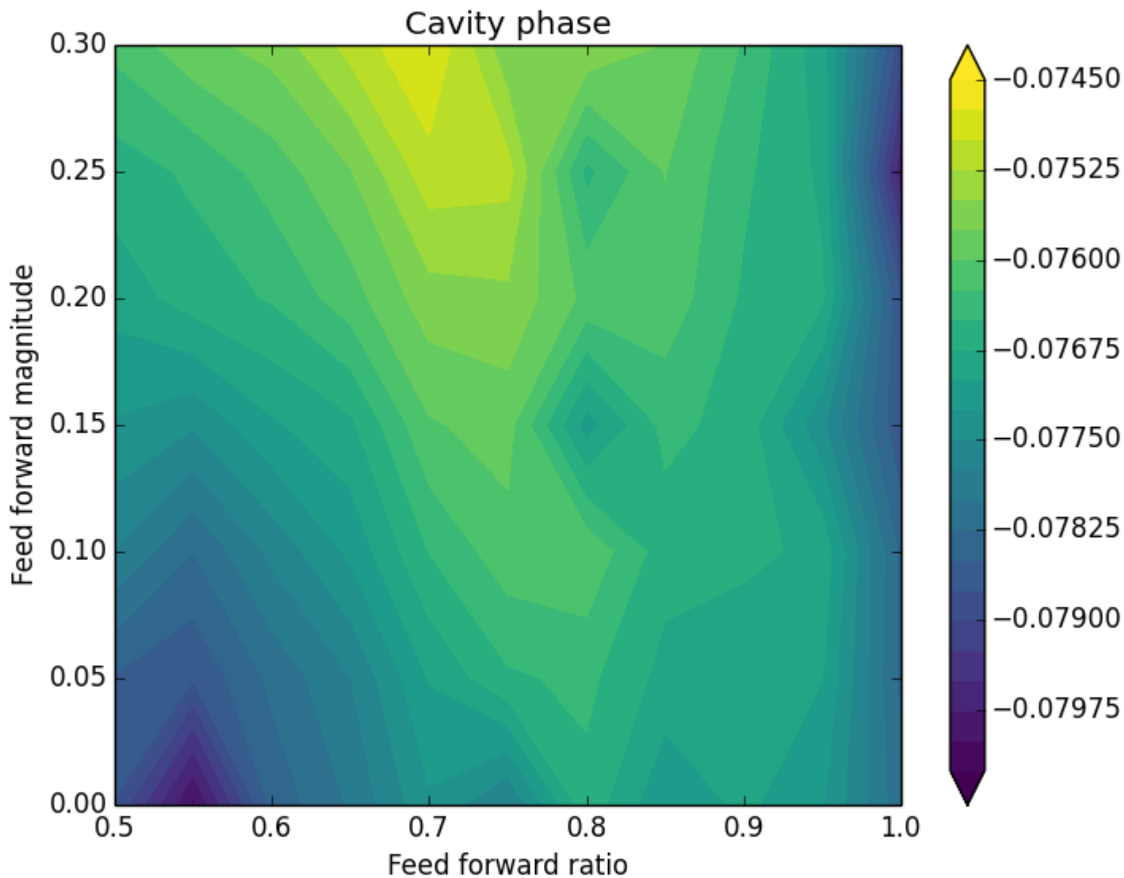
- Cavity phase at flat top as a function of the proportional and integral gains
- The target is zero phase
- Note there is no beam disturbance in this scan

