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

Dimitri Delikaris, Claudio Kotnig, Laurent Tavian

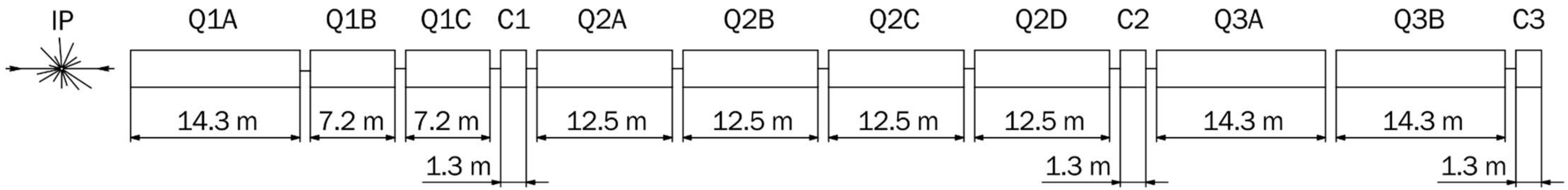
FCC WEEK 2019
BRUSSELS, BELGIUM
24 - 28 JUNE 2019
Crowne Plaza Brussels
Le Palace

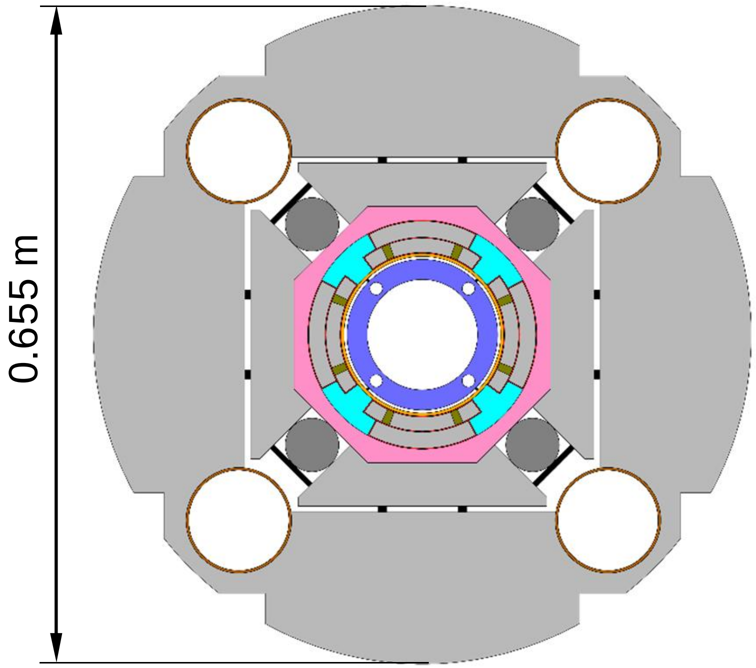
WRITING the FUTURE

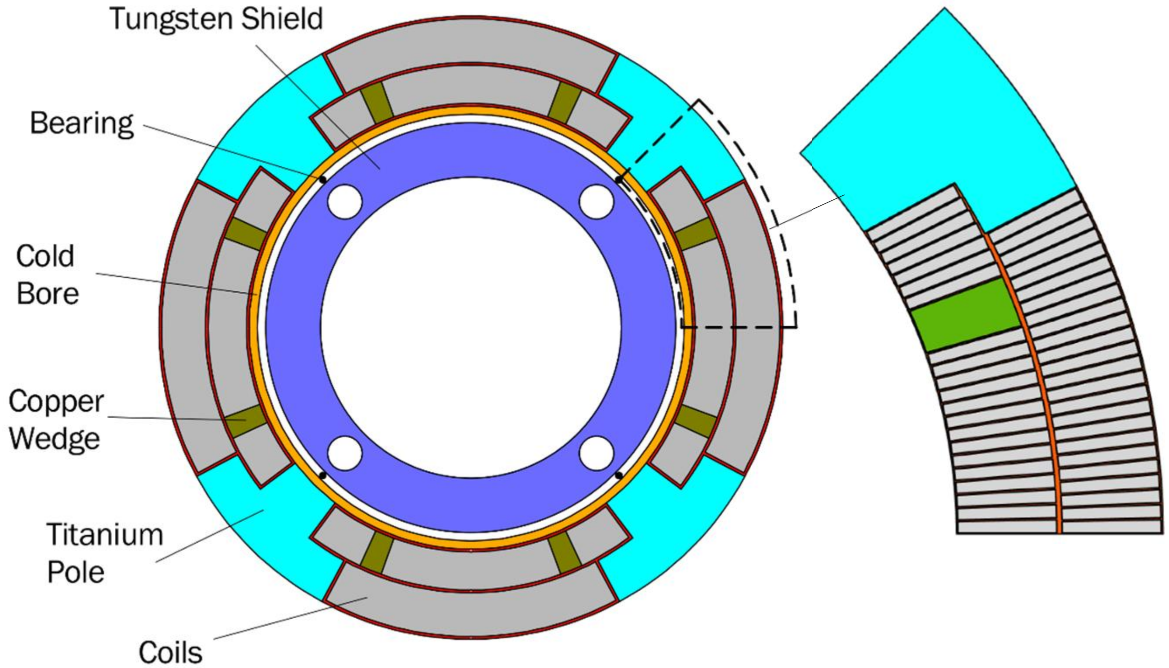
http://fccweek2019.web.cern.ch/

The FCC-hh Inner Triplets

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

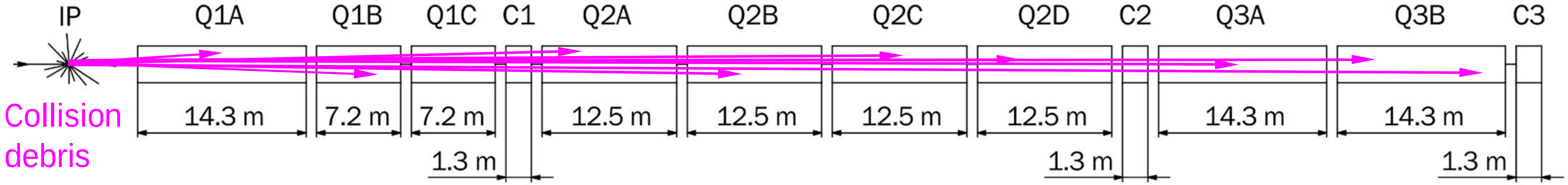


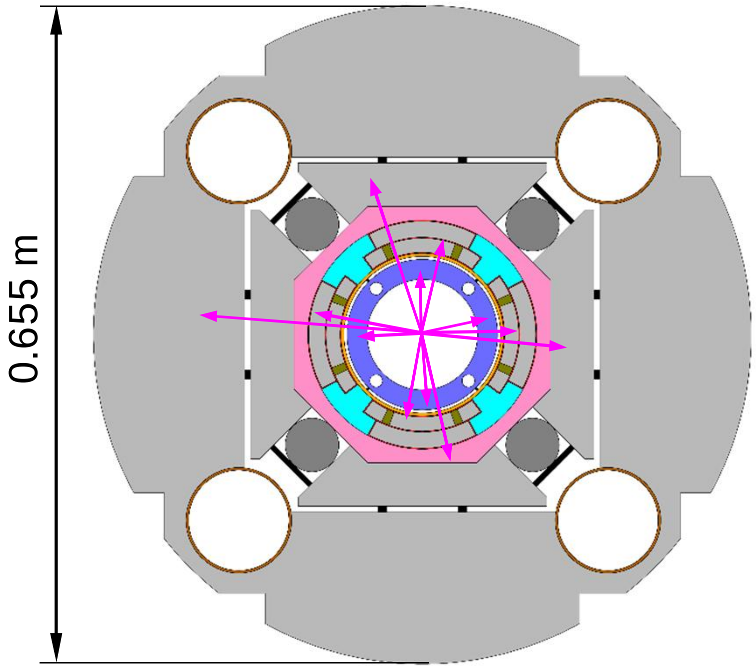


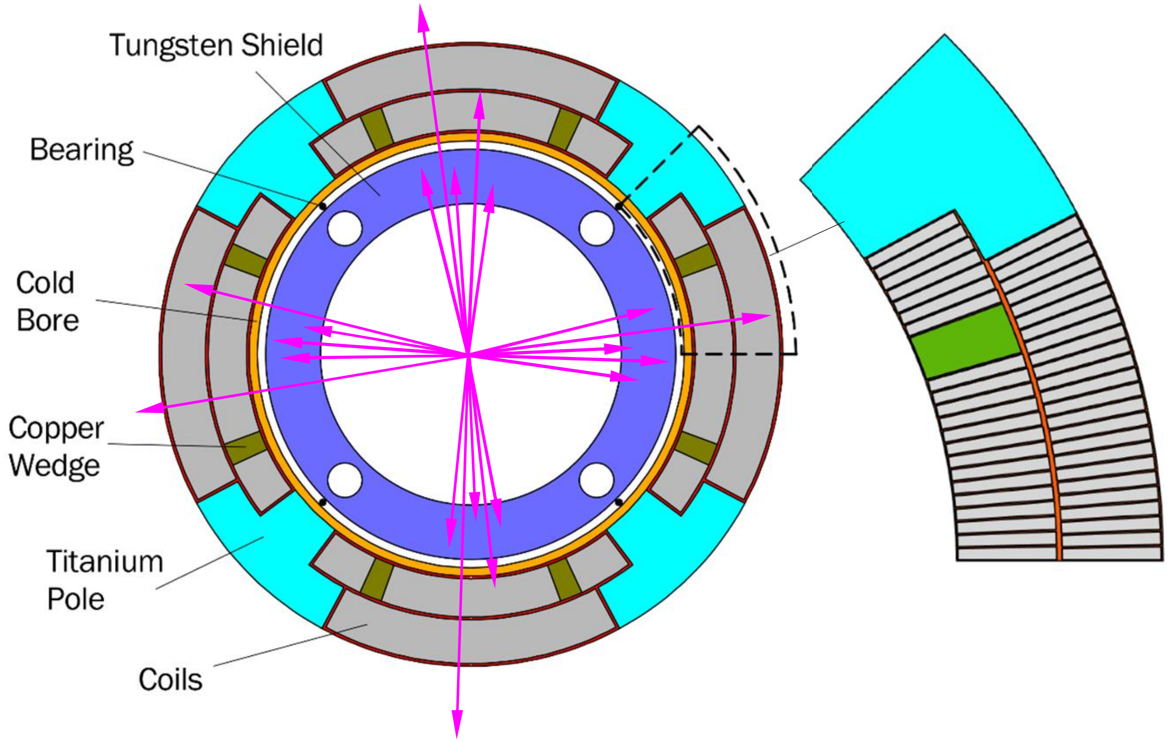


The FCC-hh Inner Triplets

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



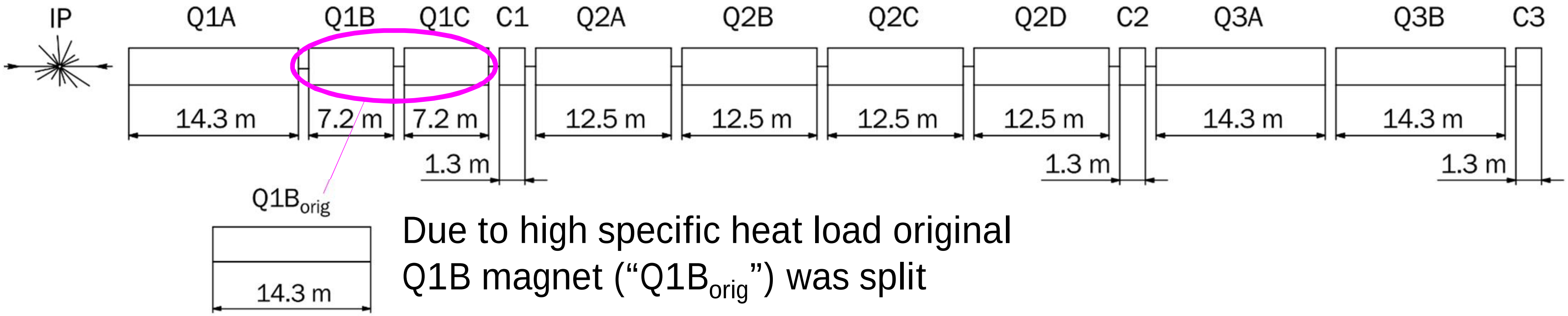




Rapid Reaction Team

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

Heat Load on the Tungsten Shield

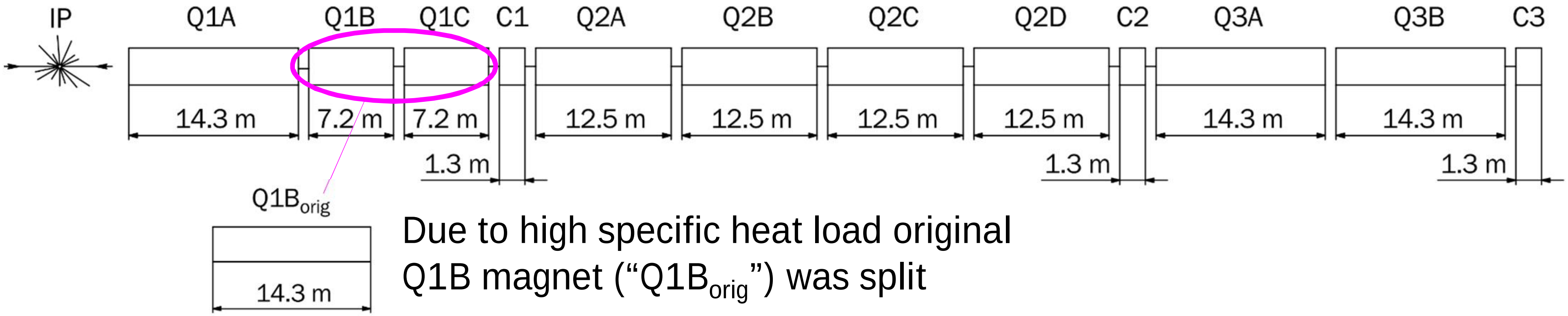


Due to high specific heat load original Q1B magnet (“$Q1B_{orig}$”) was split

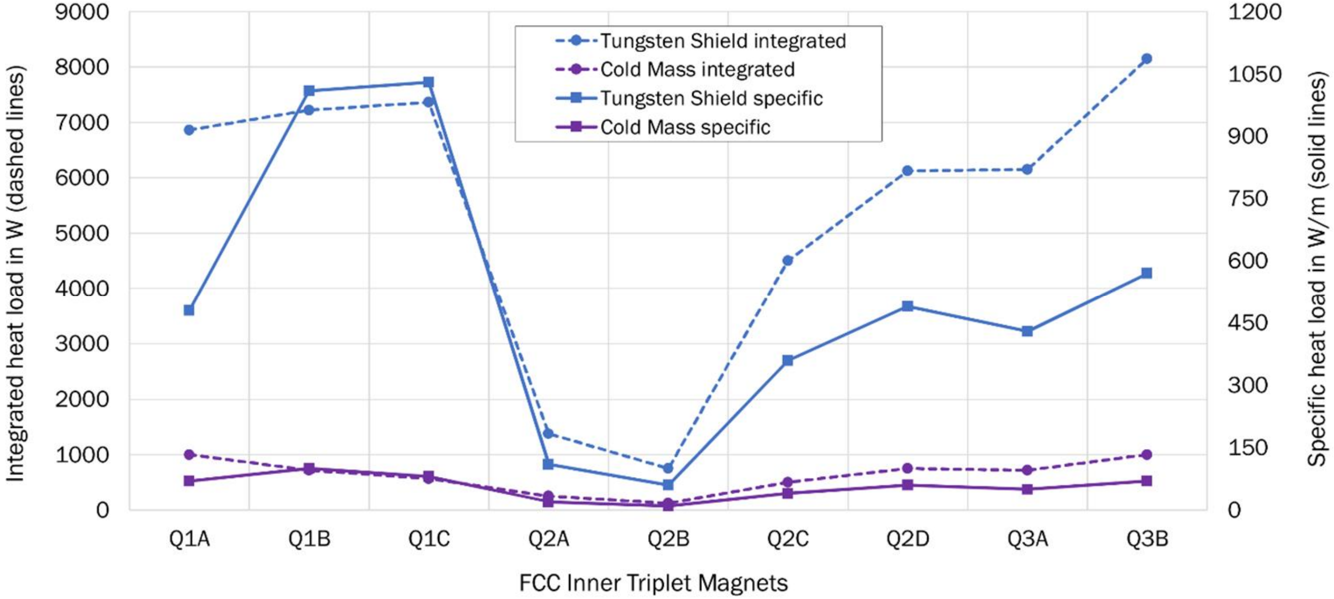
Rapid Reaction Team

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

Heat Load on the Tungsten Shield



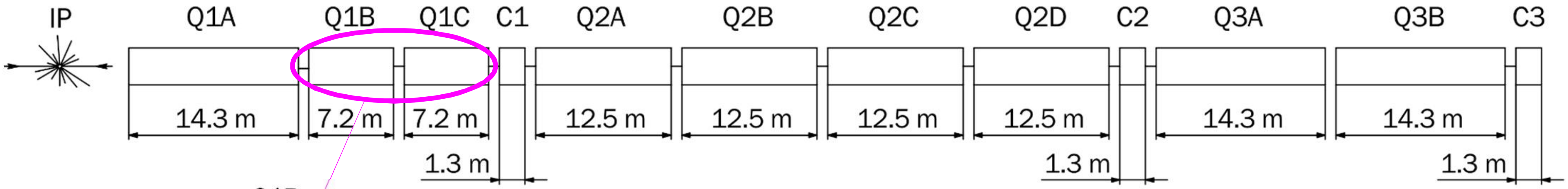
Due to high specific heat load original Q1B magnet (“$Q1B_{orig}$”) was split



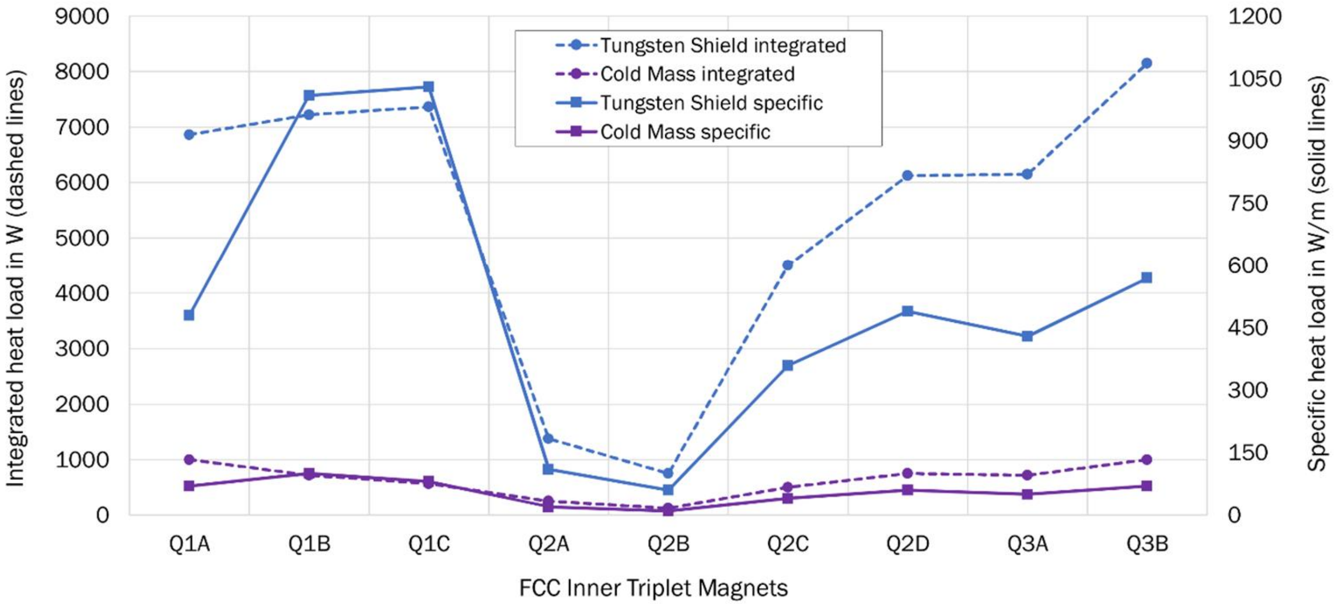
Rapid Reaction Team

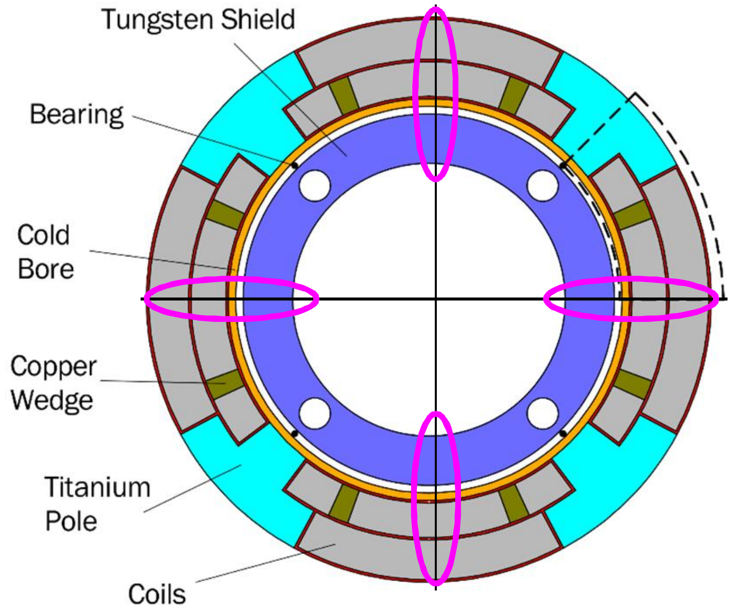
Besana MI, Cerutti F, Delikaris D, Humann B, Martin R, Schörling D, Tavian L

Heat Load on the Tungsten Shield



Due to high specific heat load original Q1B magnet ("$Q1B_{orig}$") was split



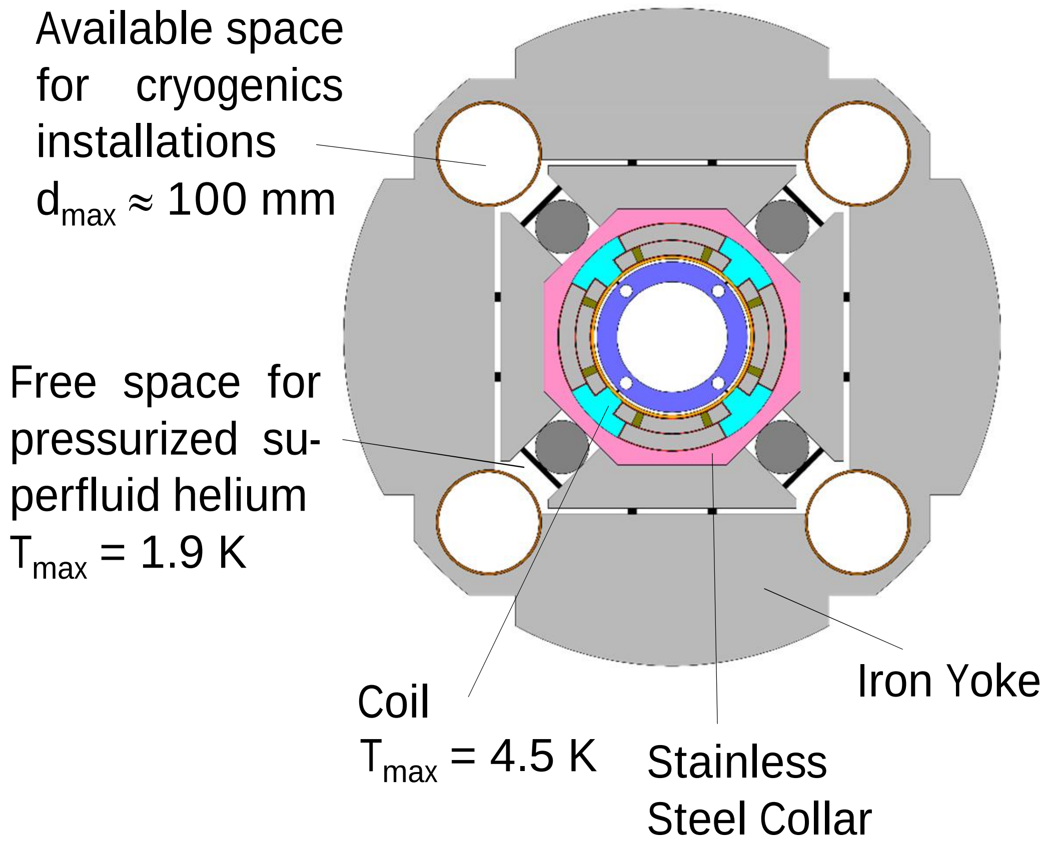


- Large cooling channels in tungsten shield possible (due to impact distribution)

- Tungsten Shield cooling between 40 – 60 K (compared to 1.8 K of Cold Mass)

