Cooling Design and Qualification for the ITk Pixel Inner System

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The ATLAS Detector and the ATLAS HL-LHC Upgrades

The LHC will undergo a series of upgrades in 2027 and will be called HL - LHC

Some Challenges of the HL- LHC upgrade:

- Increase the rate of collisions by a factor of 10
- Increase the instantaneous luminosity by a factor of 10
- Replace the whole inner tracker by a new all silicon tracker called the ITk

The ITk Tracker

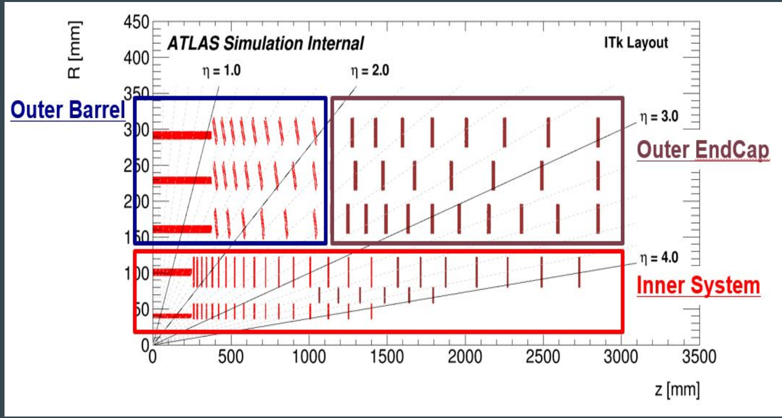
The ITk Pixel Detector will have 580 million individual readout chips

The ITk Pixel Detector is divided into three sections:

- ITk Pixel Inner System:
  - Inner System: two innermost layers (0 and 1)
  - Cylindrical barrel sections with short staves and a large number of rings in both endcaps
  - Built in independent quadrants that are integrated together

- Outer Barrel:
  - Each quadrant contains 3 staves in layer 0 (L0 Staves) and 5 staves in layer 1 (L1 Staves)

- Outer Endcap:
  - A typical quadrant contains 4 coupled rings which has sensors in both layer 0 and 1 (R0/1 Rings)
  - Two layer-1 ring with sensors only on layer 1 (R1 Ring)
  - 2 intermediate rings with sensors between layer 0 and 1 (R0.5 Ring)



Layout of the future ITk Pixel Detector

Cooling of Silicon Trackers

Why do we need to keep our ITk sensors cool?

- To Avoid Thermal Runaway
  - This happens when Joule heat dissipation of semiconductor increase exponentially with the temperature, while heat extraction through convection is linearly . At some temperature, the coolant will no longer extract all the heat produced

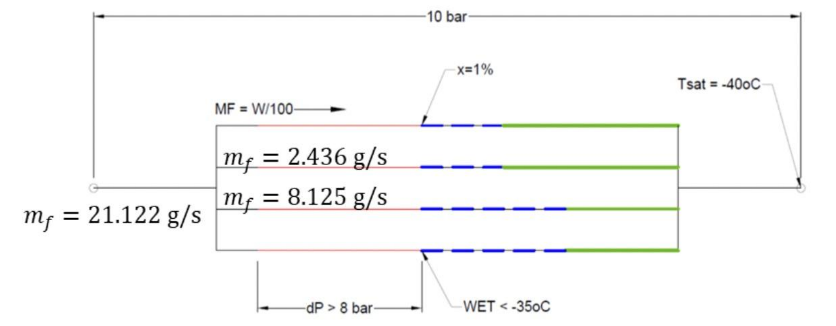
- To Minimize the Amount of Current on the Front-End Chip
  - A single FE chip reads 160,000 sensors channels and cannot handle more than 10 nA of electric current per channel

- To Minimize the Rate of Reverse Annealing
  - Reverse annealing increases the voltage necessary for full depletion of the p-n junction, and at some point, the power supplies will no longer operate the sensors

