Basic comparison of hydraulic schemes for the FCC-hh cold mass cooling with supercritical helium

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Introduction

The cold mass refrigeration at a temperature of 1.8 K is a well-established method, experienced during the longstanding operation of the LHC. Especially the large know-how, the high thermal conductivity of superfluid helium II and the possible savings of superconducting material at lower temperatures are compelling arguments to hold on to this cooling concept. Nevertheless also the cold mass refrigeration with supercritical helium I at about 4 K comes along with several advantages, for example

- Lower capital and operational costs of the cryogenic facilities
- Reduced downtime due to component failure
- Possible benefits to handle technical challenges related to a particle accelerator of this size (e.g. quench management)

The completely different thermodynamic and flow-mechanical properties of supercritical helium compared to pressurized superfluid helium at 1.8 K requires a cryogenic system based on a different concept for cooling the superconducting material. A basic analysis of different concepts adapted to the specifications of the FCC-hh in advance is important to enable the development of well-matching machinery systems.

Basic concept and conditions

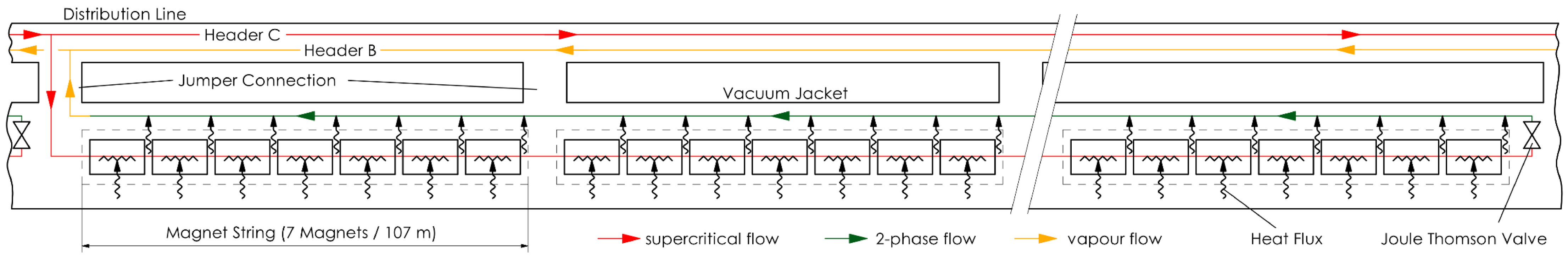


Figure. Simplified illustration of the cold mass cooling concept with supercritical helium

1) Supercritical helium (He_{sc}) passes through the magnet strings (MS / 7 magnets in series) extracting heat to keep the temperature of the superconducting coils below the necessary limit (T_{max}^{Co})

2) After cooling several magnet strings in series the helium is expanded into the 2-phase region ($He_{2\Phi}$)

3) The returning $He_{2\Phi}$ flow is completely evaporated (He_{Vap}) by cooling the counterflowing He_{sc} flow