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

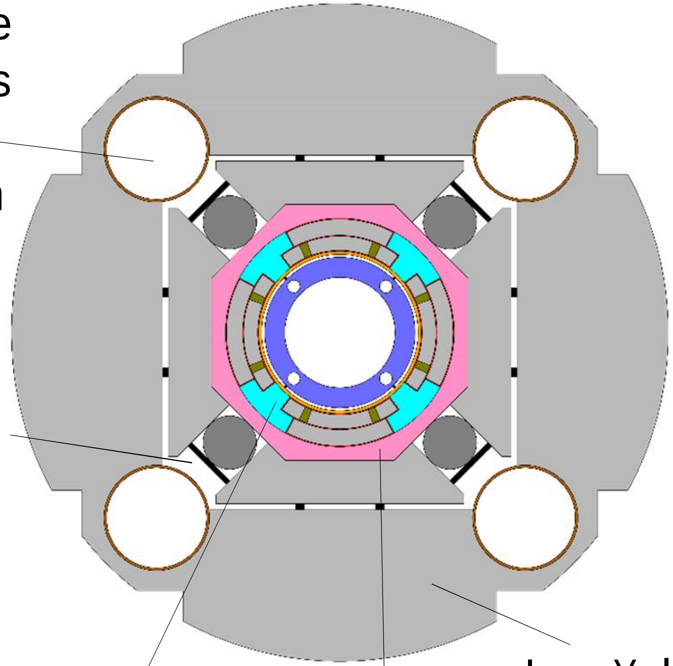


Heat Load on the Cold Mass

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

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

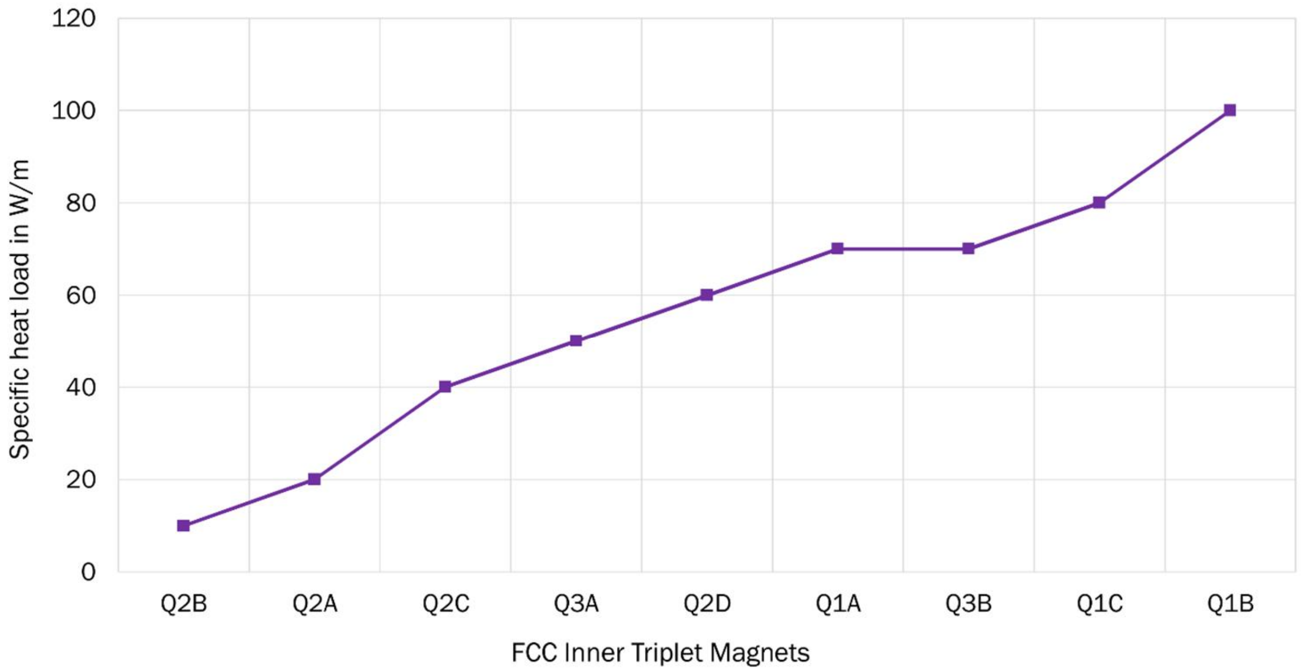
Free space for pressurized superfluid helium $T_{max} = 1.9$ K



Coil $T_{max} = 4.5$ K

Stainless Steel Collar

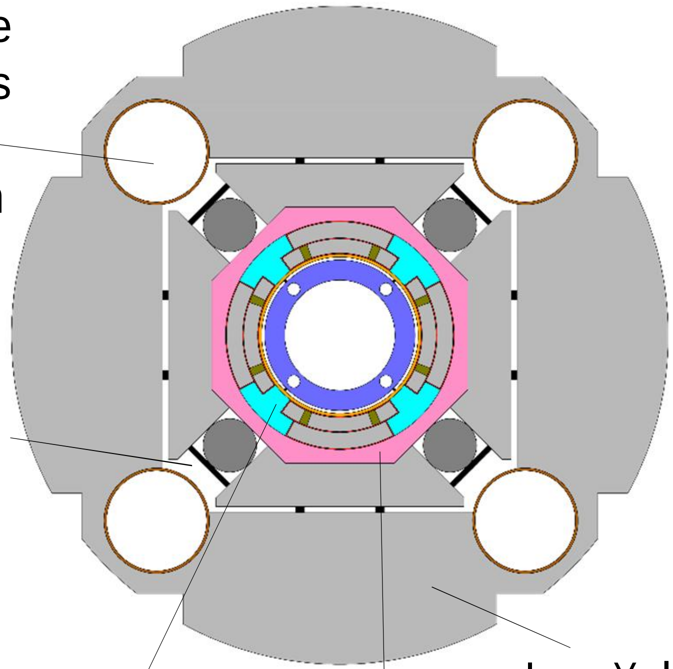
Iron Yoke

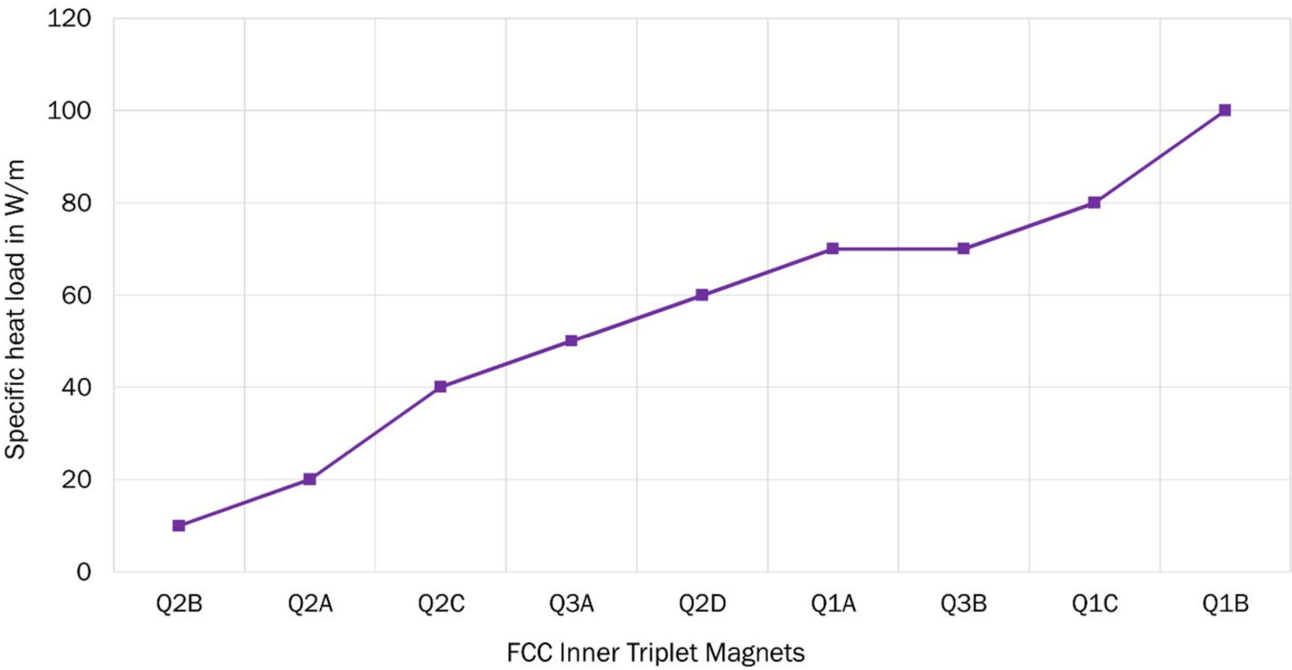


Heat Load on the Cold Mass

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

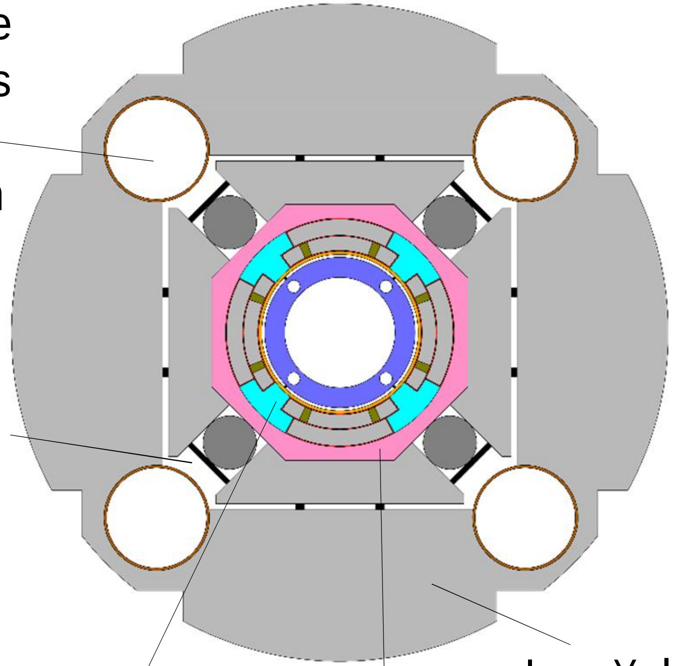


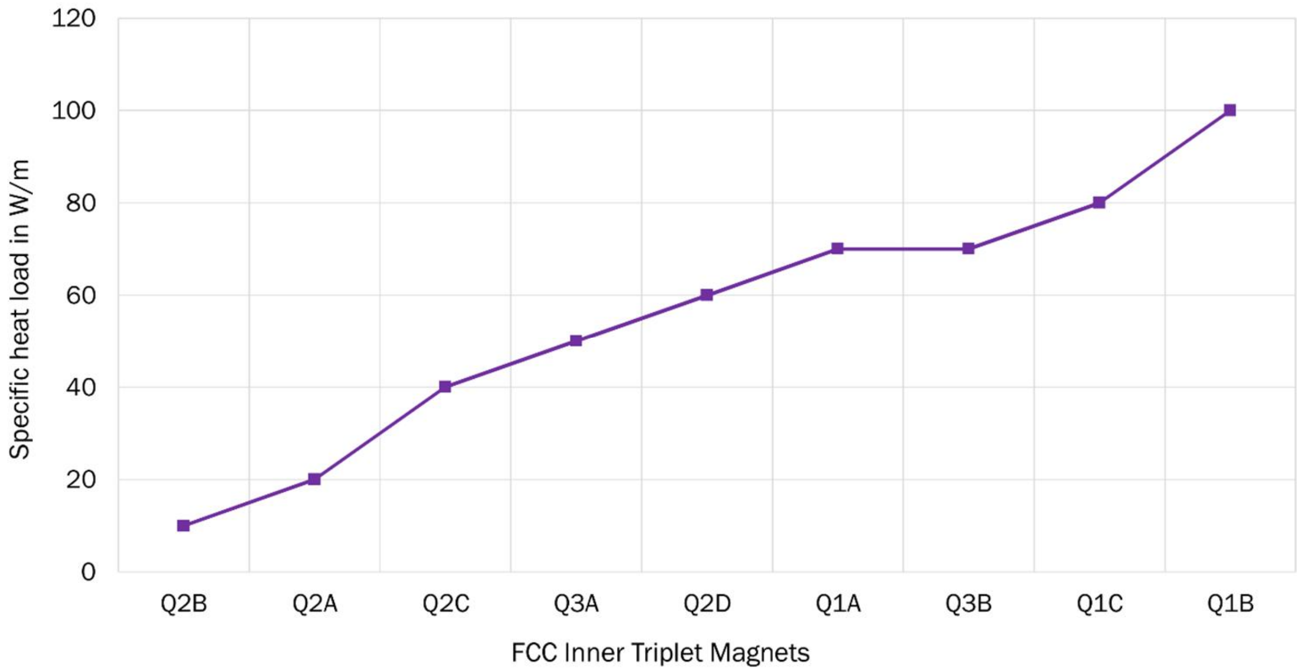


Heat Load on the Cold Mass

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

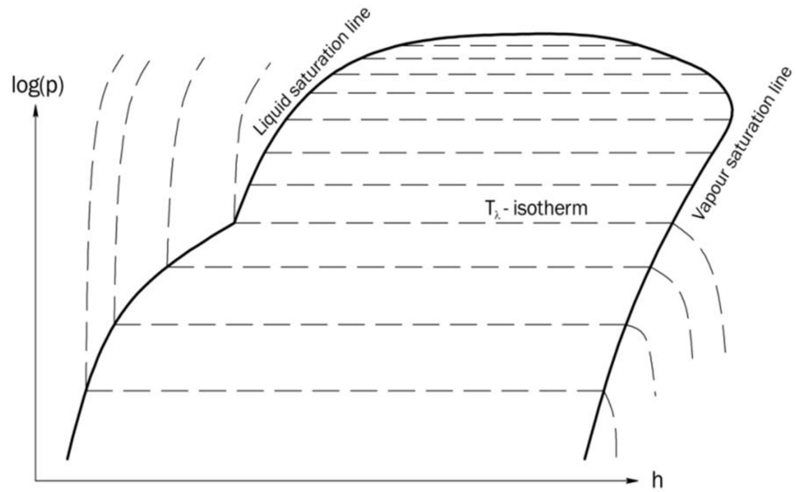


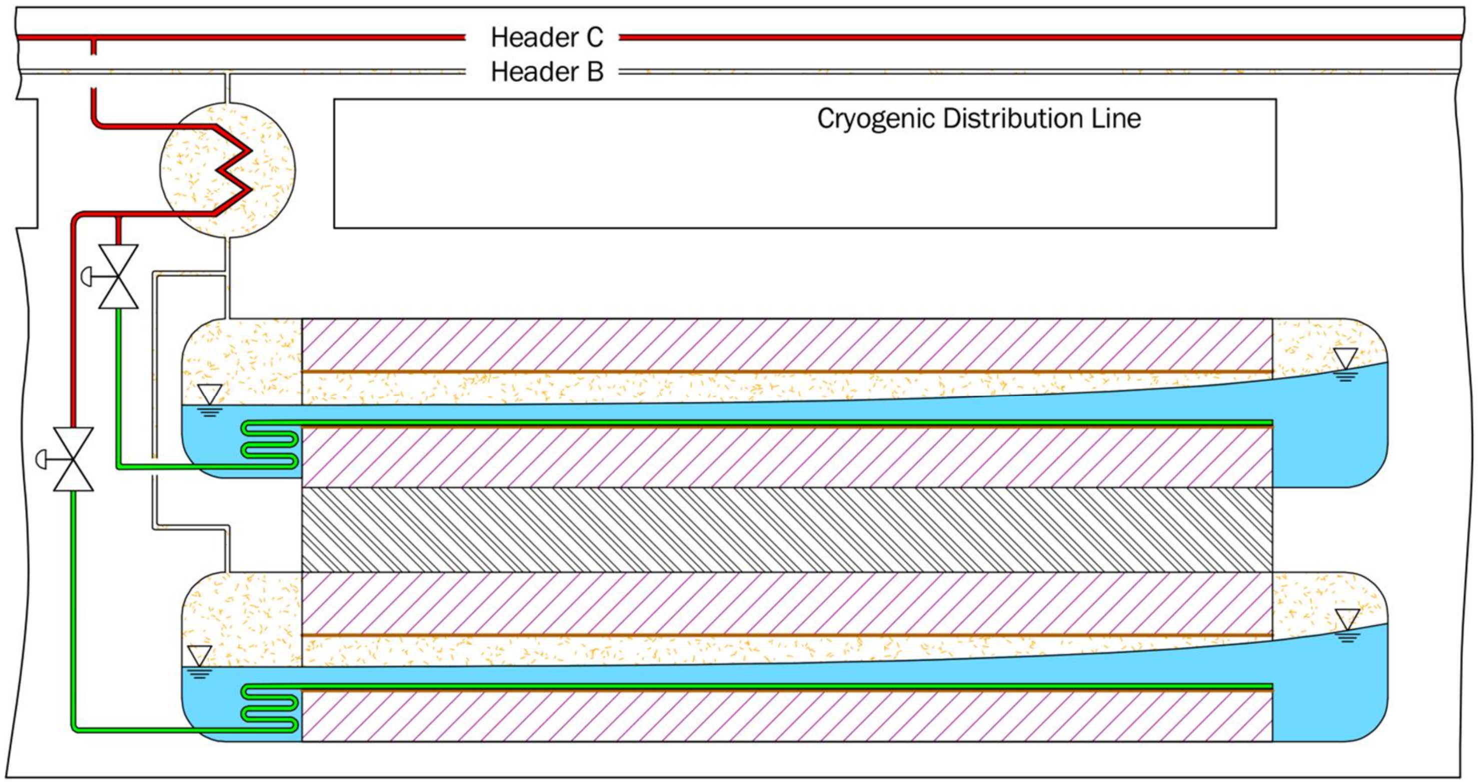


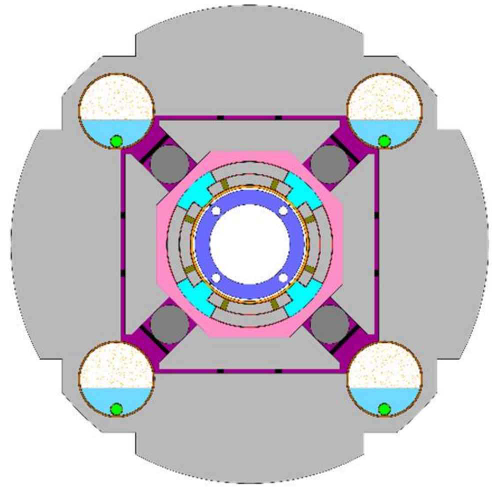
Two approved cooling concepts with superfluid He:

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

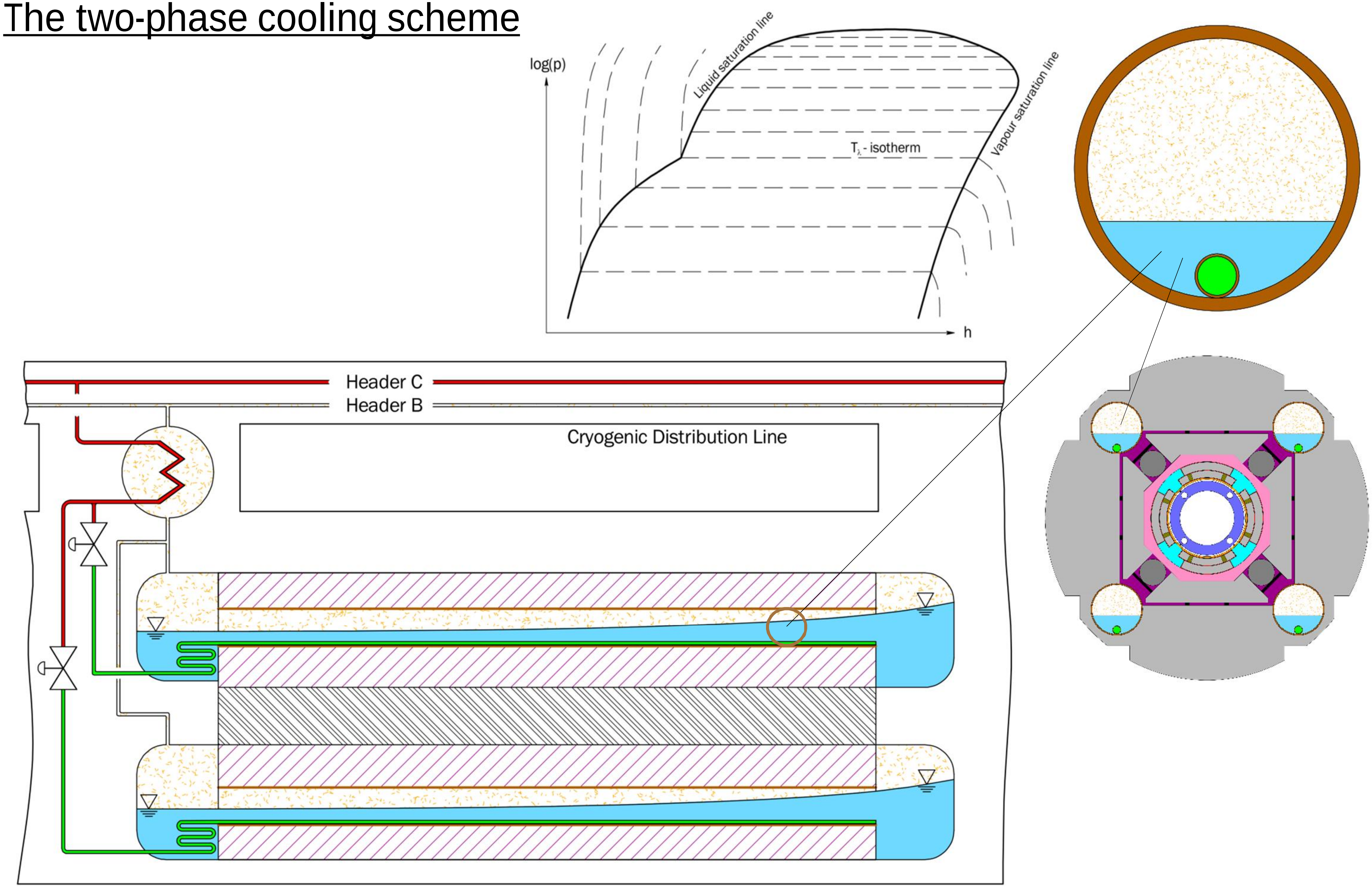
The two-phase cooling scheme



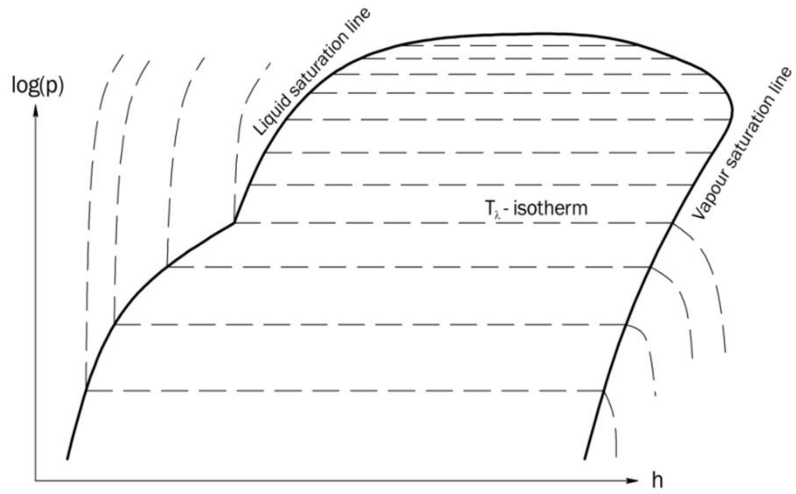


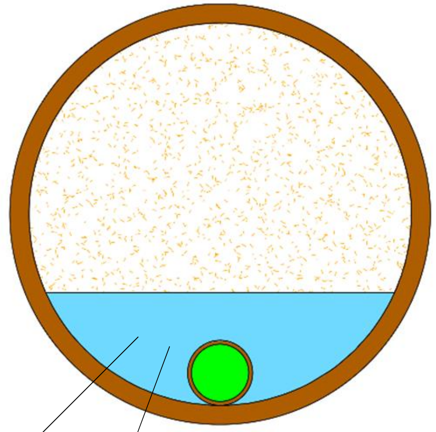


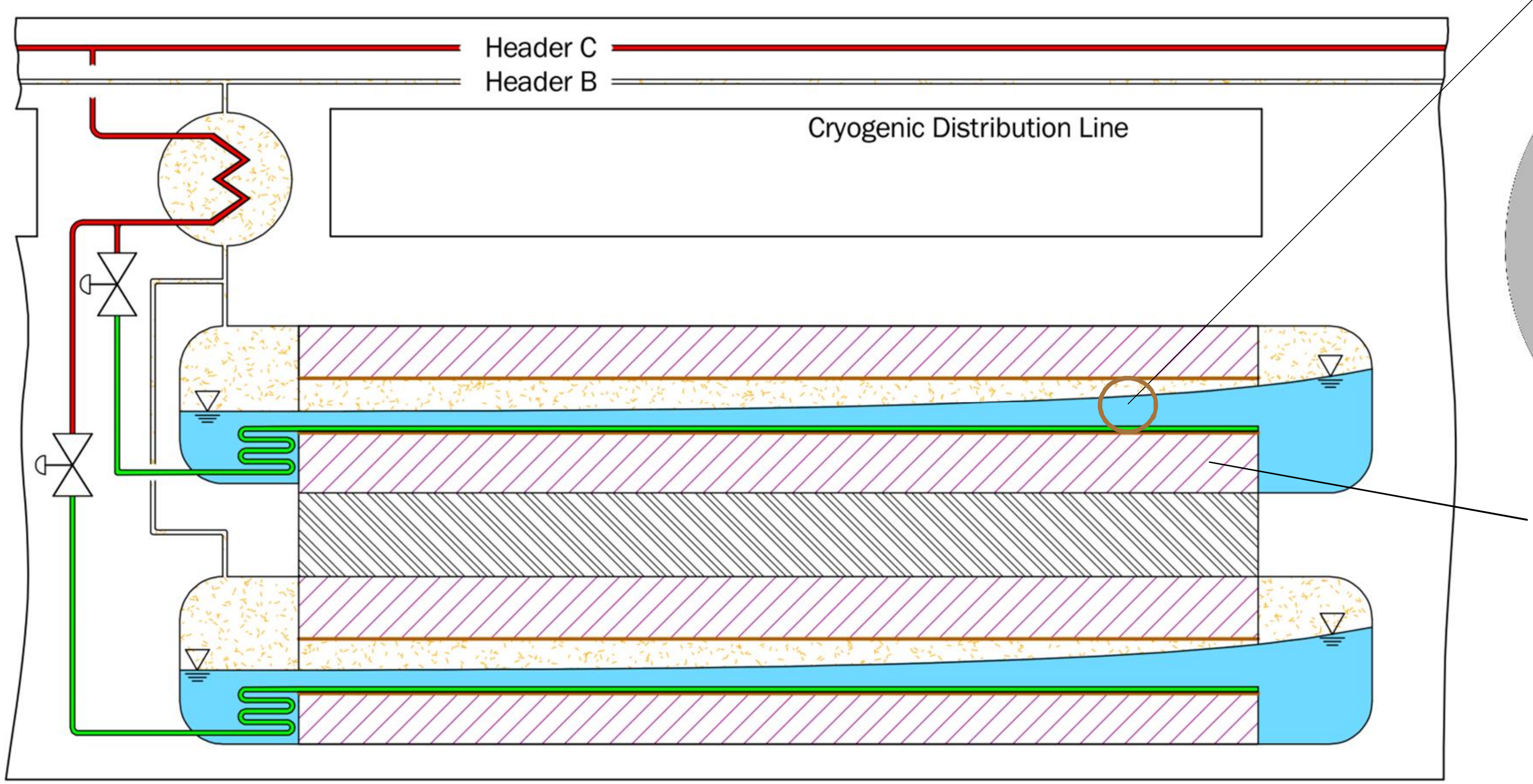
The two-phase cooling scheme

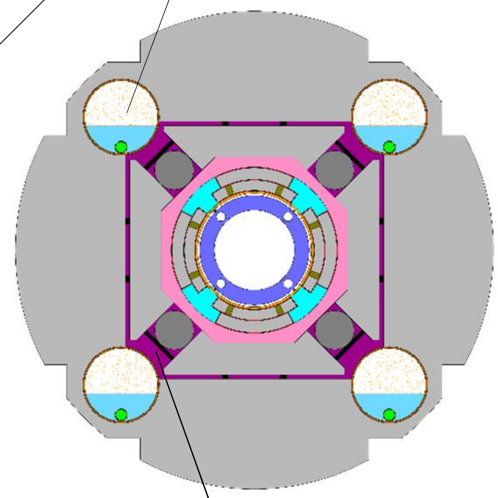


The two-phase cooling scheme







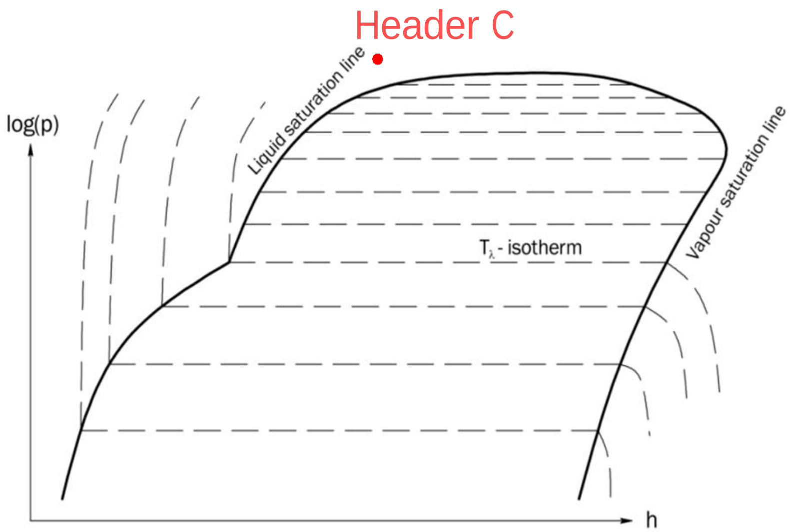


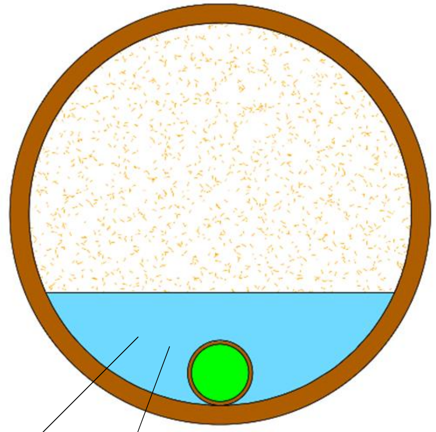
Cold mass immersed in a pressurized static bath of superfluid helium

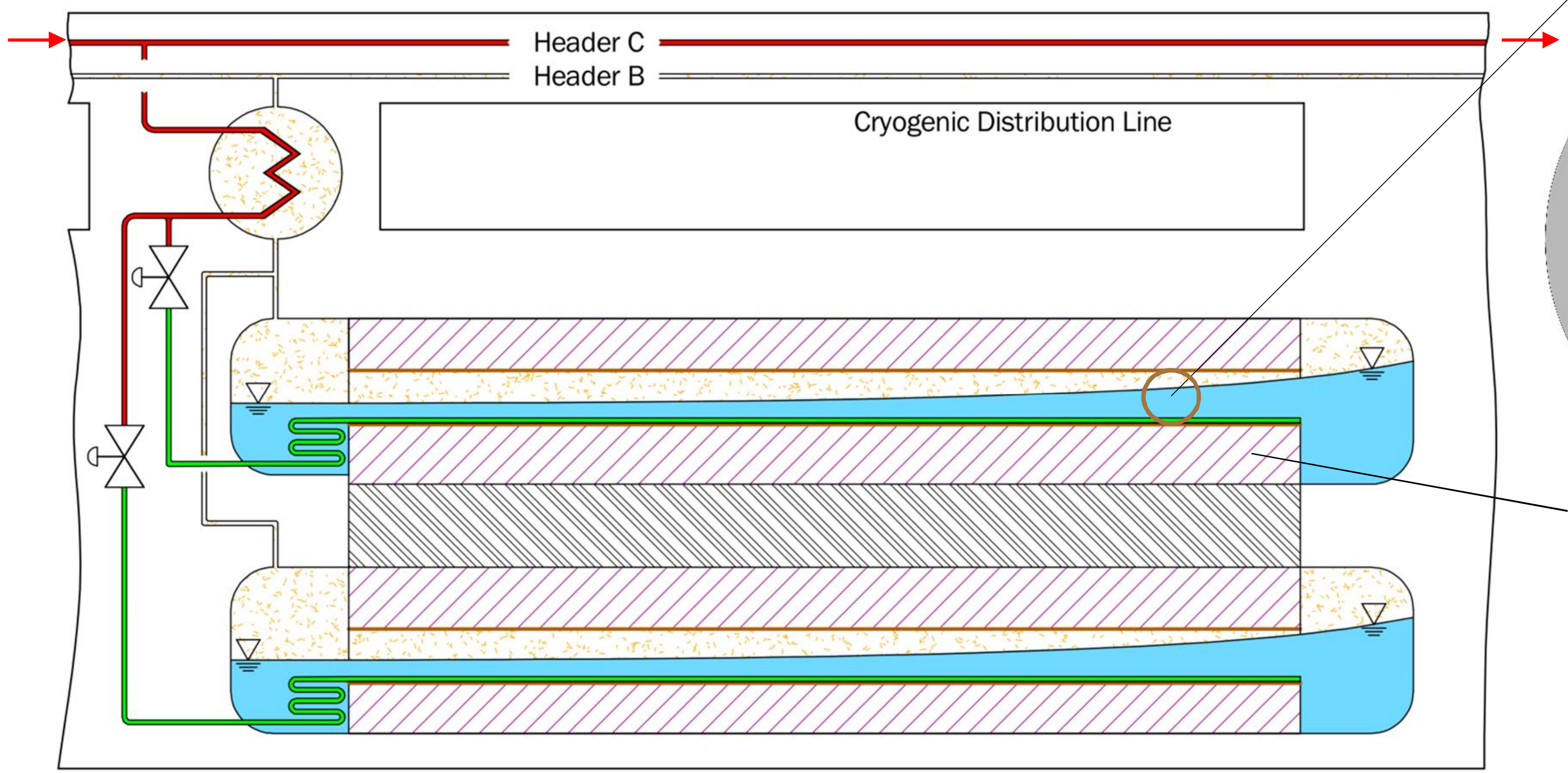
The two-phase cooling scheme

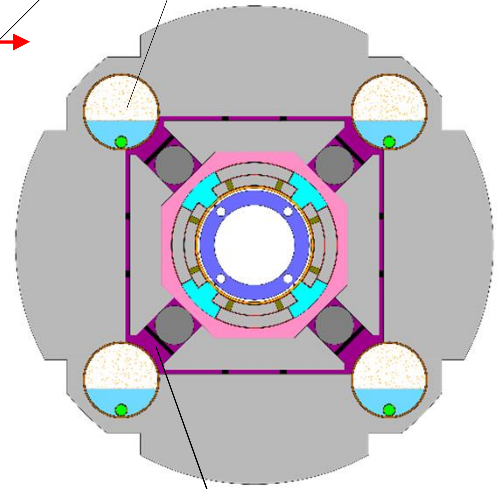
Helium supplied by header C:

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







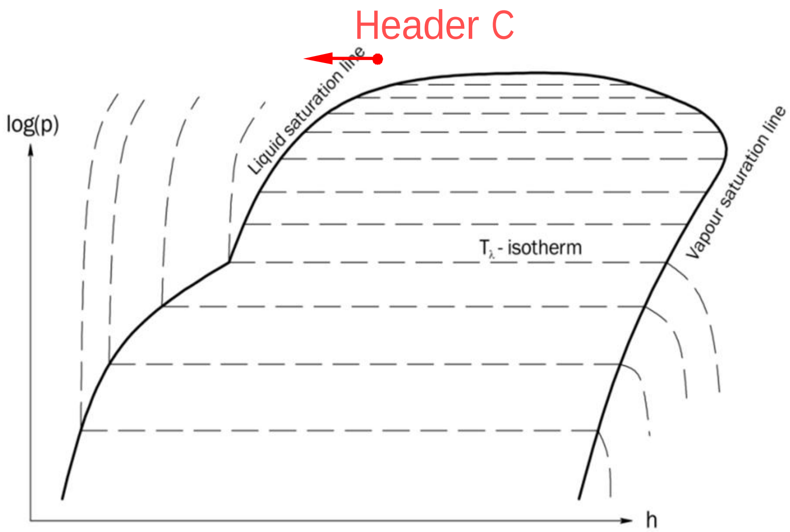


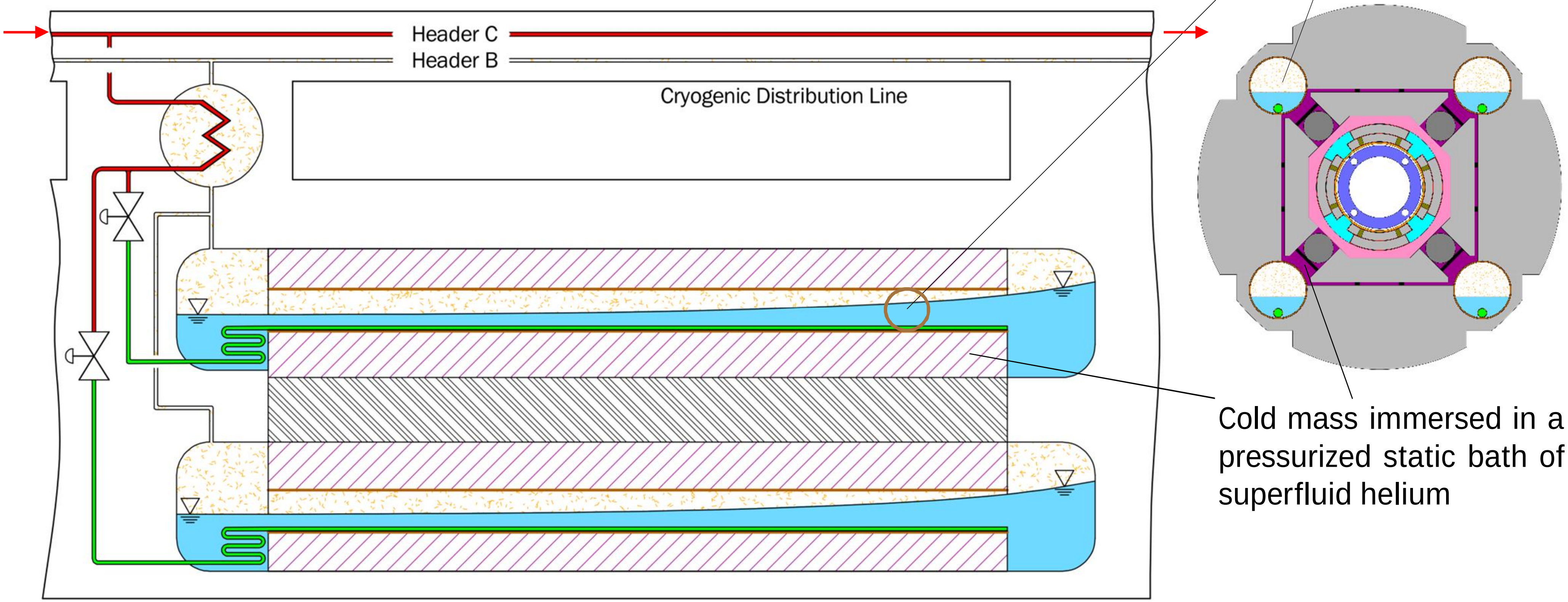
Cold mass immersed in a pressurized static bath of superfluid helium

The two-phase cooling scheme

Helium supplied by header C:

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



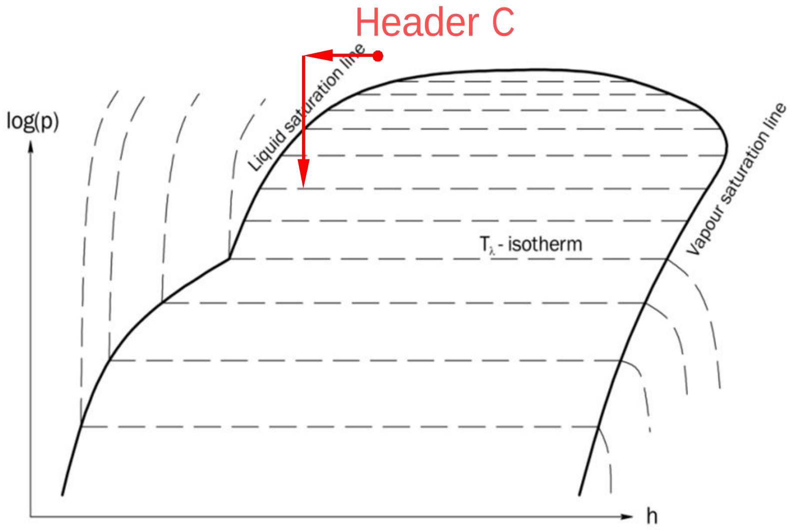


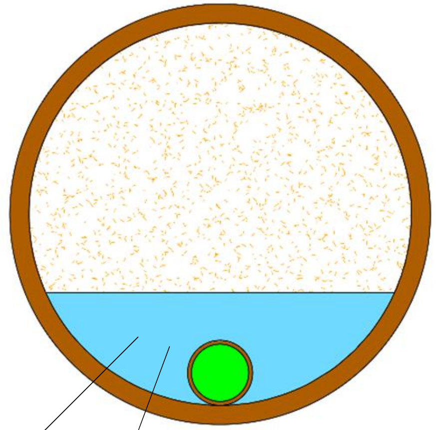
Cold mass immersed in a pressurized static bath of superfluid helium

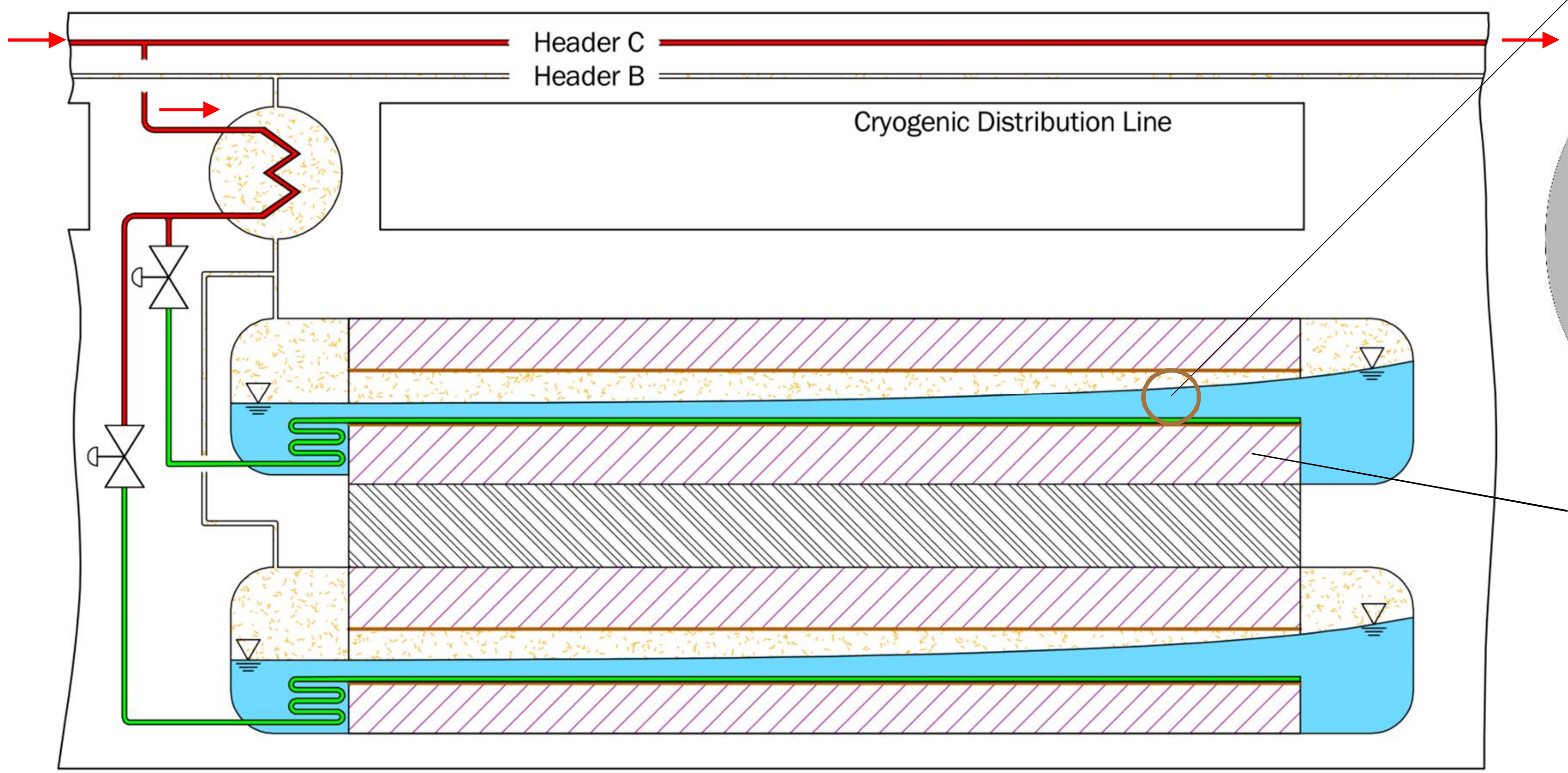
The two-phase cooling scheme

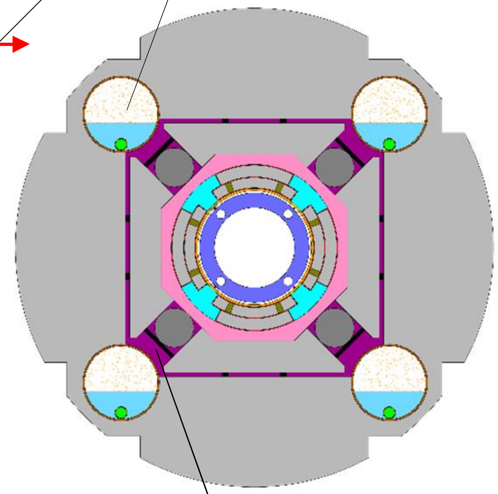
Helium supplied by header C:

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







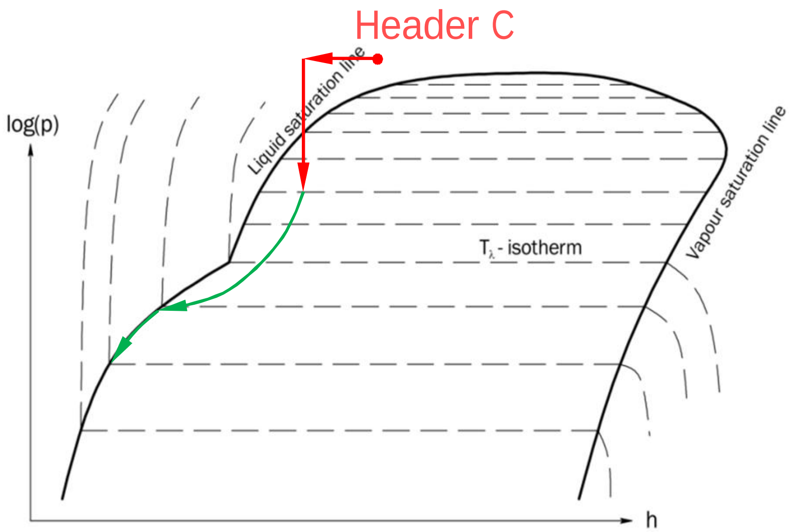


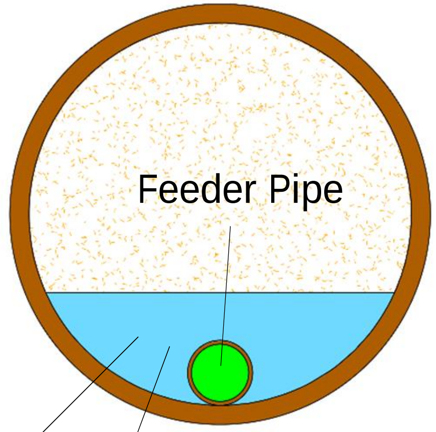
Cold mass immersed in a pressurized static bath of superfluid helium

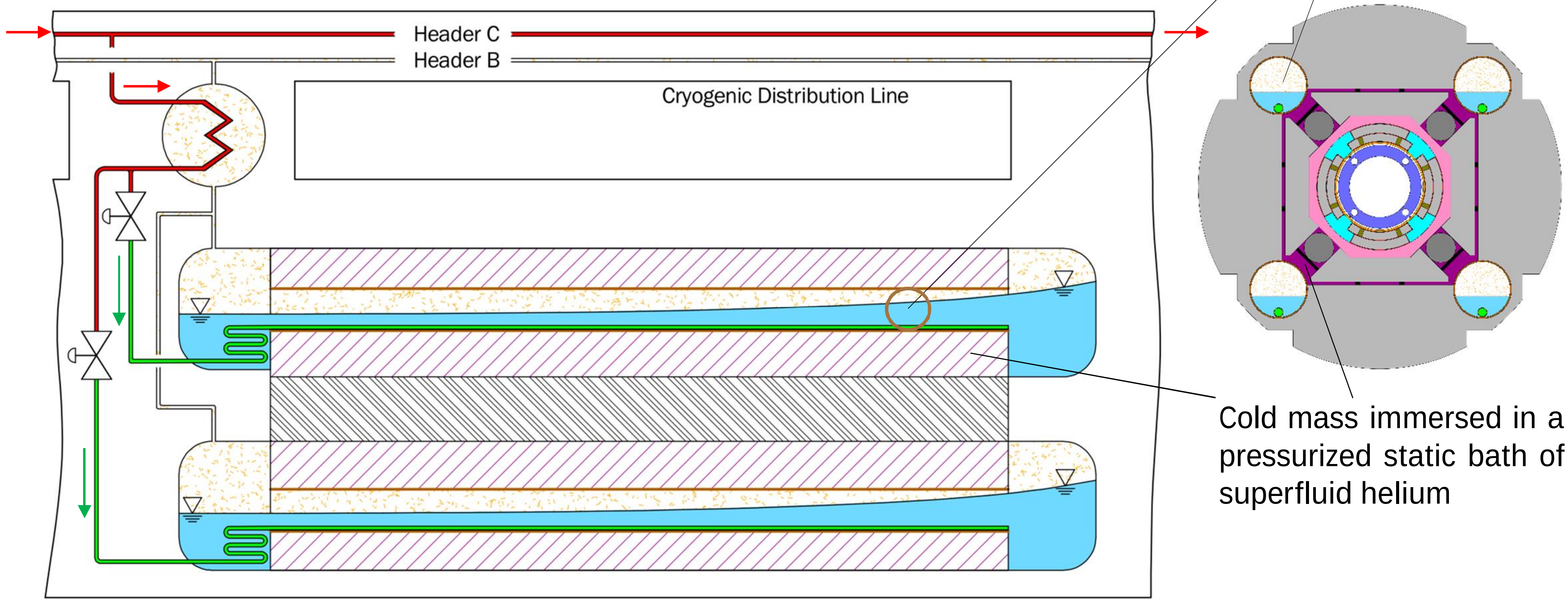
The two-phase cooling scheme

Helium supplied by header C:

T_C = 4.6 K p_C = 3 bar





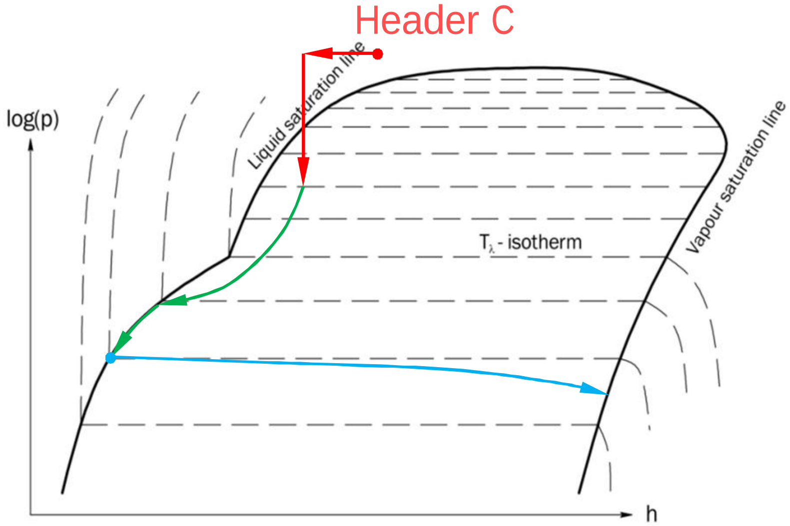


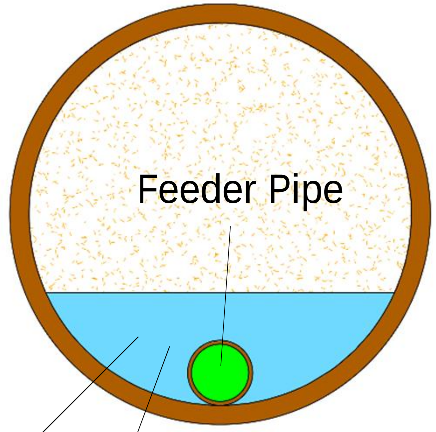
Cold mass immersed in a pressurized static bath of superfluid helium

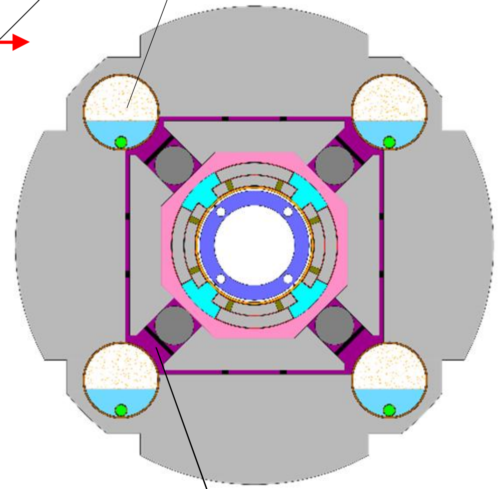
The two-phase cooling scheme

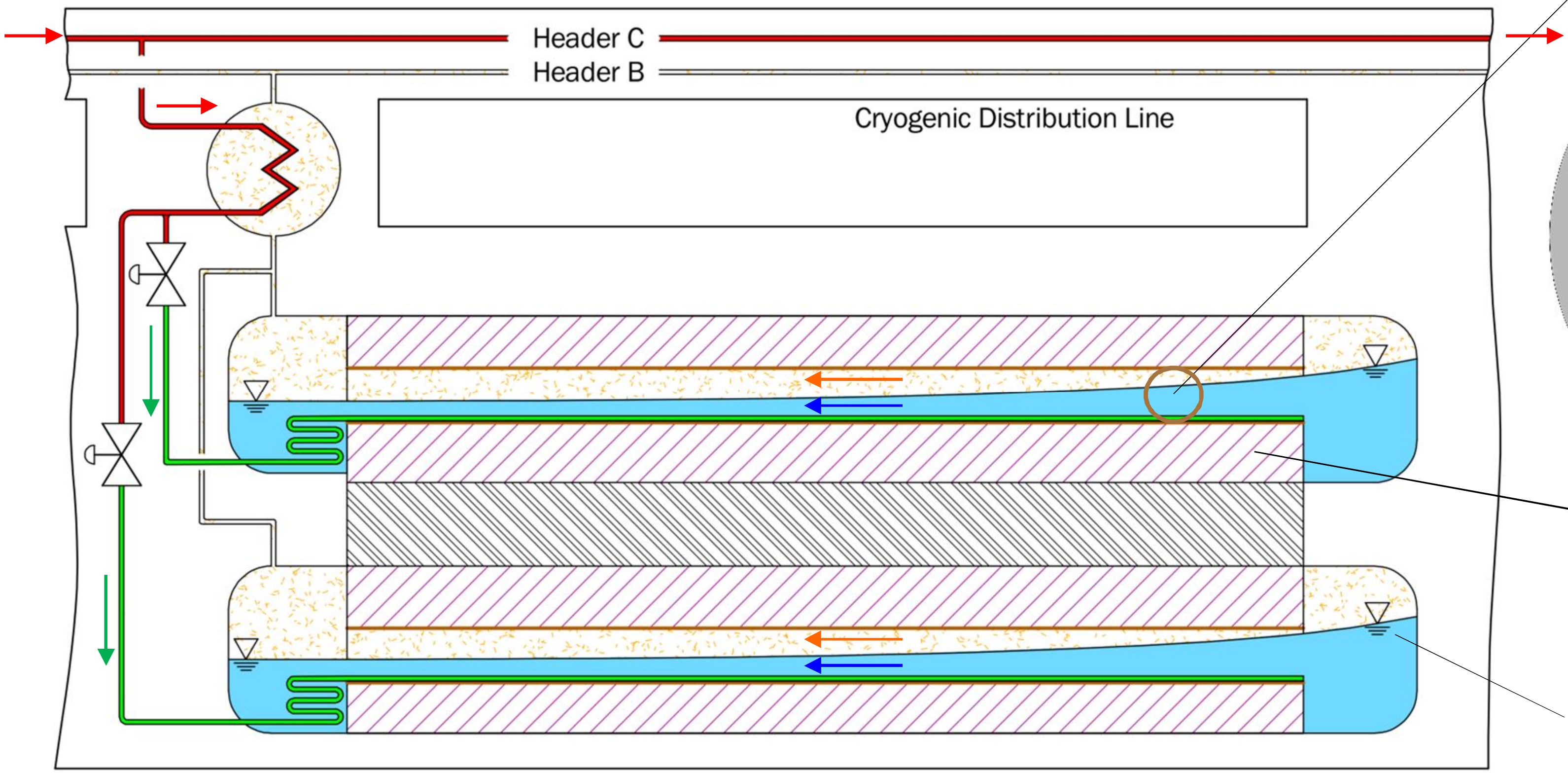
Helium supplied by header C:

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









Cold mass immersed in a pressurized static bath of superfluid helium

Level Gauge

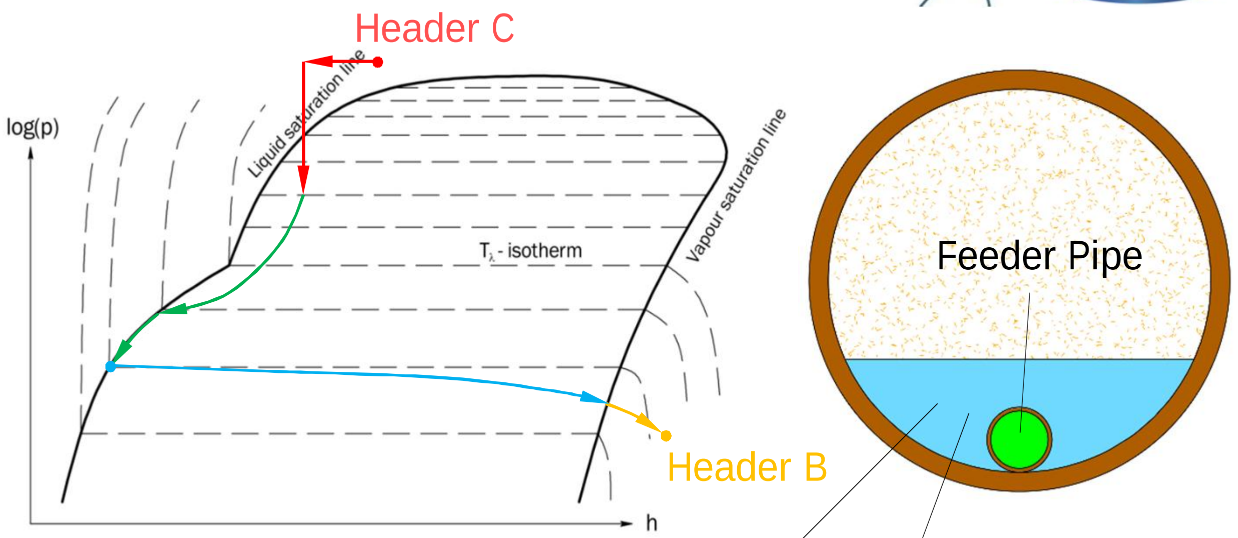
The two-phase cooling scheme

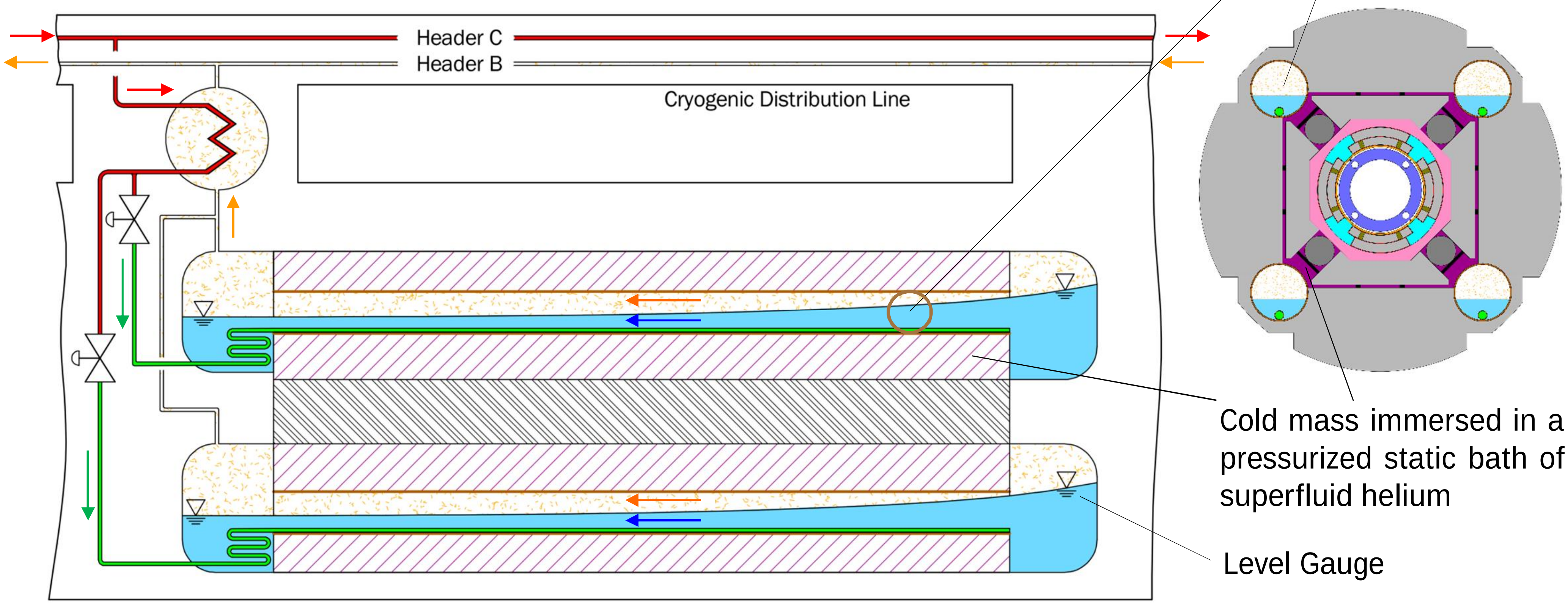
Helium supplied by header C:

T_C = 4.6 K p_C = 3 bar

Helium discharged into header B:

p_B = 16 mbar





The two-phase cooling scheme

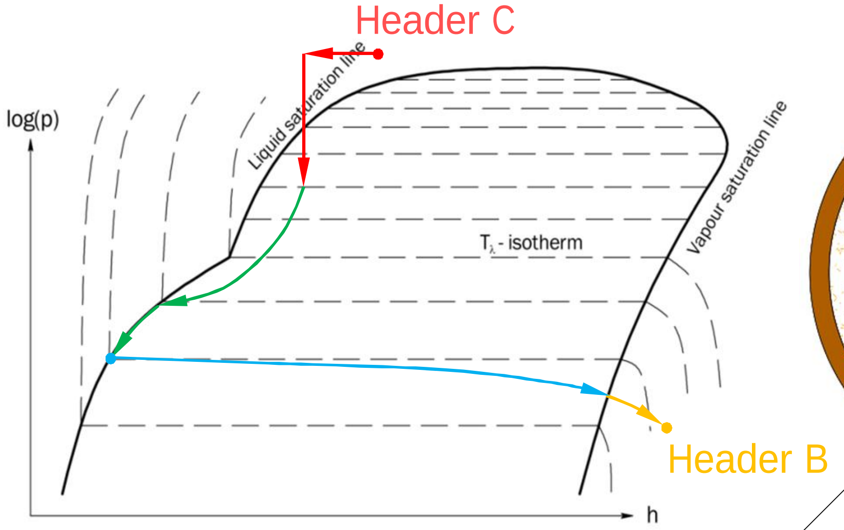
Helium supplied by header C:

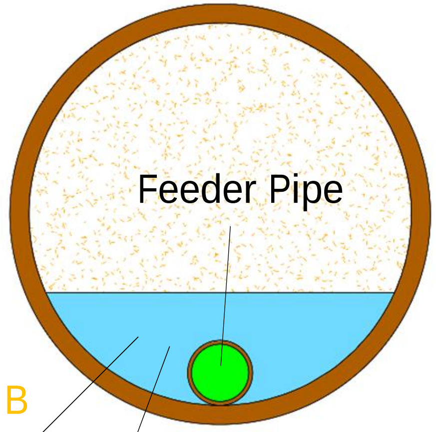
$T_C = 4.6$ K $p_C = 3$ bar

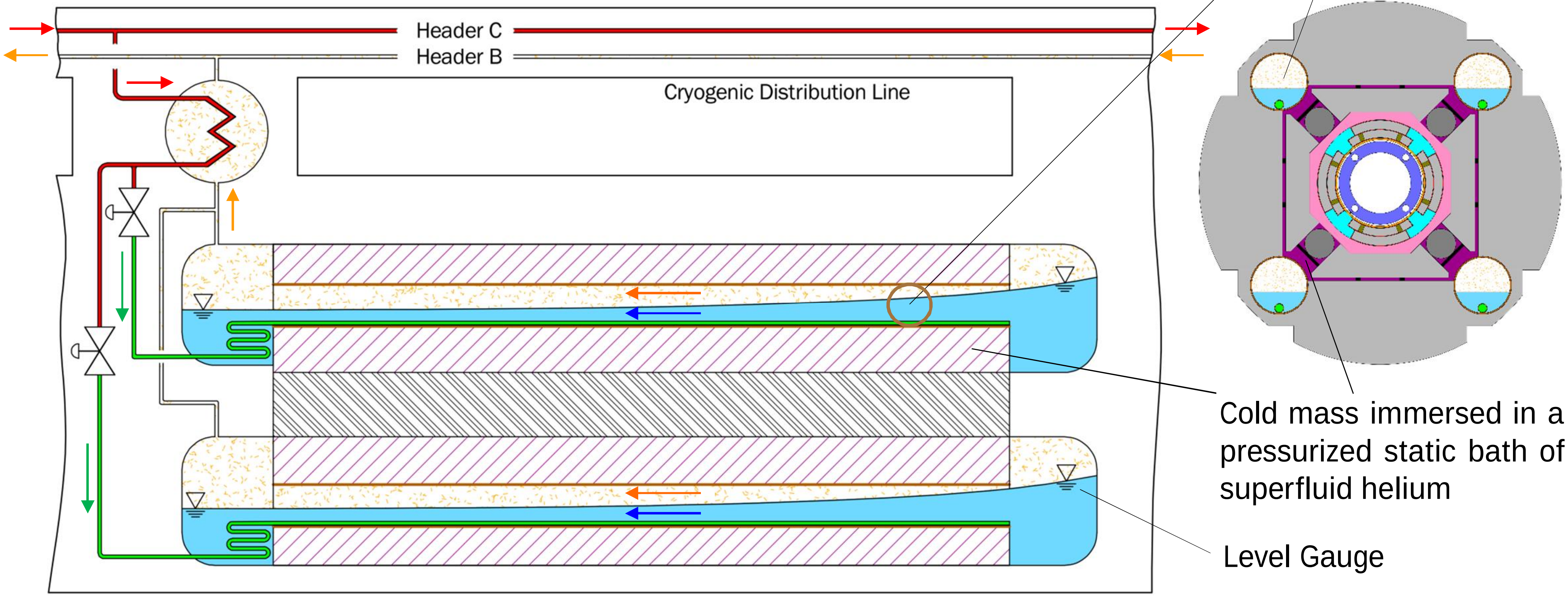
Helium discharged into header B:

$p_B = 16$ mbar

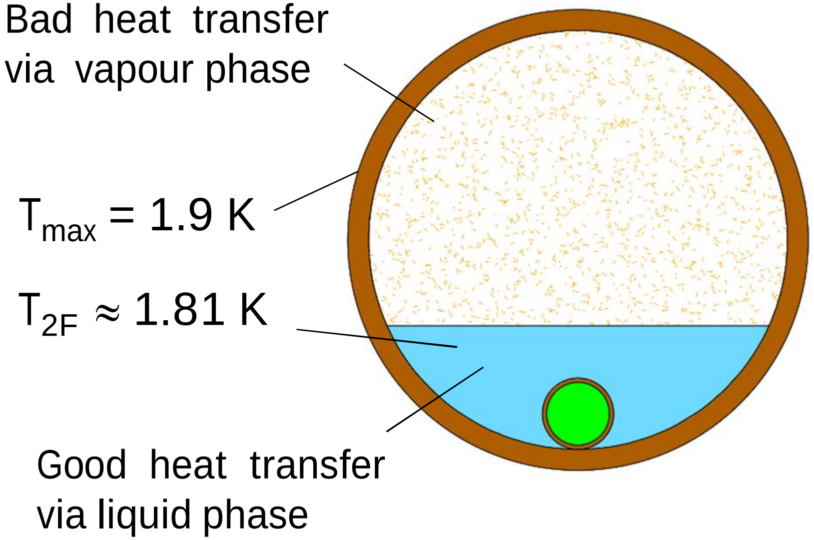
→ Determines stratified flow temperature (= $T|_{p_{Sat}=17\text{ mbar}}$)





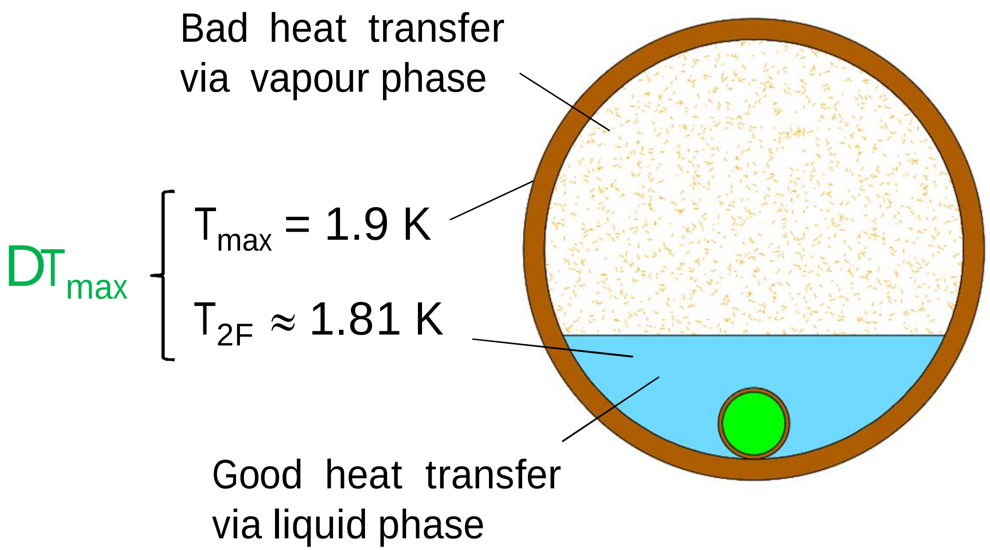


Heat extraction



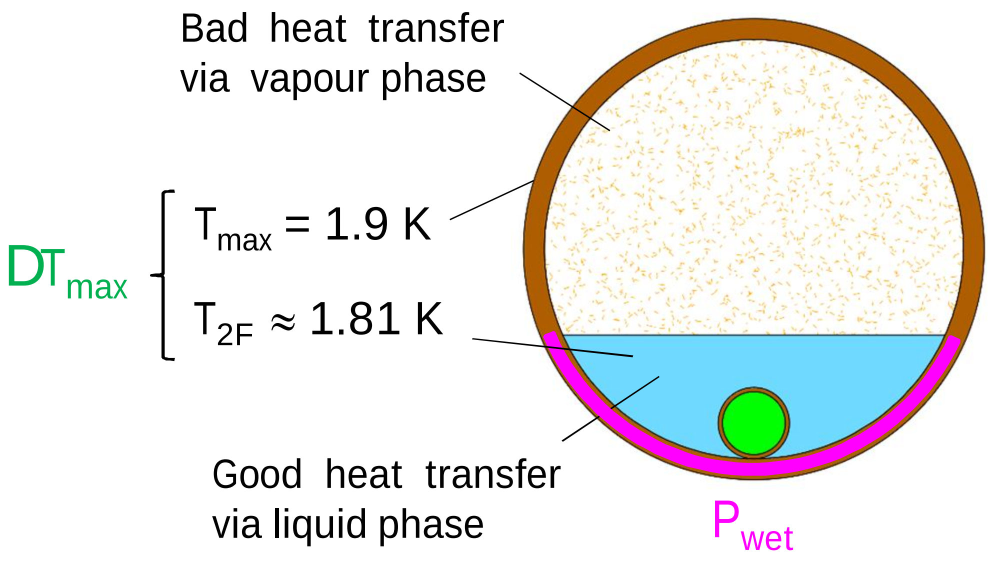
$$\frac{\dot{q}}{n_{BHX}} = \frac{\Delta T_{max}}{R_{th}} P_{wet} = \frac{\Delta T_{max}}{R_{th}} 2r\,arccos\left(1 - \frac{r}{h_{LL}}\right)$$

Heat extraction



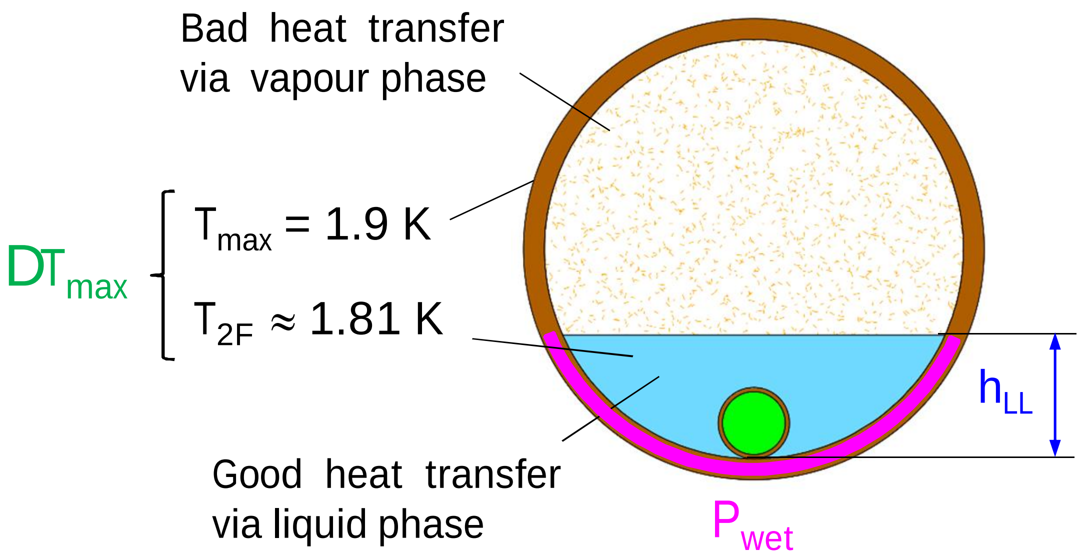
$$\frac{\dot{q}}{n_{BHX}} = \frac{\Delta T_{max}}{R_{th}} P_{wet} = \frac{\Delta T_{max}}{R_{th}} 2r\,arccos\left(1 - \frac{r}{h_{LL}}\right)$$

