Adaption of the LHC cold mass cooling system to the requirements of the Future Circular Collider (FCC)

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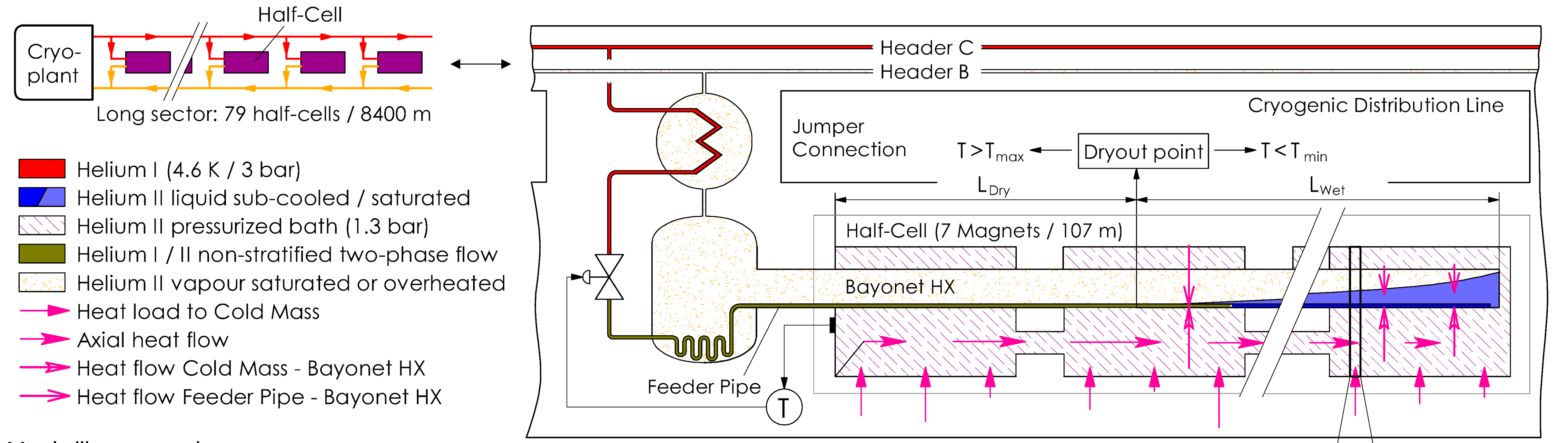
Introduction

The LHC cold mass cooling operates at temperatures below 2 K. The advantageous use of superfluid helium makes up for the increased operational costs and the elaborate cryoplants compared to cold mass cooling systems working at higher temperature level (> 4 K).

Considering one single half-cell, the adaption to the FCC requirements particularly consists of proper scaling of the bayonet heat exchanger and the free cross section area in the cold masses for the axial heat conduction due to the larger heat loads. Regarding the distribution of one (long) FCC sector, the main difficulty arises in the dependable and efficient transport of the evaporated helium back to the cold compressor stations.

Cold mass cooling concept and modelling



Modelling equations:

vapour mass fraction

"Helium Cryogenics", van Sciver S. p.230-232

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

+ → vapour phase
- → liquid phase

Axial heat conduction: $\frac{dT}{dz} = -f_k \dot{q}^m$

3.4

- → vapour phase
+ → liquid phase

Maximal expected slope of the FCC: 0.6 %

Momentum: $$-\underbrace{A_\Phi \frac{dp}{dz}}_{\text{pressure forces}} \mp \underbrace{\tau_{VL} L_{VL} - \tau_{P\Phi} L_{P\Phi}}_{\text{friction forces}} + \underbrace{g A_\Phi \rho_\Phi \sin\alpha}_{\text{weight}} =$$