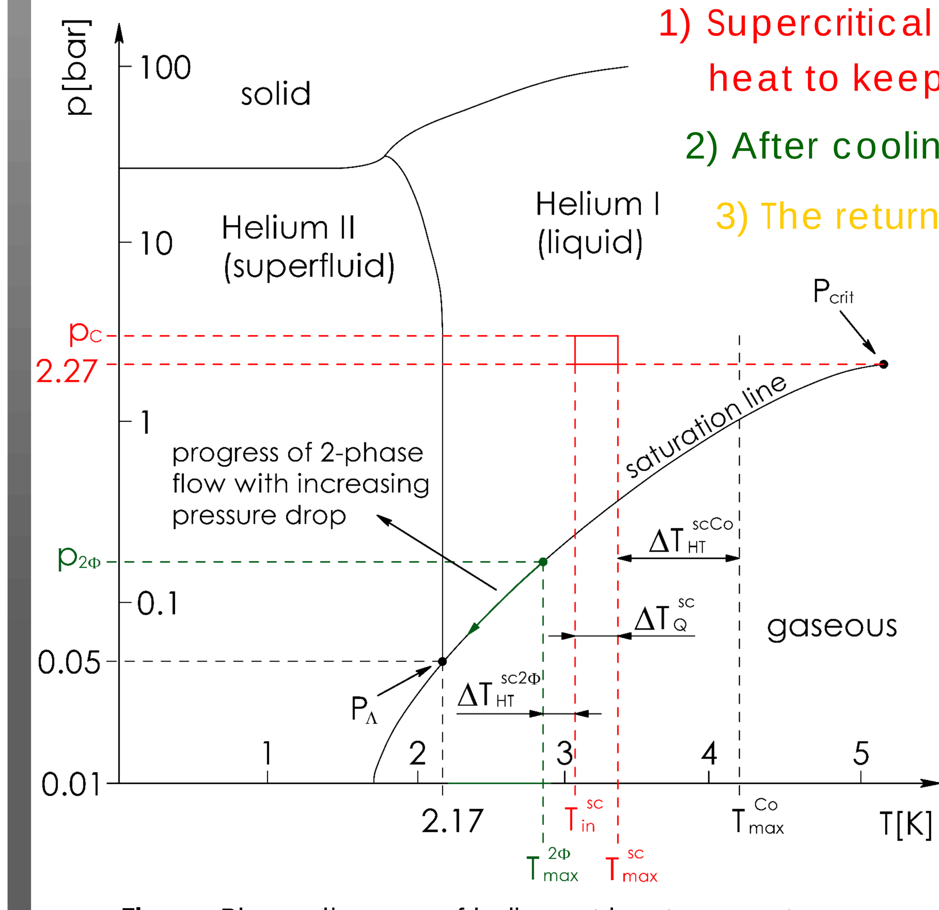


Figure. Phase diagram of helium at low temperature

ΔT_{HT}^{scCo} ... temperature difference for heat transfer from superconducting coils to He_{sc}

$\Delta T_{HT}^{sc2\Phi}$ ... temperature difference for heat transfer from He_{sc} to $He_{2\Phi}$

ΔT_{Q}^{sc} ... temperature rise of He_{sc} during cooling of one magnet / one magnet string

Thermodynamic and fluid-mechanical conditions

$p_{\min}^{sc} > p_{crit}$ The helium flow close to the coils is exposed to a high magnetic field → electrical arcs could be generated in the helium vapour phase

$T_{\min}^{2\Phi} > T_{\Lambda}\left(p_{\min}^{2\Phi} > p_{\Lambda}\right)$ Decreasing the temperature below T_{Λ} would make the cooling concept obsolete → ²He-cooling like in the LHC possible

$L_{CL} = \frac{\dot{m}\cdot(h''-h')}{\dot{q}}\cdot\lambda$ Total evaporation condition → the entire evaporation of helium connects the mass flow with the length of a cooling loop

Exergetic considerations

Specific exergy e: $e = h - h_{amb} - T_{amb}\cdot(s - s_{amb})$

Exergy transported in mass flow $\dot{E}$: $\dot{E} = \dot{m}\cdot e$

subscript amb ... (at) ambient condition
h ... specific enthalpy, T_{amb} = 300 K
s ... specific entropy, p_{amb} = 1 bar

The exergetic consumption of a scheme corresponds to the exergy difference of the helium mass flows in header C and header B (plus any circulation power).

$$\dot{X}_{tot} = \underbrace{\dot{E}_C - \dot{E}_B}_{\Delta\dot{E}_{CB} >> P_{Cir}} + P_{Cir}$$

By good approximation the mass flow (total evaporation) and the total exergetic benefit increase linearly with the number of cooled MS.

$$\zeta \approx \frac{\dot{A}_{tot}}{\Delta\dot{E}_{CB}} \approx \frac{\dot{A}_{MS}\cdot n_{MS}}{\dot{m}_{MS}\cdot\Delta e_{CB}\cdot n_{MS}}$$

As the state of helium in header C is the same for each concept, the state of helium in header B (primarily the pressure) defines the exergetic performance of a hydraulic scheme.

$$\zeta \approx \frac{\dot{A}_{MS}}{\dot{m}_{MS}}\cdot\frac{1}{\Delta e_{CB}} = f(p_B)$$

$\approx$ const. for $\dot{q}$ = const., T_{max}^{Co} = const.

