Development of a Cryogenic System for the FCC-hh Inner Triplets Cold Mass Cooling

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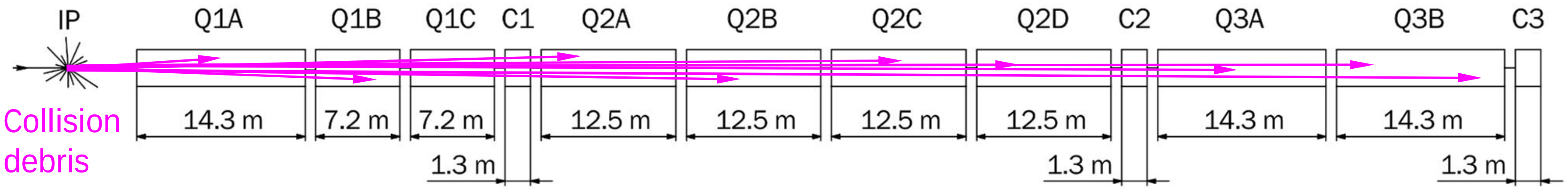
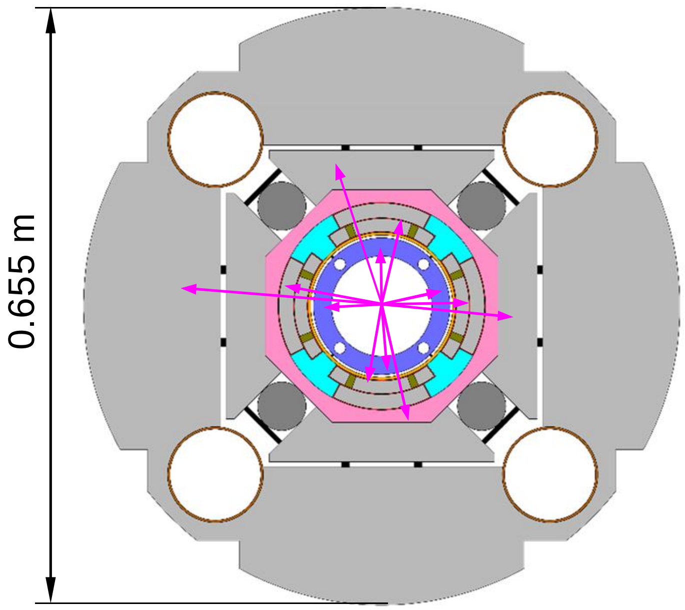
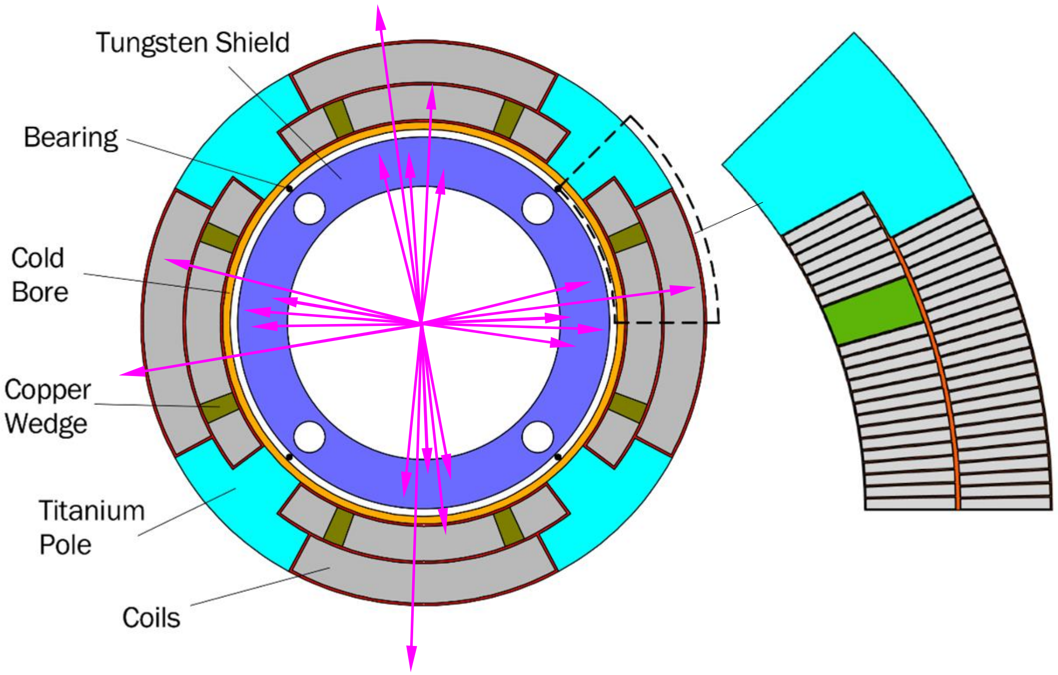
FCC Inner Triplets – Structure & Heat Source

The FCC-hh Inner Triplets

Final focussing magnets before Interaction Points (8 quadrupoles in 3 groups)





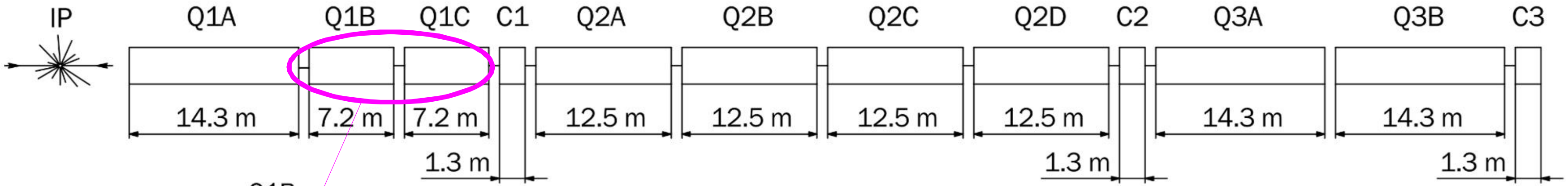


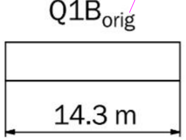
FCC Inner Triplets – Heat Load on Tungsten Shield

Heat Load on the Tungsten Shield

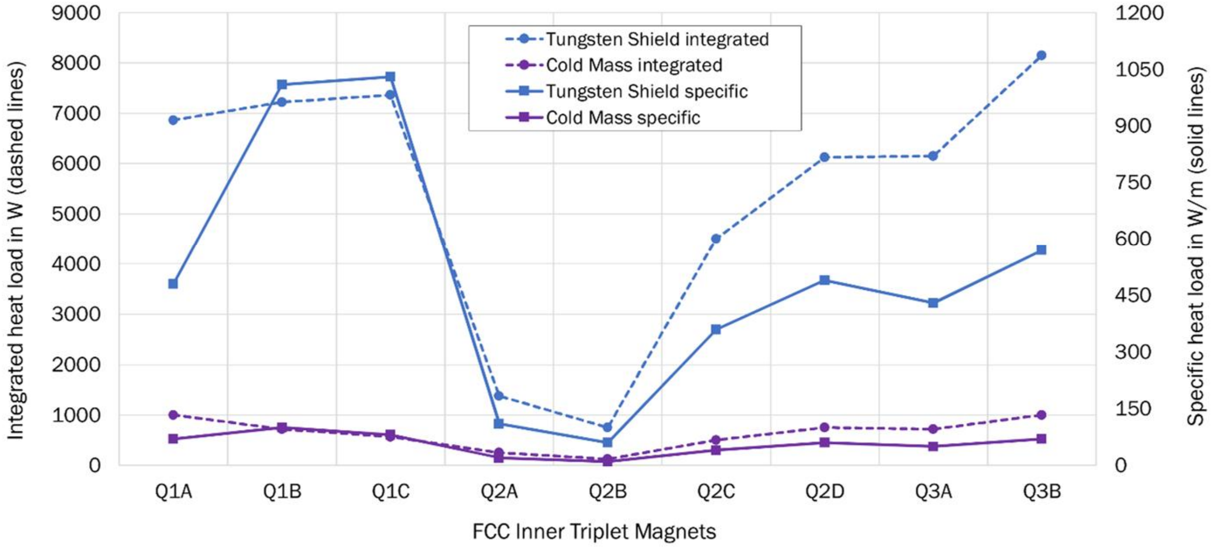
Rapid Reaction Team

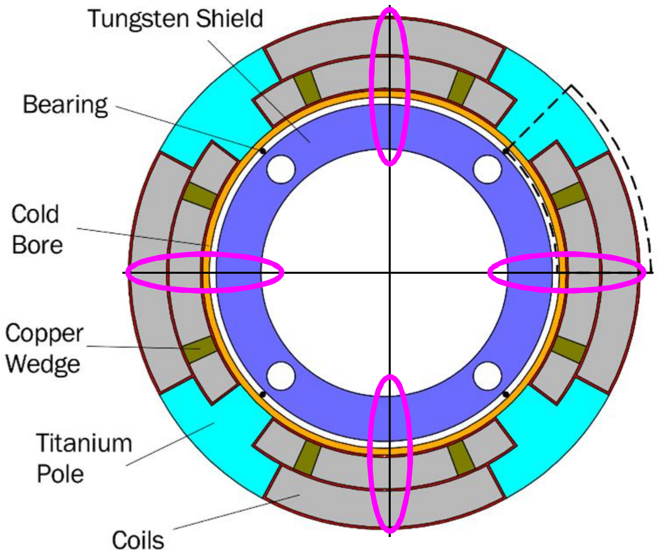
Besana MI, Cerutti F, Delikaris D, Humann B, Martin R, Schörling D, Tavian L





