RFQ Thermal Control Overview

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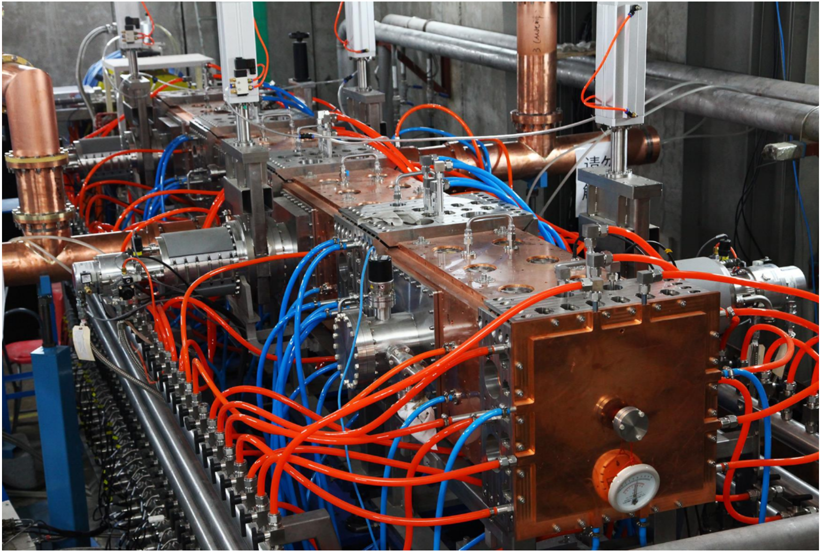
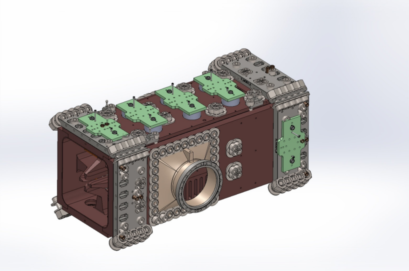
on behalf of the RFQ control group

March 31, 2015

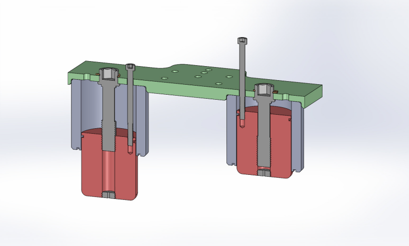
Section 1: Introduction to RFQ control issues



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.

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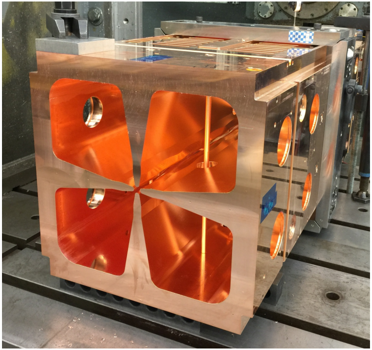
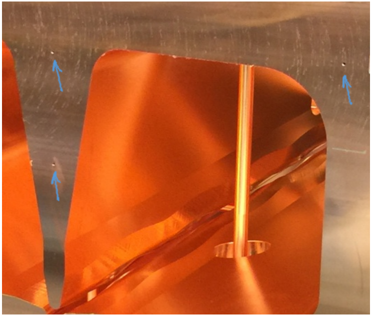
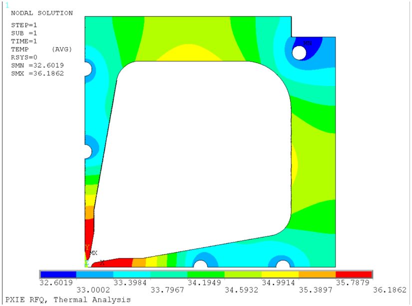
 

RFQ is water-cooled: 4.1 L/s in vane circuits, 5.7 L/s in wall circuits. Blue arrows highlight locations of water channels.

RFQ frequency is sensitive to cooling water temperature variations.