Heat extraction



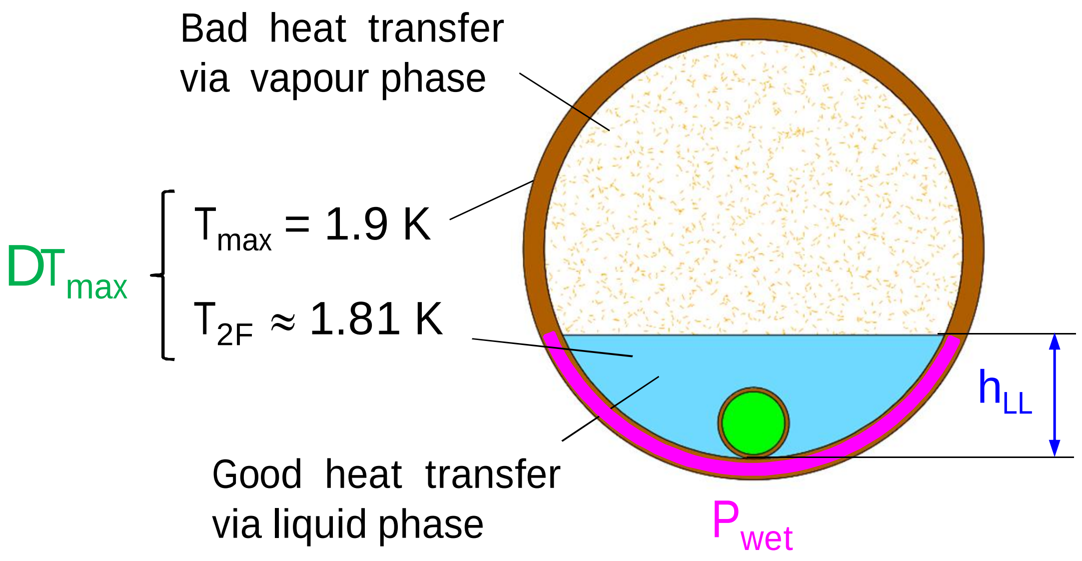
$$\frac{\dot{q}}{n_{BHX}} = \frac{\Delta T_{max}}{R_{th}} P_{wet} = \frac{\Delta T_{max}}{R_{th}} 2\,r\,arccos\left(1 - \frac{r}{h_{LL}}\right)$$

Heat extraction



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

Heat extraction



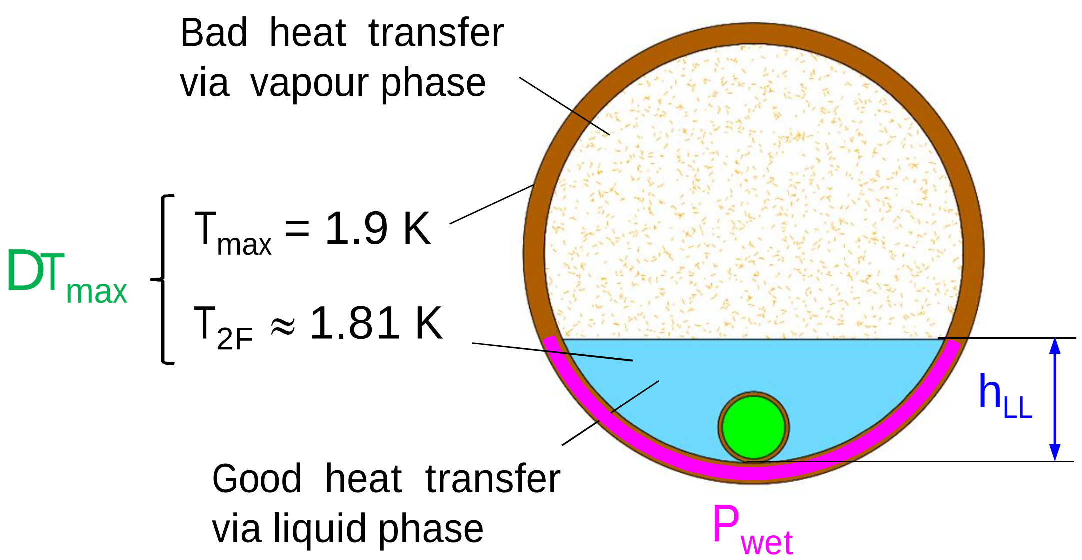
$$\frac{\dot{q}}{n_{BHX}} = \frac{\Delta T_{max}}{R_{th}} P_{wet} = \frac{\Delta T_{max}}{R_{th}} 2\,r\,arccos\left(1 - \frac{r}{h_{LL}}\right)$$

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

Minimal h_{LL} for sufficient heat transfer

Two-phase cooling - The two main constraints

Heat extraction



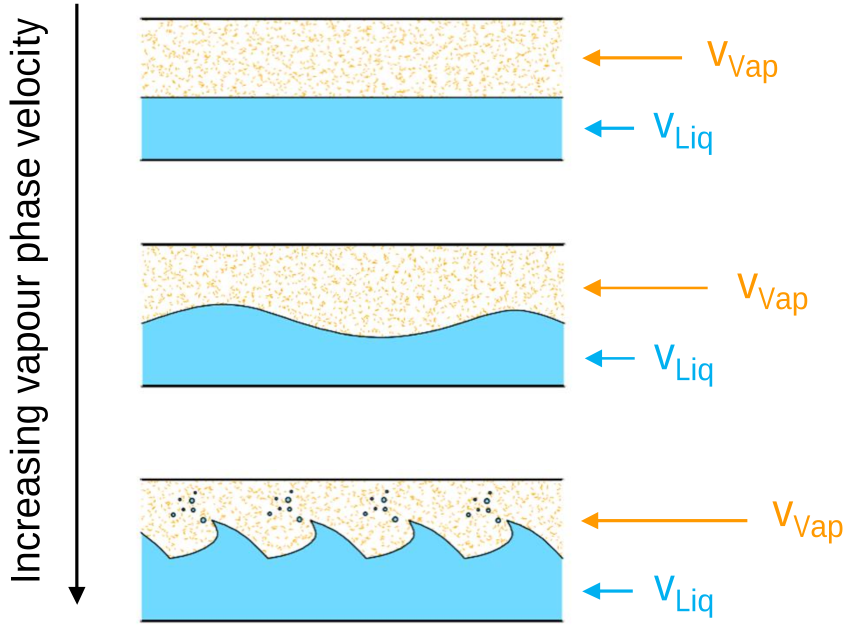
$$\frac{\dot q}{n_{BHX}} = \frac{\Delta T_{max}}{R_{th}} P_{wet} = \frac{\Delta T_{max}}{R_{th}} 2\,r\,arccos\left(1-\frac{r}{h_{LL}}\right)$$

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

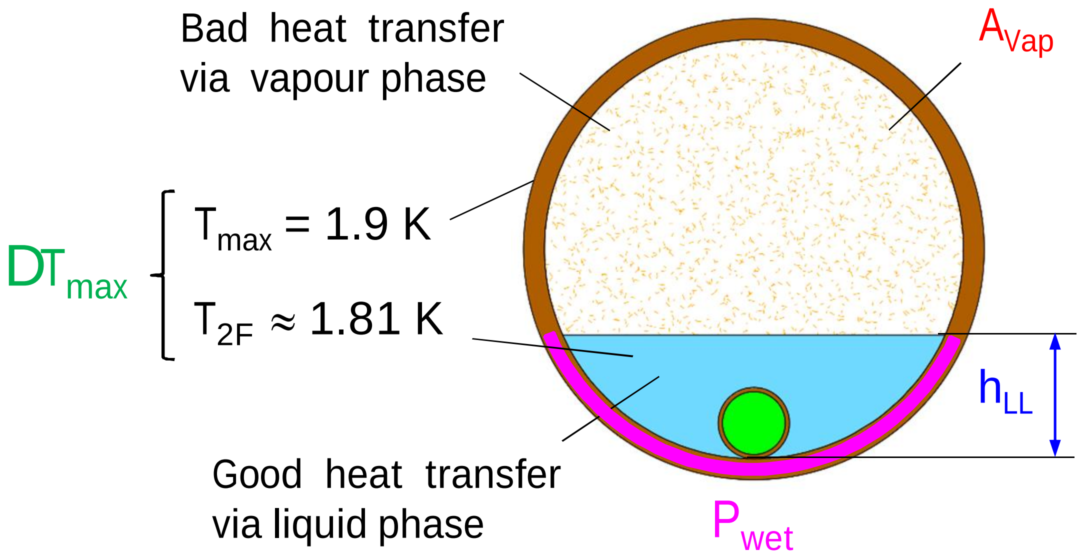
Minimal h_{LL} for sufficient heat transfer

Vapour velocity

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



Heat extraction



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

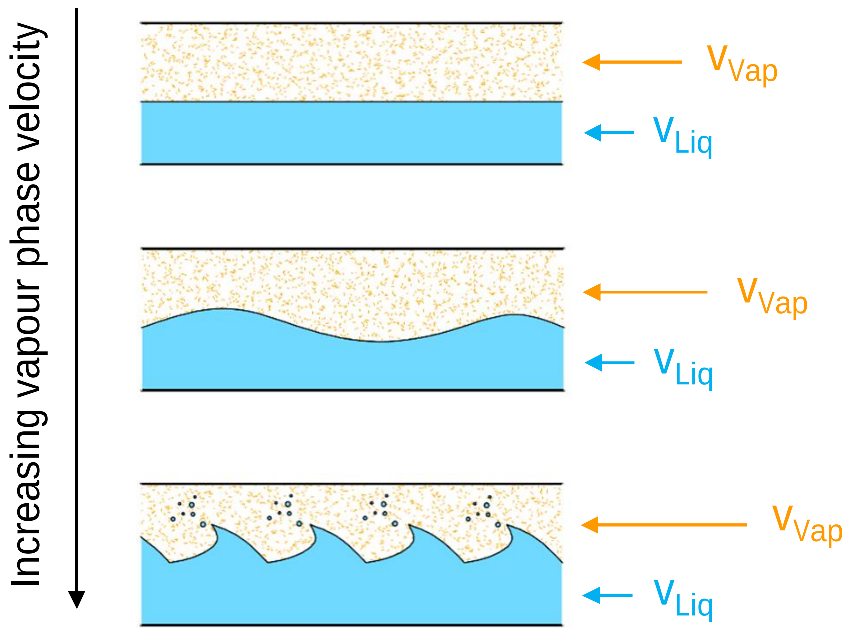
$$\rightarrow \quad h_{LL} = r\left[1 - cos\left(\frac{R_{th}\,\dot{q}}{2\,r\,n_{BHX}\,\Delta T_{max}}\right)\right]$$

Minimal h_{LL} for sufficient heat transfer

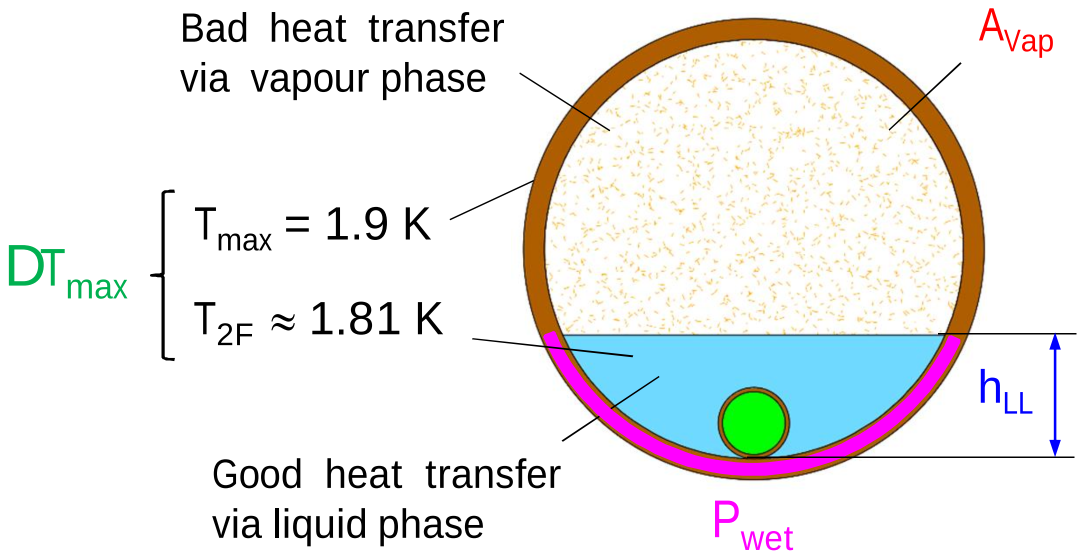
$$\rightarrow \quad v_{Vap} = \frac{\dot{m}}{\rho_{Vap} A_{Vap}} = \frac{\dot{q}\,L}{n_{BHX}\,\rho_{Vap}\,(h'' - h_{JT})\left[r^2 arccos\left(1 - \frac{h_{LL}}{r}\right) - (r - h_{LL})\sqrt{2rh_{LL} - h_{LL}^2}\right]} \leq 5\,m/s$$

Vapour velocity

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



Heat extraction



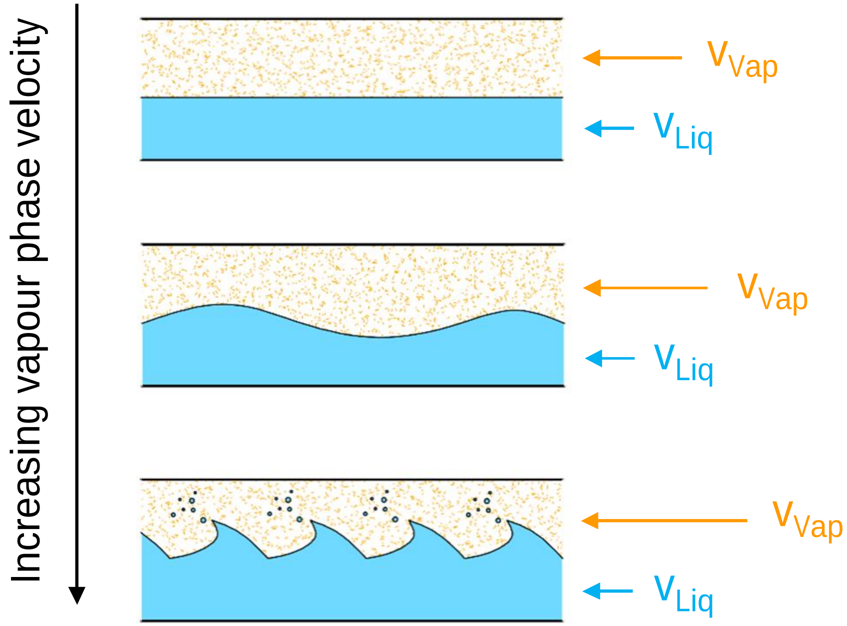
$$\frac{\dot{q}}{n_{BHX}} = \frac{\Delta T_{max}}{R_{th}} P_{wet} = \frac{\Delta T_{max}}{R_{th}} 2\,r\,arccos\left(1-\frac{r}{h_{LL}}\right)$$

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

Minimal h_{LL} for sufficient heat transfer

Vapour velocity

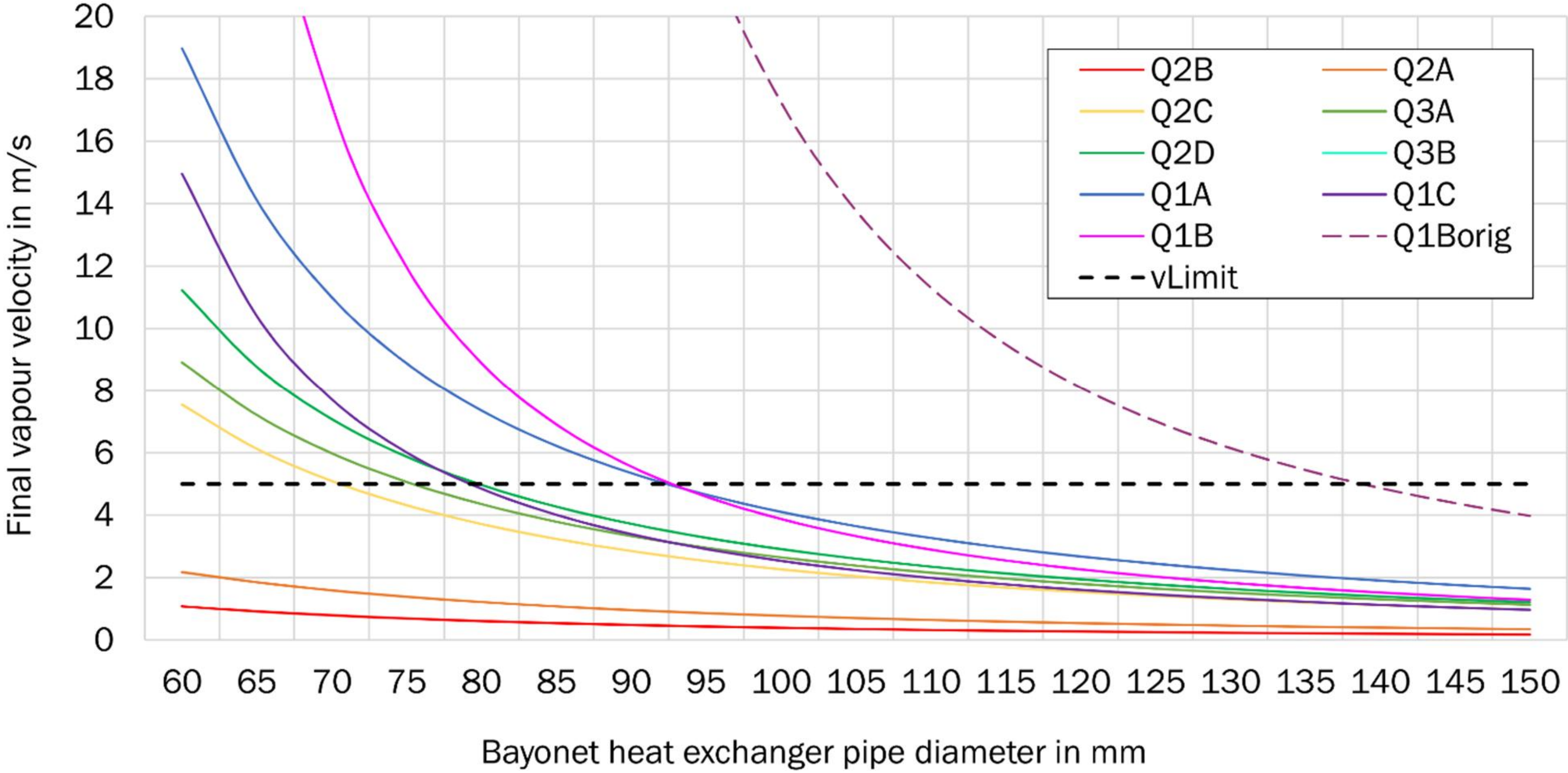
Relative movement between liquid and vapour phase determines shape of the surface:



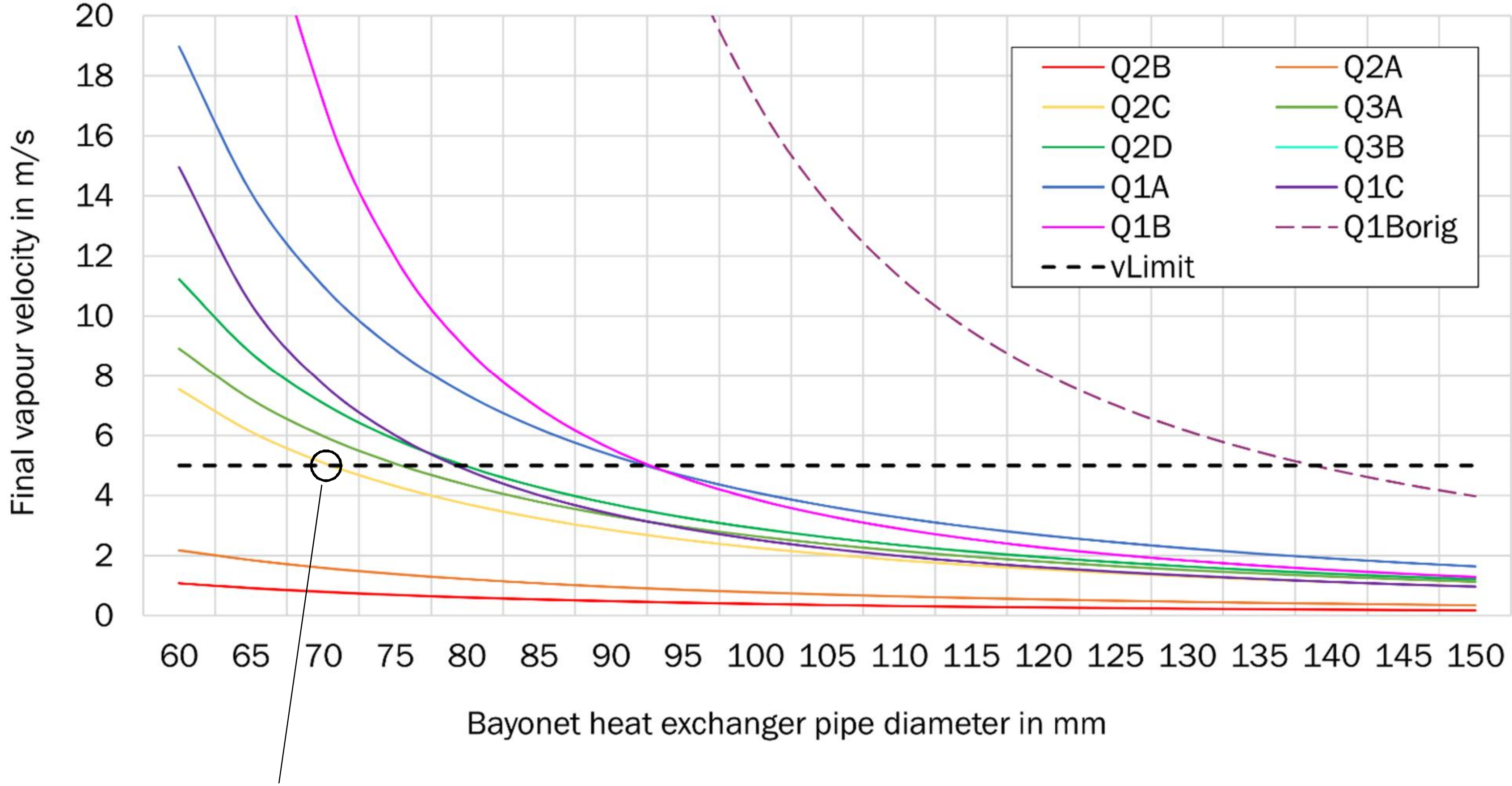
Maximal v_{Vap} determined in experimental setup

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

Analytical estimation



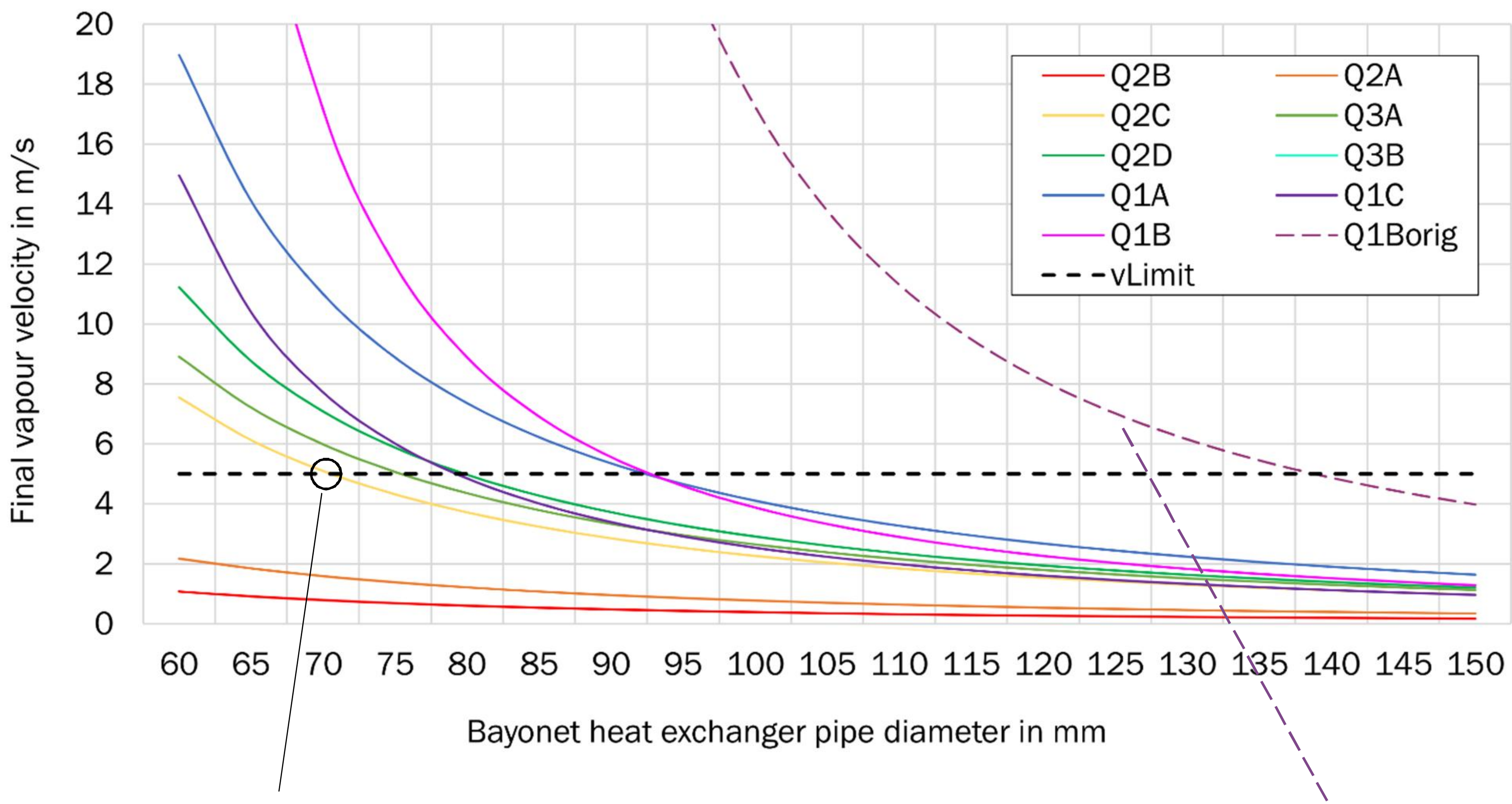
Analytical estimation



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

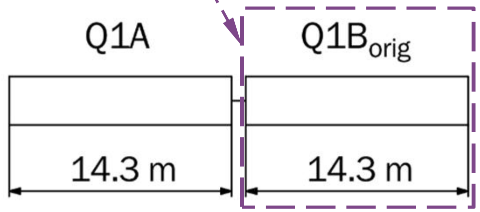
→ for Q2C the minimal inner diameter is about 70 mm