Optimization for a short pulse



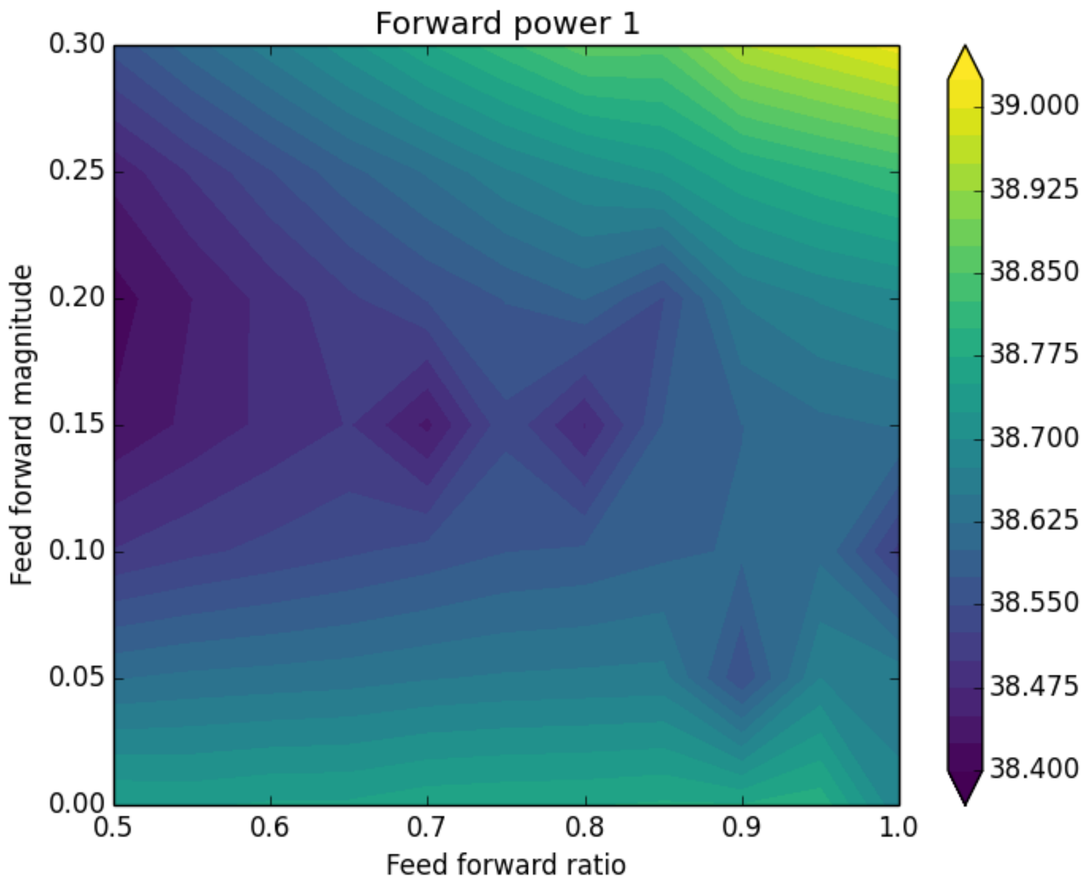
- Cavity voltage as a function of the feed forward magnitude and the feed forward ratio
- Adding some feed-forward can help to reduce the error
- These parameters help to ensure a smooth turn on as will be shown a little later

Optimization for a short pulse



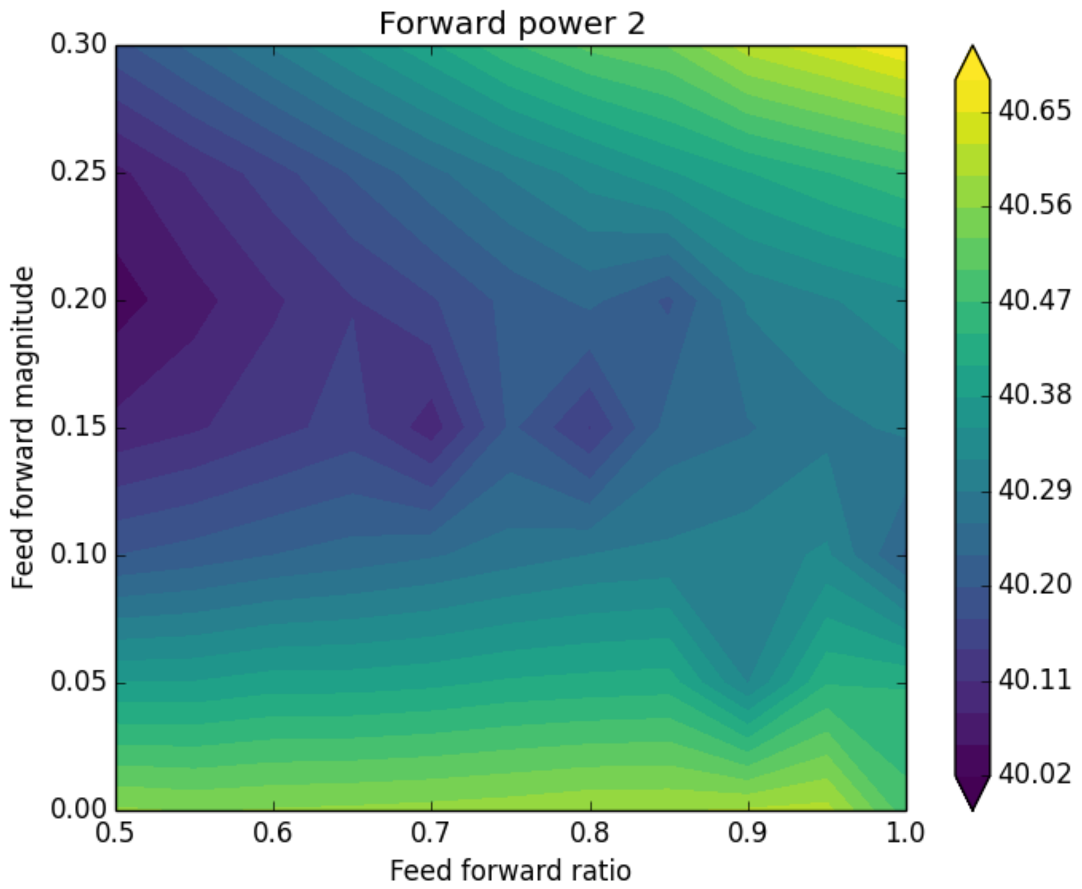
- Cavity phase as a function of the feed forward magnitude and the feed forward ratio.
- There is little to no effect on the cavity phase due to the changes in the feed-forward magnitude. This is intuitive and expected
- These parameters help to ensure a smooth turn on as will be shown a little later