Design parameters of the ITk Pixel cooling

Design Parameters:

- Saturation temperature at heat exchange is -40°C
- Total differential pressure (ΔP) will be kept at 10 bar
- The flow is obtained by carefully designing the capillary in each branch such that, for a total of 10 bar, the desired flow is obtained
- Vapour quality at the beginning of the evaporator is 1%
    - Avoid subcooled liquid with low HTC just beneath the sensors
- The sizing of the exhaust lines are driven by the requirement of a minimum of 8 bar pressure drop in capillaries
    - Temperature of the fluid inside the evaporator to be at most -35ºC



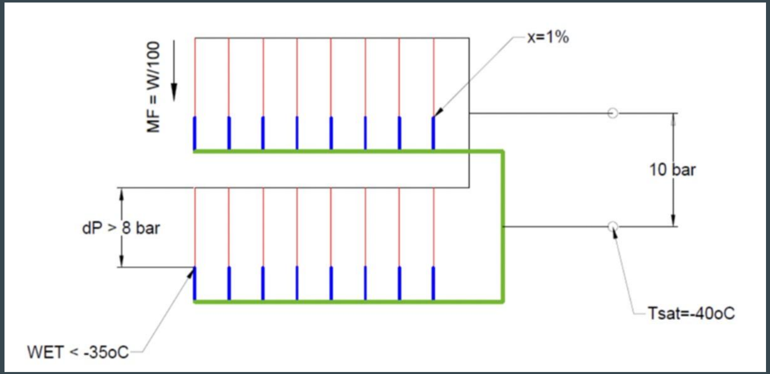


Diagram of the Barrel (top) and Endcap (bottom) Cooling Manifold for the ITk Pixel Inner System

Simulation of the Cooling Manifold

Simulation is Performed into Two Steps:

- Single Branch
  - Phenomenological model for pressure drop and heat transfer in tubes (Thomé Model)
    - Starts from the last element where the saturation temperature is fixed at -40ºC to design and initial enthalpy fixed on the conditions of vapour quality at 1%
    - Then loops backwards calculating the new thermodynamic quantities of each element based on pressure drop from the element after and also the input of heat
    - ΔP depends on pressure and enthalpy given by Thomé parameterization

- Different Branches of Manifold
  - Changing the flow on each branch until one branch gets equal pressure drops

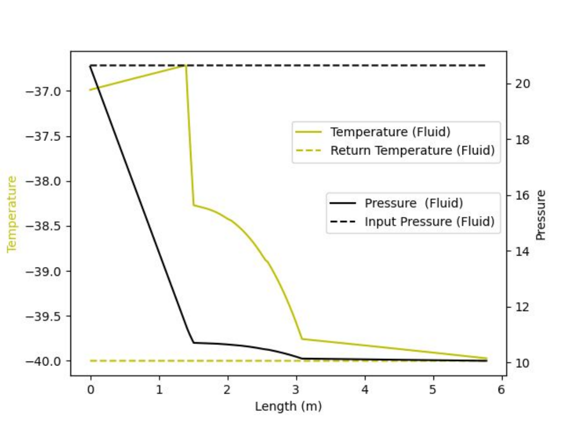
Simulation of the Cooling Manifold

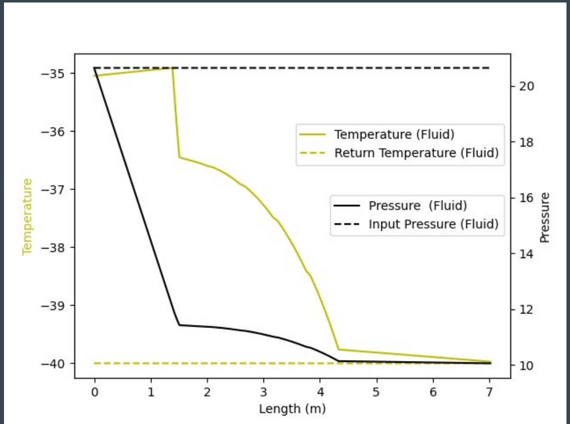
<u>Results Obtained</u>

Simulation tested with a pessimistic model for pressure drop (2x Thome’s phenomenological model)