$\dot{X}$ ... exergetic effort $\dot{A}$ ... exergetic benefit ζ ... exergetic efficiency n_{MS} ... number of cooled MS in series

Pressure in return header B

The final pressure of the returning helium vapour in header B depends on

1. the pressure drop in the returning $He_{2\Phi}$.
2. the necessary temperature of the $He_{2\Phi}$ to enable a sufficient heat transfer to keep the coil temperature below its limit.

a) Hydraulic schemes with magnet-internal heat exchange (Concepts 1 & 2)

- the magnet design allows adaptions for cryogenic applications to enable a sufficient heat transfer within the magnets from the $He_{2\Phi}$ to the He_{sc} (cross flow cooling)
- the He_{sc} is recooled after each magnet; the „high-frequent" heat exchange enables small He_{sc} mass flows without lowering the temperature of the returning $He_{2\Phi}$ too much $\dot{m}_{sc} = \frac{\dot{Q}_{Mag}}{c_p\cdot\Delta T_Q^{sc}}$
- the crucial effect causing the p_B-decrease with increasing cooling loop length is the pressure drop of the $He_{2\Phi}$ (→ ζ-decrease in Concept 1); with separators and an additional vapour return line, the pressure p_B can be increased also at a larger number of cooled MS in series (Concept 2)

b) Hydraulic schemes with magnet-external heat exchange (Concepts 3, 4 & 5)

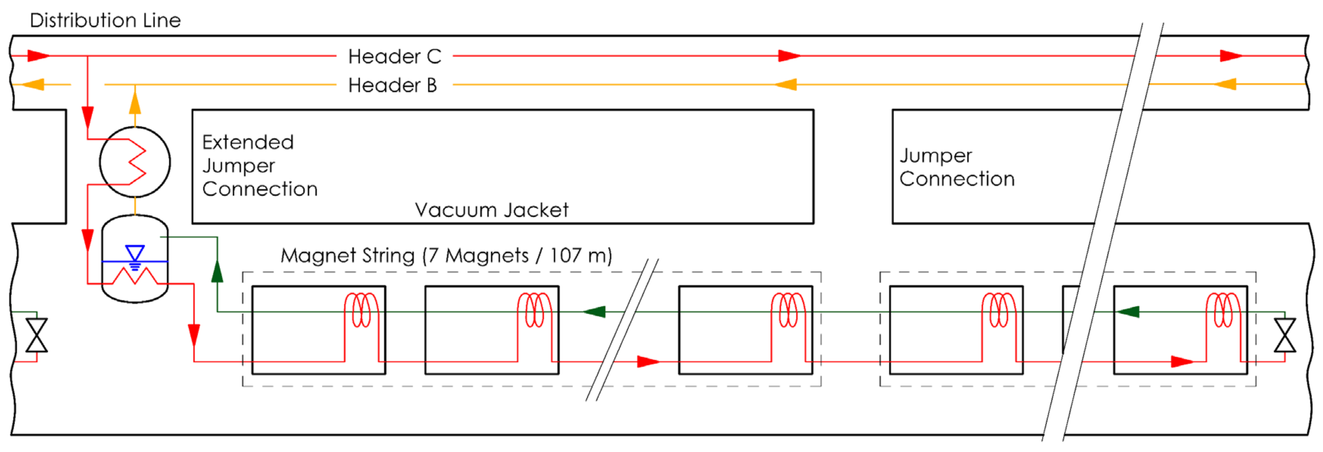
- a sufficient heat transfer within the magnets from the $He_{2\Phi}$ to the He_{sc} can't be realized → heat exchange between two adjacent MS
- large He_{sc} mass flows are necessary to keep the coil temperature below its limit → high pressure drops in the He_{sc} violate the $p_{\min}^{sc}$ - limit $\dot{m}_{sc} = \frac{\dot{Q}_{MS}}{c_p\cdot\Delta T_Q^{sc}}$
- a reduction of He_{sc} mass flow to decrease the pressure drop can be achieved by decreasing the $He_{2\Phi}$ temperature (↔ pressure) in the separators; as a result the pressure in the return header B decreases too
- in the concepts 4 and 5 a decrease in the exergetic efficiency can be found with very high and very low He_{sc} mass flows
  → low He_{sc} mass flows cause low necessary temperatures in the separators
  → high He_{sc} mass flows cause high circulation powers to extract at cryogenic temperatures