Optimization for a short pulse



- Forward power from the right amplifier during turn on as a function of the feed forward magnitude and feed forward ratio
- This is an averaged parameter and therefore dominated by the LLRF system trying to get to full field
- Turn on is smoothest for a feed forward amplitude of about 0.2 with a feed forward ratio between 0.5 and 0.8

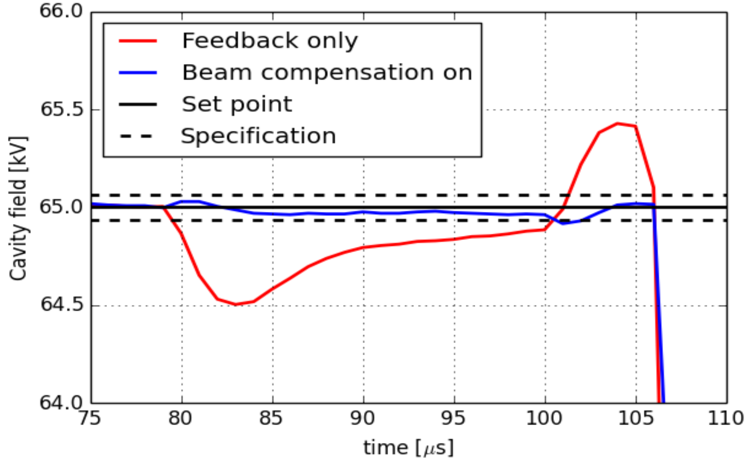
Optimization for a short pulse

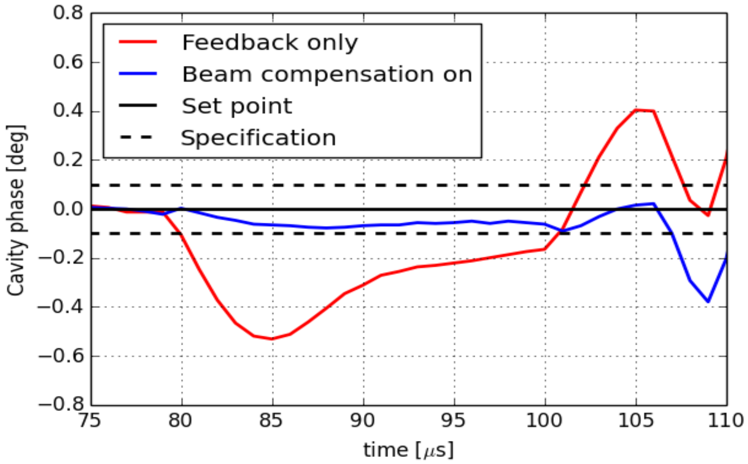


- Forward power from the left amplifier during turn on as a function of the feed forward magnitude and feed forward ratio
- This is an averaged parameter and therefore dominated by the LLRF system trying to get to full field
- Turn on is smoothest for a feed forward amplitude of about 0.2 with a feed forward ratio between 0.5 and 0.8