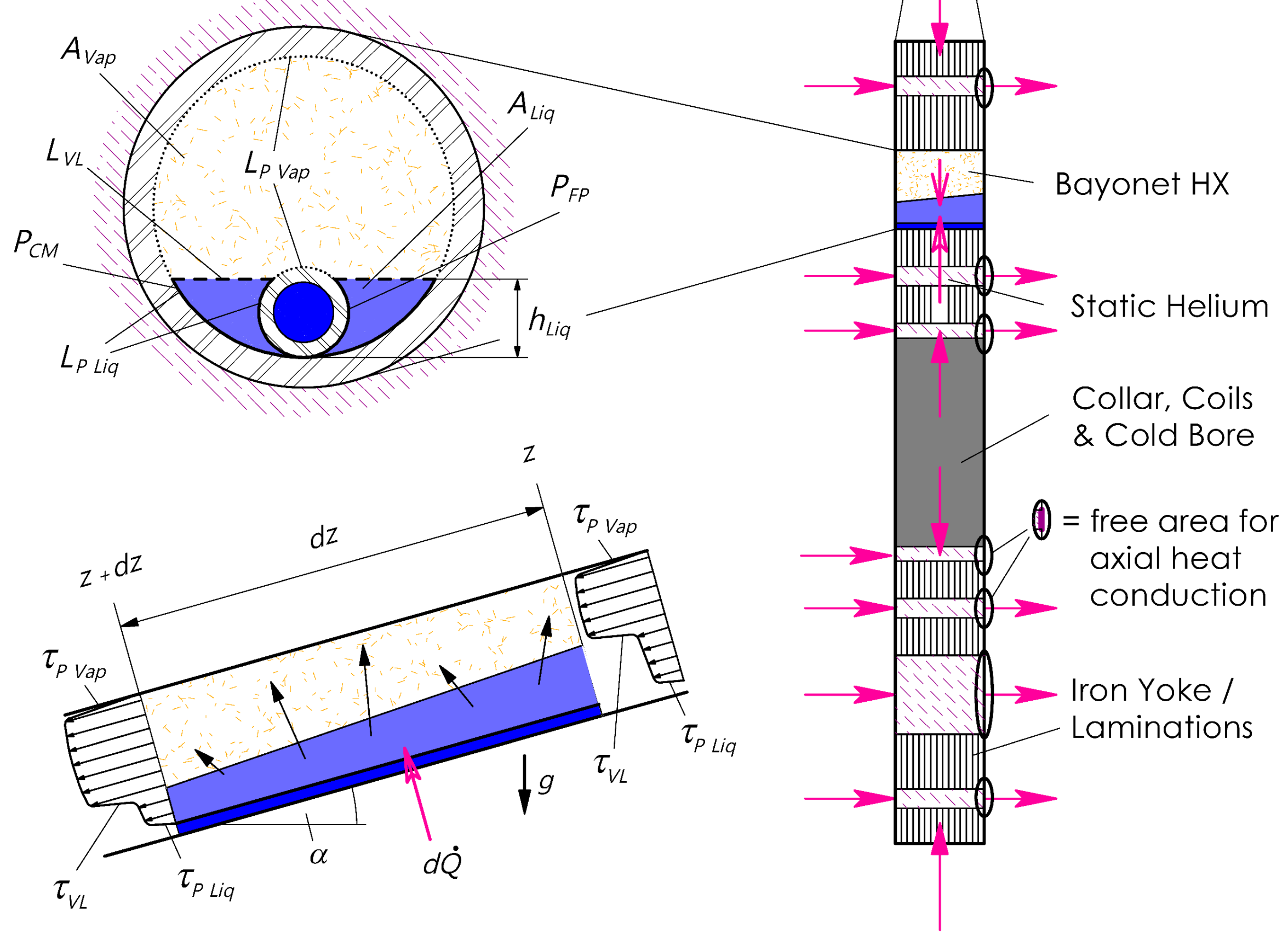
pressure constant over entire flow cross section

Wall friction factors: Churchill's formula
Interfacial friction factor: Andritsos & Hanratty

$$= \underbrace{\dot{m}_\Phi \frac{dv_\Phi}{dz} + \dot{m}\frac{dx}{dz}\Delta v_{VL}}_{\text{Change of momentum}} \quad \begin{cases} = 0 & \text{... for the liquid phase} \\ = v_{Vap} - v_{Liq} & \text{... for the vapour phase} \end{cases}$$

Energy: $$\underbrace{\left(h'' - h'\right)}_{\text{latent heat}} dx = \frac{\dot{q}_{CM} P_{CM} + \dot{q}_{FP} P_{FP}}{\dot{m}} dz$$