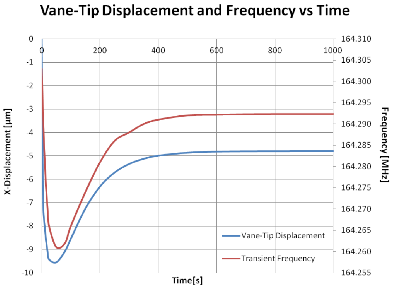


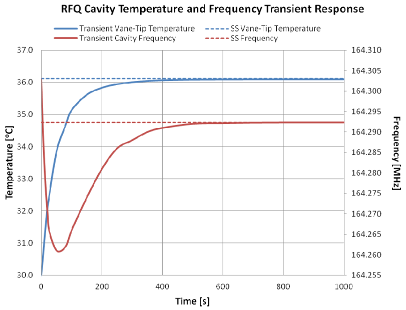
Frequency sensitivity

- 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.



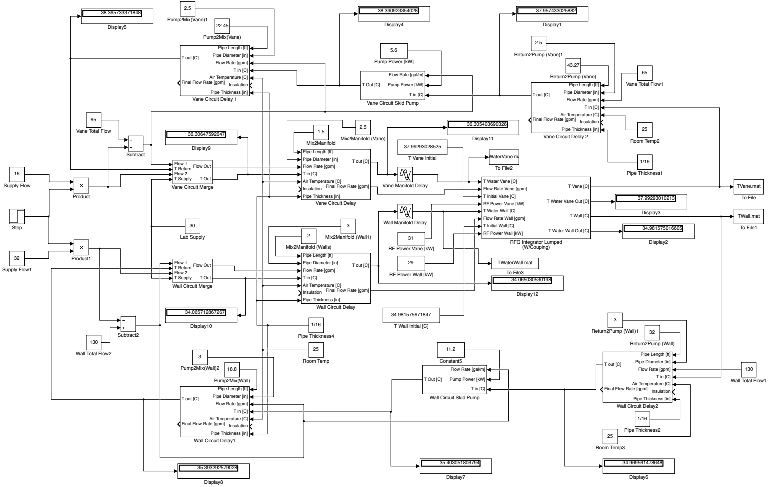


ANSYS transient simulations. Power applied to RFQ (at room temp.) at $t = 0$.

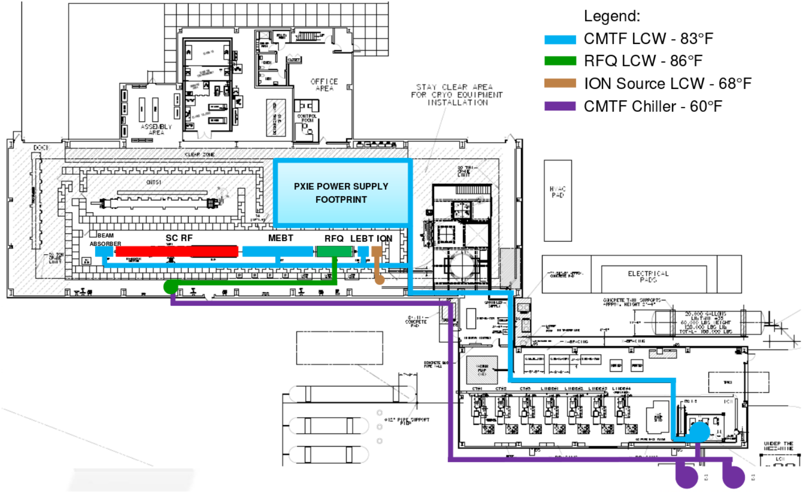
Goals of the thermal control group

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

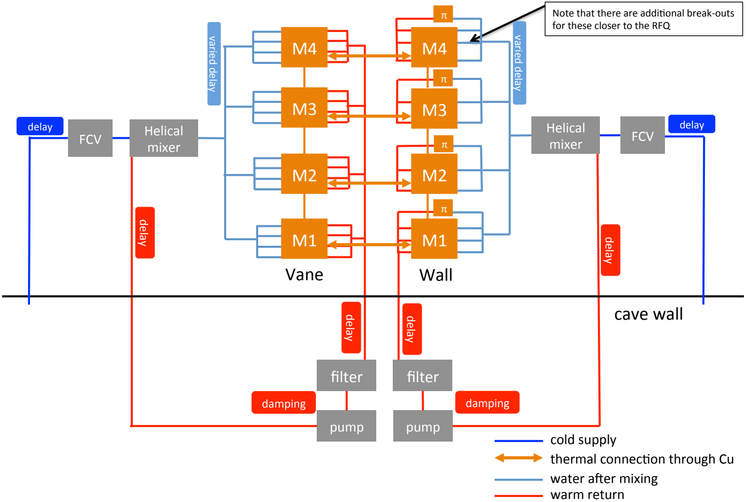
- Members of the group include myself, Jim Steimel, Brian Chase, Curtis Baffes, and a contingent from CSU: Sandra Biedron, Stephen Milton, and students Auralee and Jonathan Edelen.
- We're working closely with Maurice Ball and Yurick Czajkowski.