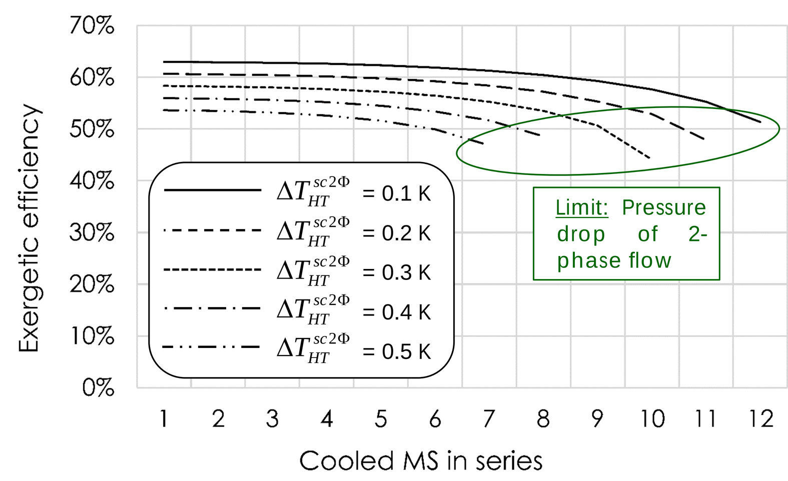
General Assumptions

Helium supply: 4.6 K / 3 bar	He_{sc} pipes (in magnets): 4 Pipes / ⌀ 20 mm
Total heat load: 1.5 W/m	$He_{2\Phi}$ pipes (in magnets): 2 Pipes / ⌀ 50 mm
TTD Separators: 0.1 K	He_{sc} return pipe: 1 Pipe / ⌀ 150 mm
TTD heat exchangers: 0.5 K	He_{Vap} pipe: 1 Pipe / variable ⌀
Max. coil temperature: 4.2 K	Temperature difference He_{SC} and coils: 1.1 K