- only thermal energy
- no longitudinal heat conduction in stratified flow



Temperature profile along a half-cell

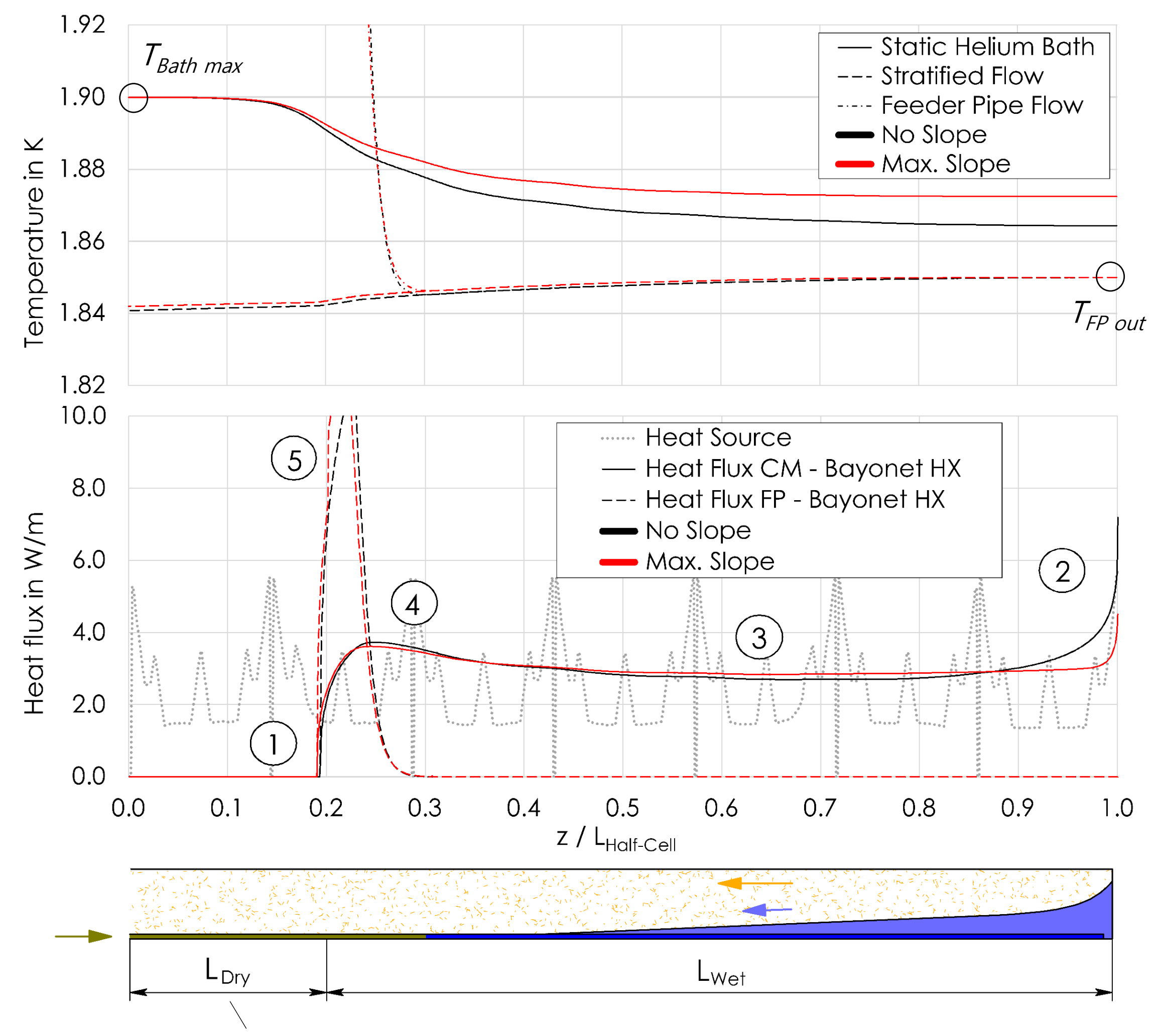
① Marks the dryout point; also the inflection points of the temperature profiles of the helium bath and the maximal axial heat flux occur

② At the half-cell's end, the heat flux extracted from the cold mass is high due to the large wetted perimeter of the bayonet heat exchanger - in inclined half-cells the liquid level decreases faster due to the gravitational influence

③ With decreasing liquid level and increasing cold mass temperature the heat flux profile shows a convex shape with a local minimum

④ Close to the dryout point the driving temperature difference increases, causing a high heat transfer before it suddenly vanishes due to the total evaporation of the liquid helium

⑤ The heat flux entering from the feeder pipe is large corresponding to the high driving temperature difference - after passing a short distance the feeder pipe flow is liquefied entirely and the temperature is assimilated to the stratified flow temperature