Due to high specific heat load original Q1B magnet ("Q1B$_{orig}$") was split





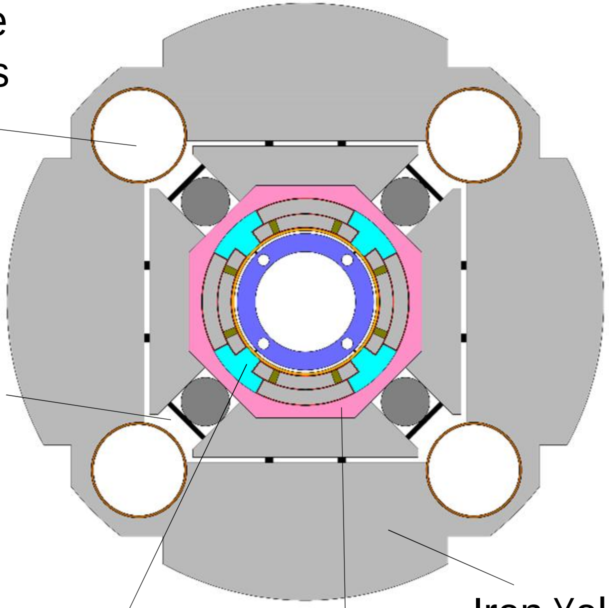
- Large cooling channels in tungsten shield possible (due to impact distribution)
- Tungsten Shield cooling between 40 – 60 K (compared to 1.8 K of Cold Mass)

FCC Inner Triplets – Cold Mass Cryogenics

Heat Load on the Cold Mass

1. Available space for cryogenics installations is limited
2. Available driving temperature range for heat extraction is limited
3. The range of specific heat loads varies strongly for the single magnets

→ Small, reliable and possibly uniformly designed cryogenic system needed



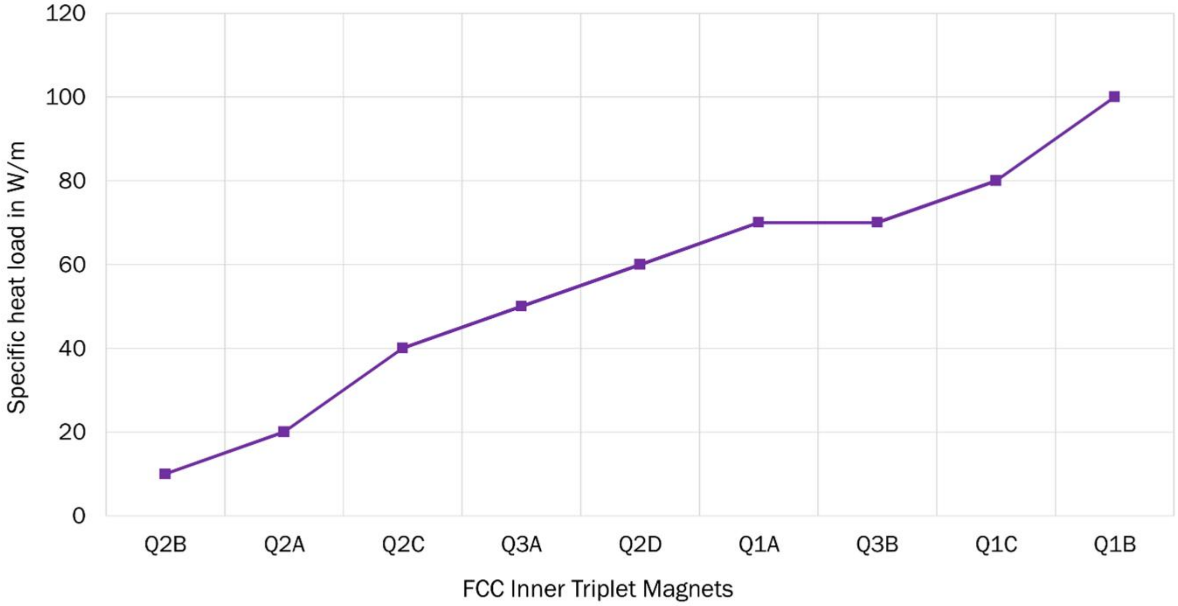
Available space for cryogenics installations $d_{max} \approx 100$ mm

Free space for pressurized superfluid helium $T_{max} = 1.9$ K

Coil $T_{max} = 4.5$ K

Stainless Steel Collar

Iron Yoke



Two approved cooling concepts with superfluid He:

1. Two-phase cooling with bayonet heat exchanger pipe
2. (Pure) Conduction cooling

FCC Inner Triplets – Two-phase cooling

The two-phase cooling scheme

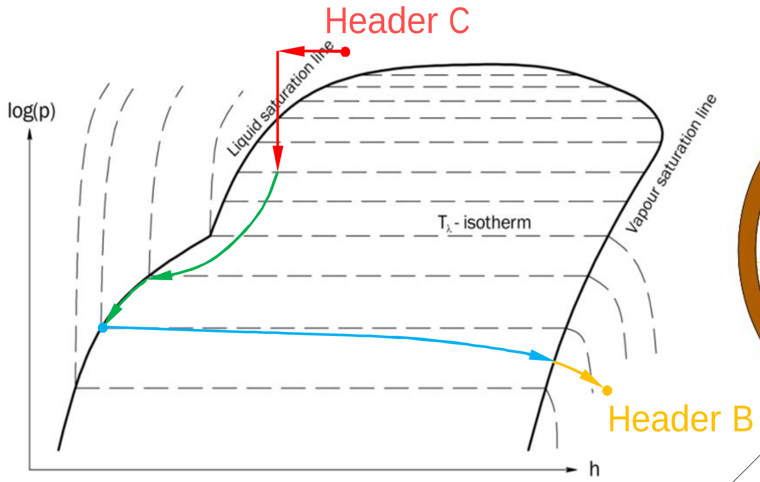
Helium supplied by header C:

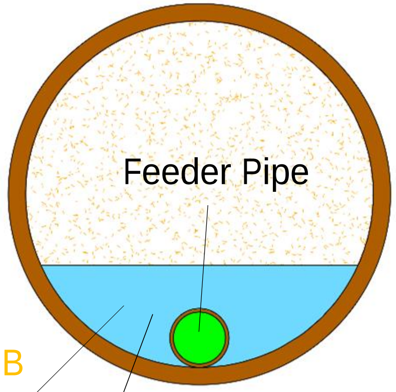
$T_C = 4.6$ K $\quad p_C = 3$ bar

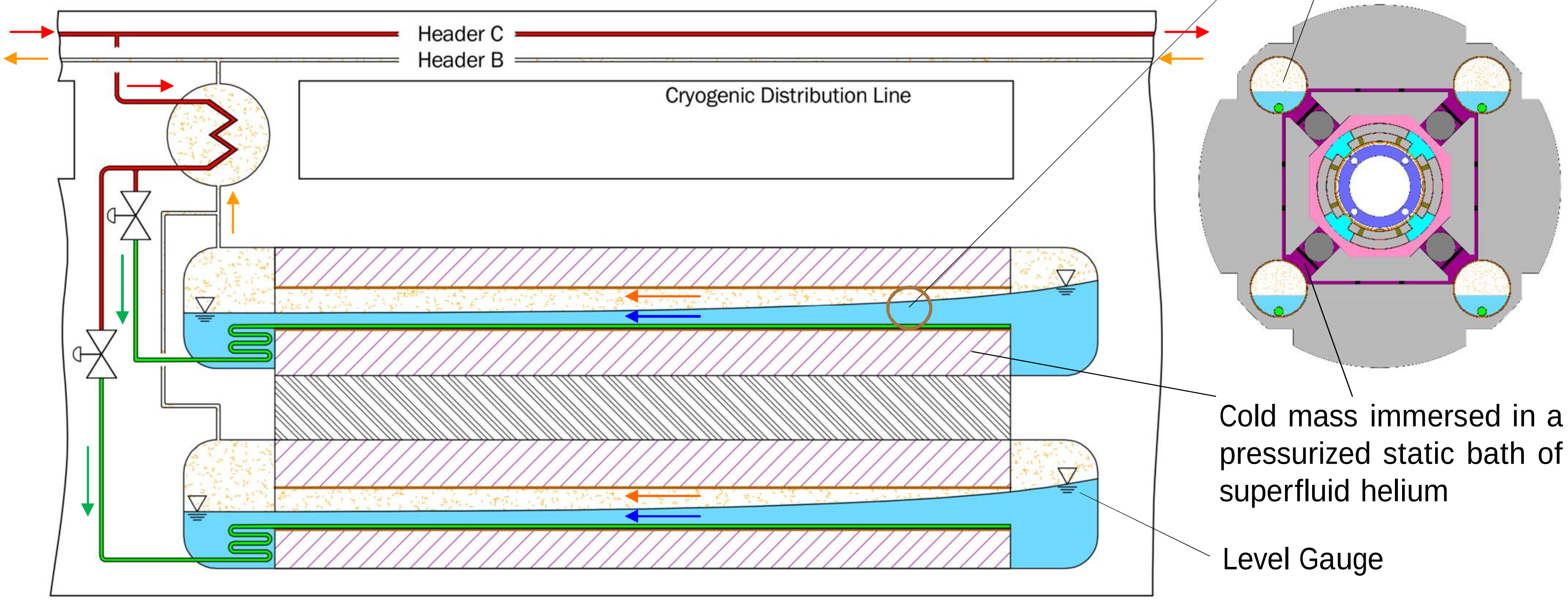
Helium discharged into header B:

$p_B = 16$ mbar

→ Determines stratified flow temperature $(= T\big|_{p_{Sat}=17\ \text{mbar}})$





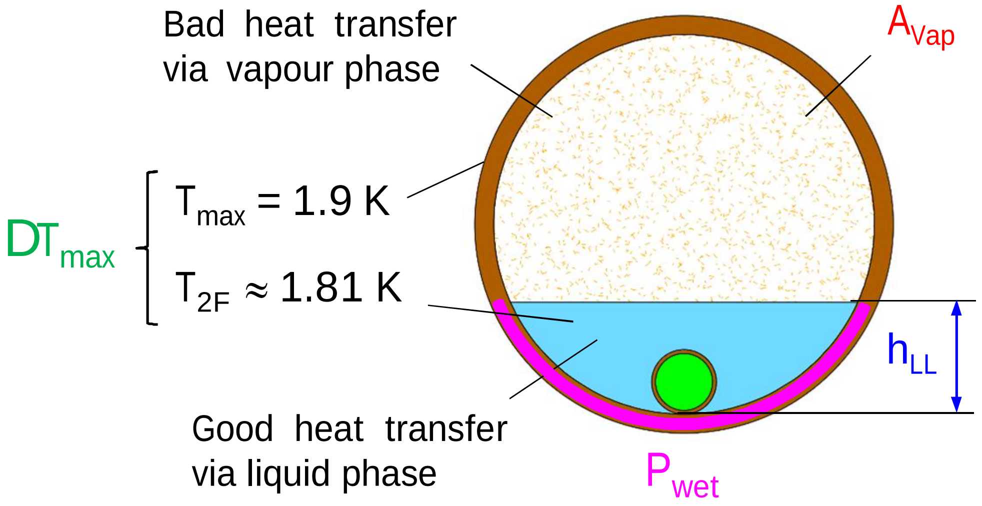


Cold mass immersed in a pressurized static bath of superfluid helium

Level Gauge

Two-phase cooling - The two main constraints

Heat extraction



$$\frac{\dot{q}}{n_{BHX}} = \frac{\Delta T_{max}}{R_{th}} P_{wet} = \frac{\Delta T_{max}}{R_{th}} 2\,r\,arccos\left(1-\frac{r}{h_{LL}}\right)$$

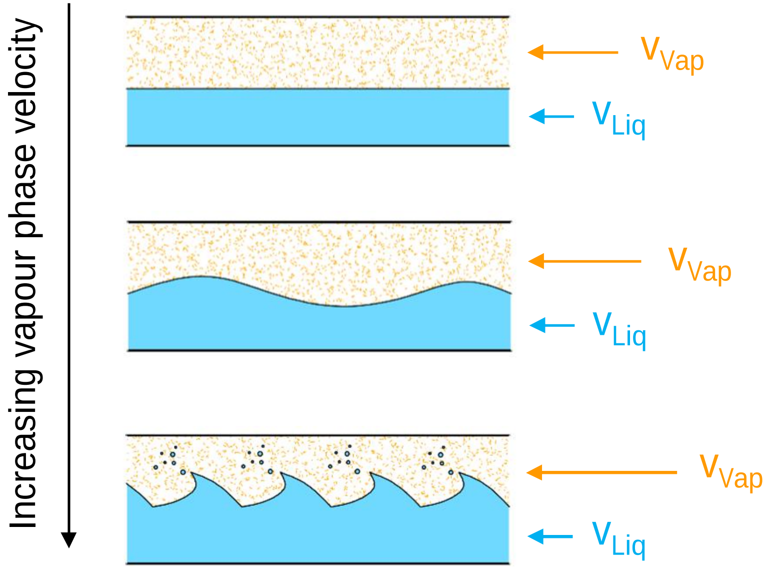
→

$$h_{LL} = r\left[1-cos\left(\frac{R_{th}\,\dot{q}}{2\,r\,n_{BHX}\,\Delta T_{max}}\right)\right]$$

Minimal h_{LL} for sufficient heat transfer

Vapour velocity

Relative movement between liquid and vapour phase determines shape of the surface:



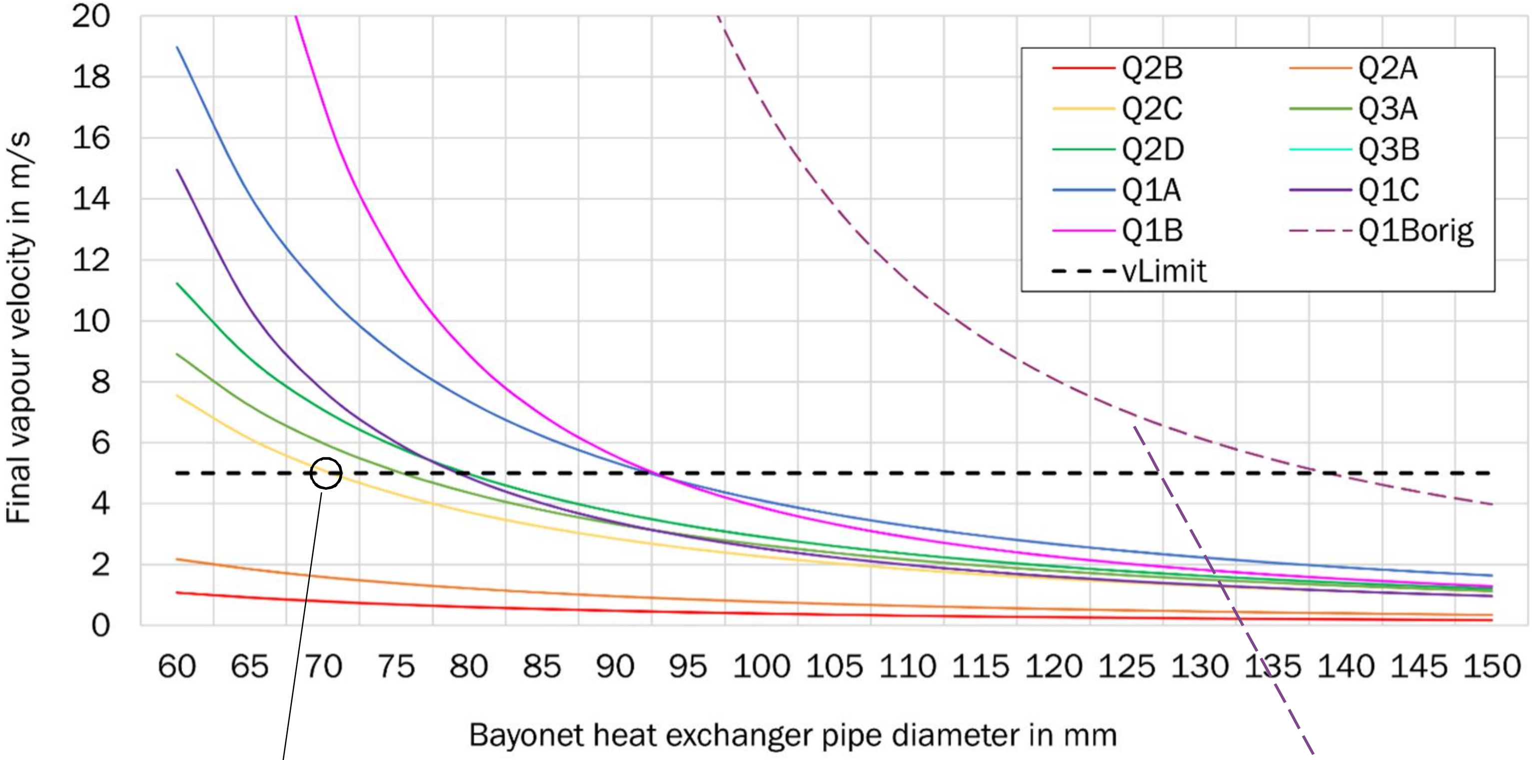
Maximal v_{Vap} determined in experimental setup

→

$$v_{Vap} = \frac{\dot{m}}{\rho_{Vap} A_{Vap}} = \frac{\dot{q}\,L}{n_{BHX}\,\rho_{Vap}\,(h''-h_{JT})\left[r^2\,arccos\left(1-\frac{h_{LL}}{r}\right)-(r-h_{LL})\sqrt{2rh_{LL}-h_{LL}^2}\right]} \leq 5\,m/s$$

