Preliminary hydraulic layout of the beam screen cooling for the FCC-hh

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Introduction

Increasing the particle energies to reveal more secrets of matter, the Large Hadron Collider (LHC) is about to reach its limits. For future experiments colliders of a new magnitude are planned; among others the Future Circular Collider (FCC) with an circumference of 100 km and a centre of mass energy of 100 TeV.

Due to the high particle energies the proton beams emit a large amount of synchrotron radiation and generate image currents in the beam tube containing the beams and located in the center of the superconducting magnets. Despite of the thermal insulation a large heat load from the ambiance is expected, caused by the sheer size of the machine.

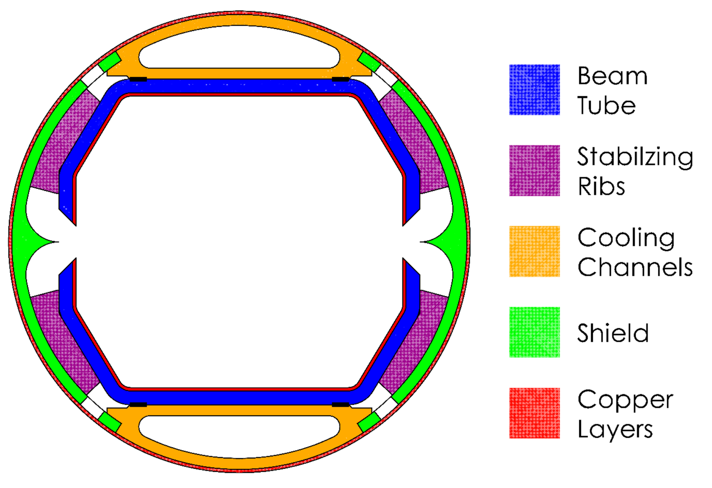


Figure. Beam Screen

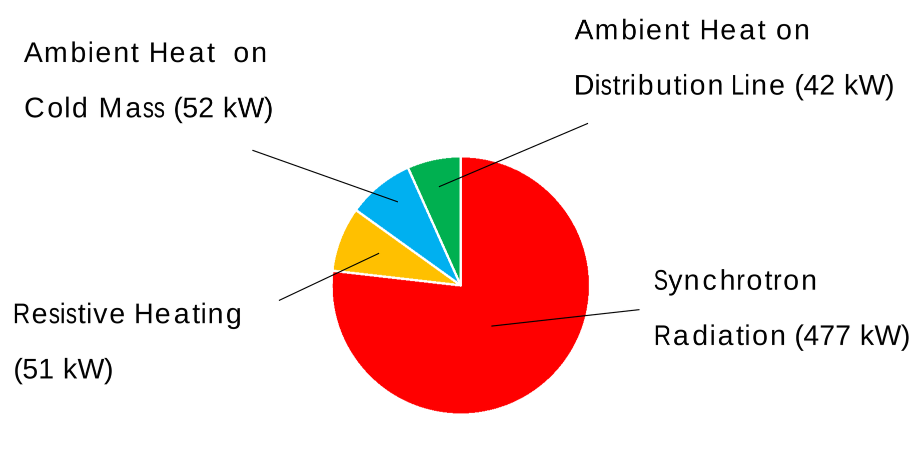


Figure. Heat load on a long FCC sector (10.4 km) in nominal operation

Altogether a total heat flux of more than 600 kW per sector has to be extracted at cryogenic temperature level (40 K - 60 K), to be completed by an additional circulation heat load unavoidable to drive the beam screen cooling system.

Hydraulic Scheme

The FCC cryogenics infrastructure forsees sectors up to 10.4 km of length. The beam screen cooling system is a closed loop, connected to the Nelium refrigerator by two heat exchangers.

