ITk Cooling (AUW) Pixel Inner System

UMassAmherst

ATLAS ITk

Rafael Coelho Lopes de Sa

Anirudh J. Uppal

With inputs from Allen Zhao, Grant Lloyd, Steven Welch, and Neal Hartman

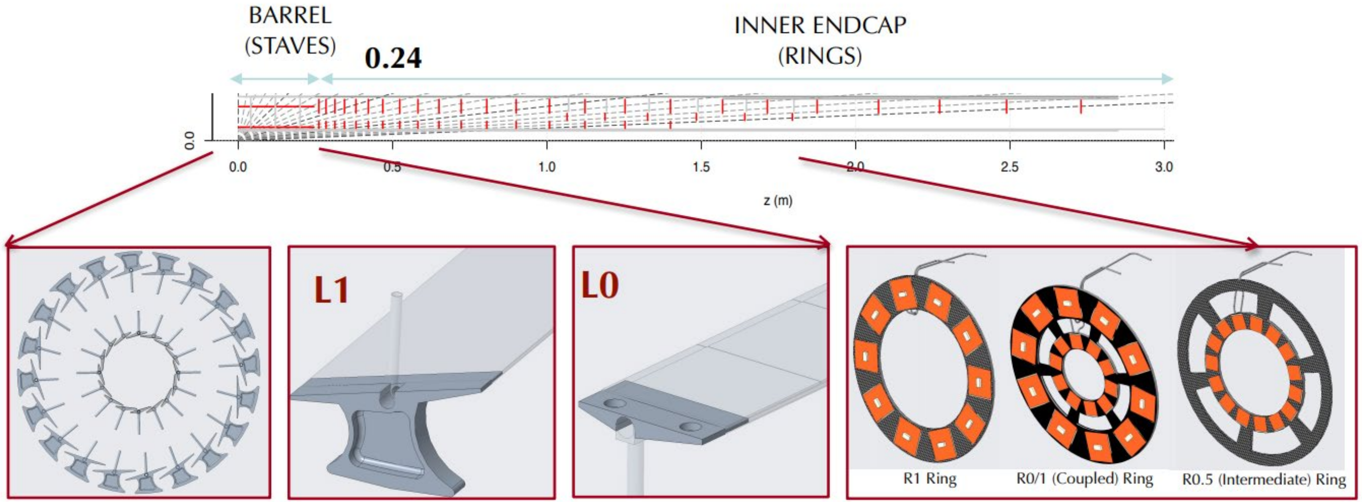
Apr 24th 2020

Requirements

- Cooling requirements in the Pixel Inner System are set by the following:
  1. Runaway temperature of the sensor
  2. Allowed current into front-end chip
  3. Temperature on front-end chip (under discussion)
- For the Pixel Inner System, item (2.) is usually the limiting factor. Ongoing discussions to set the exact requirement.
- The modeling is done in two parts:
  1. Thermo-electrical FEA model to describe heat flow from sensor to coolant
  2. Thermo-fluidic model to describe heat absorption by the coolant and flow properties. Also important to model pressure drop in capillary and evaporator (targeting total dP ~ 10bar and capillary dP ~ 8bar)
- This talk focuses on the thermo-fluidic modeling
  - The most recent update with the Inner System thermo-electrical simulation is here: http://cern.ch/go/t6NV
  - Here we focus on the region between PP1, not outside.
  - Most of the results present here were obtained to guide design. There are details to be updated. I tried to highlight them when relevant.

Pixel Local Supports

- The Pixel Inner System has a large number of mechanical structures with quite different heat load



Total power (used for thermo-fluidic modeling) per local support

L1 stave: 135W/LS

L0 stave: 67W/LS

R1 ring: 224W/LS

R0/1 ring: 274W/LS

R0.5 ring: 84W/LS

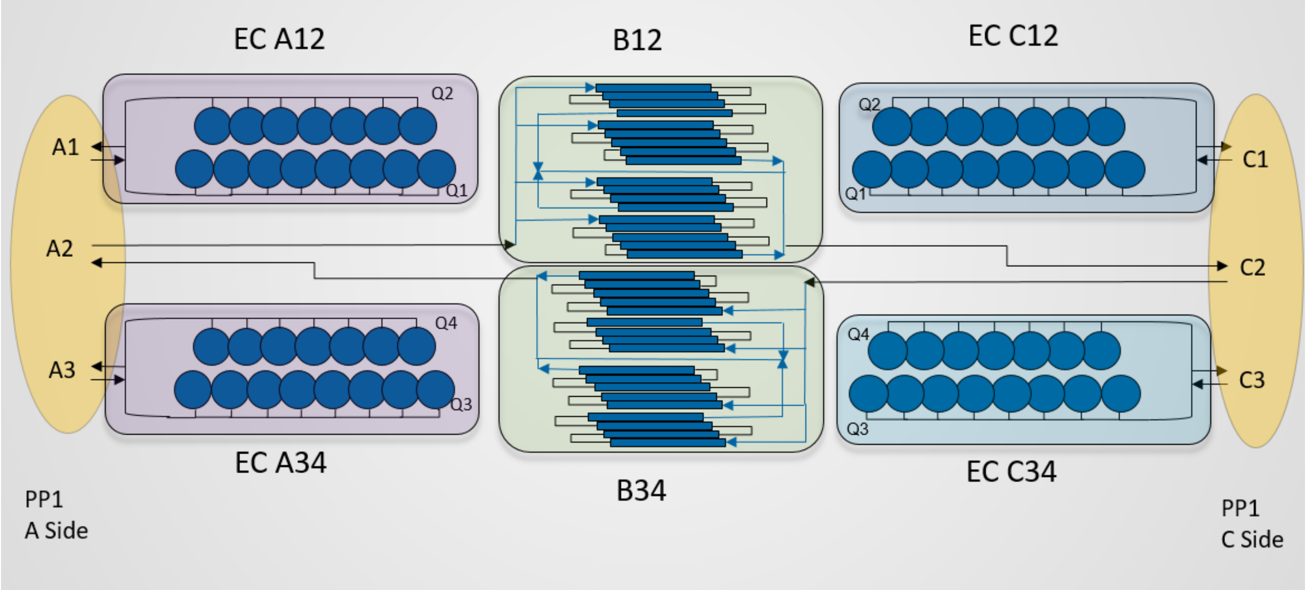
* The models and layout shown here are outdated, but the changes are small.

