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

Dimitri Delikaris, Claudio Kotnig, Laurent Tavian
The FCC-hh Inner Triplets

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

Collision debris
Heat Load on the Tungsten Shield

- 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

→ Small, reliable and possibly uniformly designed cryogenic system needed

Available space for cryogenics installations

\[ d_{\text{max}} \approx 100 \, \text{mm} \]

Free space for pressurized superfluid helium

\[ T_{\text{max}} = 1.9 \, \text{K} \]

Coil

\[ T_{\text{max}} = 4.5 \, \text{K} \]

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
The two-phase cooling scheme

Helium supplied by header C:
\[ T_C = 4.6 \text{ K} \quad p_C = 3 \text{ bar} \]

Helium discharged into header B:
\[ p_B = 16 \text{ mbar} \]

→ Determines stratified flow temperature \( = T \bigg|_{p_{\text{Sat}}=17 \text{ mbar}} \)
Two-phase cooling - The two main constraints

Heat extraction

- **Bad heat transfer via vapour phase**
  - \( T_{\text{max}} = 1.9 \text{ K} \)
  - \( T_{2\Phi} \approx 1.81 \text{ K} \)

- **Good heat transfer via liquid phase**

\[ \Delta T_{\text{max}} \]

Vapour velocity

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

\[ V_{\text{Vap}} \]

\[ V_{\text{Liq}} \]

\[ h_{\text{LL}} \] for sufficient heat transfer

\[ \dot{Q} = \frac{\Delta T_{\text{max}}}{R_{\text{th}}} P_{\text{wet}} = \frac{\Delta T_{\text{max}}}{R_{\text{th}}} 2 r \arccos \left( 1 - \frac{r}{h_{\text{LL}}} \right) \]  

\[ h_{\text{LL}} = r \left[ 1 - \cos \left( \frac{R_{\text{th}} \dot{Q}}{2 r n_{\text{BH}} \Delta T_{\text{max}}} \right) \right] \]

\[ v_{\text{Vap}} = \frac{\dot{m}}{\rho_{\text{Vap}} A_{\text{Vap}}} = \frac{\dot{Q} L}{n_{\text{BH}} \rho_{\text{Vap}} (h'' - h_{JT})} \left[ r^2 \arccos \left( 1 - \frac{h_{\text{LL}}}{r} \right) - (r - h_{\text{LL}}) \sqrt{2 r h_{\text{LL}} - h_{\text{LL}}^2} \right] \leq 5 \text{ m/s} \]
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: \[ 1) \pm \dot{m} \frac{d \xi}{dz} = \frac{d}{dz} (A_\Phi \rho_\Phi v_\Phi) \]

Momentum balance: \[ 2) \frac{d}{dz} (A_\Phi \rho_\Phi v_\Phi^2) = -A_\Phi \frac{d \Pi_L}{dz} \pm \]
\[ \pm \tau_{V_L} L_{V_L} - \tau_{P_\Phi} L_{P_\Phi} + g A_\Phi \rho_\Phi \left( \sin \alpha \pm \cos \alpha \frac{dh_{L_L}}{dz} \right) - \dot{m} \frac{d \xi}{dz} \Delta v_{V_L} \]

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

Thermal conduction in superfluid helium: \[ 4) \frac{dT}{dz} = -f_k \dot{q}^{\text{m}} \]
Two-phase cooling - Numerical results

Numerical solutions

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

$\rightarrow$ 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

\[
\Delta T_{\text{max}} = \int_{0}^{L_{\text{Mag}}} \frac{\dot{q} x^m f_k}{A^m} dx = \frac{\dot{q}^m L_{\text{Mag}}^{m+1} f_k}{A^m (m+1)}
\]

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

\[
A^m = \frac{\dot{q}^m L_{\text{Mag}}^{m+1} f_k}{\Delta T_{\text{max}} (m+1)} \rightarrow d = \sqrt[4]{\frac{4 \dot{q}}{\pi n_{BHX}} \sqrt[6]{\frac{L_{\text{Mag}}^{m+1} f_k}{\Delta T_{\text{max}} (m+1)}}} \propto L_{\text{Mag}}^{0.65} \sqrt[4]{L_{\text{Mag}}^{0.5}}
\]

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, ...)

![Numerical results graph](image)

- Conduction One-Side-Cooling
- Conduction Two-Side-Cooling
- Two-Phase Cooling (fulfilling mass conservation)
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
"What starts out as science fiction today may wind up being finished tomorrow as a report."

Norman Mailer
Wall Shear Stress

\[ \frac{L_{\text{PL,liq}}}{A_{\text{liq}}} \]

\[ \frac{h_{\text{LL}}}{d} = \]

- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7

\[ \alpha \tau_{\text{Liq-Wall}} \]

Bayonet heat exchanger pipe diameter in mm

C.Kotnig
FCC Week 2019 in Bruxelles, Cryogenics, 26.06.2019
Two-Sides vapour extraction could decrease bayonet HX diameter size requirement.
Conduction Cooling Arrangements

- **General HX for Two-Sides Cooling** to assure balancing
- **Combined helium baths for adjacent magnets**
- **One Jumper connection (HX, valve) for two adjacent magnets for One-Side Cooling**

Diagram showing the cryogenic distribution line with headers labeled as Header A and Header B, indicating the cooling arrangements for two sides and one side.
Supplemental – Conduction Cooling Vapour Generation (1/2)

Conduction Cooling Vapour Generation (1/2)

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