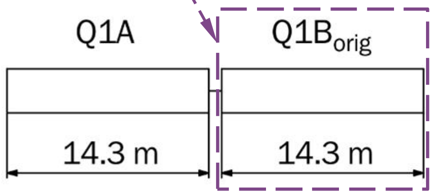
Two-phase cooling – Analytical estimations

Analytical estimation



Intersection point with helium 5 m/s-isotach yields minimal diameter

→ for Q2C the minimal inner diameter is about 70 mm



Two-phase cooling – Mathematical Model

Steady-State Calculation

Conditions:

- I. Longitudinal pressure drop in the two phases equal
- II. Solving for minimal HX pipe diameter
- III. Smooth stratified flow regime in HX pipe

Modelling 1D-equations:

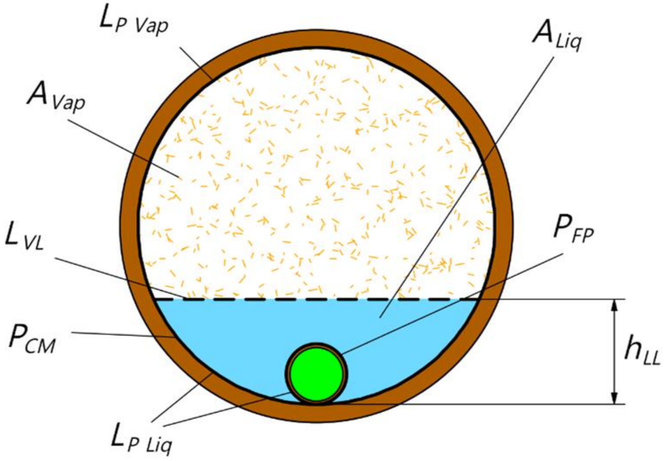
Mass balance: $$1)\ \pm\dot{m}\frac{d\xi}{dz} = \frac{d}{dz}\left(A_\Phi\,\rho_\Phi\,v_\Phi\right)$$

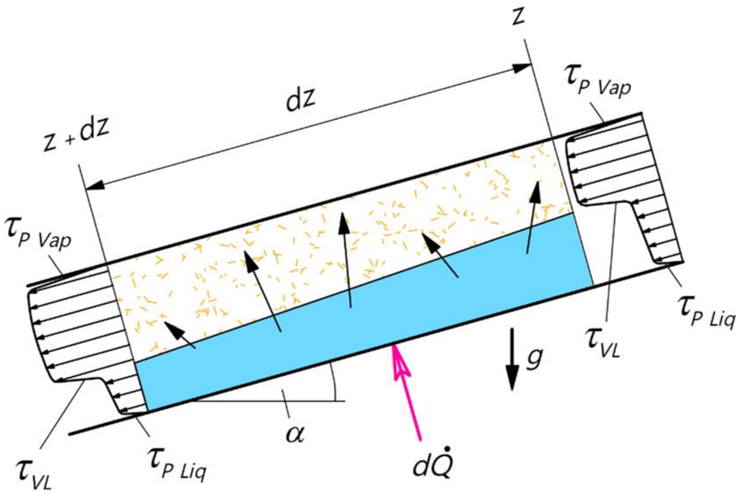
Momentum balance: $$2)\ \frac{d}{dz}\left(A_\Phi\,\rho_\Phi\,v_\Phi^2\right) = -A_\Phi\,\frac{dp_{IF}}{dz}\pm$$

$$\pm\tau_{VL}\,L_{VL} - \tau_{P\Phi}\,L_{P\Phi} + g\,A_\Phi\,\rho_\Phi\left(sin\alpha \pm cos\alpha\,\frac{dh_{LL}}{dz}\right) - \dot{m}\frac{d\xi}{dz}\Delta v_{VL}$$

Thermal energy balance: $$3)\ \left(h'' - h'\right)\,d\xi = \frac{\dot{q}_{CM}\,P_{CM} + \dot{q}_{FP}\,P_{FP}}{\dot{m}}dz$$

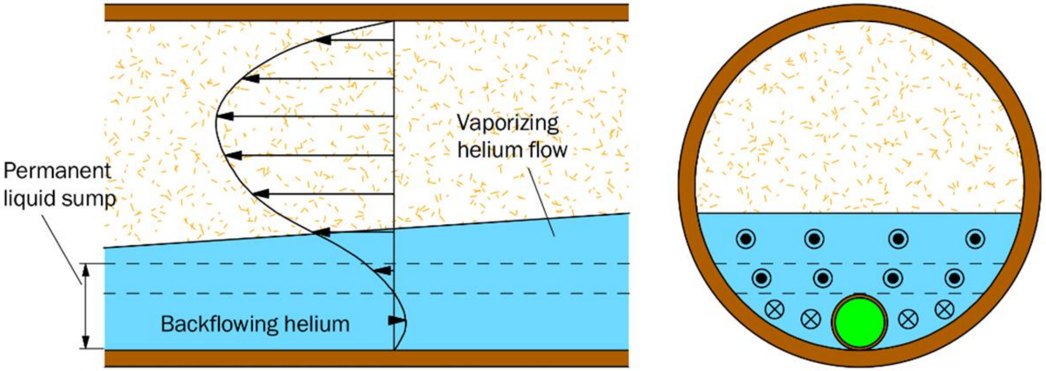
Thermal conduction in superfluid helium: $$4)\ \frac{dT}{dz} = -f_k\,\dot{q}^m$$





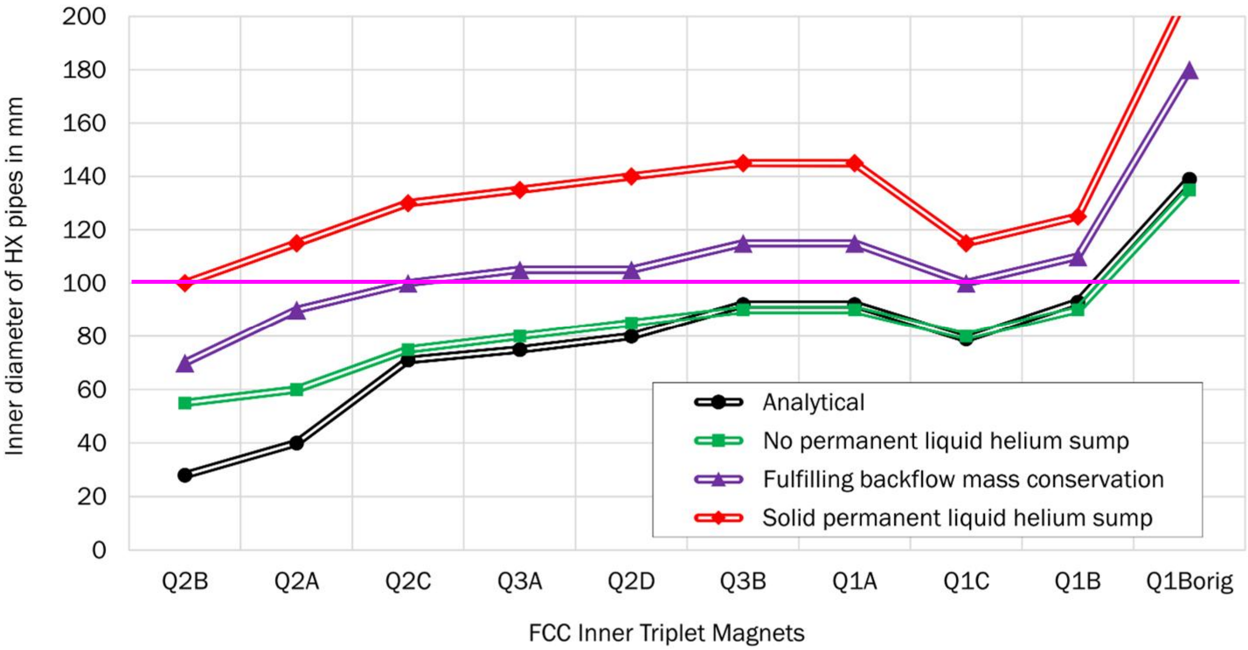
Two-phase cooling – Numerical results

Numerical solutions

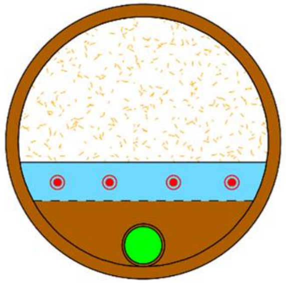


Comparisons with former experimental results indicate an over-estimation of the wave generation of the model ($v_{Vap} < 5m/s$)

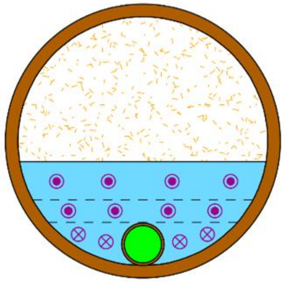
→ The requested maximal diameter of 100 mm seems to be feasible