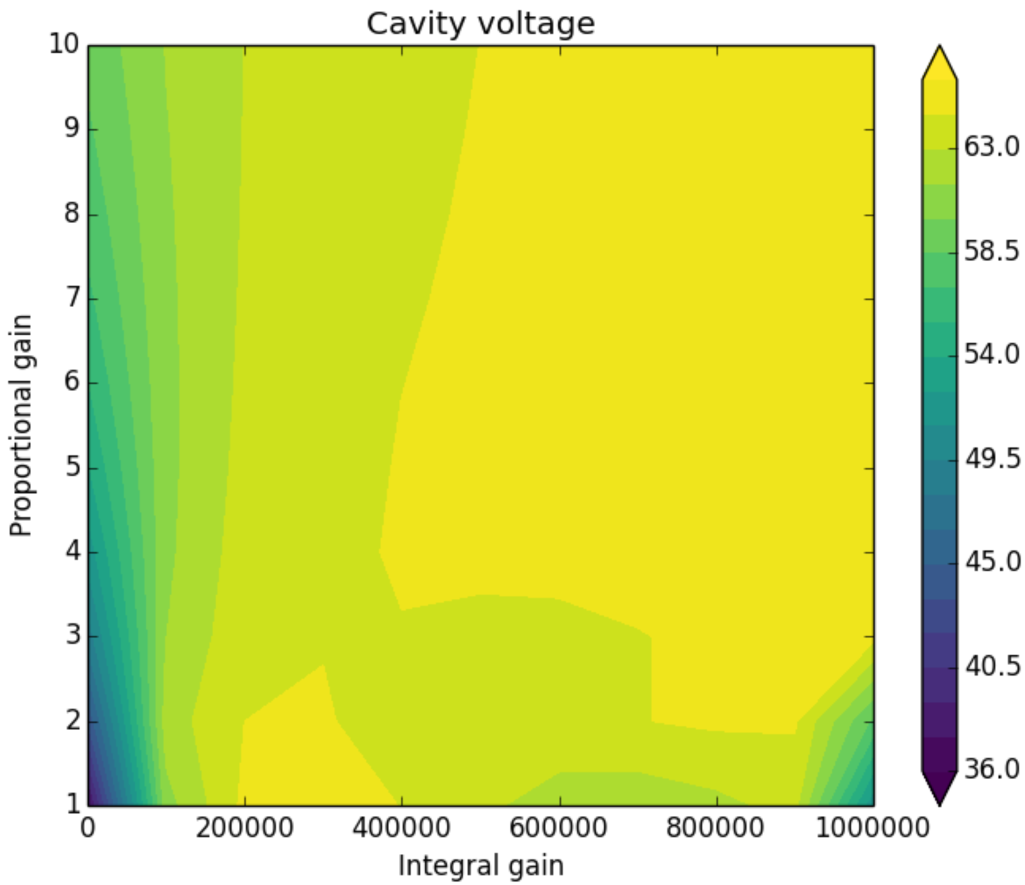
Feedback with a short pulse and beam loading

- Feed-back reduces the beam disturbance
- Feed-forward further improves the beam loading compensation
- We are still working on our adaptive feed-forward algorithm