* Additional rings for luminosity monitors with very low power usage.

* **Numbers here obtained with 0.7 W/cm^2**

Cooling design

- The large number of different structures make the cooling strategy challenging since different solutions are necessary. The diagram below shows a high level diagram of the strategy.



- 3 connections in each PP1.
- Pixel Inner System built in quarter (shells). Cooling in half (cylinders)
- Barrel staves receive coolant in series.
- Endcap rings receive coolant in parallel.
- Cross-flow in the barrel.

Diagram copied from Allen Zhao (ANL)
https://indico.cern.ch/event/865155/contributions/3645245/attachments/1951100/3238998/Inner_System_Barrel_Manifolding_11252019.pptx

Barrel cooling design

- Why a series (daisy-chain) distribution in the barrel?
  - Higher heat per branch → higher coolant flow → larger evaporator → better heat extraction by conduction. Takes a hit from reduced HTC, but more efficient conduction greatly improves the design (especially for L1 stave)
  - Single distribution tube over endcap quarter shell which can also serve as capillary. These capillaries have larger diameter and are safer.
    - Tray on QS for tubes has 14.5 x 18.1mm
  - Evaporator diameters are basically defined by integration constraints (upper limit) and thermo-fluidic constraints (lower limit)

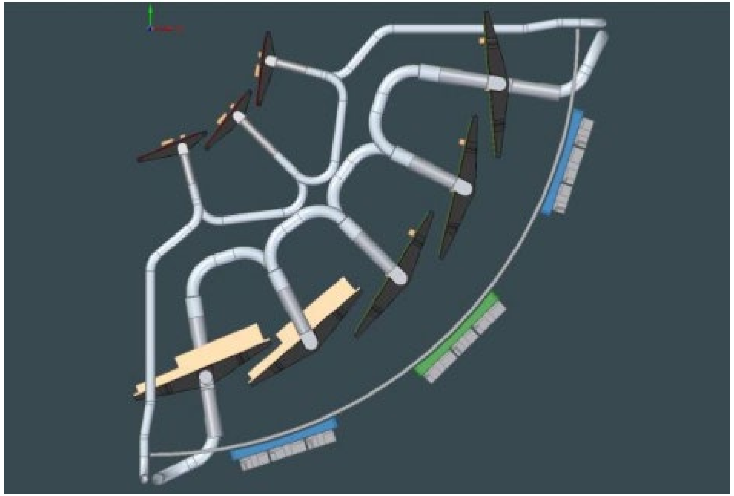
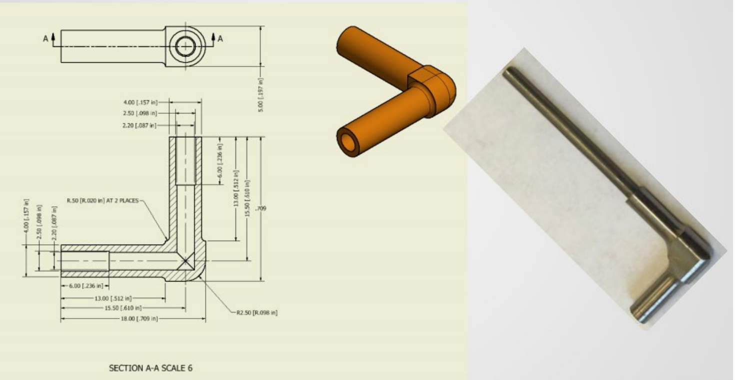


Diagram from Grant Lloyd (SLAC)

L1 stave evaporator ID: 3.0mm
(5 staves in series)

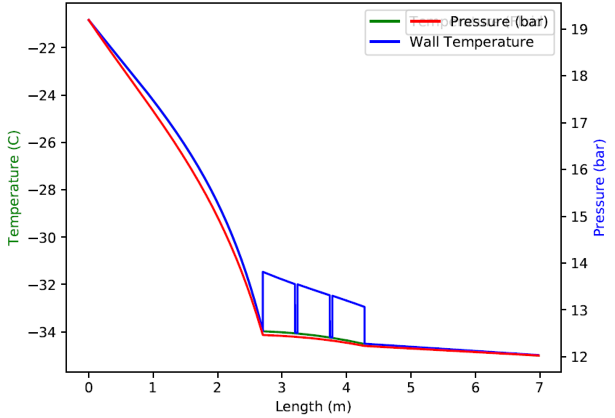
L0 stave evaporator ID: 2.3mm
(3 staves in series)