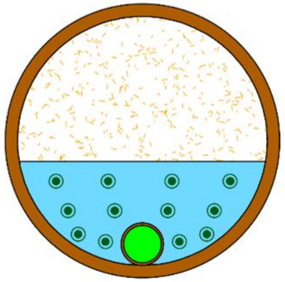
Solid permanent liquid helium sump



Fullfilling backflow mass conservation



No permanent liquid helium sump



FCC Inner Triplets – Conduction Cooling

The conduction scheme

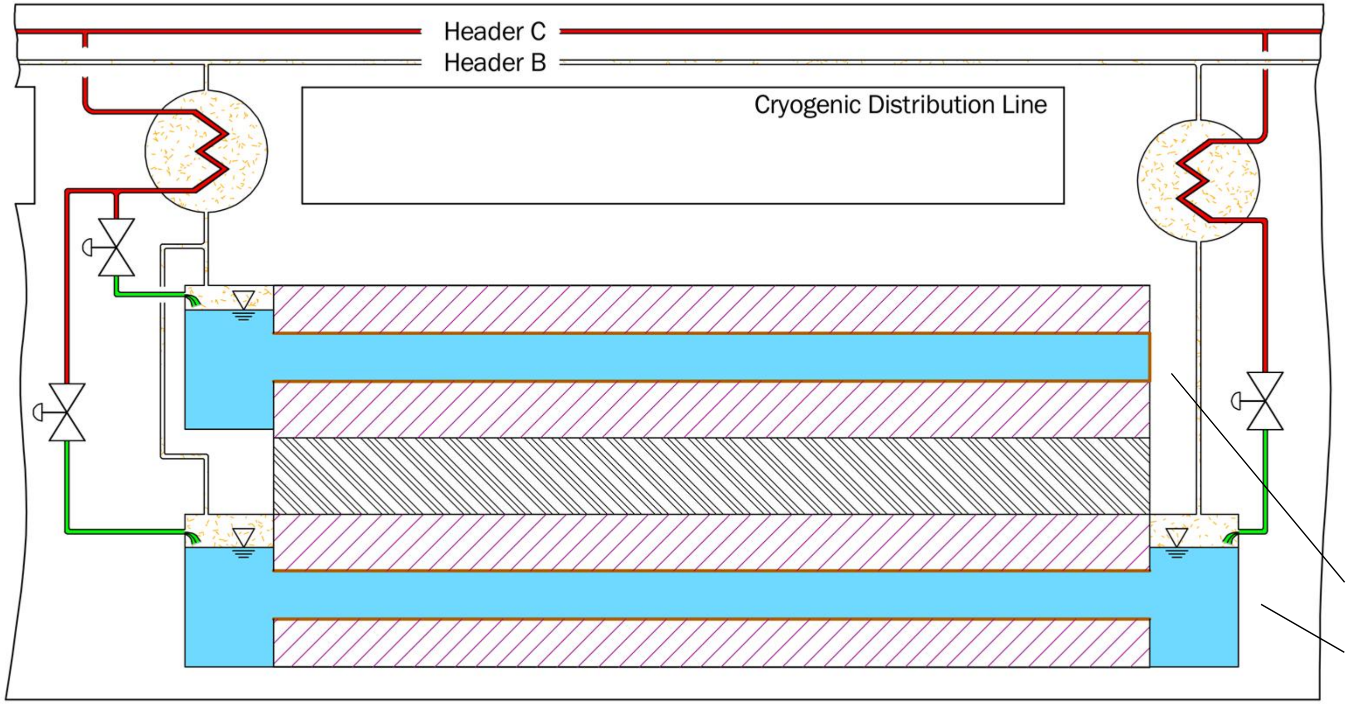
$$\Delta T_{max} = \int_0^{L_{Mag}} \frac{(\dot{q}\,x)^m \; f_k}{A^m} dx = \frac{\dot{q}^m \, L_{Mag}^{m+1} \, f_k}{A^m \; (m+1)}$$

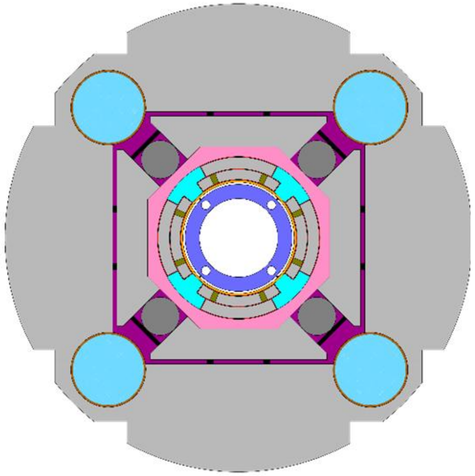
Needed cross section area for heat conduction α $L^{1.3}$

→ Conduction cooling is advantegeous for short magnets (like in the Inner Triplets)

→

$$A^m = \frac{\dot{q}^m \, L_{Mag}^{m+1} \, f_k}{\Delta T_{max} \; (m+1)} \rightarrow d = \sqrt{\frac{4\,\dot{q}}{\pi \, n_{BHX}} \sqrt[m]{\frac{L_{Mag}^{m+1} \, f_k}{\Delta T_{max} \; (m+1)}}} \propto L_{Mag}^{\frac{m+1}{2m}} \sqrt{\dot{q}} \approx L_{Mag}^{0.65} \dot{q}^{0.5}$$





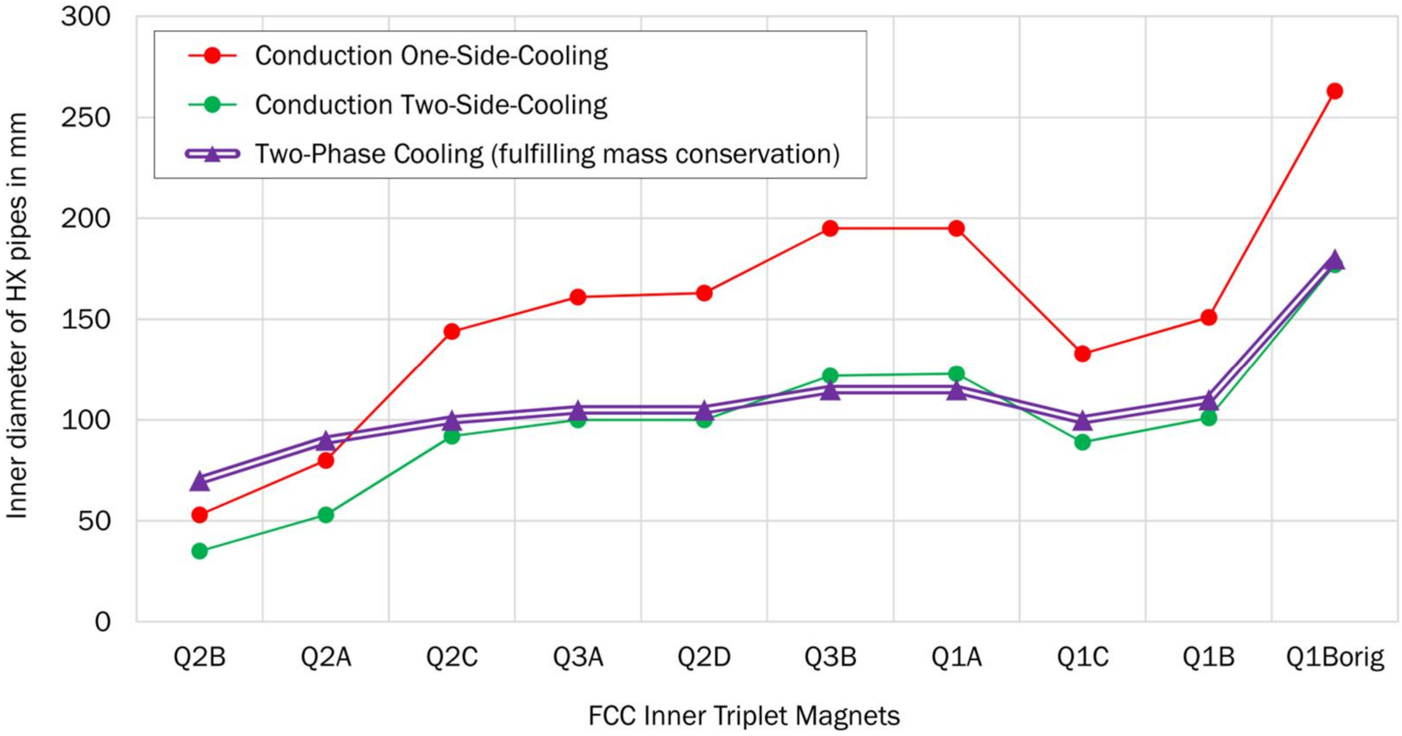
Two possible designs:

Option 1: One-Side-Cooling

Option 2: Two-Sides-Cooling

Conduction cooling – Numerical results

Numerical solutions



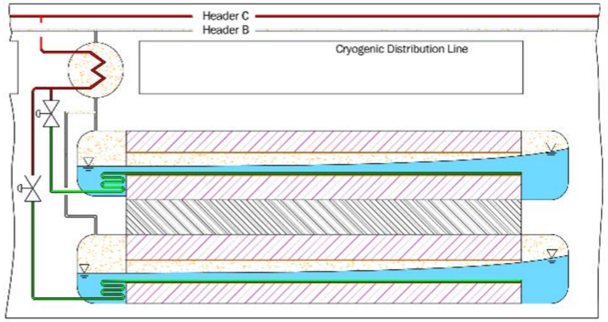
- The Two-Side Conduction cooling option and the Two-Phase cooling need similar space in the cold mass for cryogenics - both concepts seem to be in the feasibility's range
- The choice could be made by different aspects (required space between adjacent magnets, transient behavior, controlling effort, reliability, ...)