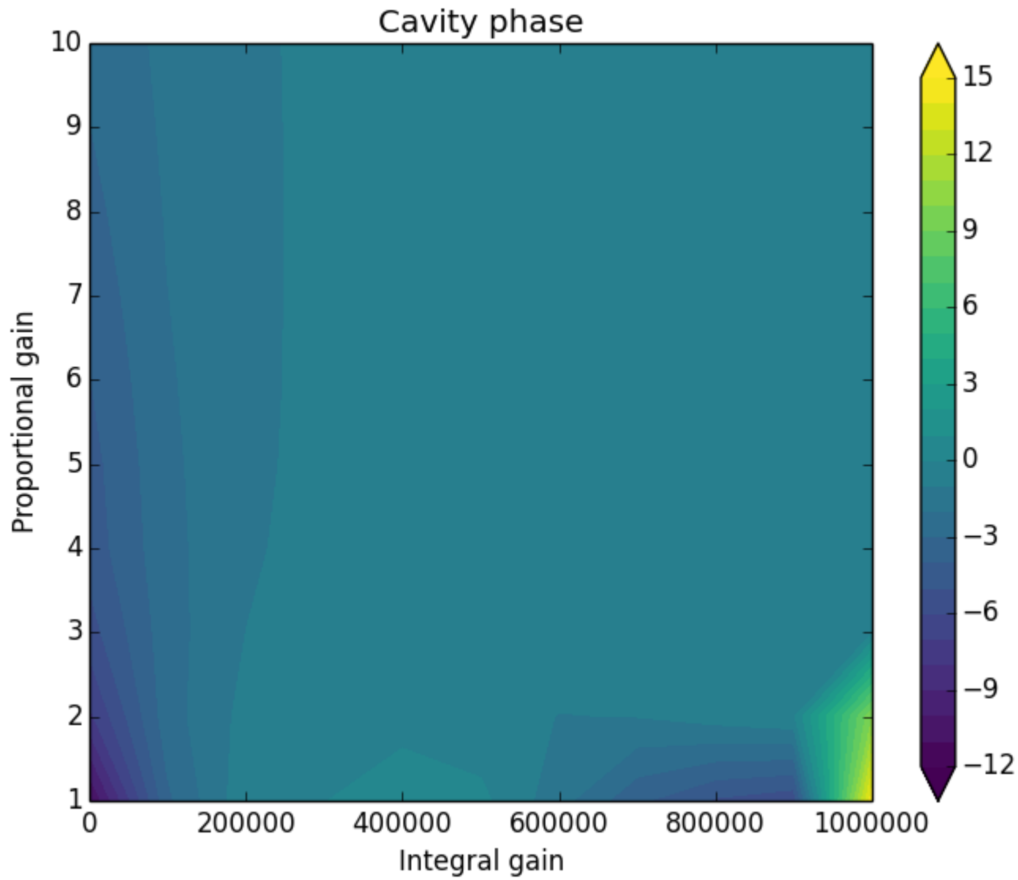


Feedback beam compensation (gain scans)



- Cavity voltage at flat top as a function of the proportional and integral gains with a the beam disturbance
- Optimal gain region is shown in yellow

Feedback beam compensation (gain scans)