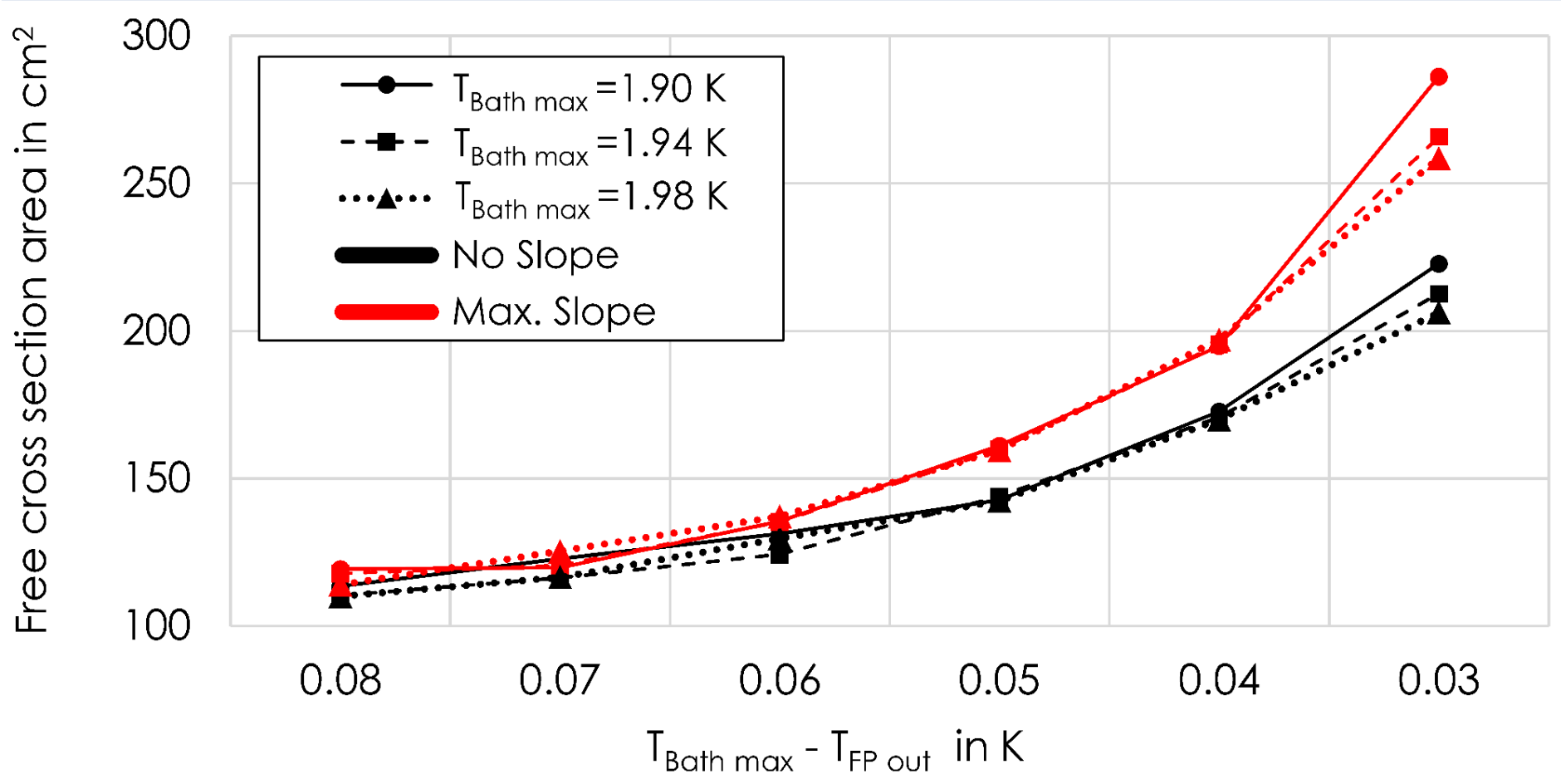


Minimal dry length for dependable controlling: 20 % of the half-cell length

Bayonet heat exchanger

1. To avoid liquid entrainment the bayonet heat exchanger is designed to keep the two-phase superfluid helium flow in the stratified flow regime (vapour phase velocity $v_{Vap} \leq 5$ m/s)
2. In steady-state operation the helium flow is entirely evaporated before reaching the separator – the dryout point splits the baynet HX into a dry and a wetted section
3. Due to the low pressure heat is only transferred radially when the bayonet HX is partially wetted. The heat load on the dry section has to be conducted inside the cold mass to the wetted part in a superfluid pressurized helium bath