Barrel Manifold:
Around 10% effect in the total pressure drop, perfectly acceptable. Vapour quality at the end of the exhaust is also acceptable because it never exceeds more than 35%

Endcap Manifold:
Pessimistic scenario has negligible effect on the total pressure drop and on the vapor quality.





L0 branches (top) and L1 branches (bottom)

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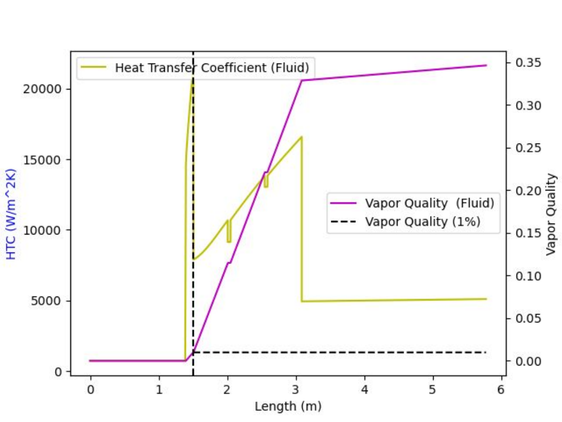
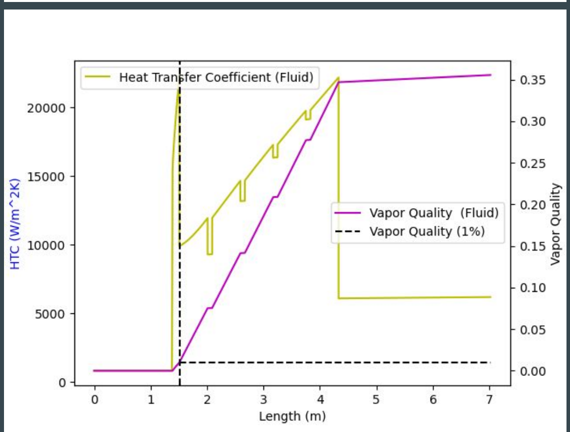




L0 branches (top) and L1 branches (bottom)

Barrel Cooling Demonstrator

Barrel Cooling Prototype: exact replica of the manifold without flexlines

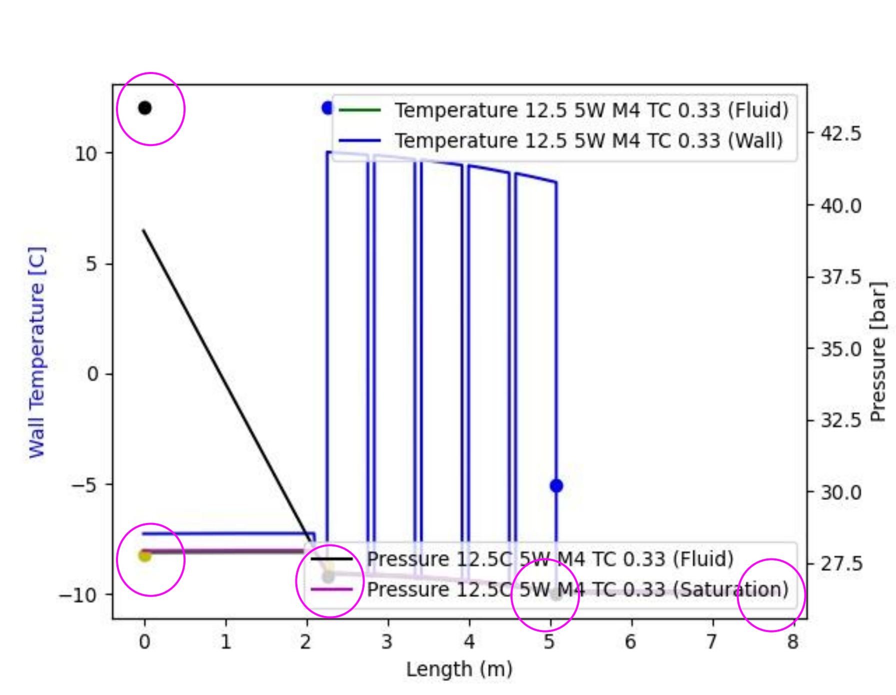
Runs	Flow (g/s)	Return Temp (ºC)	L0 Branch Power (W)	L1 Branch Power (W)	Subcooling (ºC)
1	19	-10	298	653	16.7
2	19	-5	298	653	15.7
3	10	0	298	653	14.7