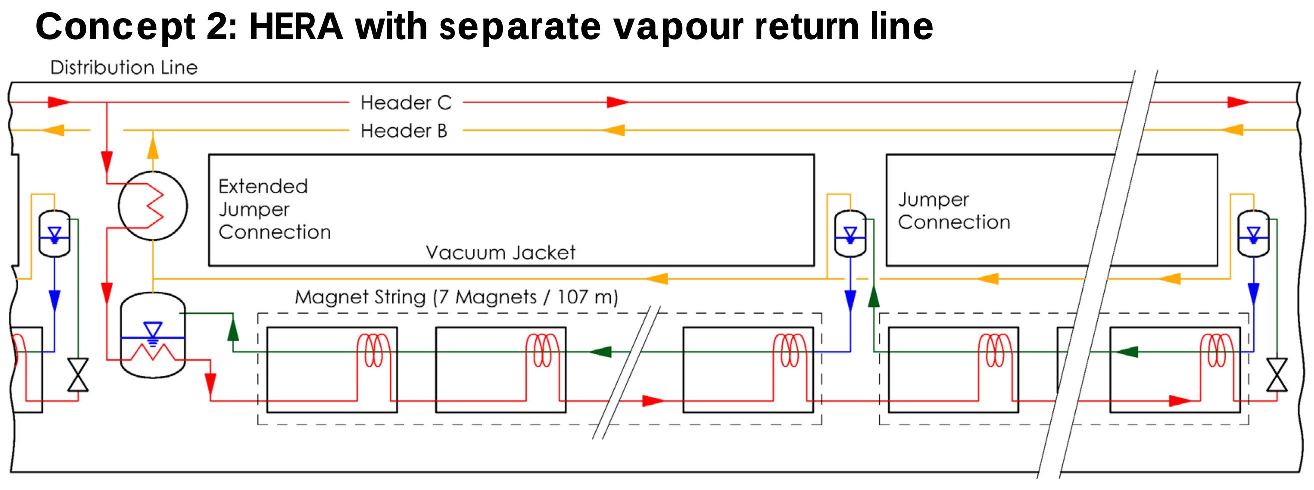
Comparison of different concepts

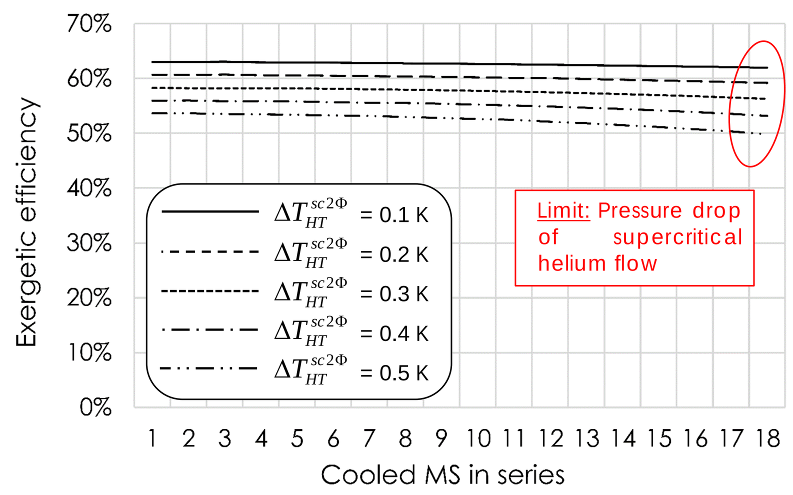
Concept 1: HERA



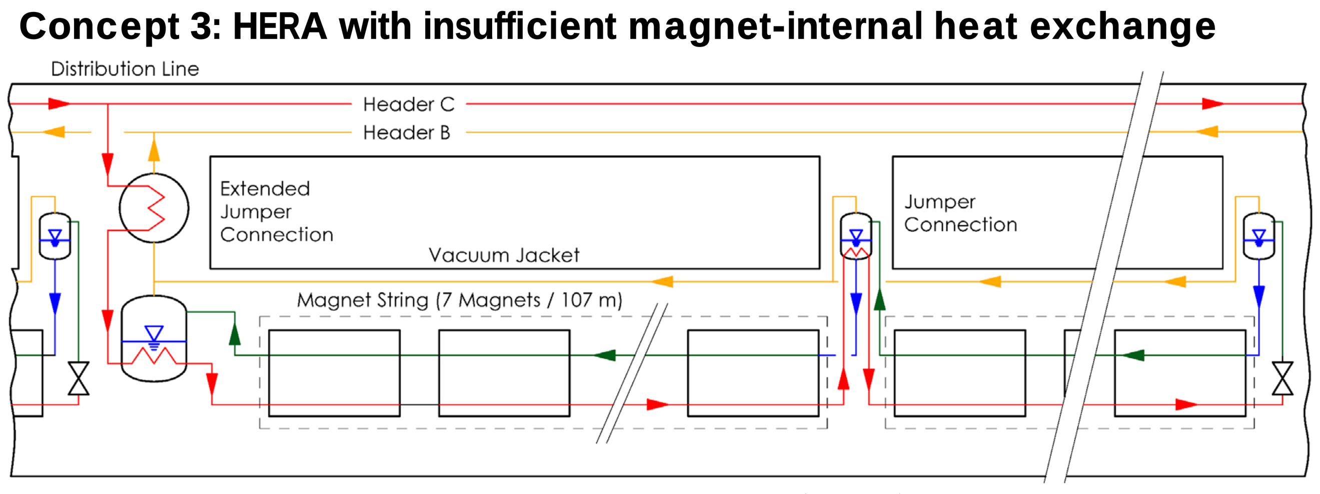


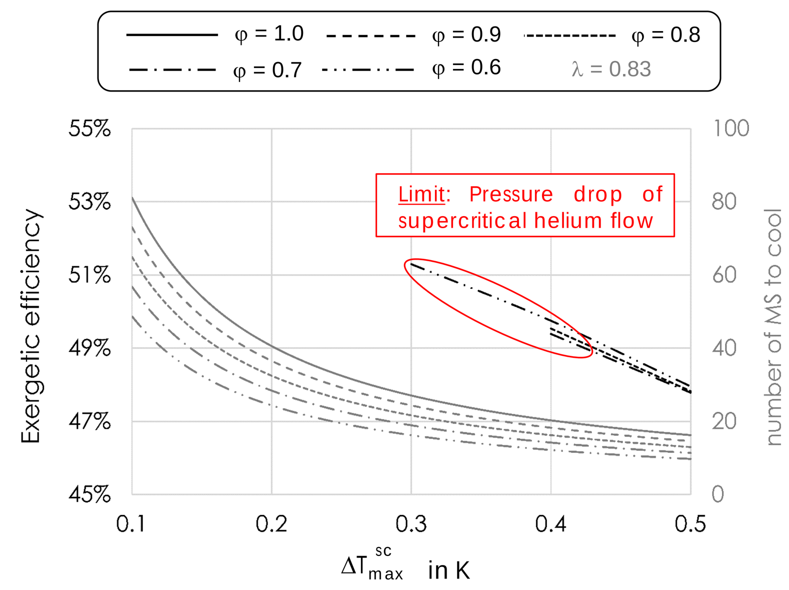
Concept 2: HERA with separate vapour return line