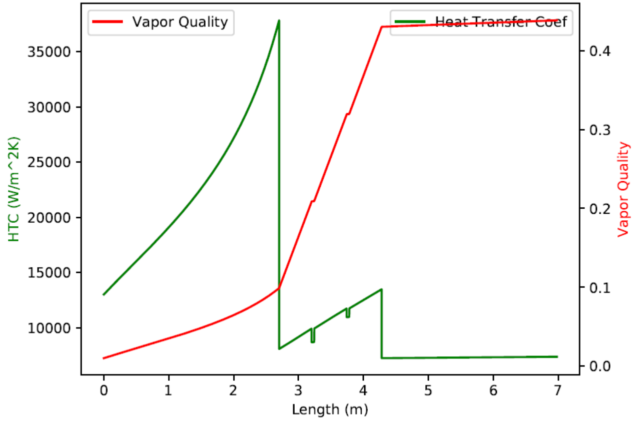
Simulations and demonstrator



- Simulations performed with private code very similar to CoBra
  - 1D model simulated with Thome correlations
  - No modeling of tube roughness
  - No modeling of elbow connectors
- CO_2 "set" temperature: -35oC (not -40oC… maybe relevant given the heat exchanger discussion… to be updated)
- Flow in each branch: 1g/s per 100W
- Simulations extended to manifolds
- No thermo-fluidic demonstrator performed yet for Pixel Inner System
  - No resources to prepare demonstrator before the several Local Support prototypes are ready (prototypes 19-0, 19-1, and 19-2)
  - Currently scheduled for later this year. But COVID closures will have an impact on these plans.

Result for L0 staves



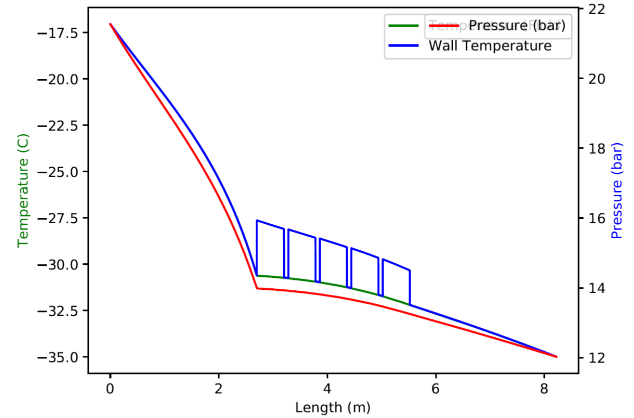


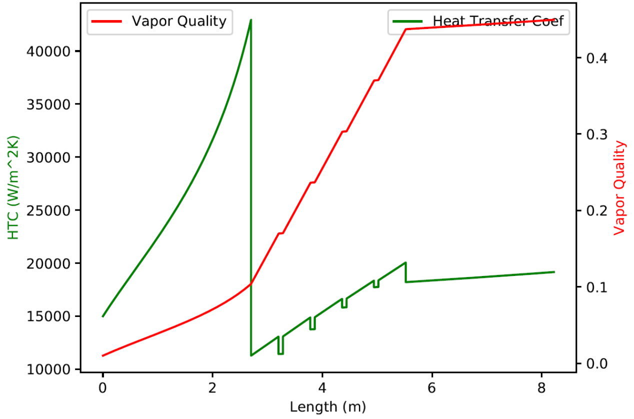
- Capillary
  - ID = 0.8mm
  - Length = 2.7m (full QS)
- Environmental temp = -10oC
- Exhaust tube ID = 3mm
- Capillaries only absorb heat from convection
  - Very little dependence on environmental temperature.
  - Little dependence on whether or not capillary is insulated.
- Very sensitive to capillary ID
  - Total dP(ID=0.75mm) = 12.1 bar
  - Total dP(ID=0.8mm) = 7.2 bar

ATTENTION: The simulations presented here have 2-phase already in the beginning of the capillary. This will be fixed soon.

ATTENTION 2: We will not try to fine tune the 10 bar here. The dimensions of the system are still too open.

Result for L1 staves





- Capillary
  - ID = 1.2mm
  - Length = 2.7m (full QS)
- Environmental temp = -10oC
- Exhaust tube ID = 3mm
- Capillaries only absorb heat from convection
  - Very little dependence on environmental temperature.
  - Little dependence on whether or not capillary is insulated.
- Very sensitive to capillary ID and length
  - Total dP(ID=1.1mm) = 18.6 bar
  - Total dP(ID=1.2mm) = 9.5 bar

NOTE: It is possible to use the same capillary as the L0 stave (ID=0.8mm) if length is reduced.