38.365733371848
Display5
2.5
Pump2Mix(Vane)1
22.45
Pump2Mix(Vane)
Vane Circuit Delay 1
38.390923354028
Display4
5.6
Pump Power [kW]
Vane Circuit Skid Pump
37.957433025882
Display1
2.5
Return2Pump (Vane)1
43.27
Return2Pump (Vane)
65
Vane Total Flow1
Vane Circuit Delay 2
25
Room Temp2
1/16
Pipe Thickness1
65
Vane Total Flow
Subtract
36.30647592647
Display9
1.5
Mix2Manifold
2.5
Mix2Manifold (Vane)
36.305403690326
Display11
37.99293028525
T Vane Initial
To File2
16
Supply Flow
Product
Vane Circuit Merge
Vane Circuit Delay
Vane Manifold Delay
RFQ Integrator Lumped
(W/Couping)
TVane.mat
To File
37.99293010213
Display3
TWall.mat
To File1
Step
Wall Manifold Delay
34.981575016605
Display2
30
Lab Supply
2
Mix2Manifold (Walls)
3
Mix2Manifold (Wall1)
31
RF Power Vane [kW]
29
RF Power Wall [kW]
TWaterWall.mat
To File3
32
Supply Flow1
Product1
Wall Circuit Merge
Wall Circuit Delay
34.065030530198
Display12
34.065712867267
Display10
34.981575671847
T Wall Initial [C]
Subtract2
130
Wall Total Flow2
1/16
Pipe Thickness4
25
Room Temp
3
Pump2Mix(Wall)2
18.8
Pump2Mix(Wall)
Wall Circuit Delay1
11.2
Constant5
Wall Circuit Skid Pump
3
Return2Pump (Wall)1
32
Return2Pump (Wall)
130
Wall Total Flow1
Wall Circuit Delay2
1/16
Pipe Thickness2
25
Room Temp3
35.393292579028
Display8
35.403051806794
Display7
34.969561478648
Display6

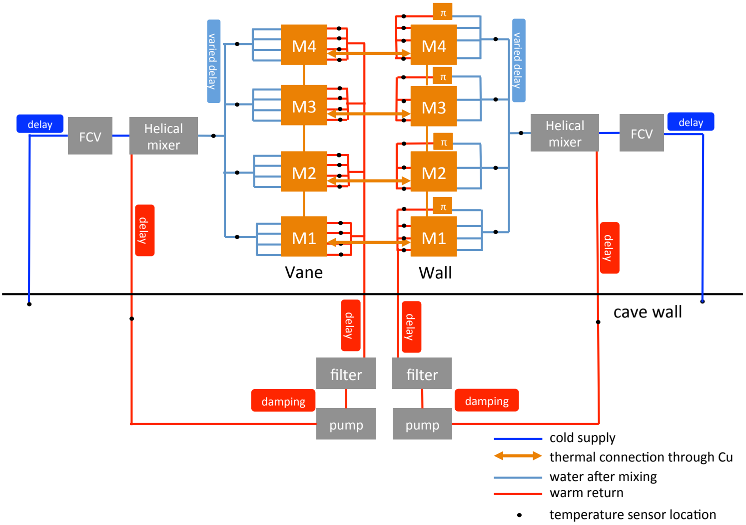
PXIE water plan (from M. Ball, J. Liebfritz's talk on 12/16/2014)