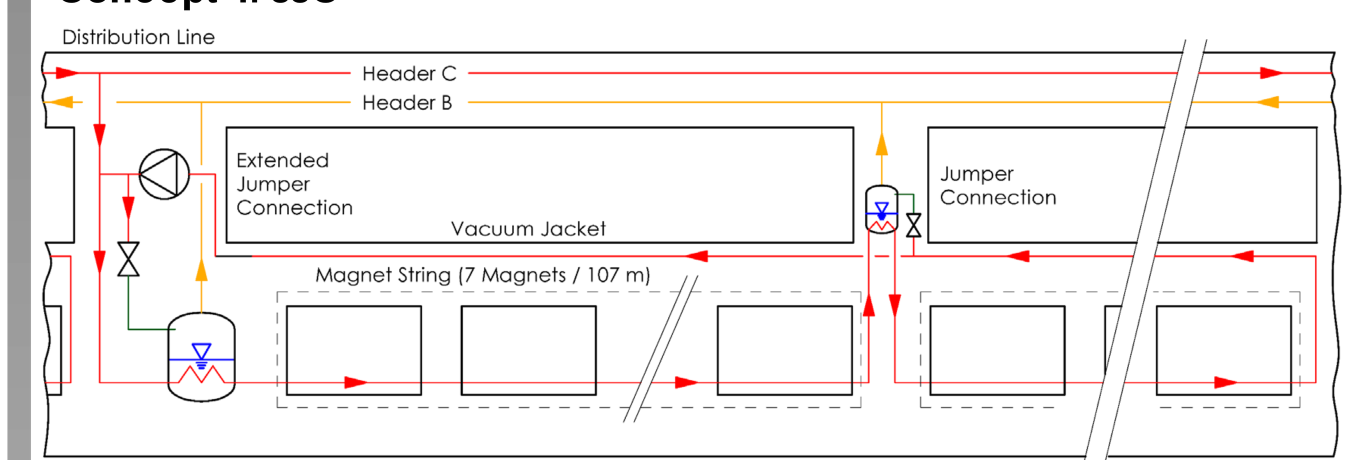
Concept 3: HERA with insufficient magnet-internal heat exchange