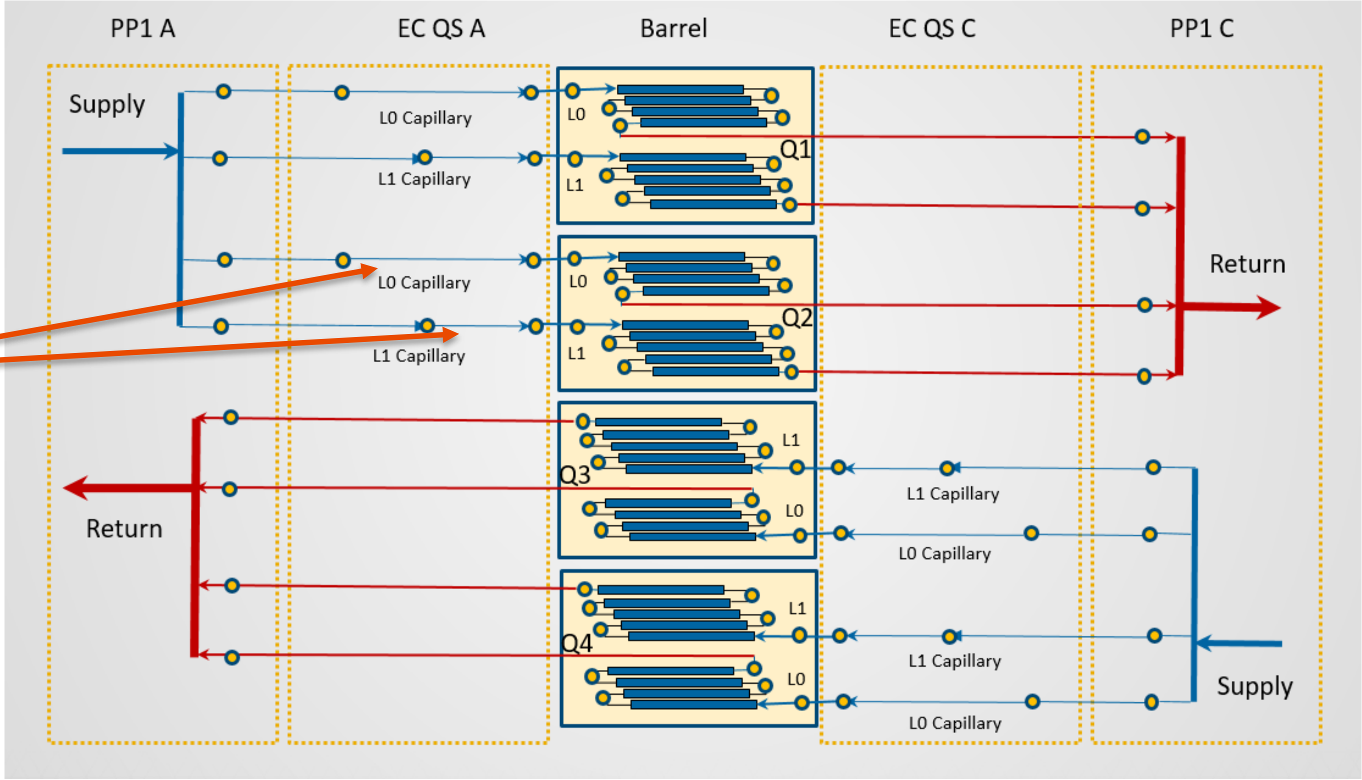
Reduced capillary for L1 staves

We can have both L0 and L1 capillaries with ID=0.8mm by reducing the L1 capillary.

2.7m for L0
0.4m for L1

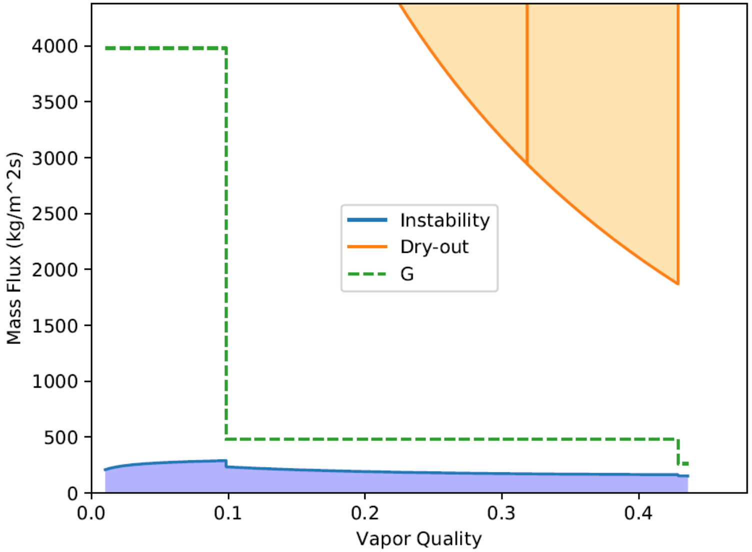
This particular configuration has not been simulated yet.

Need more inputs from system designers.

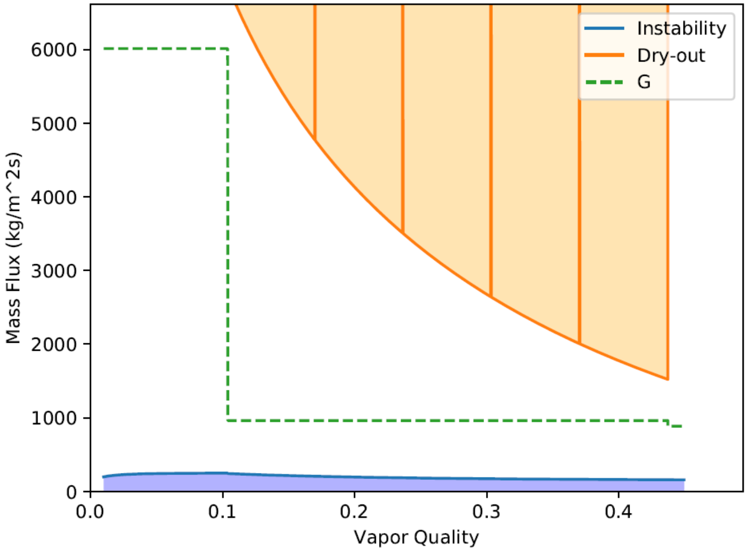


Flow quality in the barrel

L0 staves (ID=2.3mm)



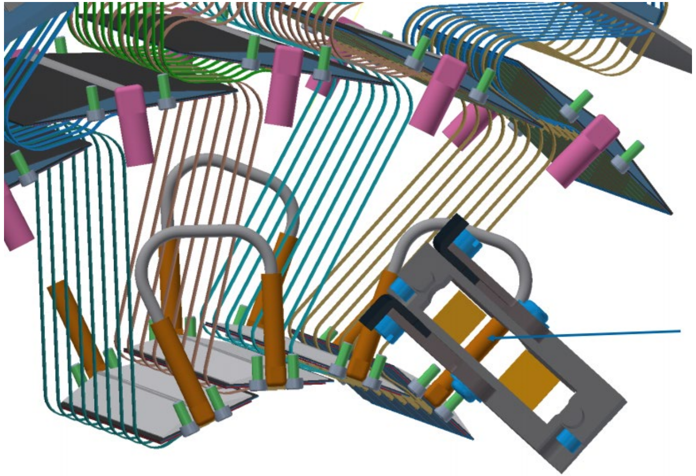
L1 staves (ID=3mm)