Summary & Outlook

Summary

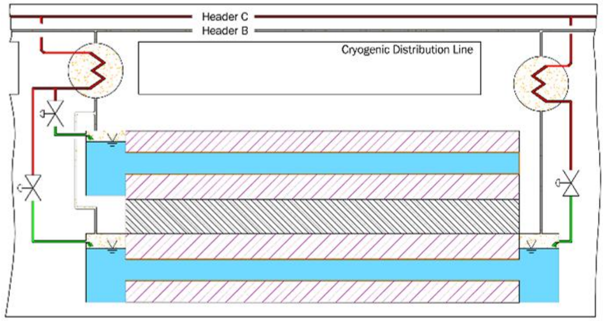
- Very high, but strongly non-uniform heat loads on the FCC Inner Triplet Magnets challenge the cryogenics design (structure was changed to be able to design a reliable cooling system for the available space)
- Two well-established cooling concepts were investigated

Two-Phase Flow Cooling



+ Less space needed for cryogenics

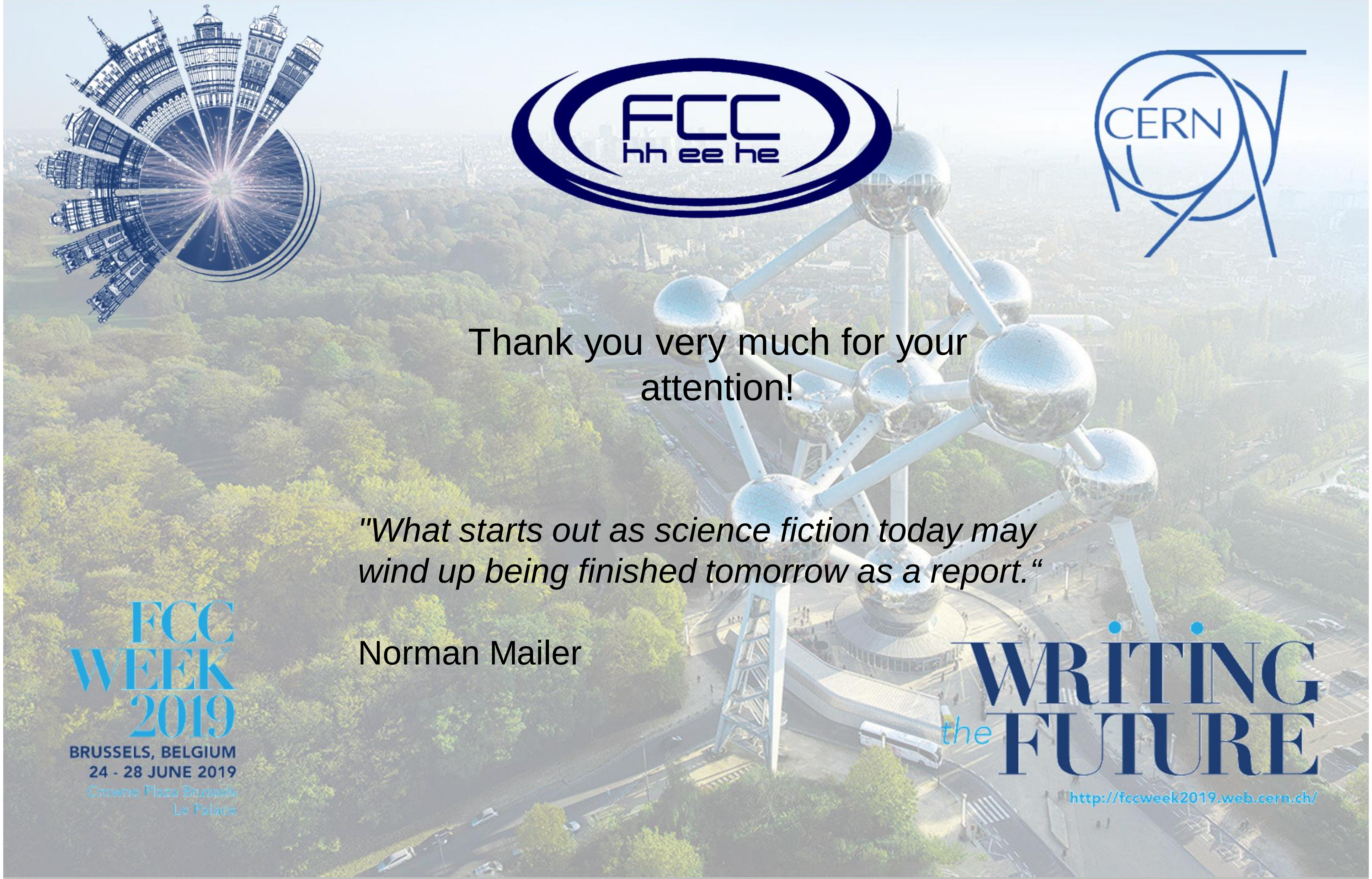
Pure Conduction Cooling



+ Robust concept and simple controlling

- With both cooling concepts the space requirements are in the range of feasibility – the possibility of choosing between different designs provides freedom of choice for taking into account other aspects as well

The end



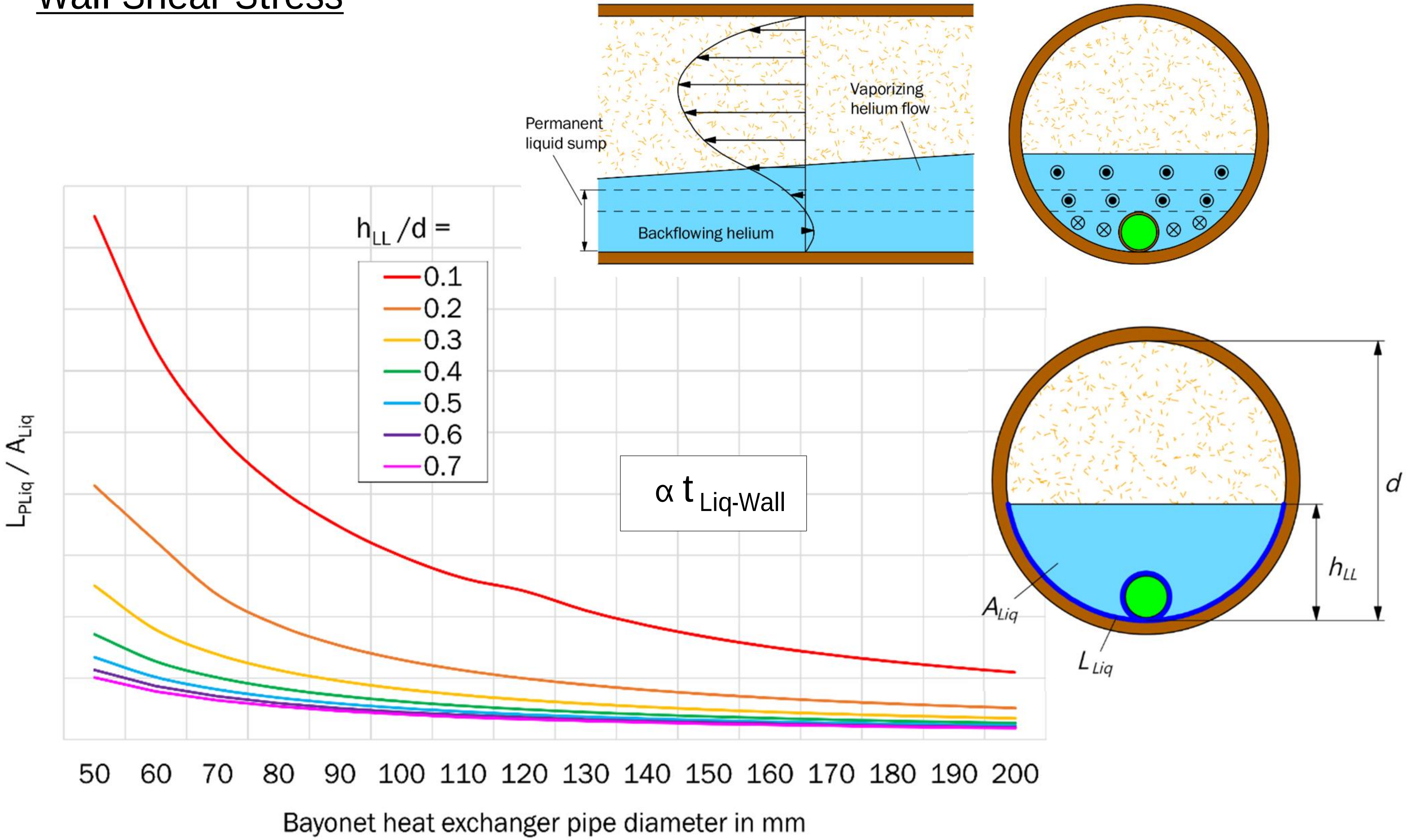
Thank you very much for your attention!