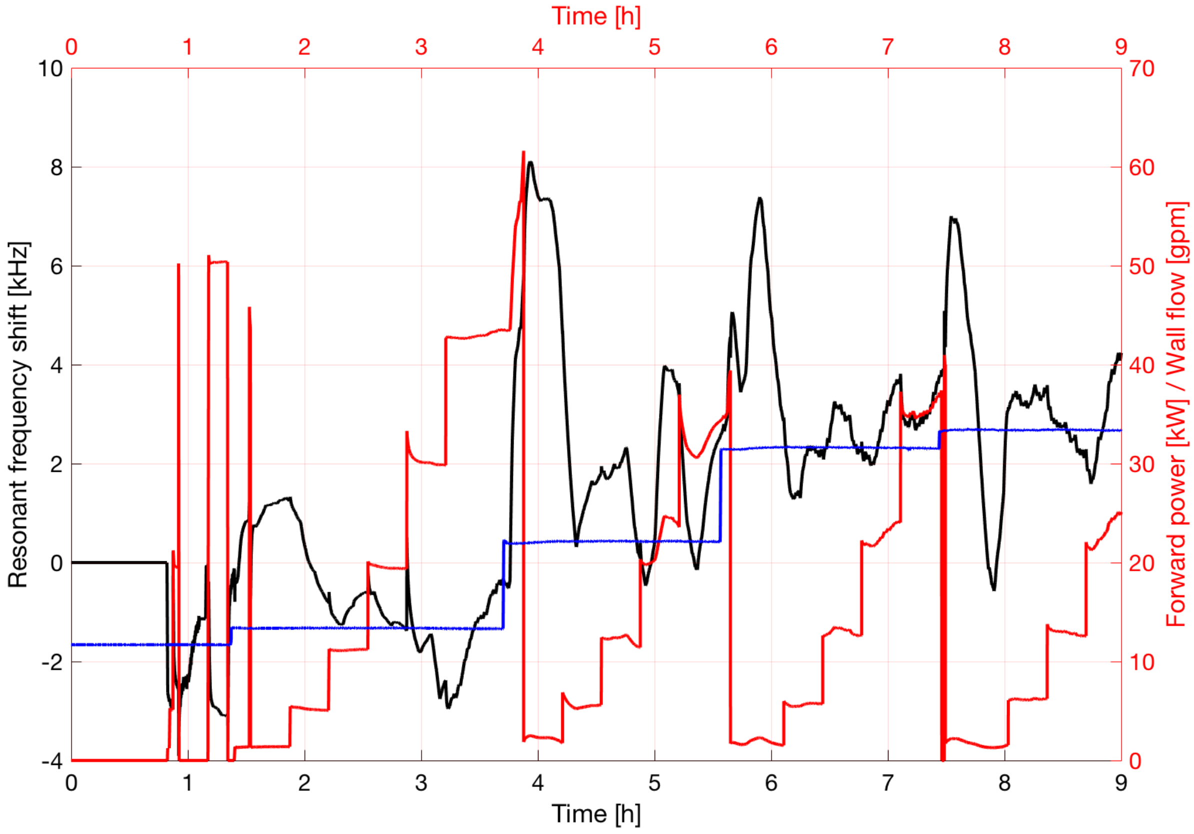


- Cavity phase at flat top as a function of the proportional and integral gains with a the beam disturbance
- Optimal gain region is shown in yellow

Temperature effects on the RFQ resonant frequency

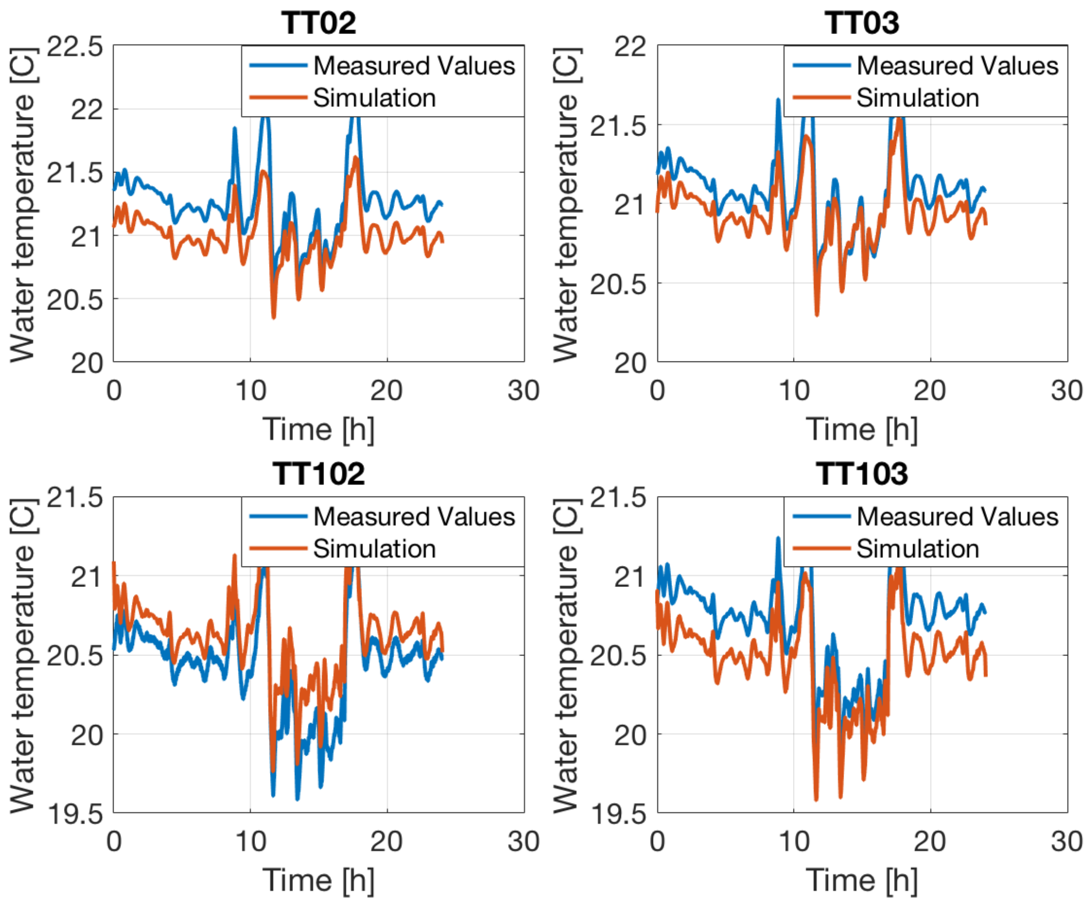
- Over several days of testing we measured transient frequency response in the RFQ due to changes in the water system and with changes in the RF heating
- Ongoing effort to compare these results with simulation
  - Continuing to refine the thermal model
  - Generally speaking the model is a very good representation of the system
  - Currently working on a manuscript describing the technique and showing performance
- These data will be used by Auralee to design a data-driven resonance controller for pulsed operation