- ID for L1 stave evaporator in safe region
- ID for L0 stave closer to instability region (2.3mm was chosen based on market availability and may be re-evaluated)

Barrel manifold

- L1 and L0 stave branches are manifolded close to PP1
- We simulate a half-cylinder barrel manifold:
  - (2x) 5 L1 stave 3mm evaporators in series and 1.2mm/2.7m capillaries
  - (2x) 3 L0 stave 2.3mm evaporators in series and 0.8mm/2.7m capillaries.
- Total CO_2 flow in barrel PP1 connection 17.4 g/s (in each direction).
- Small changes in flows. Total dP = 8.9 bar with multiline simulation (done here more to validate multiline simulation algorithm, to be honest).
  - Of course, this is not the 10 bar in the requirements.
  - But given uncertainties in the design, this is enough to provide necessary inputs.



Endcap cooling design

- Different strategy. Each local support on a manifold branch. Capillary length fixed by mechanical/integration design (72 cm).
- The power dissipated in each branch can vary wildly (from 224W in R0/1 coupled ring to 84W in R0.5 intermediate ring). Very difficult to find common dimensions for evaporators and capillaries.
- Number of local supports on each QS varies:
  - Q1: 4 R0/1, 2R0.5, 2R1
  - Q2: 4 R0/1, 2R0.5, 2R1
  - Q3: 4 R0/1, 1R0.5, 2R1
  - Q4: 3 R0/1, 1R0.5, 2R1

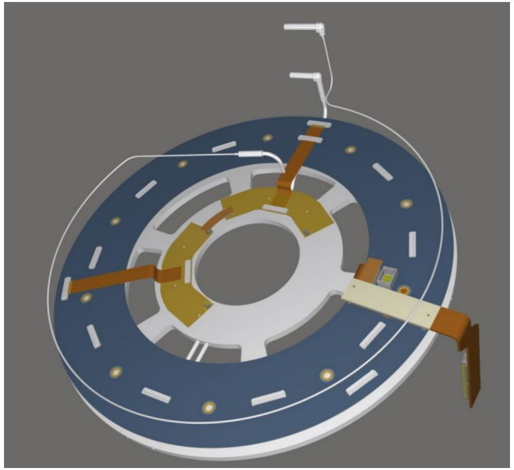
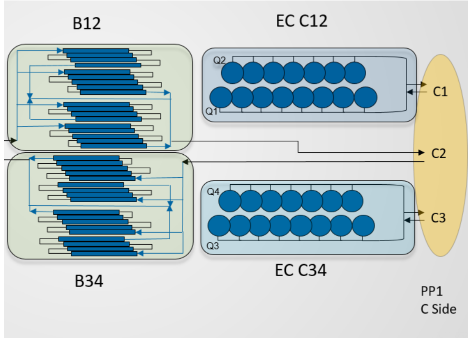


Diagram from Steven Welch (Oklahoma State)



A1/C1 17.6 + 17.6 = 35.2 g/s

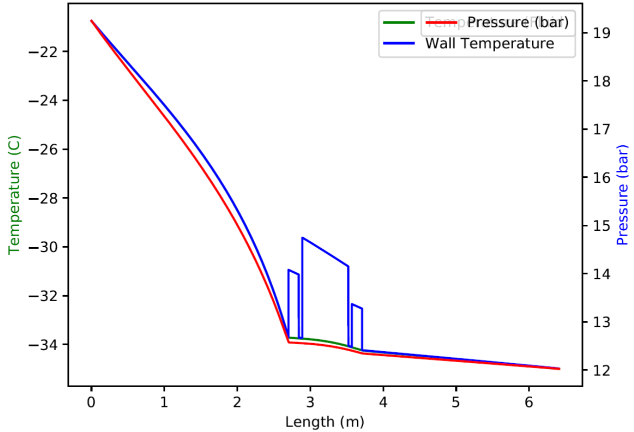
A2/C2 8.8 + 8.8 = 17.4 g/s

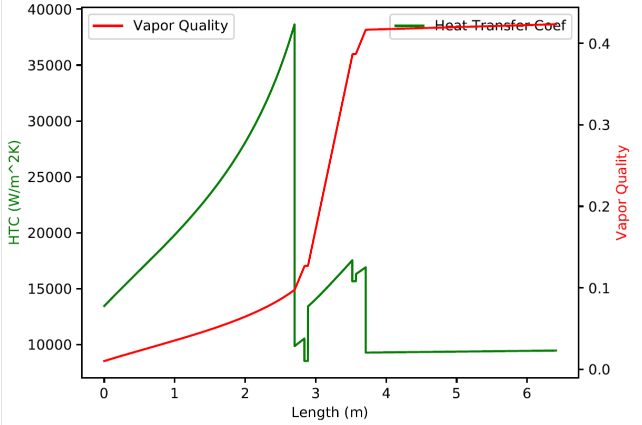
A3/C3 16.7 + 13.9 = 30.6 g/s

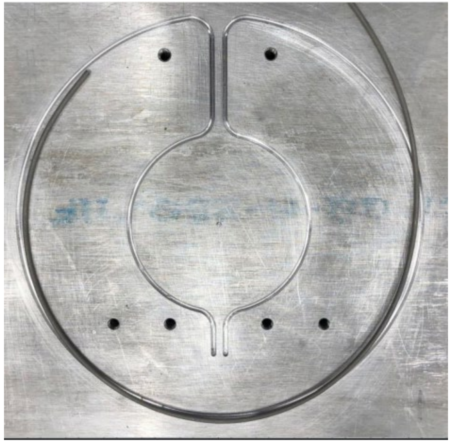
[CO2 flow in each PP1 feedthrought used for thermo-fluidic modeling]

Results for R0/1 (coupled ring)

- We use the same evaporator as for the L0 stave: ID = 2.3mm
- Capillary always non-insulated (but negligible effect) with ID=0.65mm. Again, large dP dependence with ID.
  - Total dP(0.6mm) = 17.2 bar, total dP(0.65mm) = 8.95 bar.