Cold mass free area

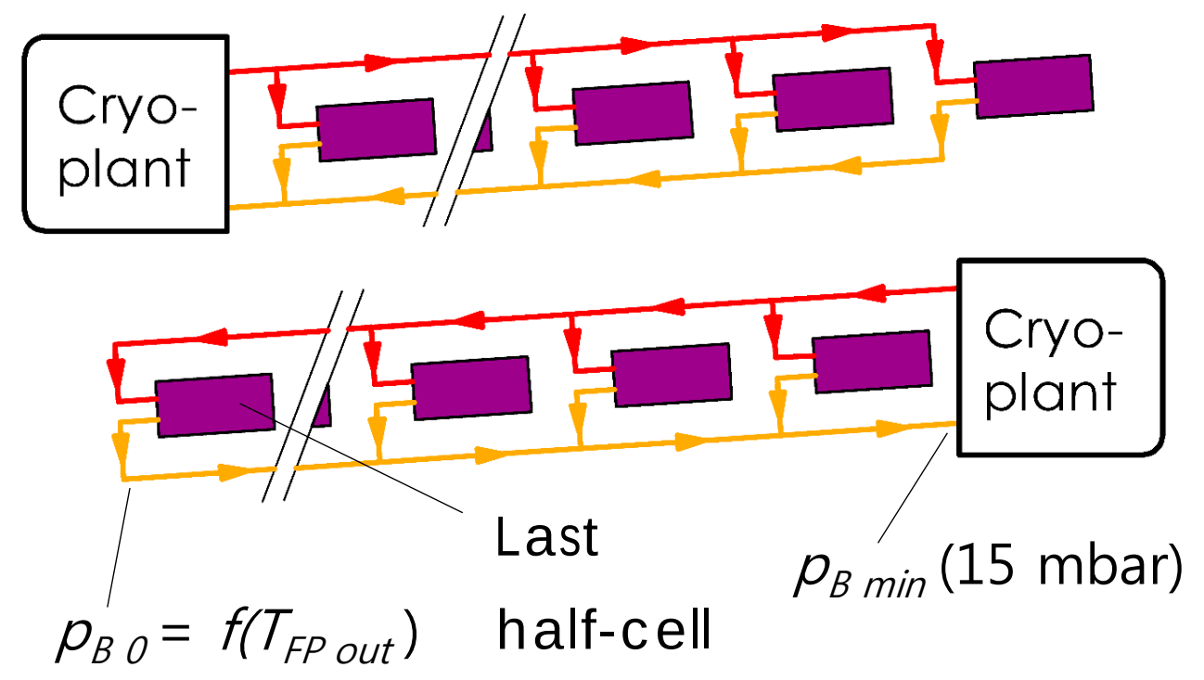


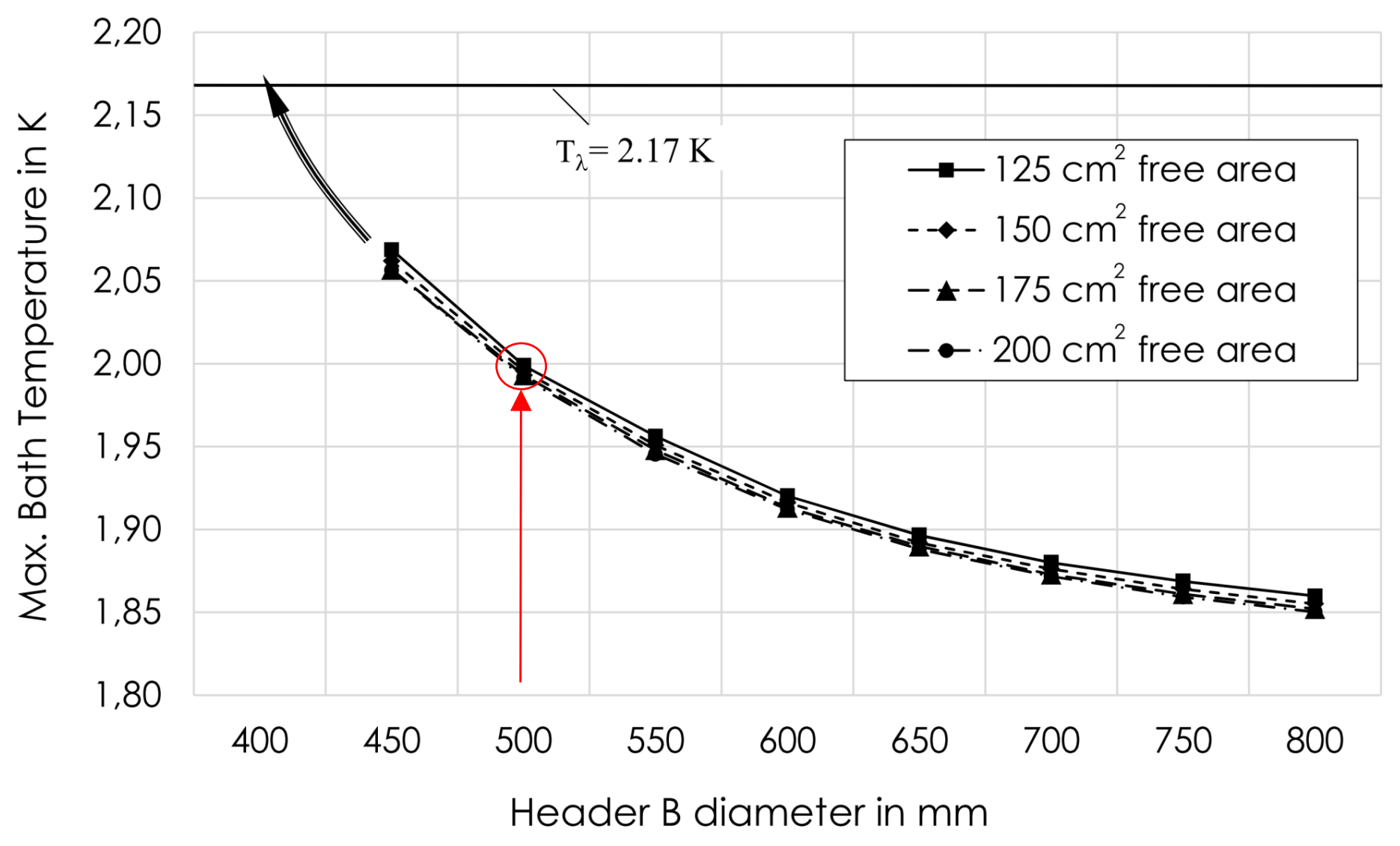
- Small available temperature ranges increase the efficiency and the necessary free area in the CM
- The influence of the temperature level on the free area requirement is of secondary order
- Inclined half-cells are the critical design case

