RFQ Resonance Control Update: Control Framework and Initial Results

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RFQ Cooling System

![Diagram of RFQ Cooling System]

- LCW supply
- Cooling skid
- Warm return
- Cool supply
- WT1 control valve
- WT2 pump
- WT3 helical mixer
- VT1 control valve
- VT2 pump
- VT3 helical mixer
- RFQ walls
- RFQ vanes
- Coupling through Cu

- Wall channels
- Vane channels
Main Framework

- SEL/GDR switching
  - GDR: reflected power (< 1 kW), detuning (< 1000 Hz), and cavity field set vs. read (< 0.5 kV)
- Resonant frequency calculated in both SEL and GDR
- Detects trips and holds water temperature until RF returns
- User-requested operational states:
  - Monitoring/No action
  - PI or MPC temperature control with default or user set point
  - PI or MPC resonance control
  - LLRF startup and controlled RF recovery after a trip
  - PLC control
- Modular for easy adjustments/additions:

![Diagram showing the main framework with sections for main code, action module, and control module.]
Tested Capabilities (8/22, 8/24, 8/25)

- Switching between requested states
  - 1 – no action, just monitoring (useful for MPC)
  - 3 – PI temperature control using default set point (hard-coded, right now 25 °C)
  - 4 – PI temperature control using user set point (given via ACNET)
  - 7 – Resonance control with PI on the vane valve

- Switching between SEL/GDR and turning RF feedback off/on
  - Sent actions are correct, but still need to fix UDP communication issue

- Basic trip handling

- Resonance control operation in pulsed mode with changing pulse width and forward power

- Resonance control operation in low power CW mode

- Also tried PI resonance control on the vanes with minor PI temperature control on the walls → needs additional tuning; right now better to move to MPC

- Caveat on data shown in the next slides: few apples-to-apples comparisons just yet
Pulsed Operation, Cavity Field at 60 kV
Pulsed Operation, Cavity Field at 60 kV
CW Operation After a Trip

121 sec. total
17 sec. most recent
within 3 kHz spec. in ~60 sec
CW Operation After a Trip

Note: this was before adjusting control blocking (should be better now)
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Present Limitations (i.e. why we’re also doing MPC)

• Fluctuations in the supply temperature

• Flow curves
  • Nonlinear + coupled
  • Intermediate skid pressure fluctuates
  → For PI, have a fitted correction for this

• Transport delays and thermal responses
  → Placed some blocking in the PI loops

• Water temperature control with PI is deliberately low gain—otherwise the loops will fight each other

• PI resonance control is only on the vanes

• Need to watch wall temperature in CW
MPC: Neural Network Model for Pulsed Operation

**Inputs:**
- Vane valve setting
- Wall valve setting
- Average RF power
- Water temperatures
- Ambient temperature and humidity

**Mean absolute prediction error:**
- 346 Hz on the test set
- 98 Hz on the validation set
- 115 Hz across all sets

See A.L. Edelen, IPAC16, THPOY20
Conclusions

- Pulsed operation with PI resonance control is operational:
  - Can set/change cavity field + pulse length arbitrarily

- CW operation with PI resonance control is operational:
  - Need to watch the supply temperature and wall temperature

- Either case:
  - Susceptible to supply temperature fluctuations
  - Could benefit from some additional tuning

- MPC will improve upon this:
  - Supply disturbance rejections
  - Simultaneous vane/wall control
  - Shouldn’t have oscillatory behavior à la PI

- To do:
  - Fix SEL/GDR switching communication
  - Finish MPC + MPC testing in framework
  - For PI: some tuning of gains and valve correction weighting (esp. in T control)
Practical Recommendations

- P127 >> rescntl 1 is the parameter page

- To set requested state, set P:QRCMOD
  - 1 is no action
  - 3 is temperature control with default set points
  - 4 is temperature control with user set points
  - 7 is resonance control with PI (should primarily be using this one)

- To set water temperature set points:
  - P:QRCTSV for the vane
  - P:QRCTSW for the wall

- For PI, the wall valve set (P:WRWSV) at 15% for pulsed, 30-40% for CW

- If having problems, check P:WISS1P (skid pressure) to make sure it isn’t consistently low (e.g. < 50 psi)

- In CW:
  - Watch WRWT03 to make sure it isn’t getting too high (e.g. > 35 deg C; increase wall valve by 10 % or so)
  - Watch P:WISLT and P:WISLST (intermediate skid and LCW temperature)—if these get too high there’s a problem with the water system (e.g. chillers)
Model Predictive Control

Reference Trajectory

\[ y_r(k) \ldots y_r(k + N_p) \]

Measured Variables

\[ u_m(k - 1) \ldots u_m(k - N_m) \]

Optimization of Controlled Variable Trajectories

Predicted Outputs

\[ y_p(k) \ldots y_p(k + N_p) \]

Cost Function

Constraints

Solver

Future Inputs

\[ u_{cv}(k) \ldots u_{cv}(k + N_c - 1) \]

Plant Model

Future Inputs

\[ u_{cv}(k) \]

Plant

\[ N_m \] previous measurements

\[ N_p \] future time steps predicted

\[ N_c \] future time steps controlled

\[ \sum_{i=1}^{N_p} \{w_y [y_r(k + i) - y_p(k + i)] \}^2 \] (output variable targets)

\[ \sum_{j=1}^{n_{cv}} \sum_{i=0}^{N_p-1} \{w_{u,j}[u_j(k + i) - u_{j,ref}(k + i)] \}^2 \] (controllable variable targets)

\[ \sum_{j=1}^{n_{cv}} \sum_{i=0}^{N_p-1} \{w_{\Delta u,j}[u_j(k + i) - u_j(k + i - 1)] \}^2 \] (movement size)
Model Predictive Control

Basic concept: use a predictive model to assess the outcome of possible future actions.
Example temperature increase during CW
Example supply temperature change