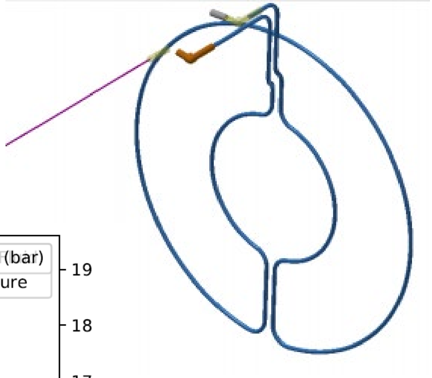


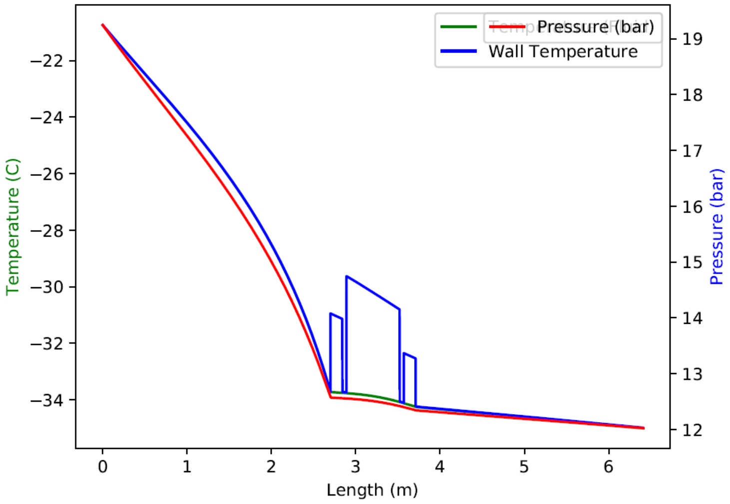


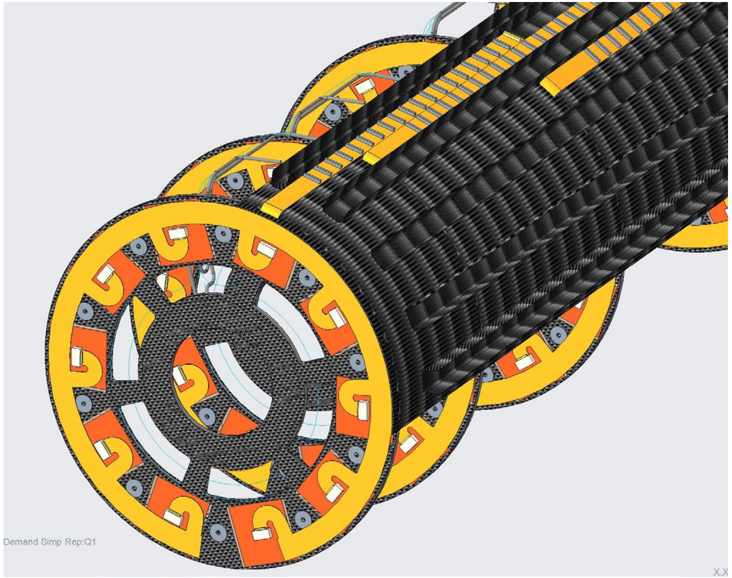
Difference in CO_2 temperature on each side of R0/1-0 ring ~ 1°C
Difference in HTC: ~ 5kW/m^{2}K
Need to propagate this observation to conductive simulation to evaluate temperature difference in the sensors.

Coupled ring integration

- The first coupled ring may need its own distribution.
- Very similar behavior with
  - Capillary ID = 0.9mm
  - Length = 2.7m