→ Available free area determines maximal saturation pressure in the bayonet HX

Helium vapour return to the cryoplant

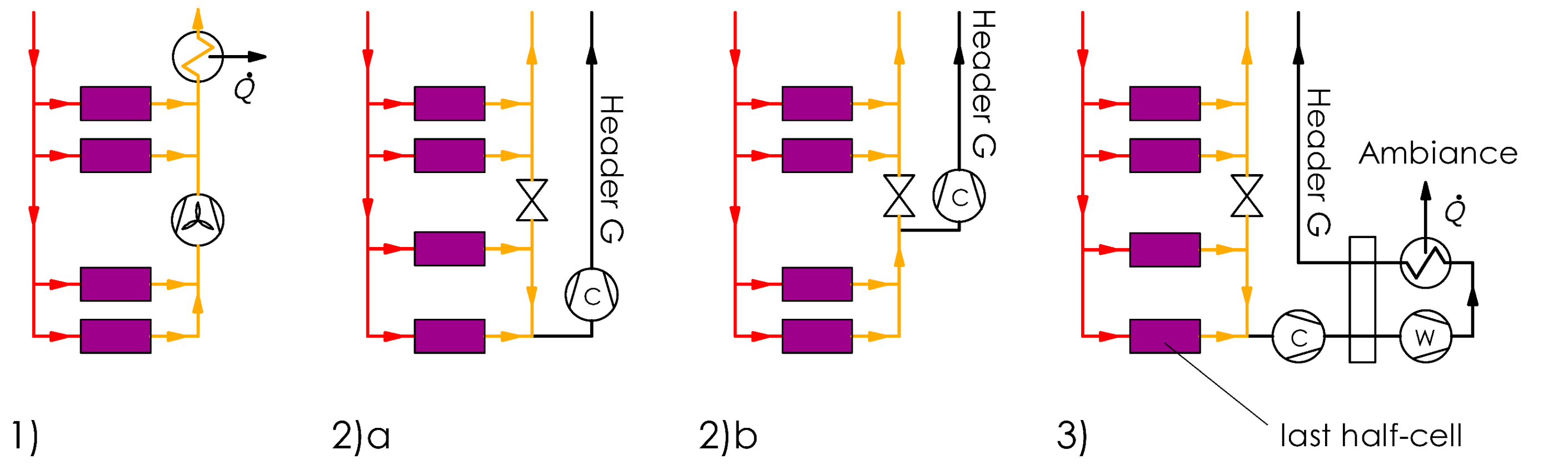
Independent on the slope of the sector and the location of the supplying cryoplant, the bayonet heat exchangers are always passed by the stratified flow in descending direction. Critical design case for the return of the helium vapour is an ascending header B, since the frictional and the gravitational pressure losses sum up.