"What starts out as science fiction today may wind up being finished tomorrow as a report.“

Norman Mailer

Supplemental – Wall Shear Stress (Liquid)

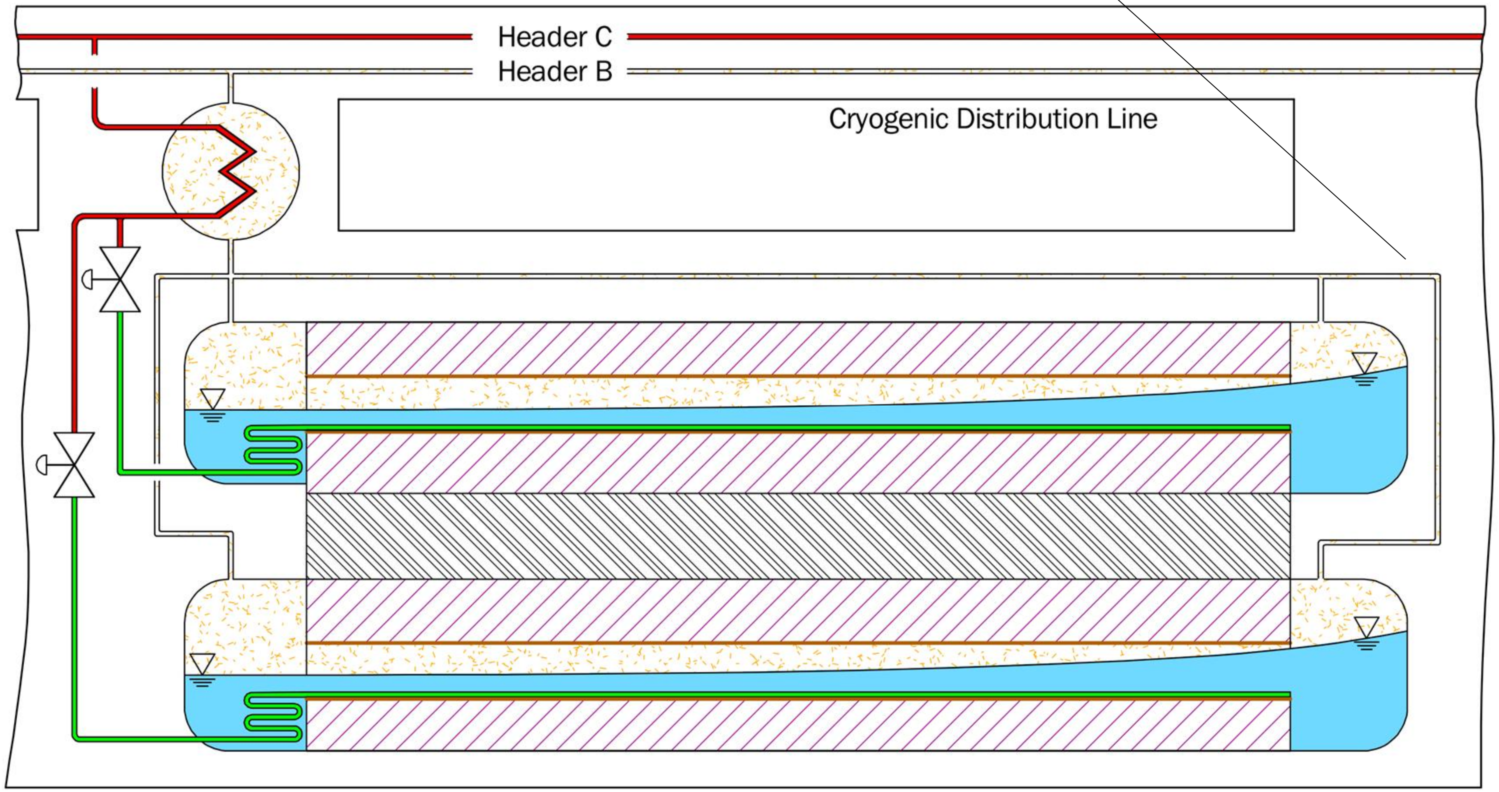
Wall Shear Stress



$\alpha \; t_{\text{Liq-Wall}}$

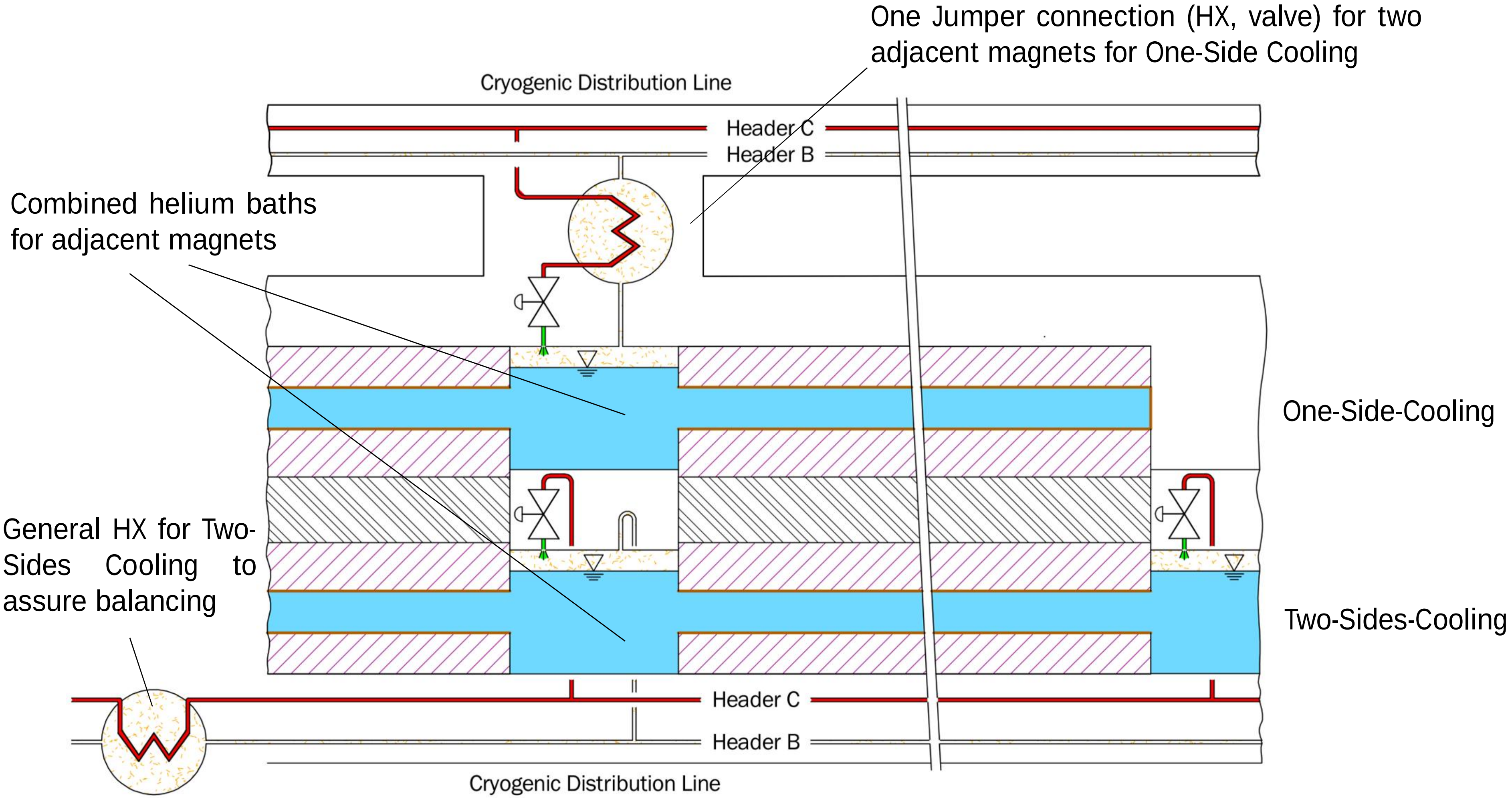
Two-Sides vapour extraction

Two-Sides vapour extraction could decrease bayonet HX diameter size requirement



Supplemental – Conduction Cooling Interconnections

Conduction Cooling Arrangements



One Jumper connection (HX, valve) for two adjacent magnets for One-Side Cooling

Combined helium baths for adjacent magnets

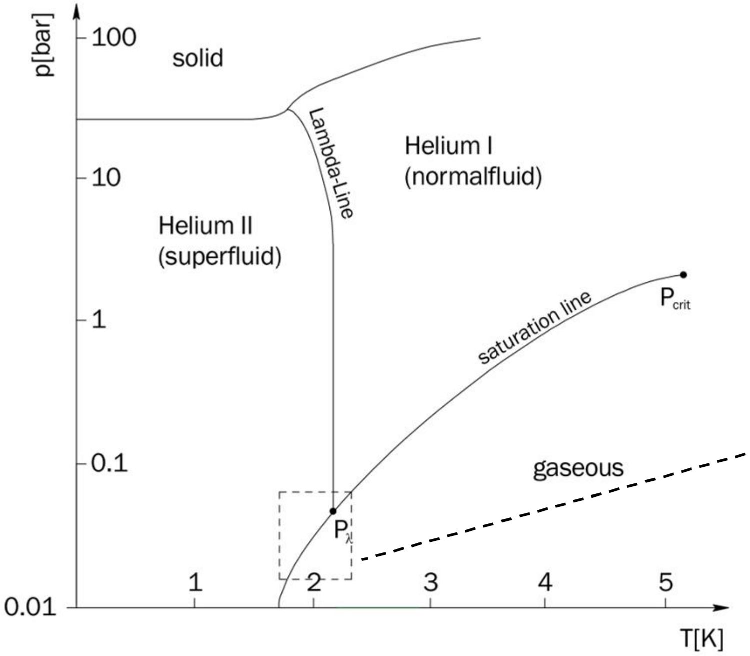
General HX for Two-Sides Cooling to assure balancing