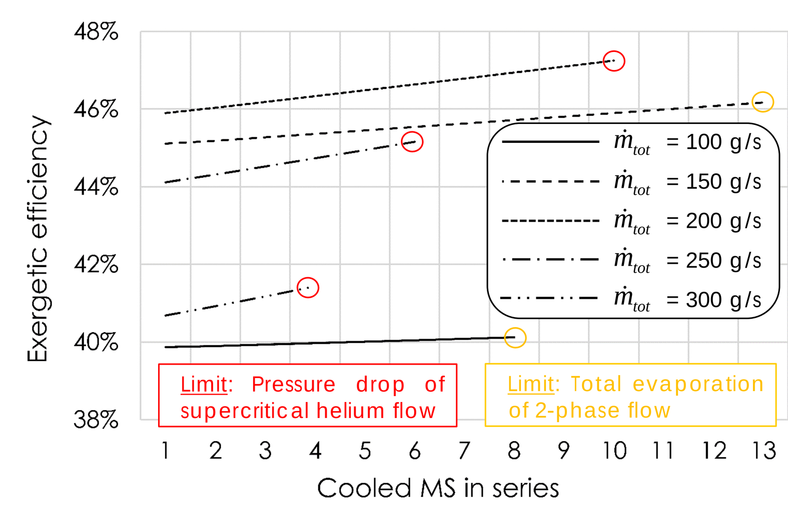




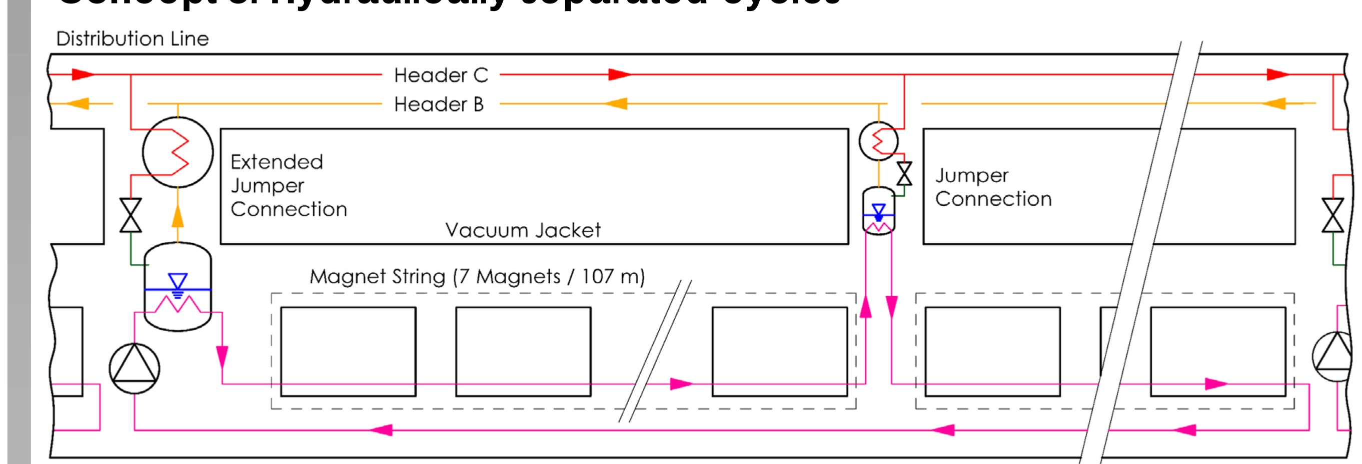
total evaporation condition defines exact cooling loop length $n_{MS} = \frac{(h''-h')\cdot\lambda\cdot\varphi}{c_p\cdot\Delta T_{\max}^{sc}}$ $\varphi = \frac{\dot{q}_{sc}}{\dot{q}_{tot}}$

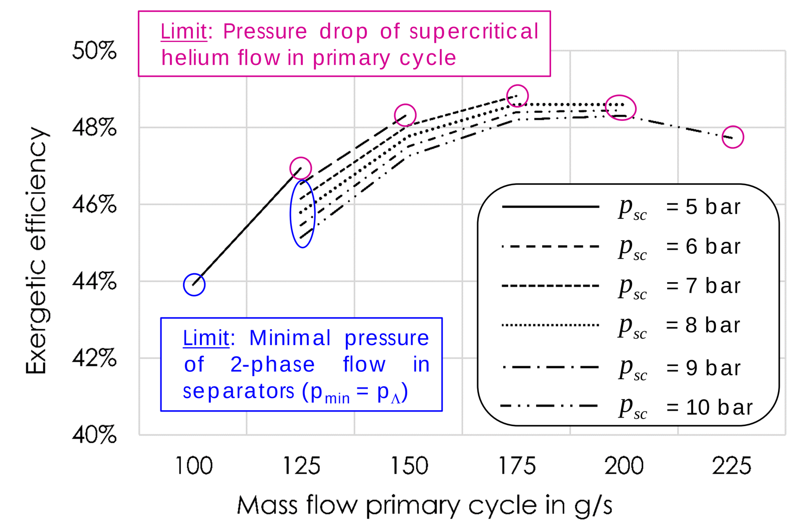
Concept 4: SSC





Concept 5: Hydraulically separated cycles



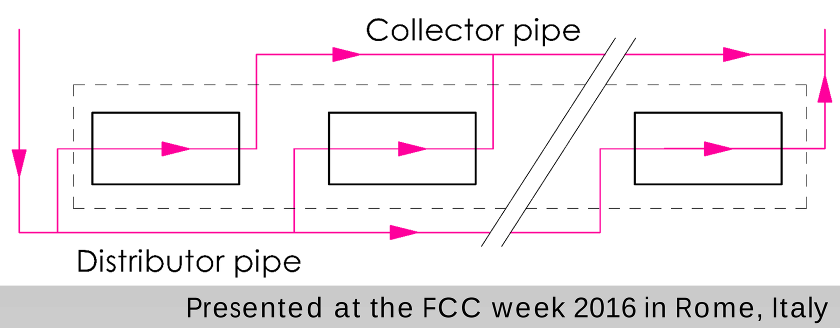


only 1 circulator per sector → cooling loop consists of 79 MS in series

Conclusion

Cooling the cold mass with supercritical helium at a operation temperature of about 4 K seems to be feasible from cryogenic's point of view. The most economic possibility is a hydraulic scheme with magnet-internal heat exchange – these concepts require big adaptions in the magnet design though. If these adjustments are inconsistent with the magnetic performance, parallel cooling of the magnets should be taken into consideration.

Figure. Parallel magnet cooling (for magnet-external heat exchange schemes) to enable an increase of the He_{sc} flow



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