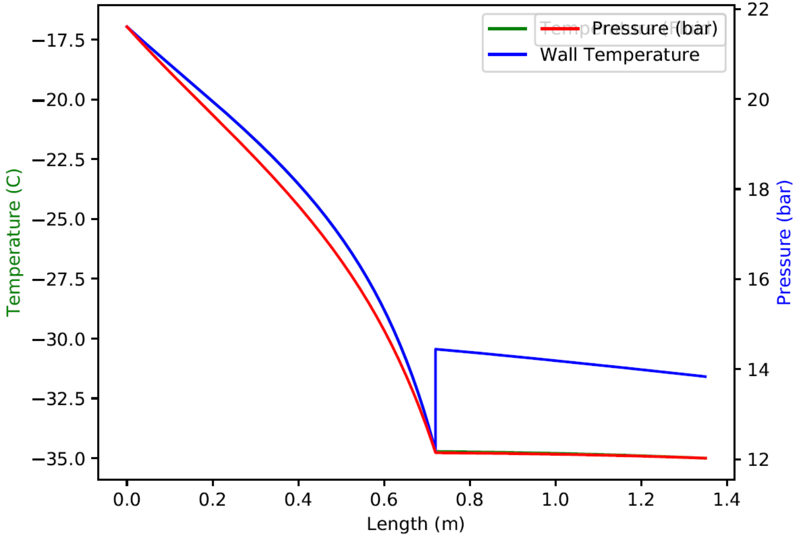


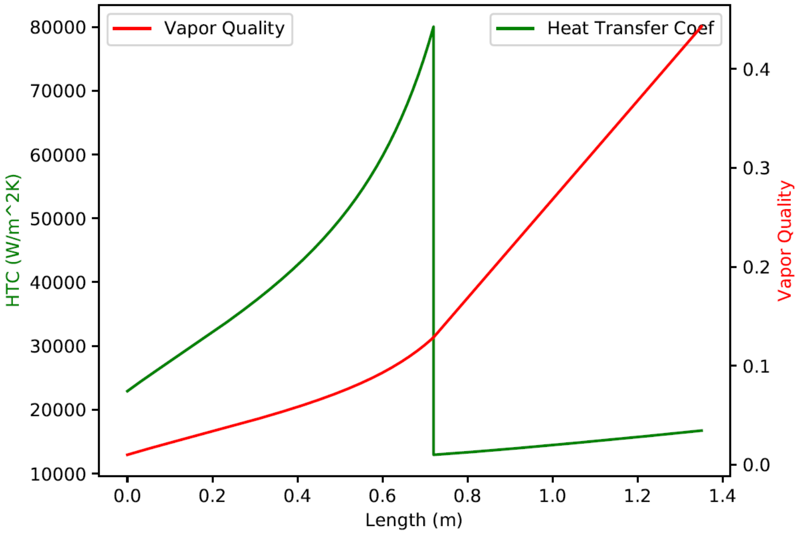


- This is a very old model, but serves the purpose.
- The rings are integrated from low to high *z*.
- The first two rings on a QS are very close (as close as 1.2cm)
- No space for a welding head.

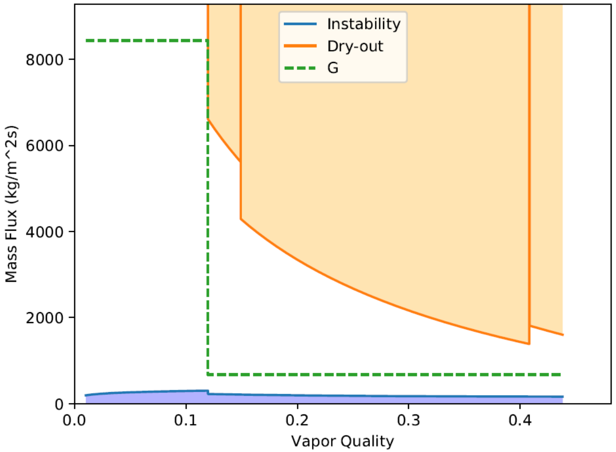
R1 Ring

- No surprises here, but can’t use the same capillary as coupled ring if welding points are exactly the same (current design).
- ID = 0.6mm, length = 72cm

