RFQ Thermal Control Overview

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on behalf of the RFQ control group

March 31, 2015
Section 1: Introduction to RFQ control issues
During operation, water cooling will be the only way to control RFQ frequency.

3D model of one RFQ module, showing location of tuning plugs.

Temporary, adjustable plugs for field flatness studies.

Once plug position is optimized, plugs will be brazed into place.
During operation, water cooling will be the only way to control RFQ frequency.

RFQ is water-cooled: 4.1 L/s in vane circuits, 5.7 L/s in wall circuits. Blue arrows highlight locations of water channels.
RFQ frequency is sensitive to cooling water temperature variations.

- **Vanes**: -16.7 kHz/°C
- **Walls**: 13.9 kHz/°C

See next pages for illustration of transient response.
2D simulations give an indication of RFQ transient response.

ANSYS transient simulations. Power applied to RFQ (at room temp.) at $t = 0$. 
Goals of the thermal control group

1. With water group, sign off on water system layout

2. Design, implement control algorithms
   - Understand the control problems of other RFQs
   - Work with LLRF group

3. Provide control software and documentation
   - Members of the group include myself, Jim Steimel, Brian Chase, Curtis Baffes, and a contingent from CSU: Sandra Biedron, Stephen Milton, and students Auralee and Jonathan Edelen.
   - We’re working closely with Maurice Ball and Yurick Czajkowski.
Section 2: System Overview
PXIE water plan (from M. Ball, J. Liebfritz’s talk on 12/16/2014)
Note that there are additional break-outs for these closer to the RFQ.
RFQ water layout + locations of temperature sensors

- Cold supply
- Thermal connection through Cu
- Water after mixing
- Warm return
- Temperature sensor location

Diagram:
- Vane
- Wall
- M1
- M2
- M3
- M4
- FCV
- Helical mixer
- Filter
- Pump
- Delay
- Damping
RFQ water layout + locations of temperature sensors

- M1, M2, M3, M4
- Wall, Vane
- Pump, Filter
- Helical mixer
- FCV
- Delay
- 30°, 35°, 37°
RFQ water layout + line delays

See subsequent slides for determination of mixing point location.
- Thermal mass of vanes = $10^4$ J/K
- Thermal mass of walls = $1.2 \times 10^6$ J/K
- Thermal mass of water in vane circuit = $4.6 \times 10^5$ J/K
- Thermal mass of water in wall circuit = $8.4 \times 10^5$ J/K
- Coupling between vane & wall ≈ 0.7 kW/K
Section 3: Current work

- Incorporating control elements into Simulink model of water system.
- Using 2D and 3D RF simulations to probe sensitivities in model.
- Interviewing other labs to learn from their experiences with similar problems.
Mixer location gives us fastest “access” to water temperature at RFQ inlet, given practical constraints.
Simulink model of water temperature at RFQ inlet. RF trips off at 90 s and no other actions are taken. What is the system response? An informal goal here is that trip recovery should take no more than 10x the trip length.
Ongoing work

- Improved estimates of thermal coupling between walls, vanes
- Assessment of heat generated by pump
- Considerations for pulsed operation
- Heater to compensate changes in return H$_2$O temperature?
- Tours of other facilities
- In-depth exploration of other control strategies
≥ 2 groups have experience relevant to our interests.

### ATLAS upgrade at ANL

- 60.625 MHz, trapezoidal vane tip modulation
- Separate cooling circuits for walls, vanes
- They keep the wall temperature static at 70°C, only control vane temperature.
- We’re making a field trip to ANL for a tour. Interested in coming?

### IMP RFQ

- Similar design done by the LBNL group.
- Successfully commissioned at CW with 10 mA beam.
- LBNL delegation will visit in late April and do some RFQ journalism for us.
Supplemental Slides
Effect of damping on water temperature at RFQ input
PID control with damping added

Addendum Damping – PID control

Temperature Prior to RFQ [°C]

Time After Simulation Start [s]

10x damping
Control Concept: Two MPCs

Basic Conceptual Control Schematic for Water Temperature Loop: Individual MPCs

Tin and Tset refer to the water temperature at the inlet
Tout refers to the water temperature at the outlet

Find inlet temperatures that reduce \( f_{\text{err}} \)
Can use \( \Delta f (\Delta T_{\text{in\_wall}}, \Delta T_{\text{in\_vane}}) \)
and then detect/make small adjustments for steady-state error

Model Predictive Control
return measured output
Tset

Model Predictive Control
Tset measured output
FCVset

Wall System
FCV
Tout
Tin

Vane System
FCV
Tin
Tout

Note that the full schematic is more complicated:
1. Each MPC will need to know both temperature set-points in order to account for coupling
2. Would also include supply temperature input under each MPC
3. If \( \Delta f (\Delta T_{\text{wall}}, \Delta T_{\text{vane}}) \) ends up being more complicated than what we have from Andrew’s technical report, then there will likely be additional inputs for that first block (e.g. related to the present operating point)
4. Will change as we incorporate more from the LLRF
5. Would need to expand to include startup routine
Control Concept: One MPC

Basic Conceptual Control Schematic for Water Temperature Loop: One MPC

Find inlet temperatures that reduce $f_{err}$
Can use $\Delta f (\Delta T_{in\_wall}, \Delta T_{in\_vane})$
and then detect/make small adjustments for steady-state error

Would also include supply temperature input under MPC