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
• 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