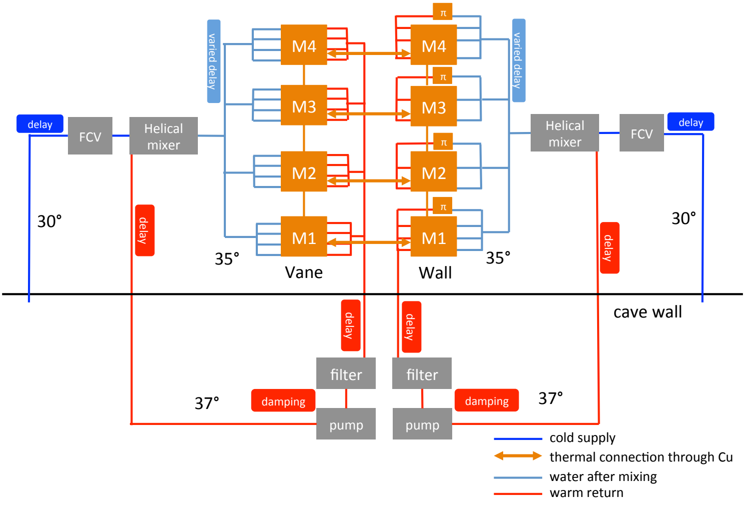
RFQ water layout



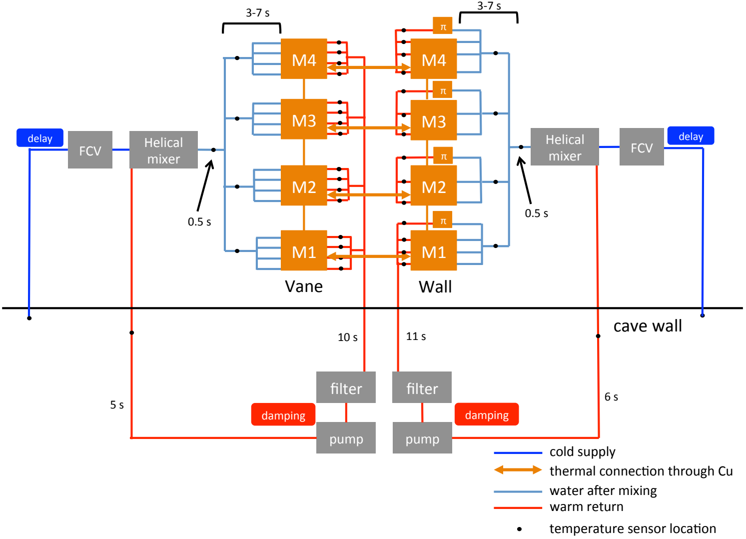
RFQ water layout + locations of temperature sensors



RFQ water layout + locations of temperature sensors

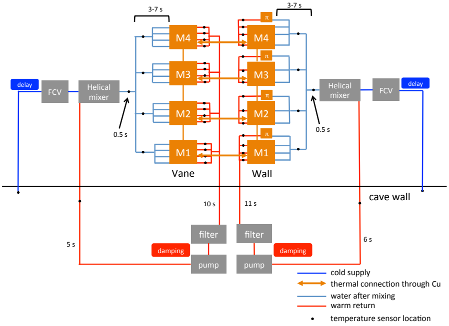


RFQ water layout + line delays



See subsequent slides for determination of mixing point location.

RFQ water layout + line delays

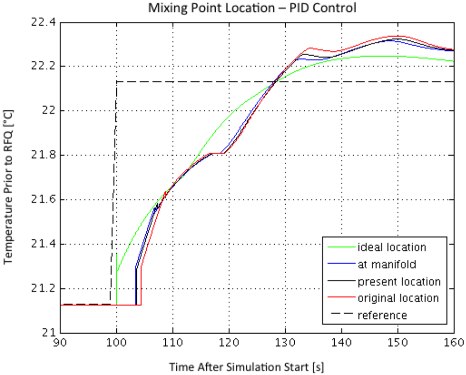


- Thermal mass of vanes $= 10^4$ J/K
- Thermal mass of walls $= 1.2 \times 10^6$ J/K
- Thermal mass of water in vane circuit $= 4.6 \times 10^5$ J/K
- Thermal mass of water in wall circuit $= 8.4 \times 10^5$ J/K
- Coupling between vane & wall ≈ 0.7 kW/K

Section 3: Current work

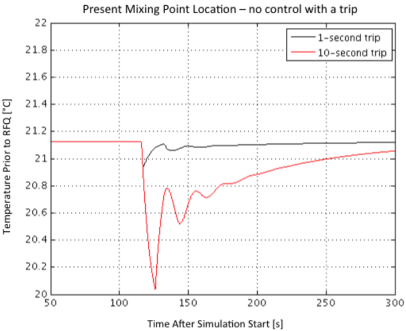
- Incorporating control elements into Simulink model of water system.
- Using 2D and 3D RF simulations to probe sensitivities in model.
- Interviewing other labs to learn from their experiences with similar problems.