Comparison of the Barrel Demonstrator with Data

Run 1

- Slightly longer capillary than designed created excessive pressure drop.
- Tested with a return saturation temperature of -10℃ (limitation of the plan)
- Simulation describes behaviour well (some markers are behind the legend)
- Slight underestimate pressure drop on capillary.

Markers indicate the data collected and lines indicate the simulation



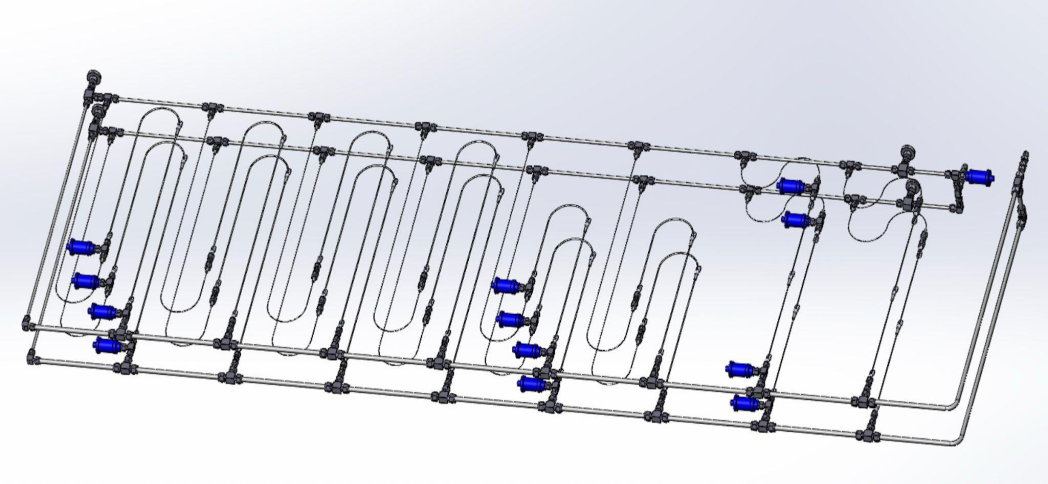
Run 1 Prototype

Endcap Cooling Demonstrator

It's designed in two layers, one for each quadrant of the half-cylinder

- Valves allow individual testing of each quadrant because the Lukazs plant cannot provide enough CO_2 flow for the full manifold.
- Pressure transducer and what it does is that it converts pressure into an analog electric signal
- Addition bypass included to study *fluid starvation effects*. In principle, no bypass is planned for the ITk Inner System

Fluid Starvation Effect could be identified by a spike in temperature of the corresponding evaporator



Endcap Cooling Demonstrator

Conclusions

- We reviewed the cooling design of the ITk Pixel Inner System
- Presented detailed simulation to validate the design in a pessimistic scenario: good results!
- Adapted the simulation to describe the barrel cooling prototype
- Compared simulation to data to validate barrel prototype: excellent results: good results!
- Designed the endcap cooling simulator that is now being built at ANL.