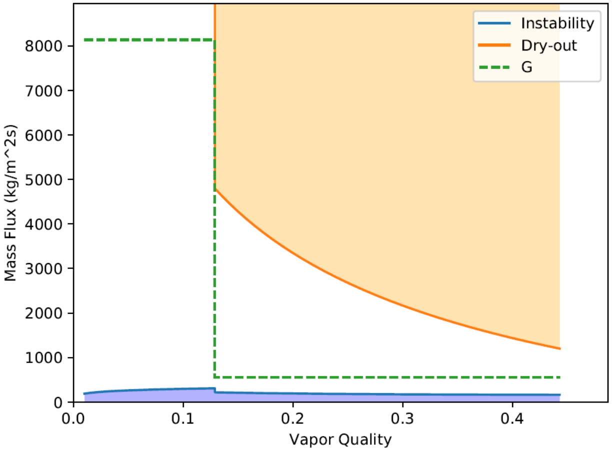




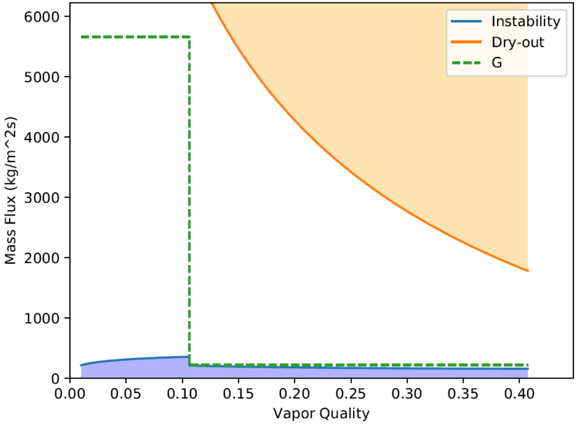
Evaporators for endcaps



R0/1 ring, evaporator ID=2.3mm
OK



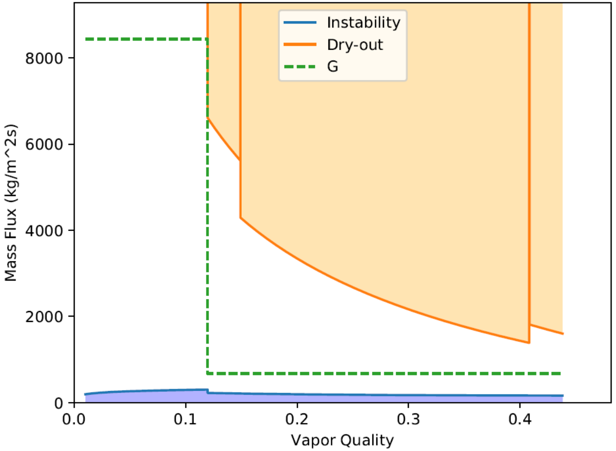
R1 ring, evaporator ID=2.3mm
OK



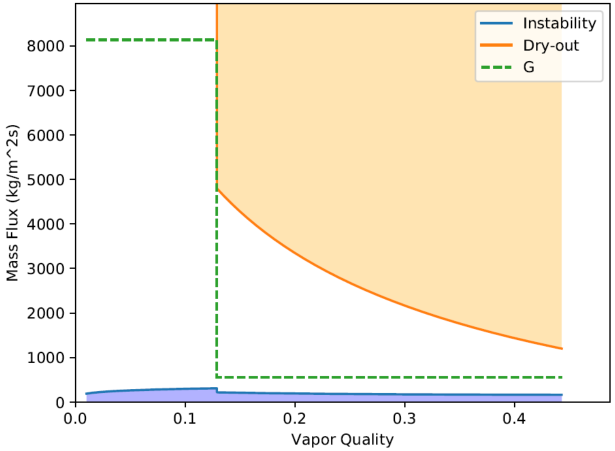
R0.5 ring, evaporator ID=2.3mm
NOT OK

Evaporators for endcaps

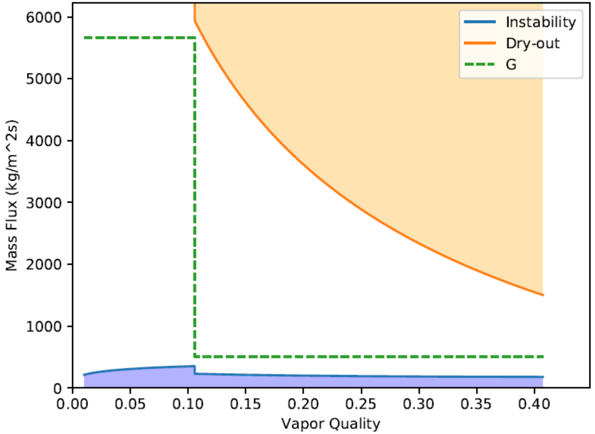
- The R0.5 intermediate ring will require smaller evaporators.
- Design still to be prepared.



R0/1 ring, evaporator ID=2.3mm
OK



R1 ring, evaporator ID=2.3mm
OK



R0.5 ring, evaporator ID=1.5mm
OK

Endcap manifold

- Endcap manifold based on a supply and return tubes modeled with ID=3mm and without heat exchange between them.
  - Pressure drop on spigots and elbows not modelled
- Model only the 4 R0/1, 2R0.5, 2R1 case:
  - R0/1, evaporator ID = 2.3mm, capillary ID = 0.65mm
  - R1, evaporator ID = 2.3mm, capillary ID = 0.6mm
  - R0.5, evaporator ID = 1.5mm, capillary ID = 0.45mm
- Once again, few changes. Total dP = 7.6 bar
  - Close to 10bar given the uncertainties in the model
  - Will become more precise as model develops.
- As in the case of the barrel, no surprise (in the simulation) when branches are connected in the manifold.

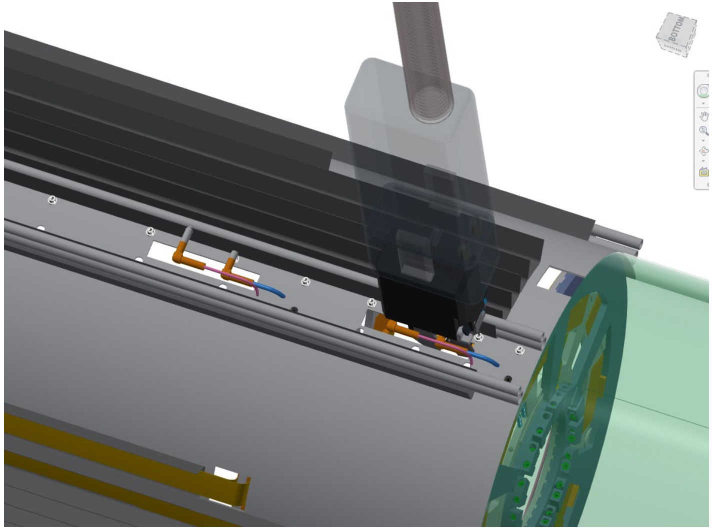


Diagram from Allen Zhao (ANL)

Thermo-fluidic demonstrator plans

- The current plan of the Pixel Inner System community is to break the thermo-fluidic in two parts.
- First part (in time for Pixel Local Support FDR):
  - Test of dP in capillary + evaporator system. For the barrel, this almost everything because of the daisy-chaining of staves. For the endcap, less so.
  - The purpose is to validate capillary design with realistic conditions (elbows, connections, etc).
- Second part (in time for Pixel Global Mechanics FDR):
  - Test of full manifolds (as suggested by CERN cooling group).
  - The purpose is to validate the manifold design.
- Separation in two phases basically driven by availability of resources in the Inner System community.

Conclusions

- Several rounds of thermo-fluidic simulation have been performed for the Inner System to guide the cooling design.
- The simulations have known imperfections and the results are very sensitive to some parameters of the system $\Rightarrow$ a thermo-fluidic demonstrator is necessary.
  - Work slightly delayed due to COVID, but still in our plans.
- We plan begin to assemble our demonstrator later this year or early next year.
- More realistic version of simulations can be performed as design becomes more mature
  - Simulations provide important input for designers, but feedback is equally important.
- Results of the thermo-fluidic simulations presented here are being included in conductive thermo-electric simulation for complete assessment of the thermal performance of the Pixel Inner System local supports.

THANK YOU