Thermal studies



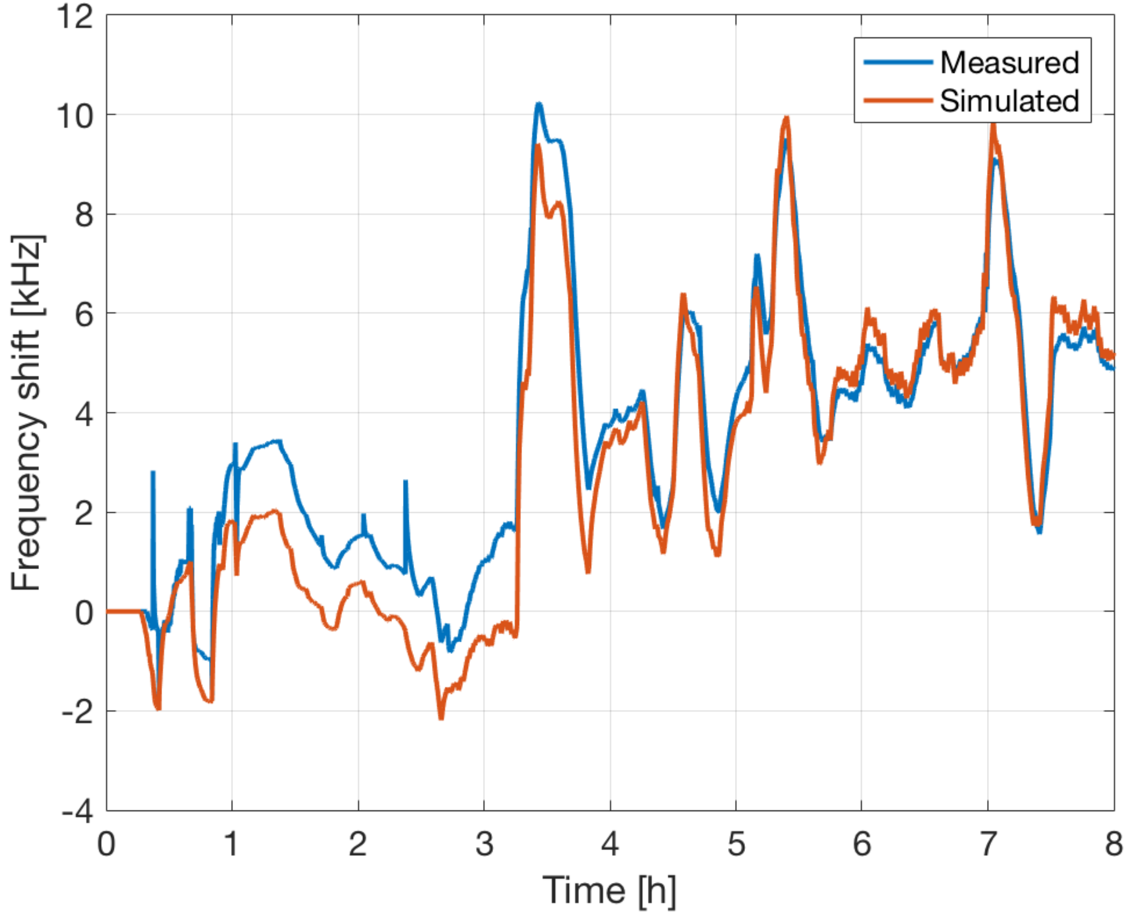
- Frequency shift as a function of time due to changes in the flow control valve and forward power
- Black is the frequency shift, red is the forward power, and blue is the wall chilled water flow