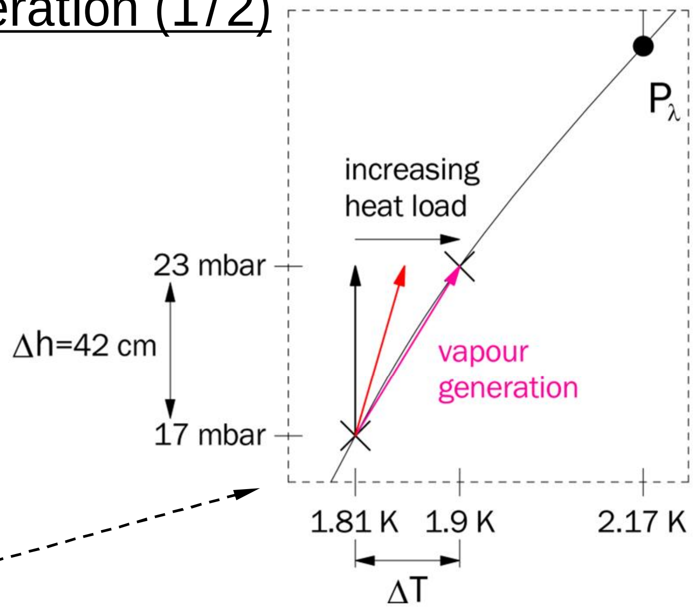
One-Side-Cooling

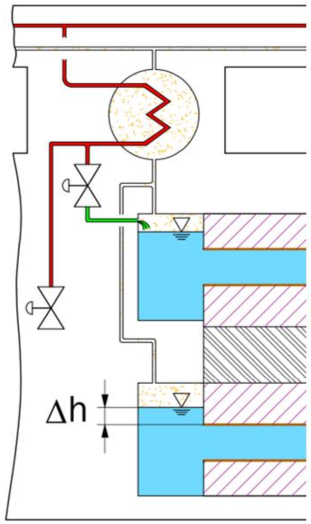
Two-Sides-Cooling

Supplemental – Conduction Cooling Vapour Generation (1/2)

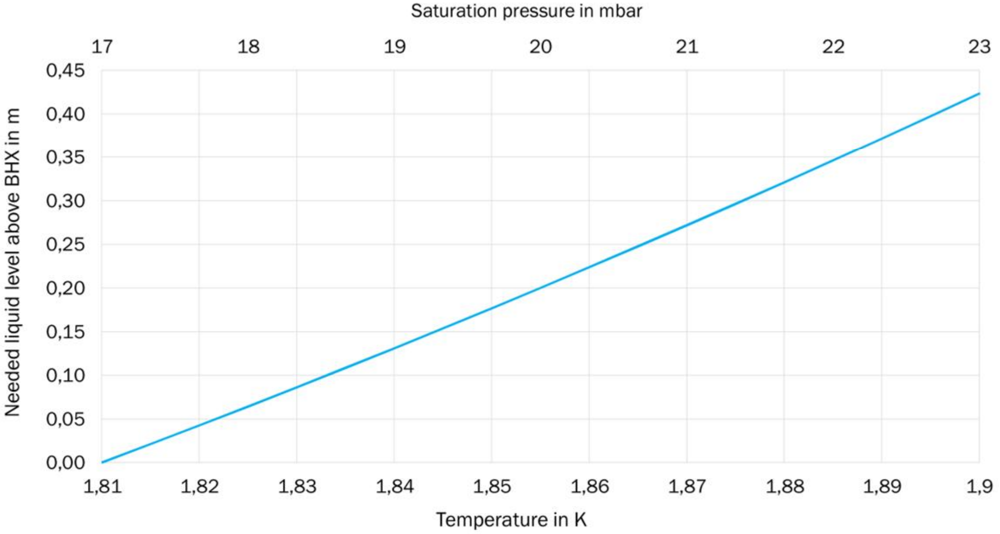
Conduction Cooling Vapour Generation (1/2)





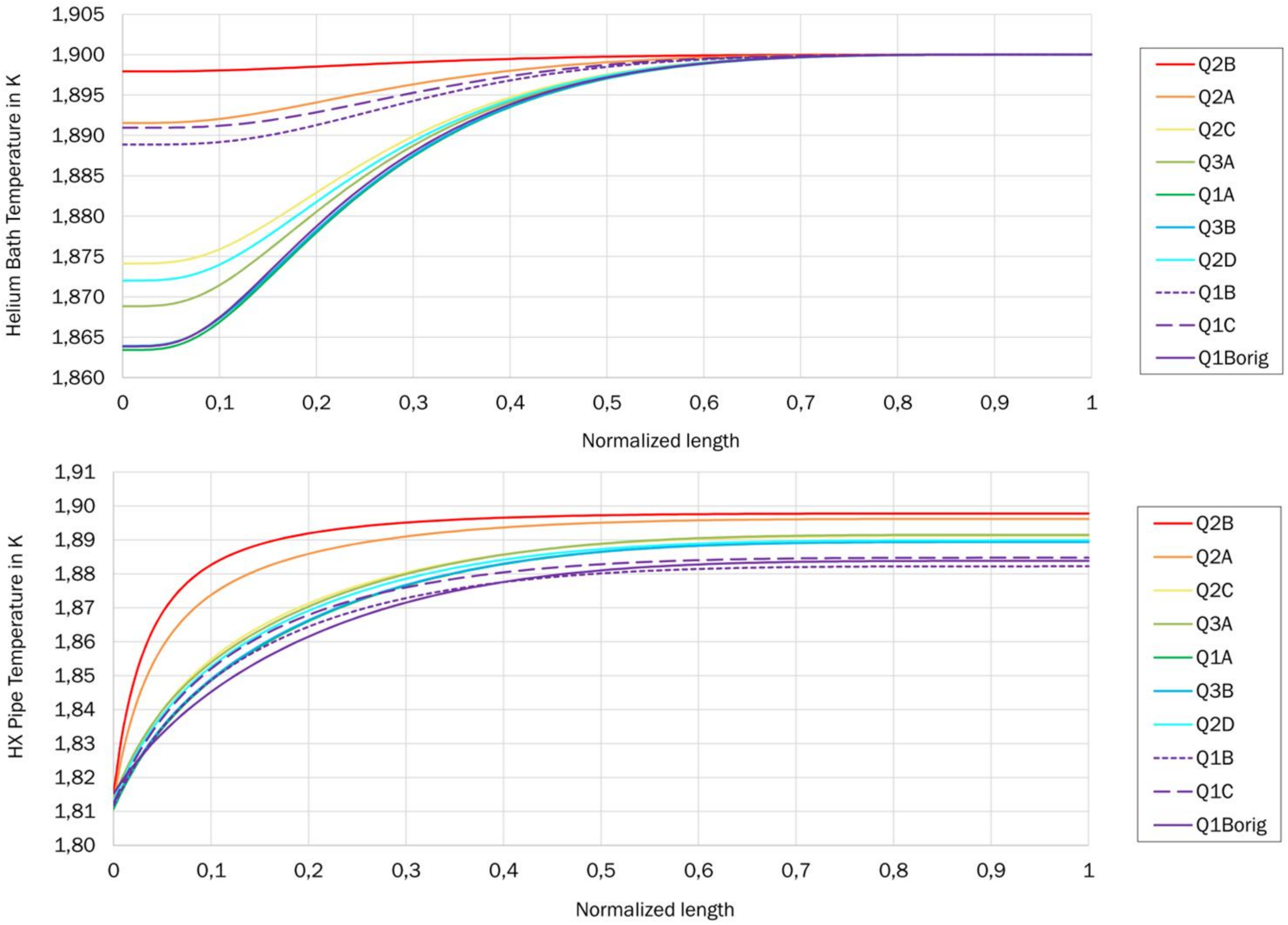


- ρ_{Liq} = 145 kg/m^3
- HX pipe diameters calculated to reach a temperature of ≈ 1.9 K
- Minimal pressure head needed to avoid saturation line (≈ 42 cm)



Supplemental – Conduction Cooling Vapour Generation (2/2)

Conduction Cooling Vapour Generation (2/2)



- Liquid helium temperature in HX pipe < 1.9 K for radial heat transfer
- Two parallel longitudinal heat fluxes (in HX pipe and static helium bath)
- Radial driving temperature difference increases towards outlet
- Limit determined by the magnets Q1A and Q3B (T = 1.887 K → 30 – 40 cm head)

Mixed Cooling

High-loaded magnets: Two-Sides Conduction Cooling

Low-loaded magnets: Combined bayonet heat exchanger cooling

High-loaded magnets: Two-Sides Conduction Cooling