Analytical estimation



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

→ for Q2C the minimal inner diameter is about 70 mm



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:

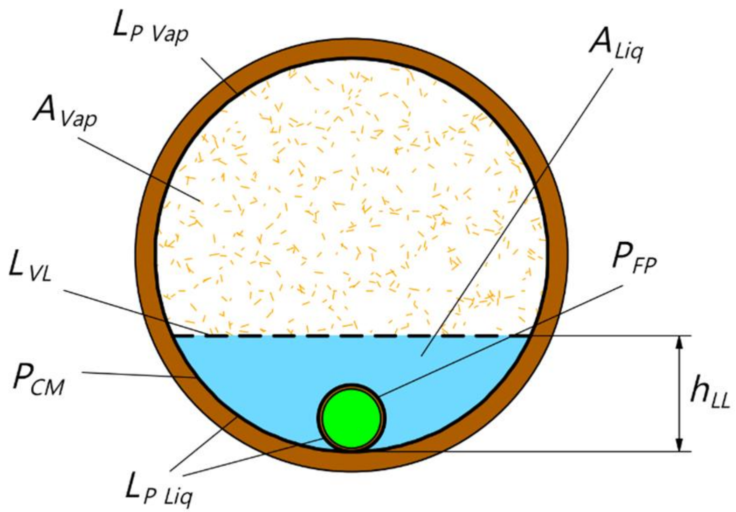
Mass balance: $$1)\ \pm\dot{m}\frac{d\xi}{dz} = \frac{d}{dz}\left(A_\Phi\,\rho_\Phi\,v_\Phi\right)$$

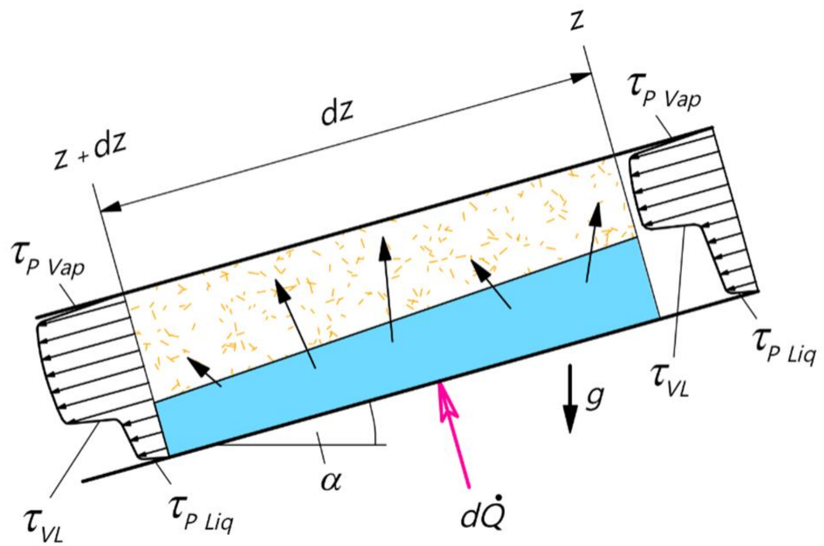
Momentum balance: $$2)\ \frac{d}{dz}\left(A_\Phi\,\rho_\Phi\,v_\Phi^2\right) = -A_\Phi\,\frac{dp_{IF}}{dz}\pm$$

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

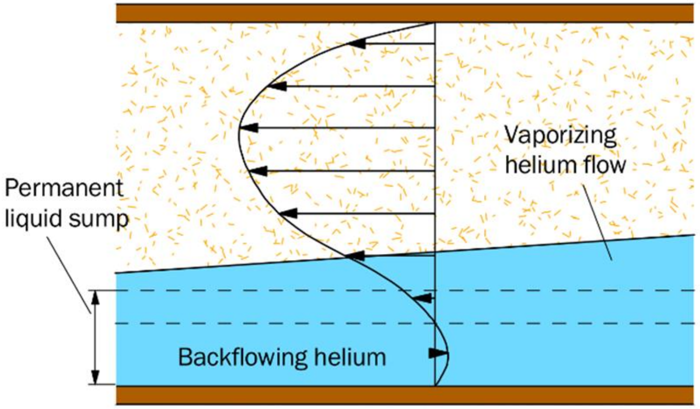
Thermal energy balance: $$3)\ \left(h'' - h'\right)\,d\xi = \frac{\dot{q}_{CM}\,P_{CM} + \dot{q}_{FP}\,P_{FP}}{\dot{m}}dz$$

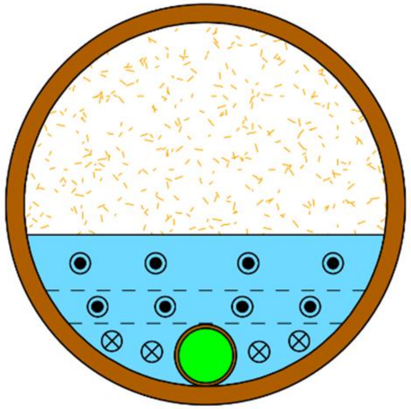
Thermal conduction in superfluid helium: $$4)\ \frac{dT}{dz} = -f_k\,\dot{q}^m$$

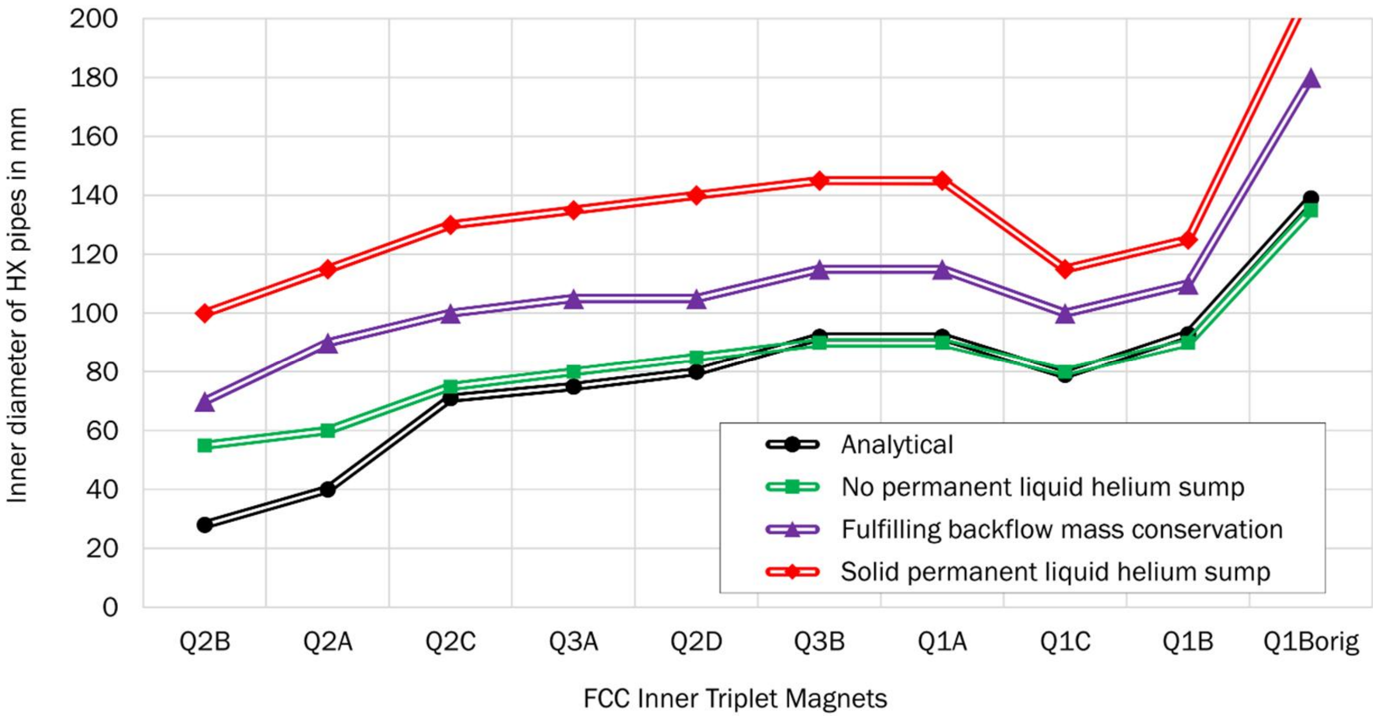




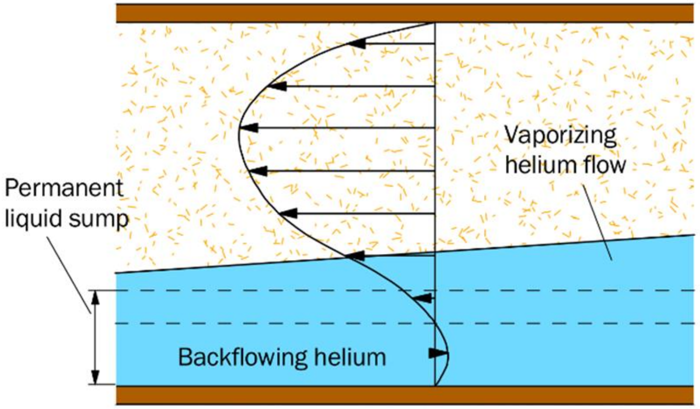
Numerical solutions

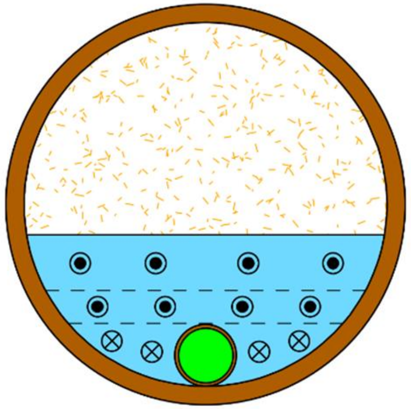


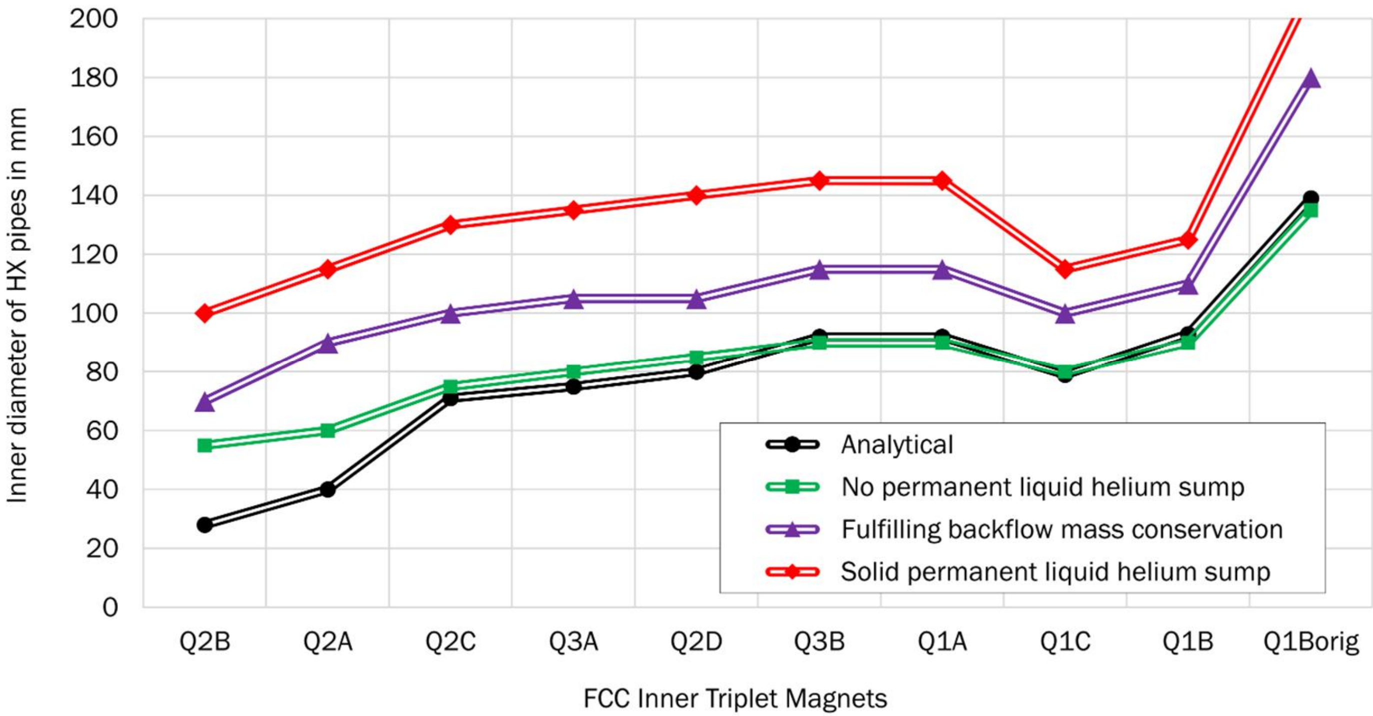




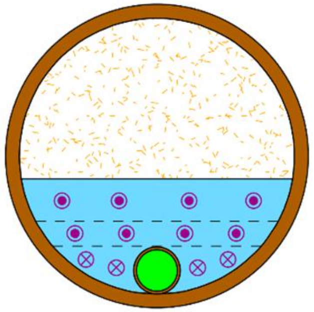
Numerical solutions



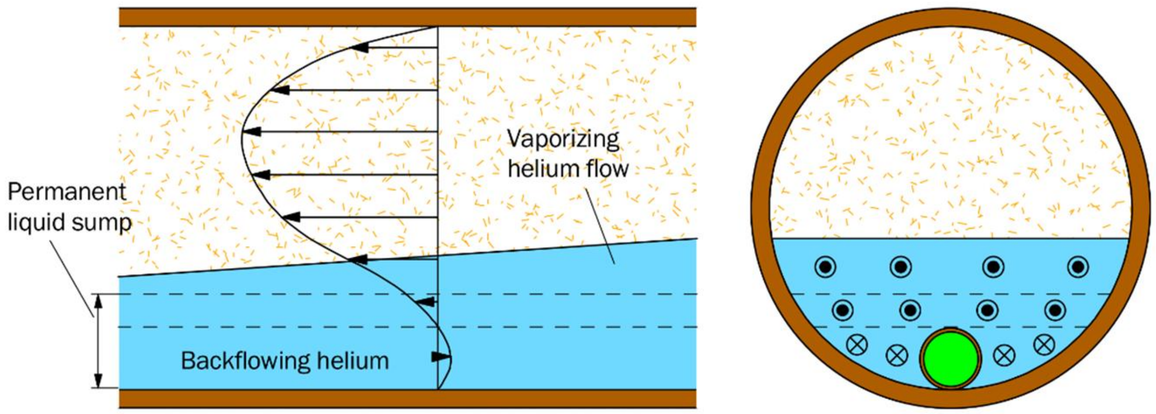


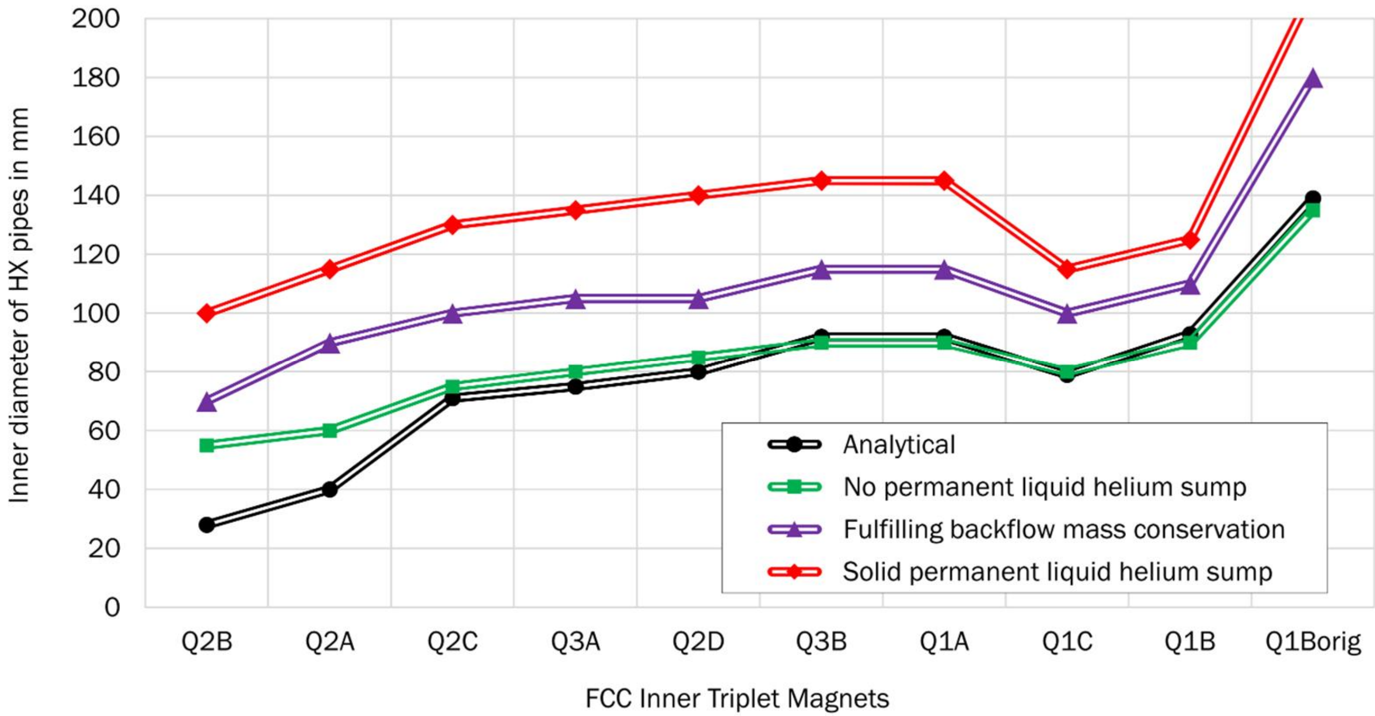


Fullfilling backflow mass conservation

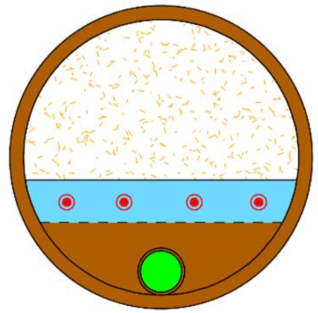


Numerical solutions

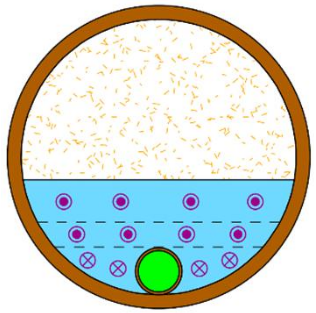




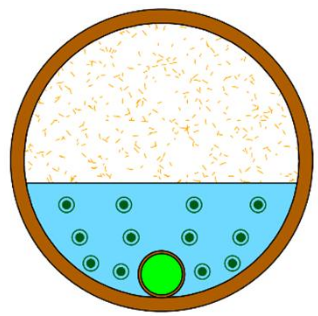
Solid permanent liquid helium sump



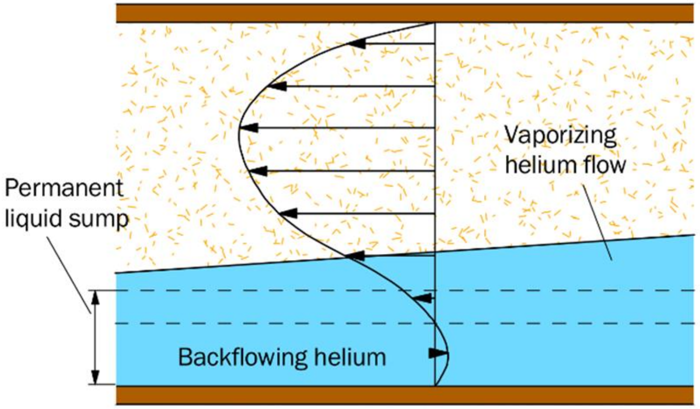
Fullfilling backflow mass conservation

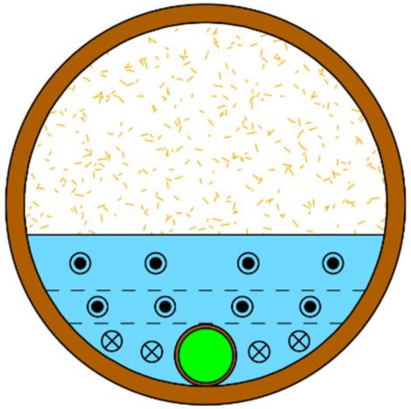


No permanent liquid helium sump

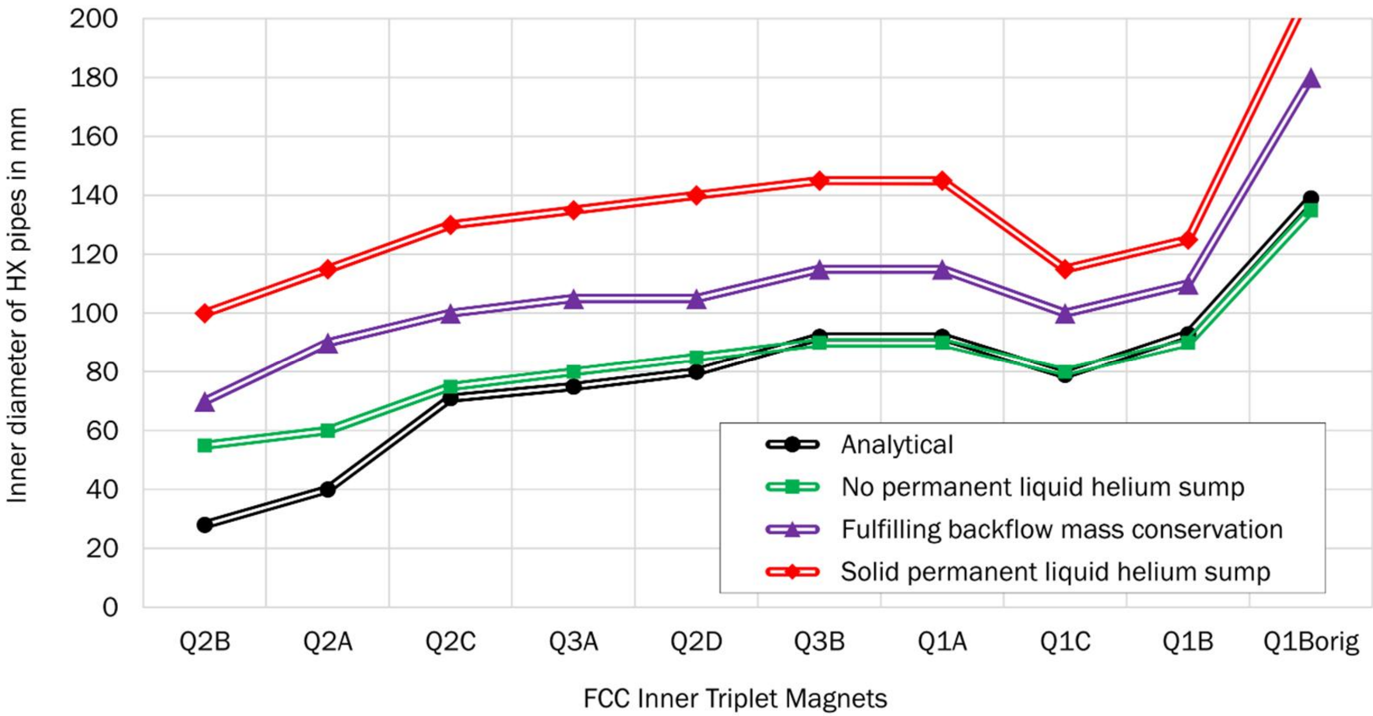


Numerical solutions

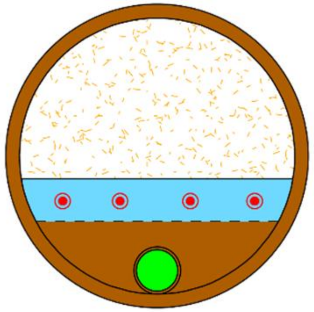




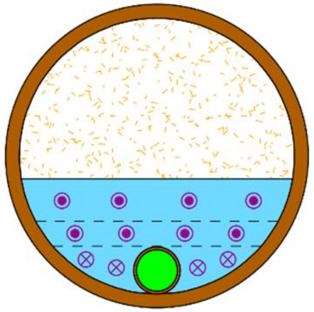
Comparisons with former experimental results indicate an over-estimation of the wave generation of the model ($v_{Vap} < 5m/s$)