Thermal simulation using data collected during testing



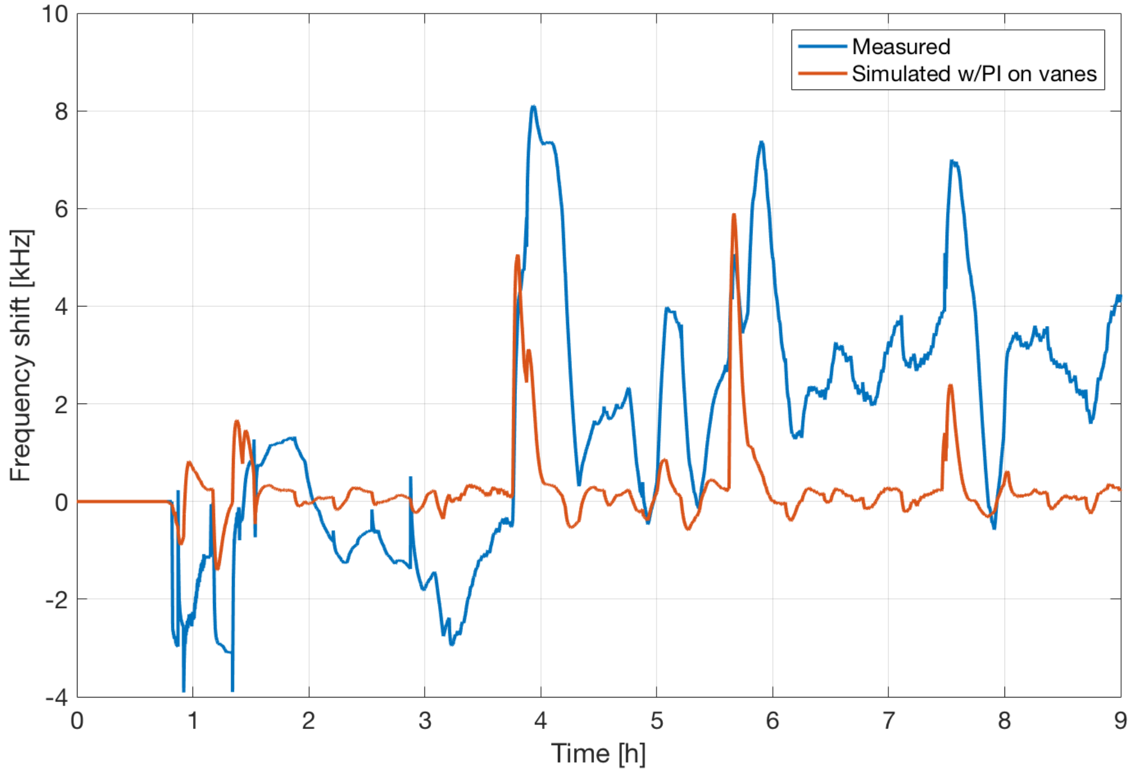
- Comparison of measurements and simulations for temperatures in the water system
- Vertical offset is likely due to slight errors in estimating the effective thermal mass of the vanes and/or walls

Frequency response simulation



- Comparison of measurement and simulation for frequency shifts throughout the test
- Vertical offset is likely due to slight errors in estimating the effective thermal mass of the vanes and/or walls

PI control simulation



- Simulation of PI control on the vanes using data gathered during thermal testing
- Spikes in resonant frequency occur when the wall valve changes

Summary

- Established stable operating points for the RFQ LLRF with a short pulse
- Investigate the conditions that cause LLRF to over drive the amplifiers
- Optimized feedback and feed-forward to compensate for beam loading
- Characterized frequency shift due to perturbations in the water system and RF system
- Demonstrated a good comparison with simulation

Ongoing work / future work

- LLRF
  - Implement firmware changes as necessary (we have a revision on its way)
  - Finish studying and commissioning the adaptive beam compensation algorithm
    - Requires software changes and some study time
  - Reduce the LLRF max output to inhibit overdriving amplifiers during cavity spark
  - Improve frequency tracking algorithm needed for CW operation
- Resonance control
  - Finish manuscript on thermal modeling of the RFQ and water system
  - Design and implement data driven controller for pulsed mode operations
  - Resonance control for CW