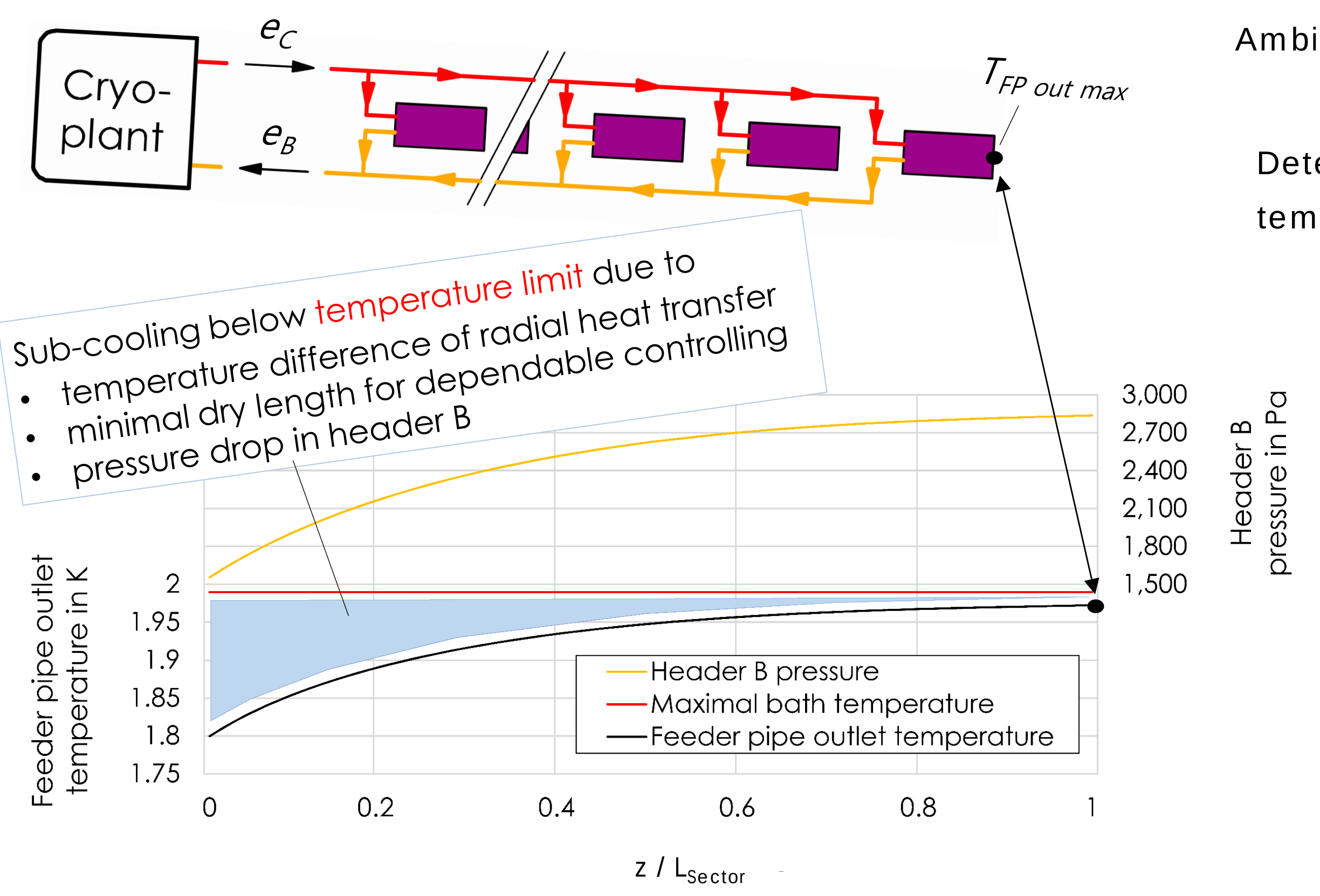


The maximal bath temperature to cool the superconducting coils and the available free area in the cold mass for axial heat conduction determine the temperature of the baynet HX in the last half-cell and therefore the helium vapour pressure in header B.

Space constraints limit the header B diameter to 500 mm yielding several combinations of a minimal free area and bath temperature. If none of these combinations are acceptable for the magnet design, additional machinery has to be installed to return the helium vapour to the cryoplants.