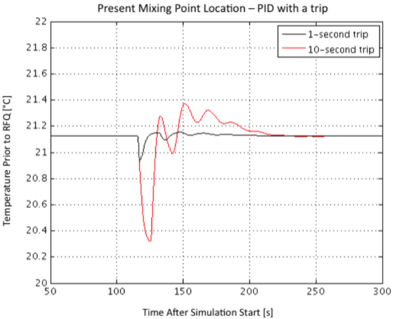
Mixing point location is “optimized”



Mixer location gives us fastest “access” to water temperature at RFQ inlet, given practical constraints.

System model of trip recovery





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

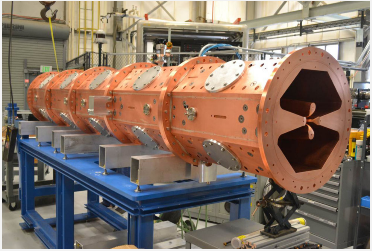
than 10x the trip length.

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_2O temperature?
- Tours of other facilities
- In-depth exploration of other control strategies

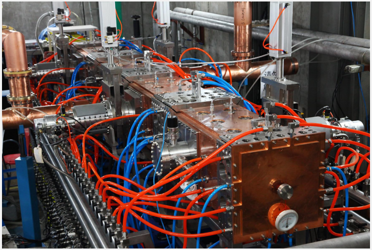
≥ 2 groups have experience relevant to our interests.

ATLAS upgrade at ANL



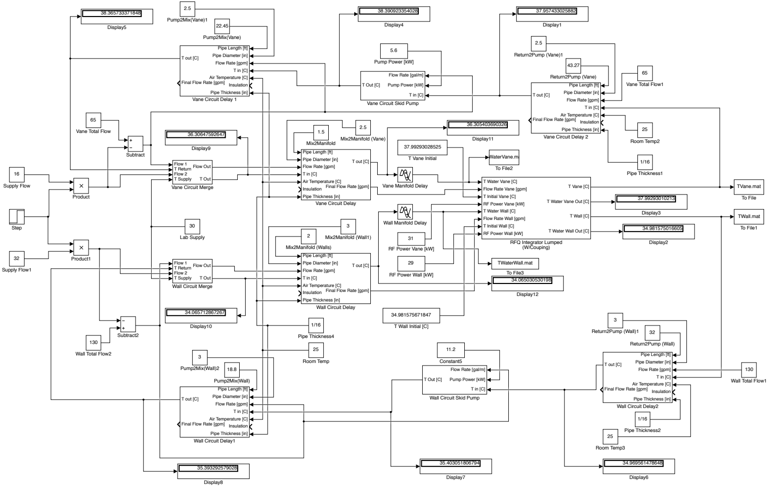
- 60.625 MHz, trapezoidal vane tip modulation
- Separate cooling circuits for walls, vanes
- They keep the wall temperature static at 70°C, only control vane temperature.
- We're making a field trip to ANL for a tour. Interested in coming?