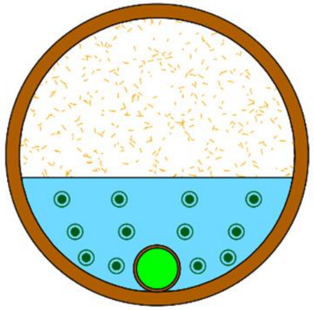
Solid permanent liquid helium sump



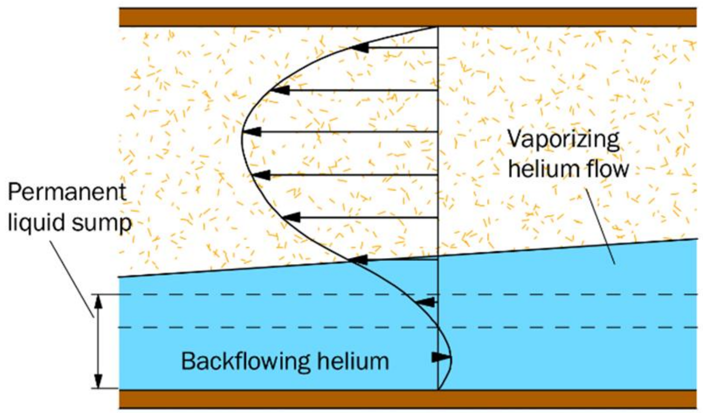
Fullfilling backflow mass conservation

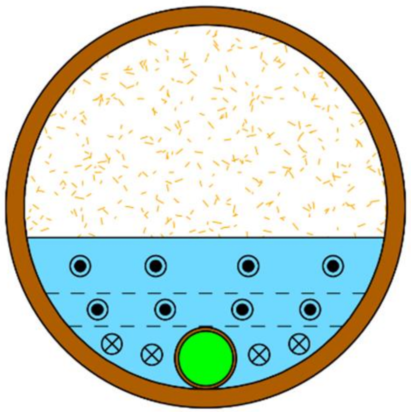


No permanent liquid helium sump



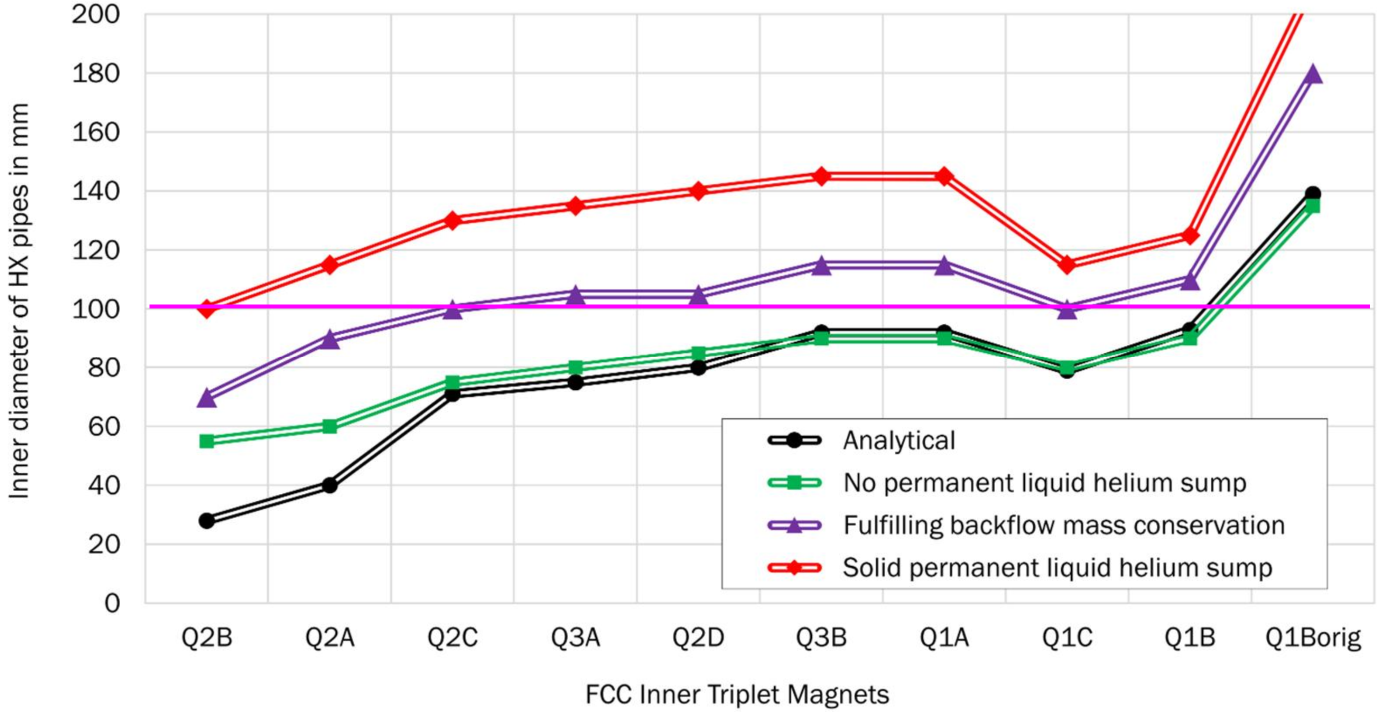
Numerical solutions



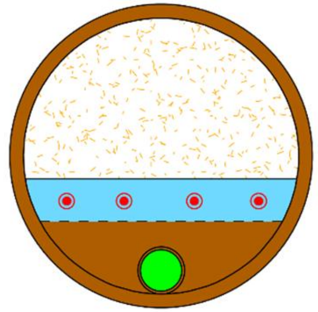


Comparisons with former experimental results indicate an over-estimation of the wave generation of the model ($v_{Vap} < 5m/s$)

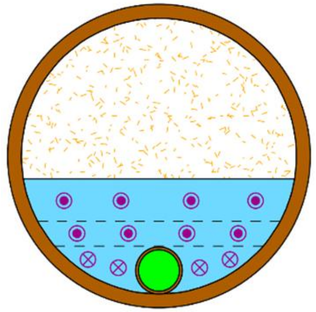
→ The requested maximal diameter of 100 mm seems to be feasible



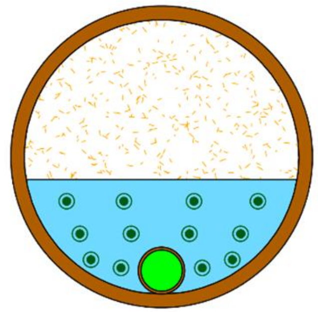
Solid permanent liquid helium sump



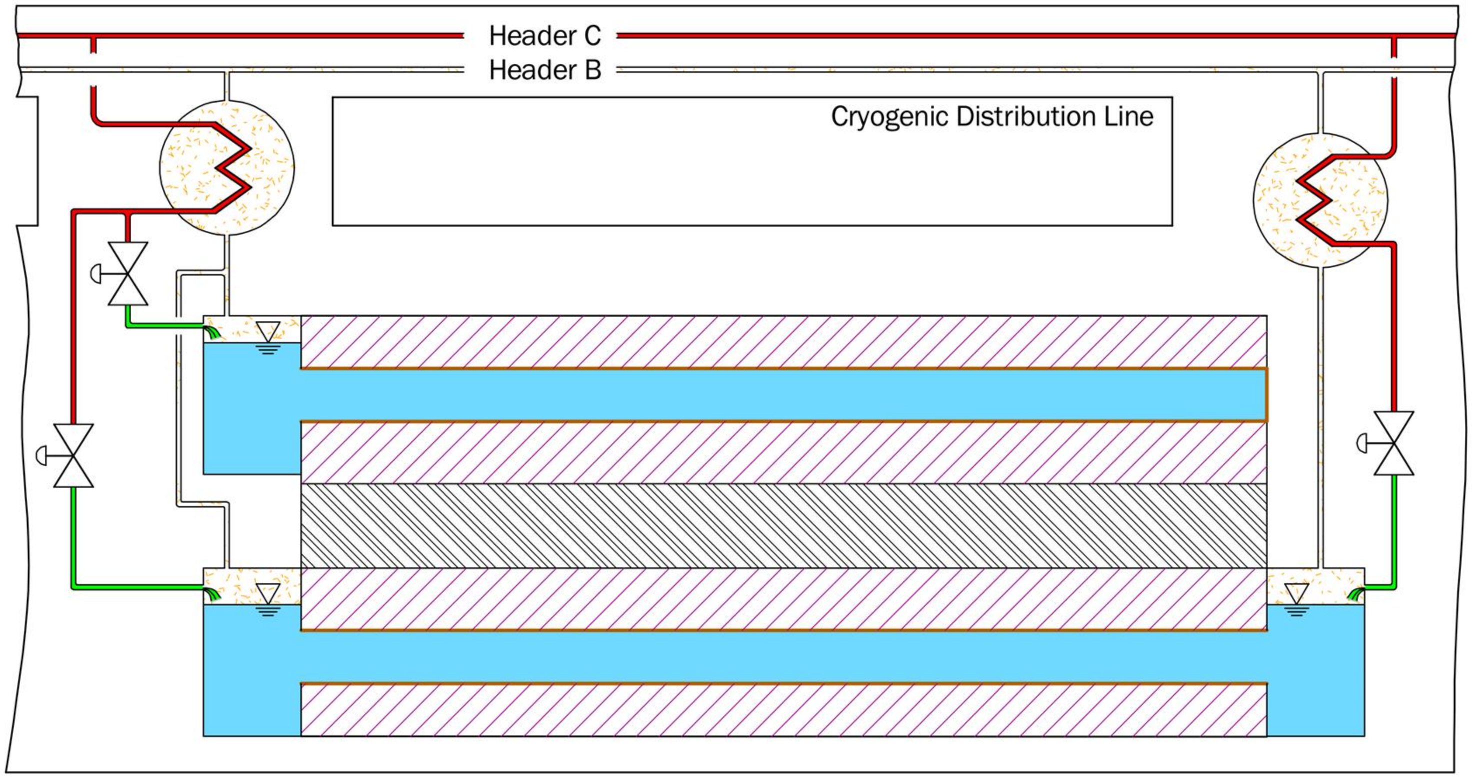
Fullfilling backflow mass conservation

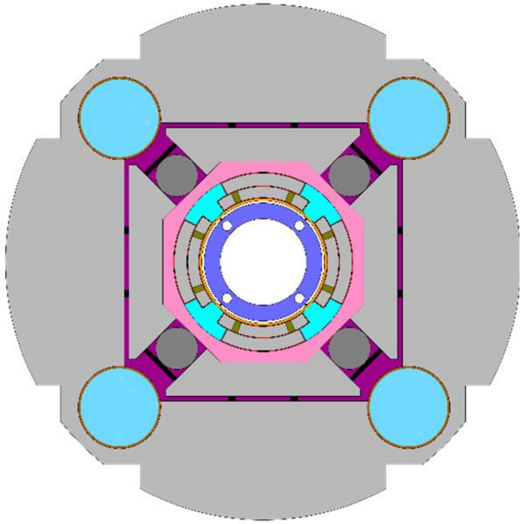


No permanent liquid helium sump



The conduction scheme





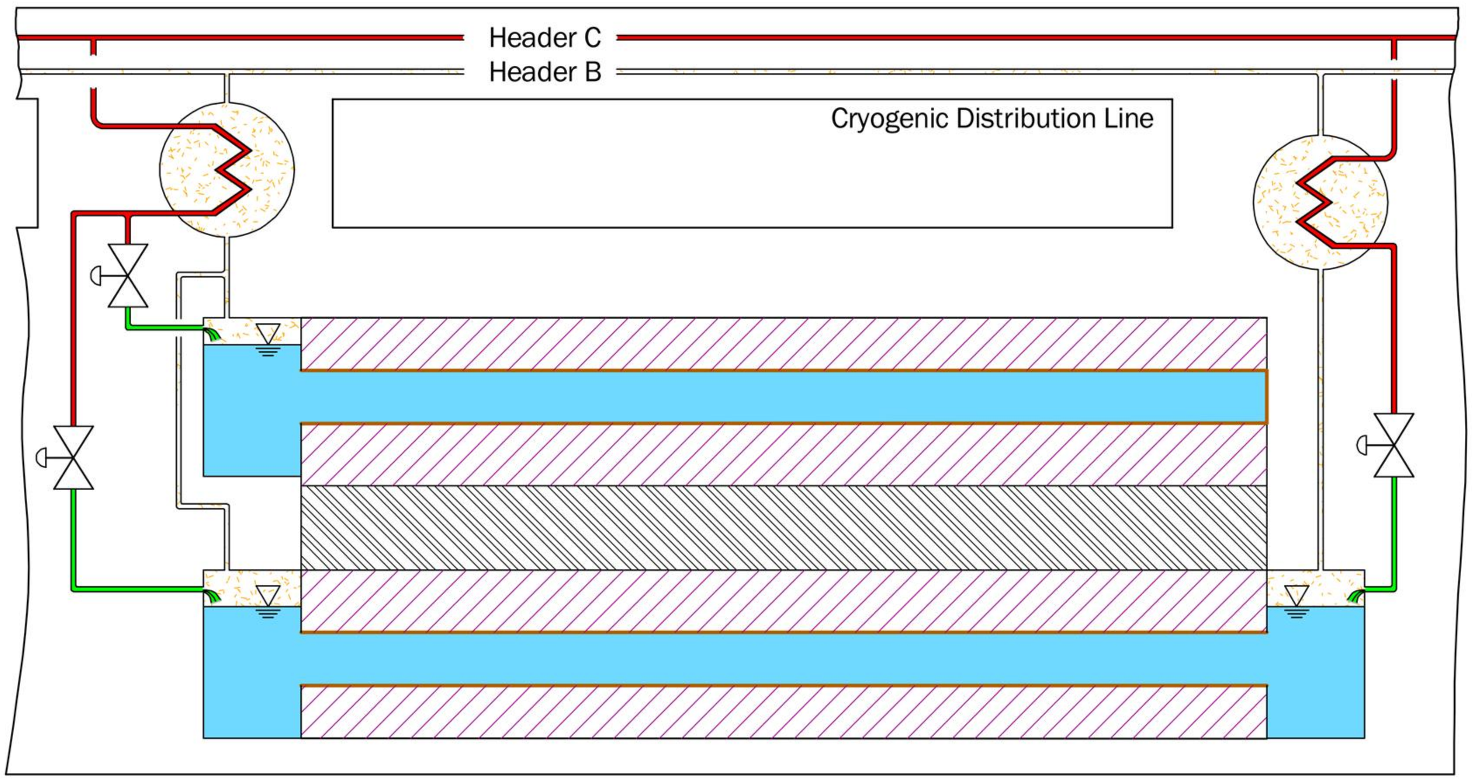
The conduction scheme

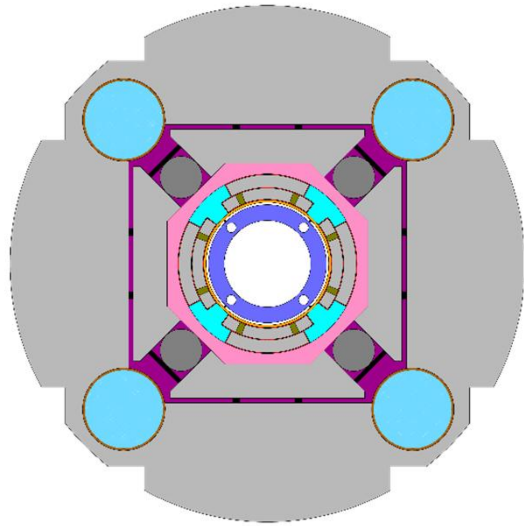
$$\Delta T_{max} = \int_0^{L_{Mag}} \frac{(\dot q x)^m f_k}{A^m} dx = \frac{\dot q^m L_{Mag}^{m+1} f_k}{A^m (m+1)}$$

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

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

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





The conduction scheme

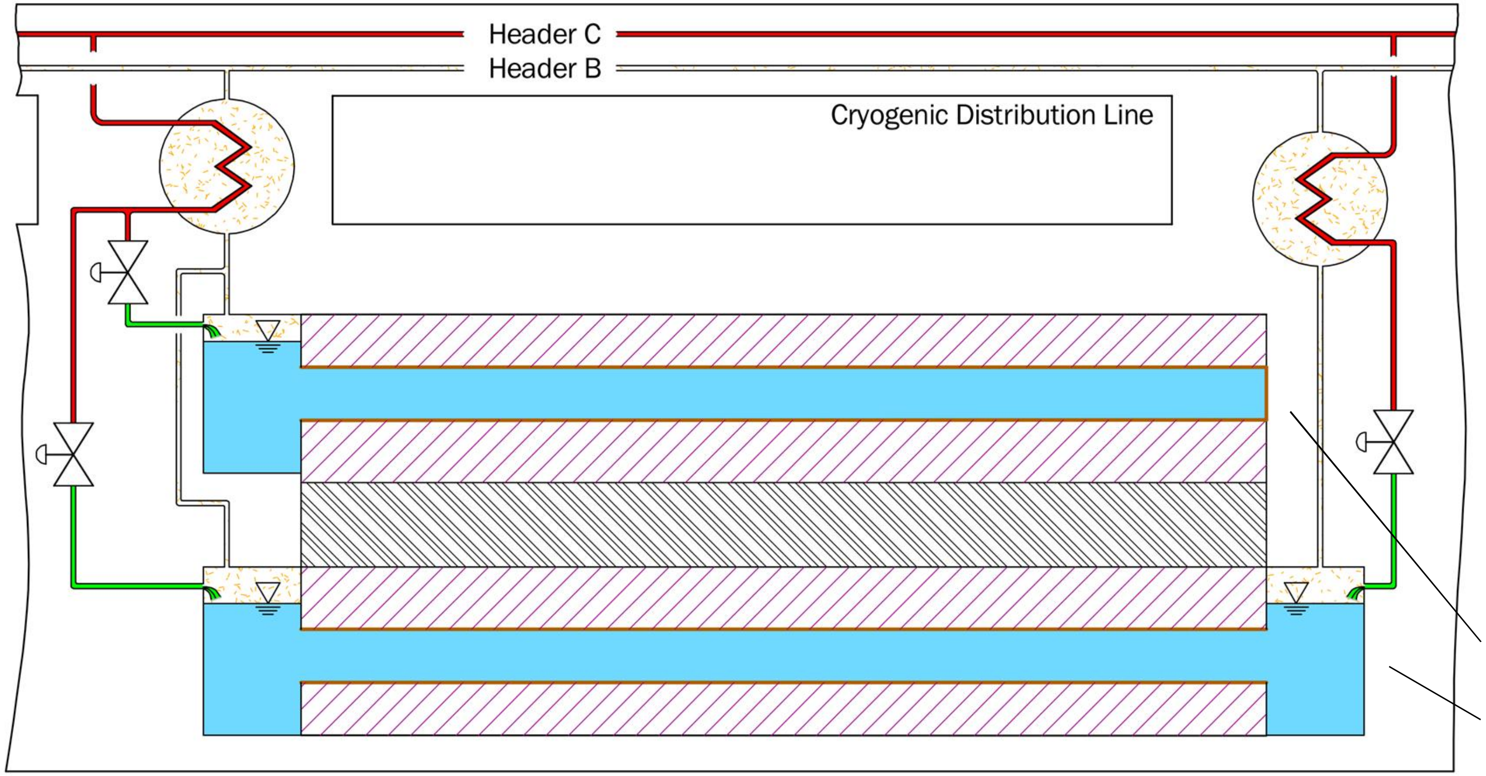
$$\Delta T_{max} = \int_0^{L_{Mag}} \frac{(\dot q x)^m \, f_k}{A^m} dx = \frac{\dot q^m \, L_{Mag}^{m+1} \, f_k}{A^m \, (m+1)}$$

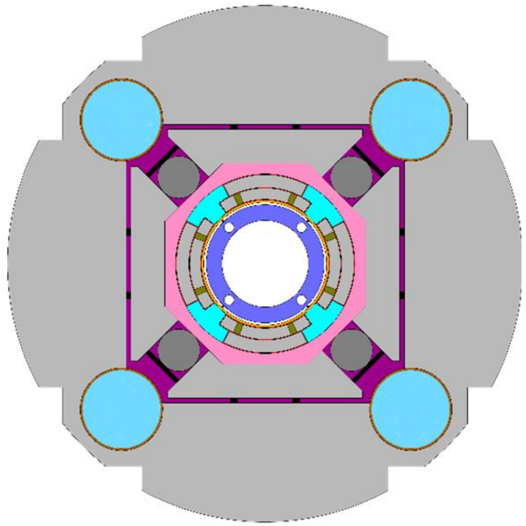
Needed cross section area for heat conduction α $L^{1.3}$

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

→

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



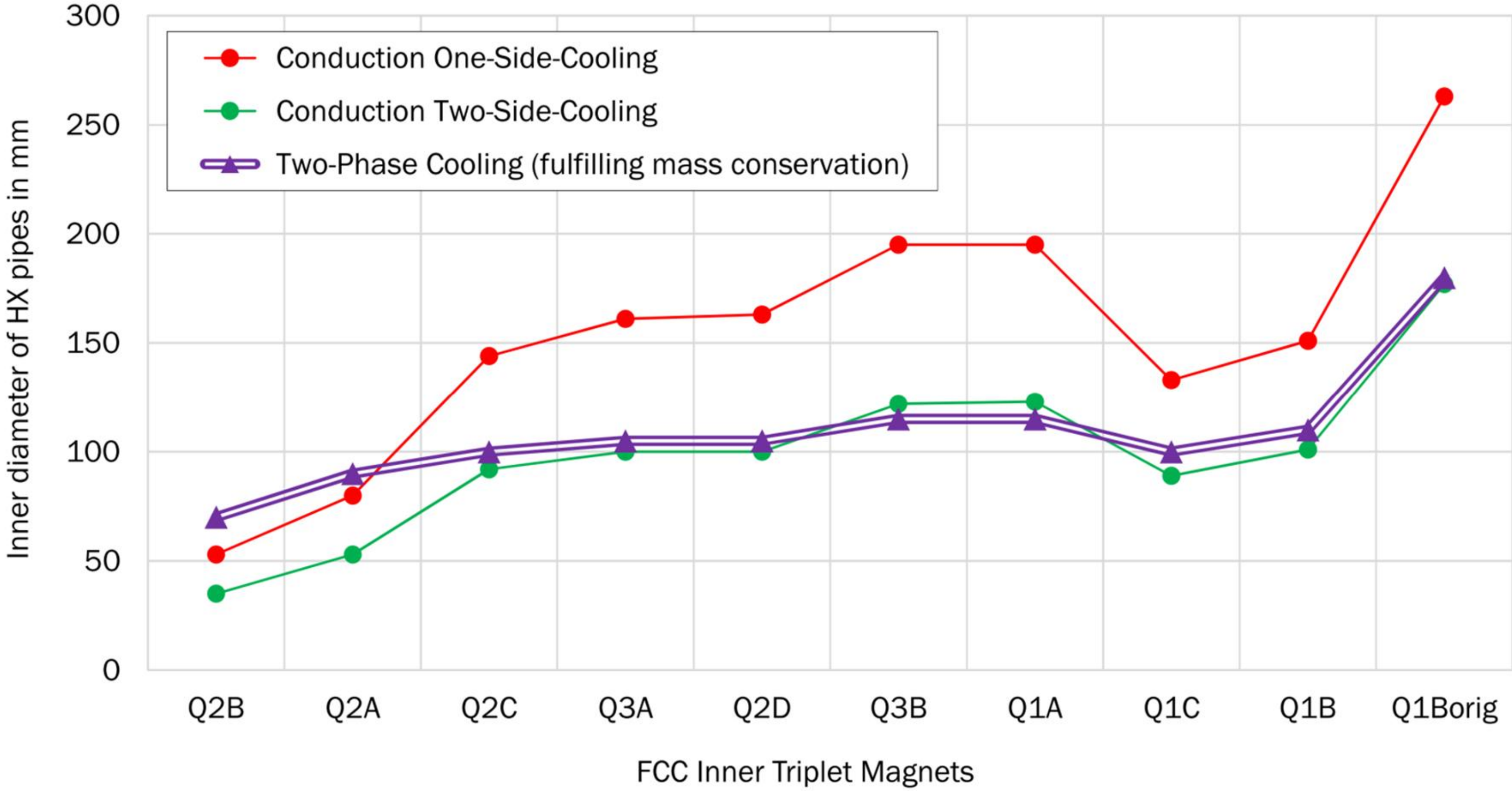


Two possible designs:

Option 1: One-Side-Cooling

Option 2: Two-Sides-Cooling

Numerical solutions

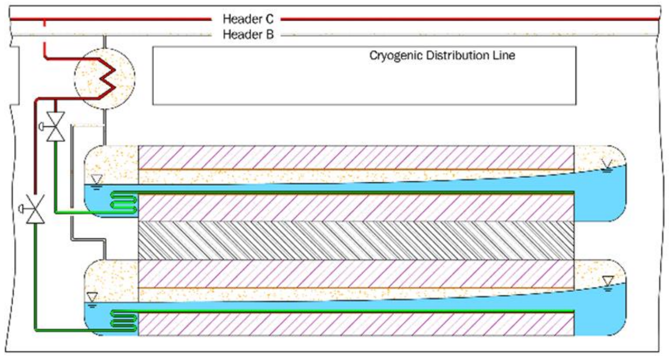


- The Two-Side Conduction cooling option and the Two-Phase cooling need similar space in the cold mass for cryogenics - both concepts seem to be in the feasibility's range
- The choice could be made by different aspects (required space between adjacent magnets, transient behavior, controlling effort,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

Summary

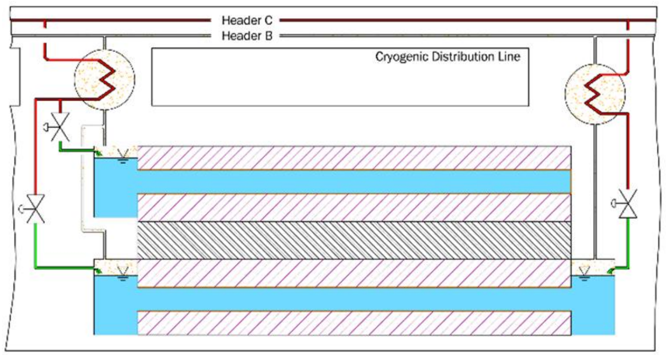
- Very high, but strongly non-uniform heat loads on the FCC Inner Triplet Magnets challenge the cryogenics design (structure was changed to be able to design a reliable cooling system for the available space)
- Two well-established cooling concepts were investigated

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

Thank you very much for your attention!