Exergetic considerations



Sub-cooling below temperature limit due to
- temperature difference of radial heat transfer
- minimal dry length for dependable controlling
- pressure drop in header B

Ambient temperature

Determined by coil temperature limit

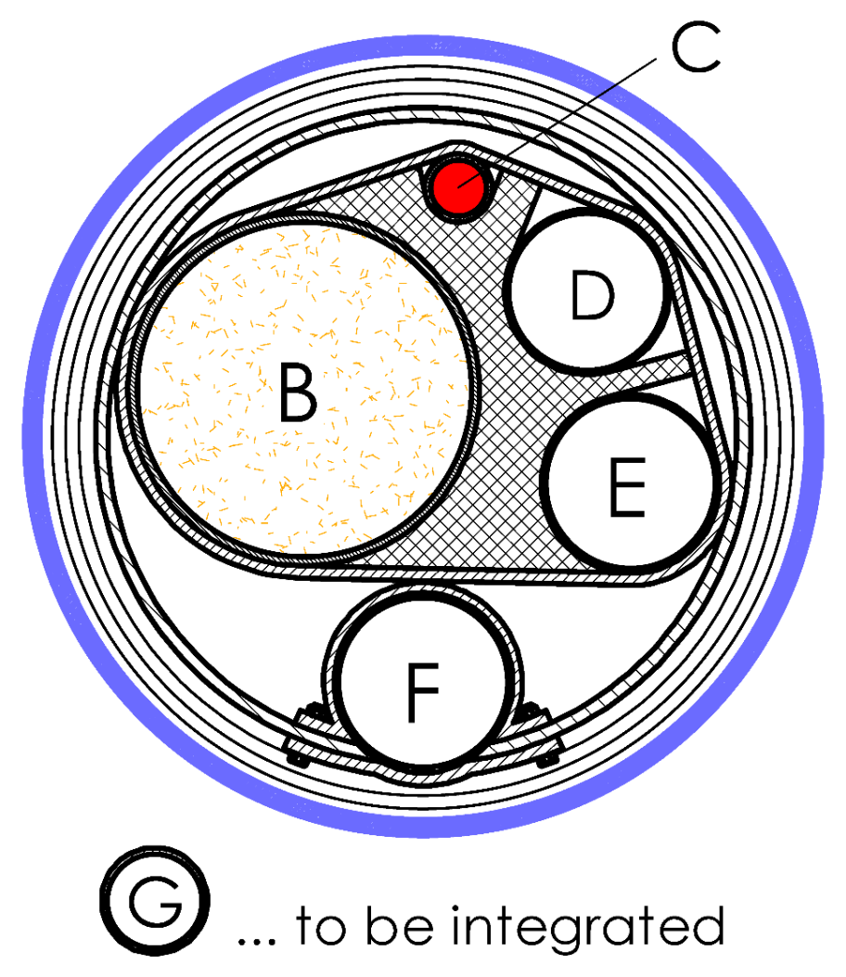
$$\zeta \propto \left(\frac{T_a}{T_{Bath\,max}} - 1\right)\frac{1}{\Delta e_{CB}}$$

Mainly a dependent on the suction pressure at the end of header B, dependent on three design parameters:

1. The maximal bath temperature determines the theoretical minimal saturation temperature (↔ pressure) in the bayonet heat exchangers.
2. The free area in the cold mass determines the difference between the maximal bath temperature and the feeder pipe outlet temperature.
3. The header B diameter determines the pressure drop in header B and therefore the operation temperatures of the half-cells.

Additional machinery

1) One or more cryogenic ventilators compress the helium vapour flow on its way back to the cryoplant.
2) The helium vapour flow is divided: One partial flow is compressed in an additional cold compressor station
   a. installed at the sector end or
   b. installed in the middle of the sector.
3) The helium vapour flow is divided: One partial flow is compressed in an additional warm compressor station installed at the sector end.



The options 2) and 3) require an additional header at cryogenic temperature level, which has to be integrated in the cryogenic distribution line without increasing its diameter.

Summary & Conclusion

- The dedicated space for the cryogenic distribution line limits the possible diameters of the contained headers (especially header B)
- The pressure drop in the return header B dictates the temperature progress of the cold masses
- The coil temperature limit and the available free area in the cold mass to conduct heat axially could impose new requirements to be able to return the helium vapour to the cryoplants
- The installation of a larger cryogenic distribution line can be circumvented by integration of additional machinery, which albeit is accompanied by increasing capital costs, operational costs and a decreasing exergetic efficiency

The superconducting coil temperature limit and the available space for cryogenics in the cold masses are crucial design parameters to bring the decision of a possible extension of the helium vapour discharge to a head. A study the analyse the feasibility and resulting costs for installation and operation is one next step in the FCC cryogenic distribution design phase.

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