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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Display5
2.5
Pump2Mix(Vane)1
22.45
Pump2Mix(Vane)
Pipe Length [ft]
Pipe Diameter [in]
Flow Rate [gpm]
T in [C]
Air Temperature [C]
Insulation
Pipe Thickness [in]
T out [C]
Final Flow Rate [gpm]
Vane Circuit Delay 1
38.390923354028
Display4
5.6
Pump Power [kW]
Flow Rate [gal/m]
Pump Power [kW]
T in [C]
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Display11
37.99293028525
T Vane Initial
WaterVane.mat
To File2
16
Supply Flow
Product
Flow 1
T Return
Flow 2
T Supply
Flow Out
T Out
Vane Circuit Merge
Vane Circuit Delay
Vane Manifold Delay
T Water Vane [C]
Flow Rate Vane [gpm]
T Initial Vane [C]
RF Power Vane [kW]
T Water Wall [C]
Flow Rate Wall [gpm]
T Initial Wall [C]
RF Power Wall [kW]
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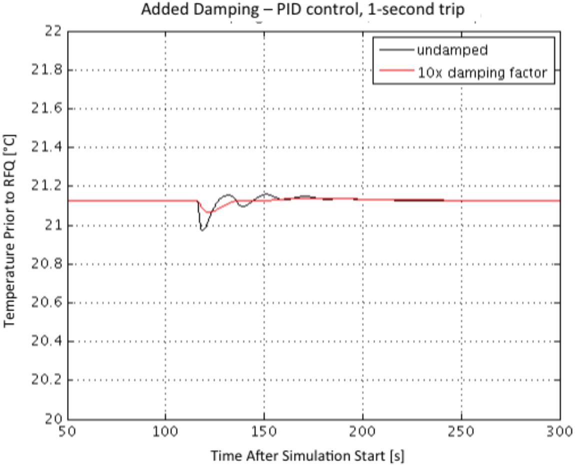
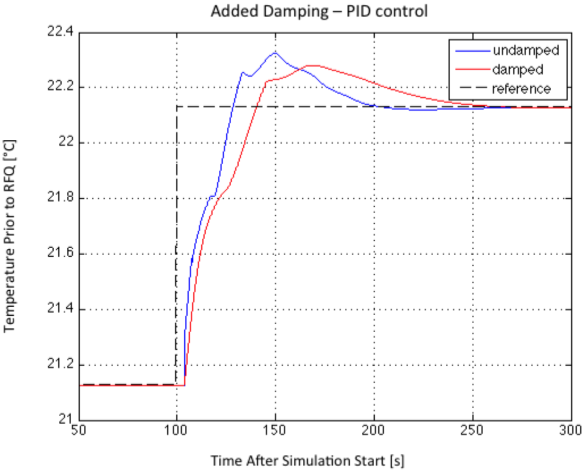
Effect of damping on water temperature at RFQ input



PID control with damping added

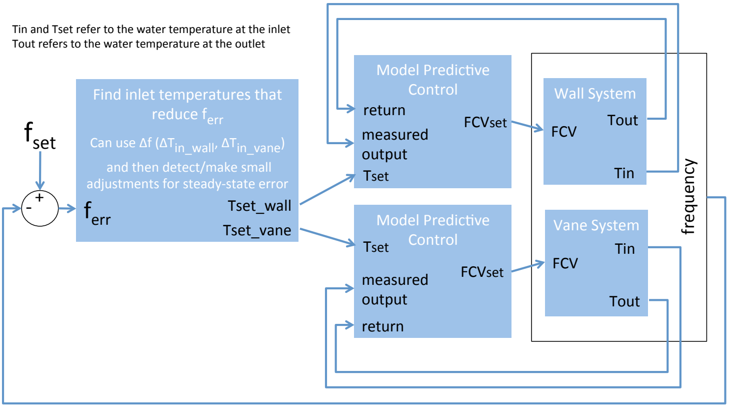


10x damping

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

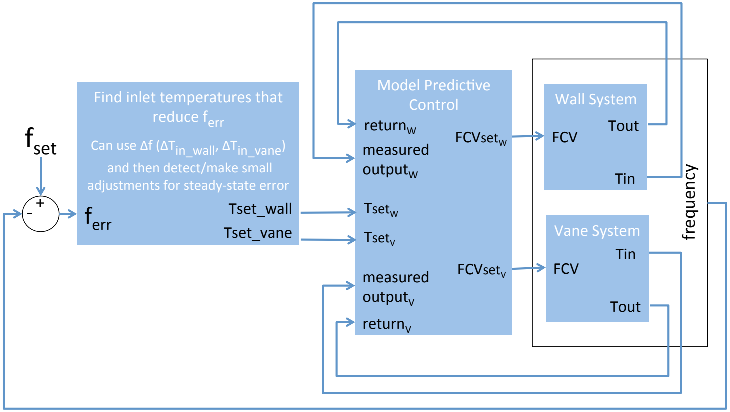


Note that the full schematic is more complicated:

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 Δf (ΔTwall, ΔTvane) 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



Would also include supply temperature input under MPC