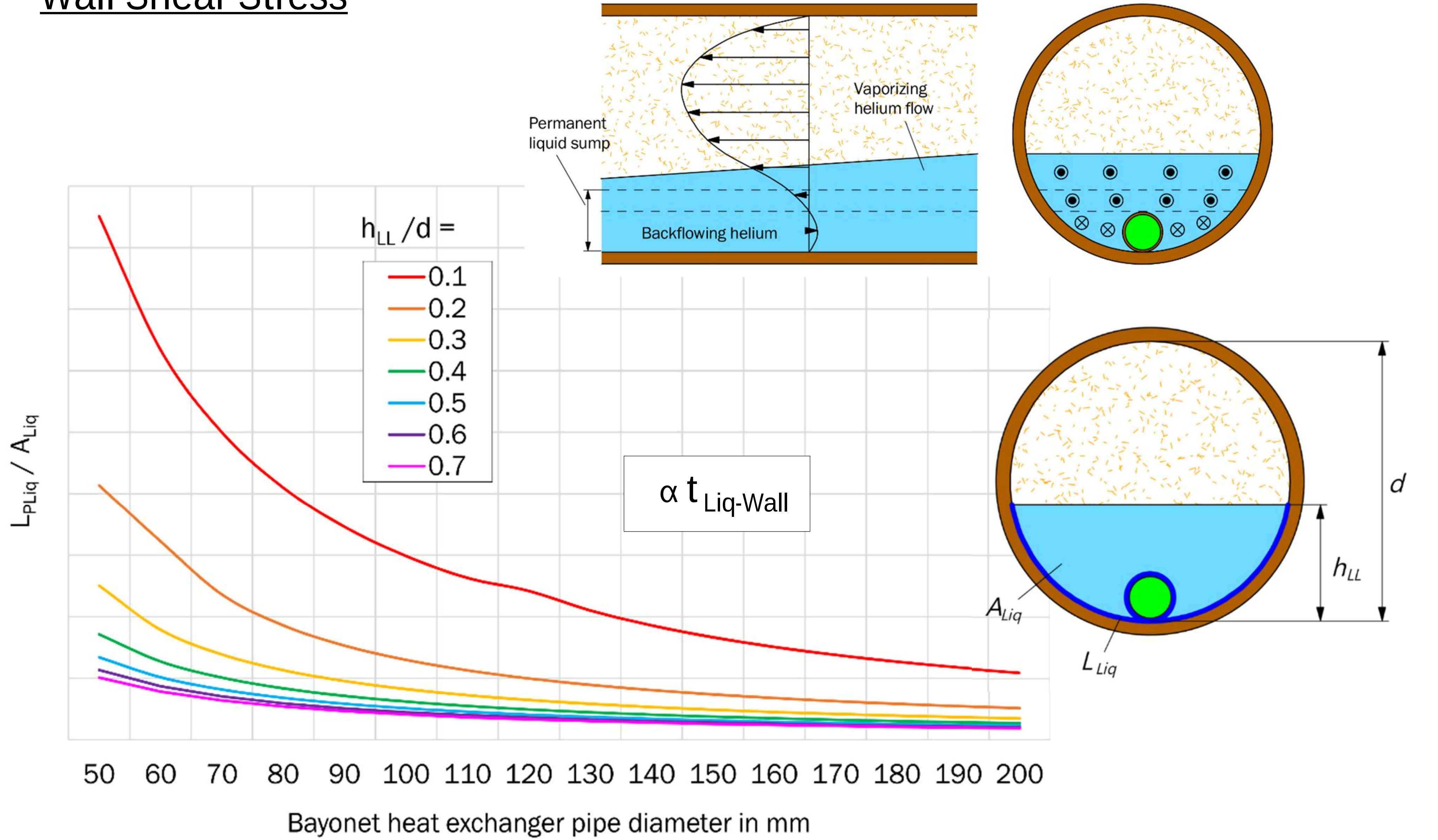
"What starts out as science fiction today may wind up being finished tomorrow as a report."

Norman Mailer

FCC WEEK 2019
BRUSSELS, BELGIUM
24 - 28 JUNE 2019
Crowne Plaza Brussels
Le Palace

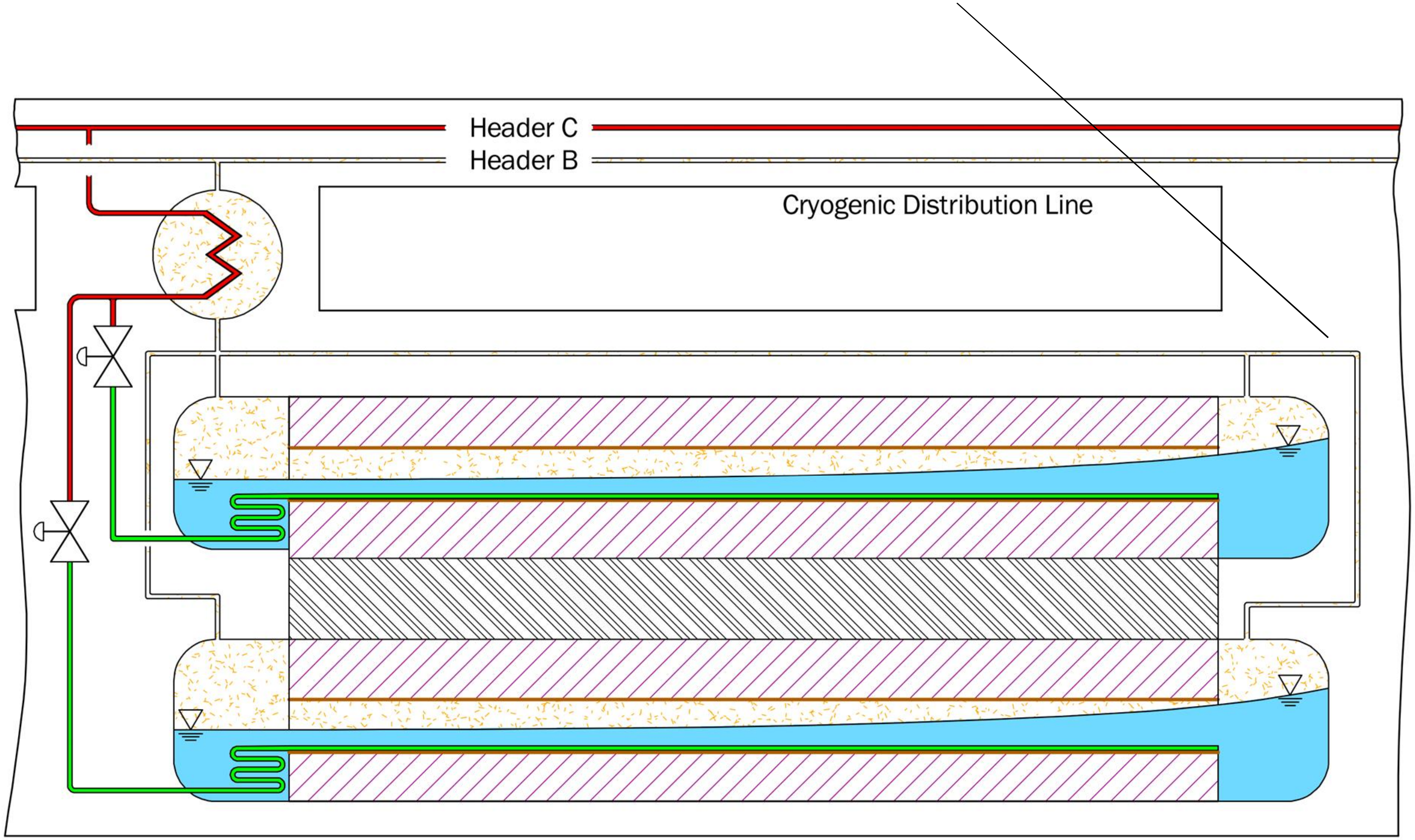
WRITING the FUTURE
http://fccweek2019.web.cern.ch/

Wall Shear Stress



Two-Sides vapour extraction

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

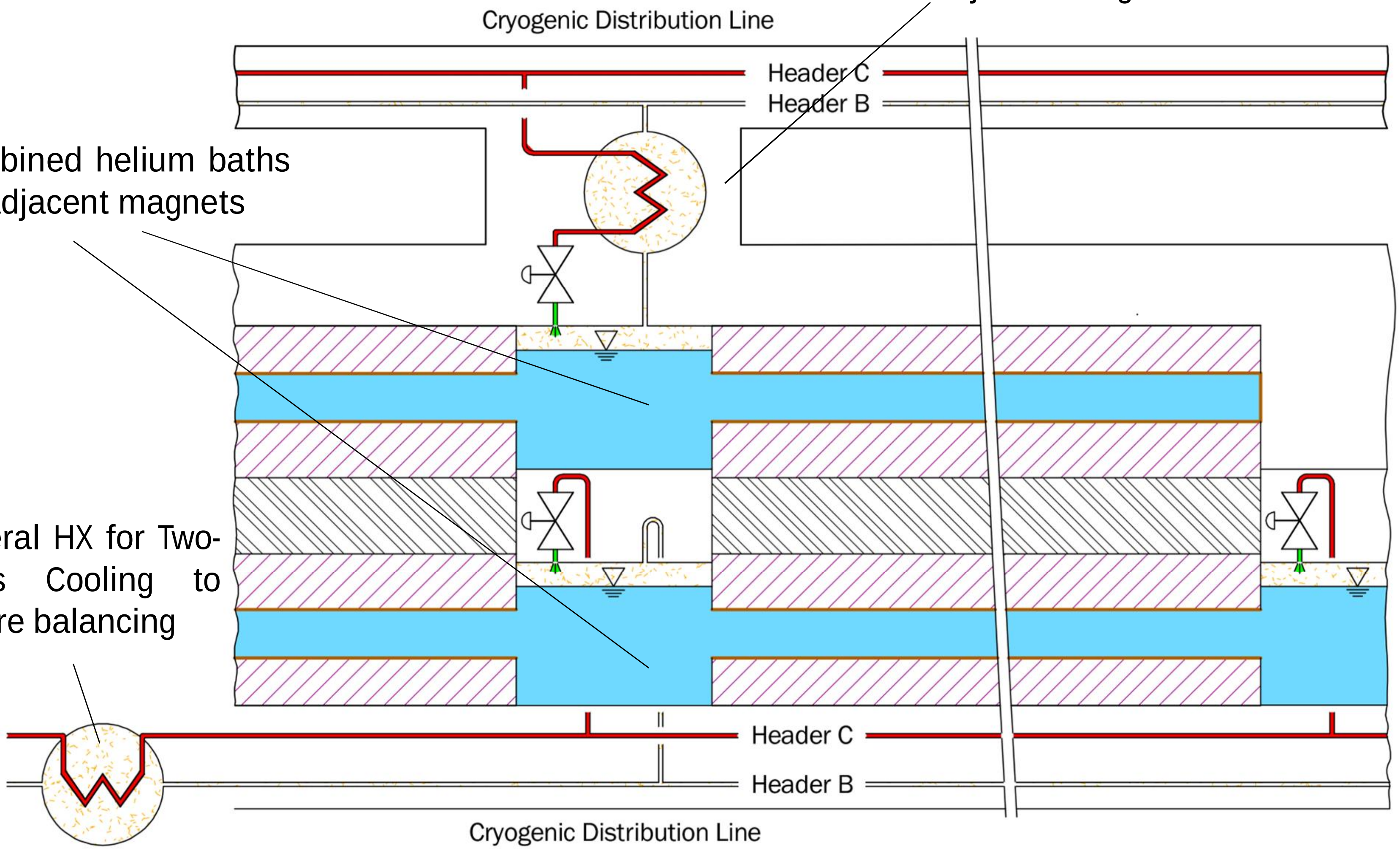


Conduction Cooling Arrangements

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

Combined helium baths for adjacent magnets

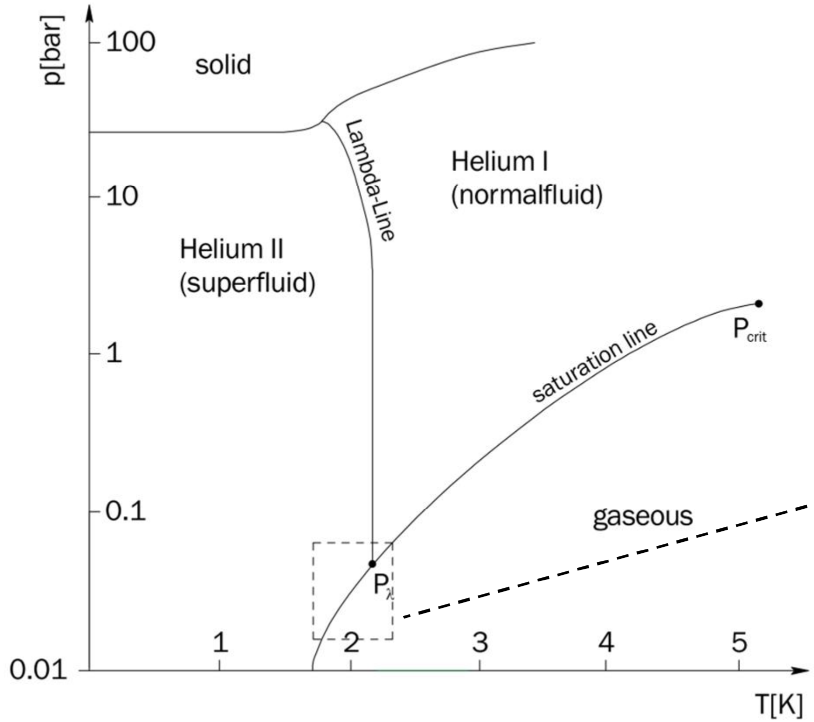
General HX for Two-Sides Cooling to assure balancing

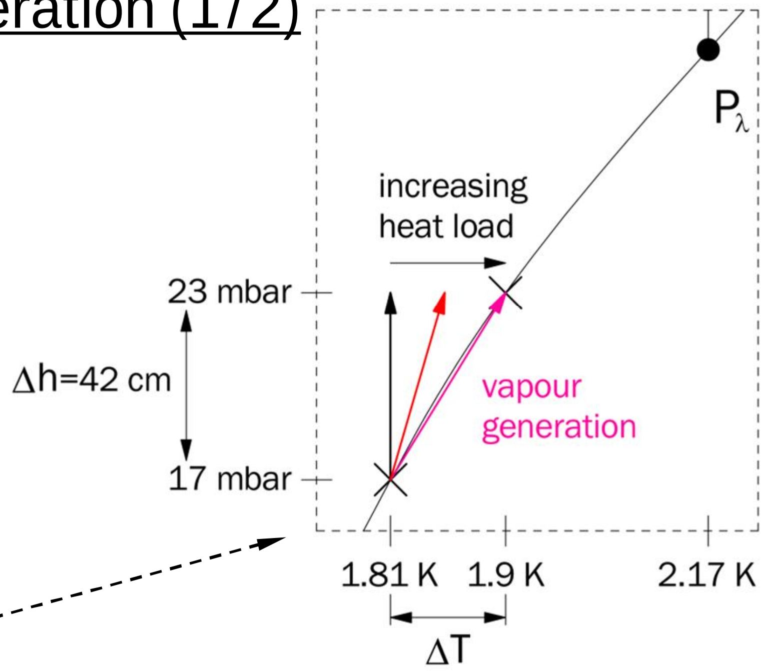


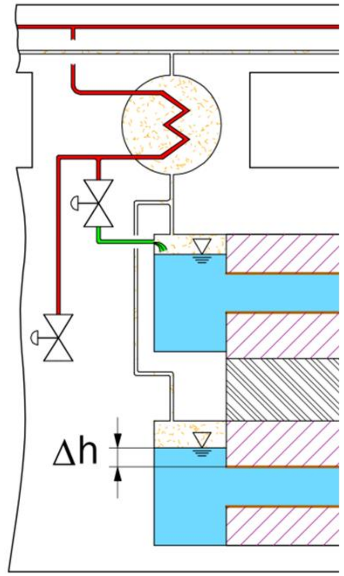
One-Side-Cooling

Two-Sides-Cooling

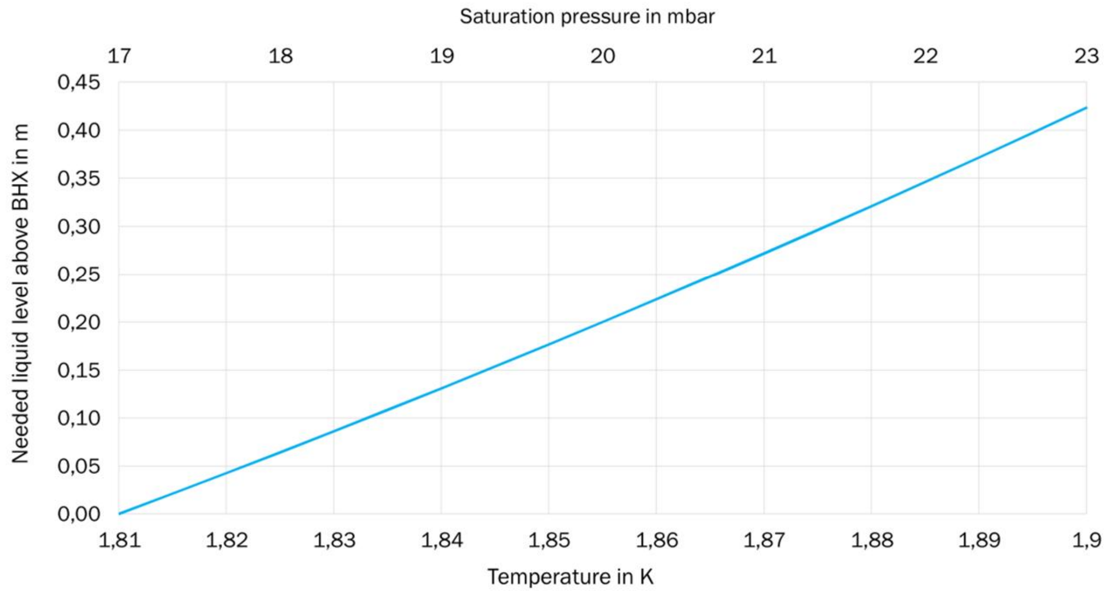
Conduction Cooling Vapour Generation (1/2)



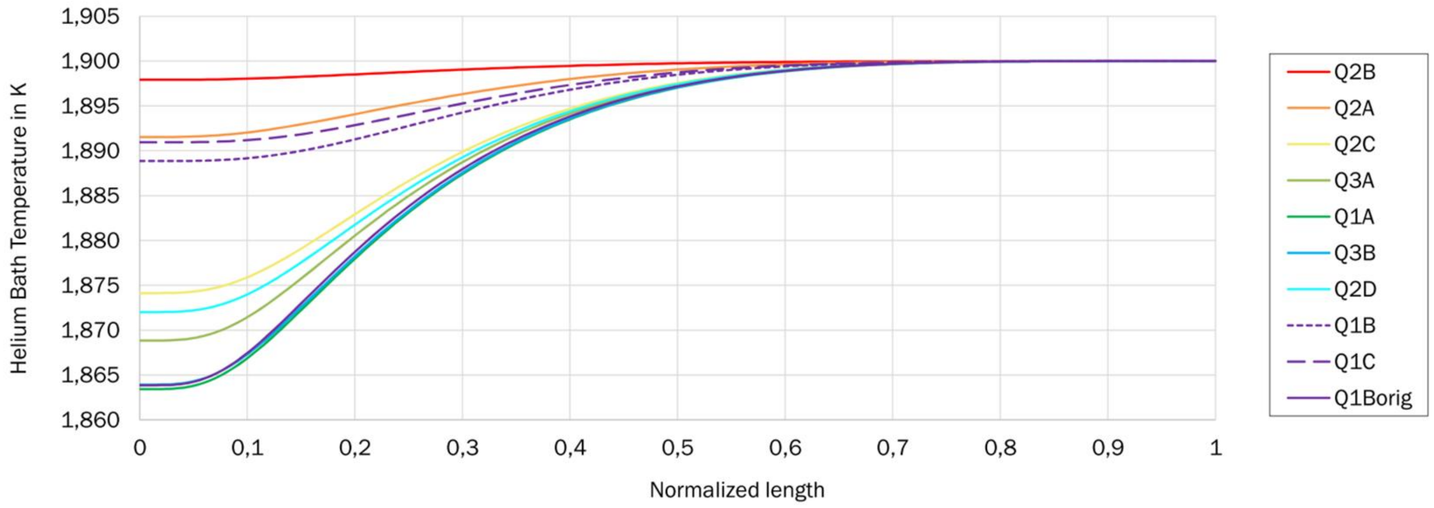


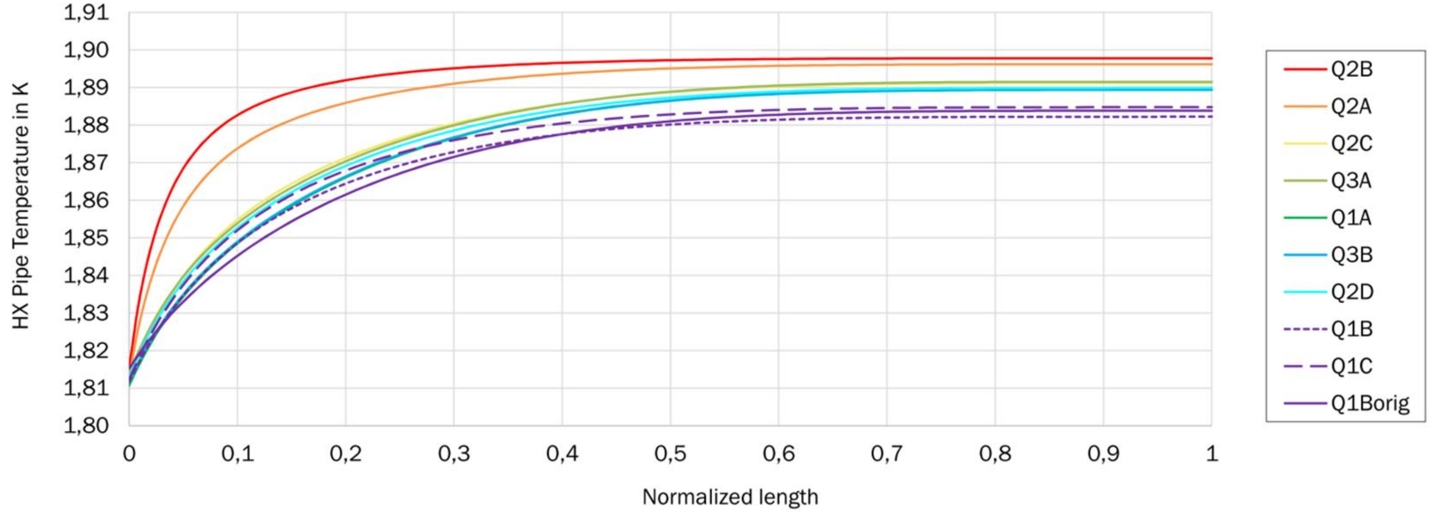


- ρ_{Liq} = 145 kg/m^3
- HX pipe diameters calculated to reach a temperature of ≈ 1.9 K
- Minimal pressure head needed to avoid saturation line (≈ 42 cm)



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