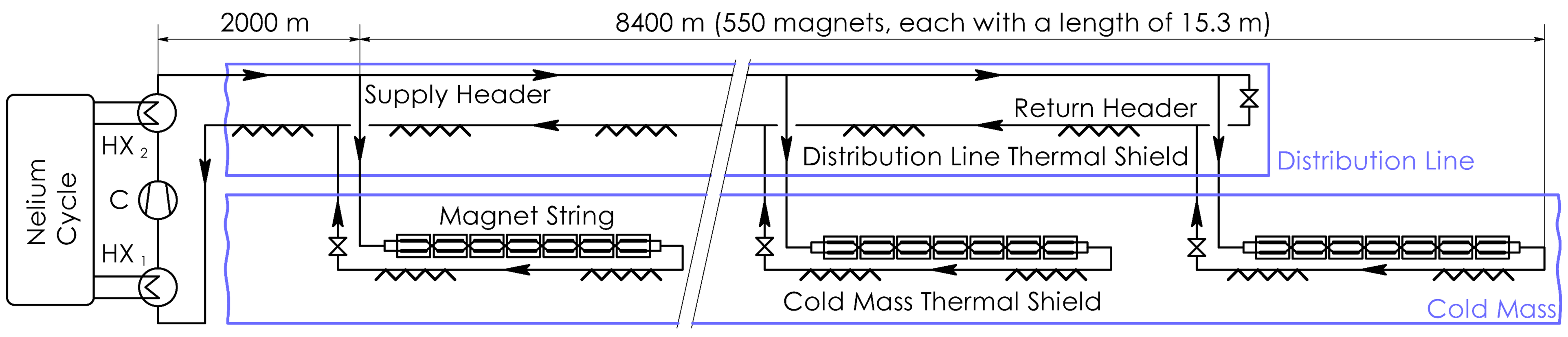


Figure. Hydraulic scheme of the beam screen cooling system with cold circulation

The helium on its way through the beam screen cooling system:

- The helium exits the circulator (**C**) with a pressure of **50 bar**
- The downstream heat exchanger (**HX$_2$**) decreases the helium temperature to **40 K**
- The helium is distributed by a thermally insulated **supply header** to the parallelly arranged magnet strings
- After cooling the beam screen in the magnet strings the warmed up helium thermally shields the cold mass (**Cold Mass Thermal Shield**)
- The helium passes the **control valves** and is collected in the **return header,** which thermally shields the distribution line (**Distribution Line Thermal Shield**)
- Before entering the circulator a heat exchanger (**HX$_1$**) decreases the helium temperature to 40 K

Influence of the pressure drop and warm circulation scheme

Cold Circulation scheme

1. The circulation power has to be extracted at cryogenic temperature level. With increasing pressure losses in the beam screen cooling system, the increasing circulation power can only be extracted with a very high exergetic effort at low temperature.

3. If the cold circulator power exceeds the heat passed the internal heat exchanger by the terminal temperature difference in the warm circulation cycle, the cold circulation cycle becomes more expensive.

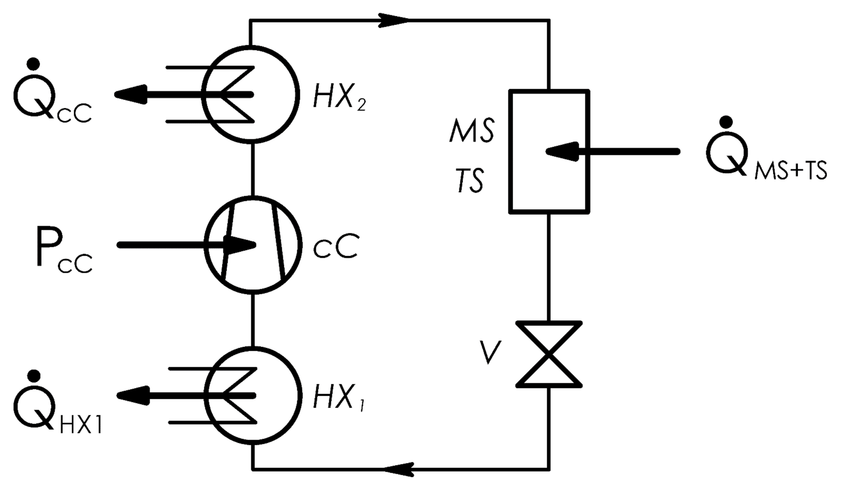


Figure. Schematic of the cold circulation cycle

$$\dot{Q}_{HX1} = P_{cC} - \dot{Q}_{cC} + \dot{Q}_{MS+TS}$$

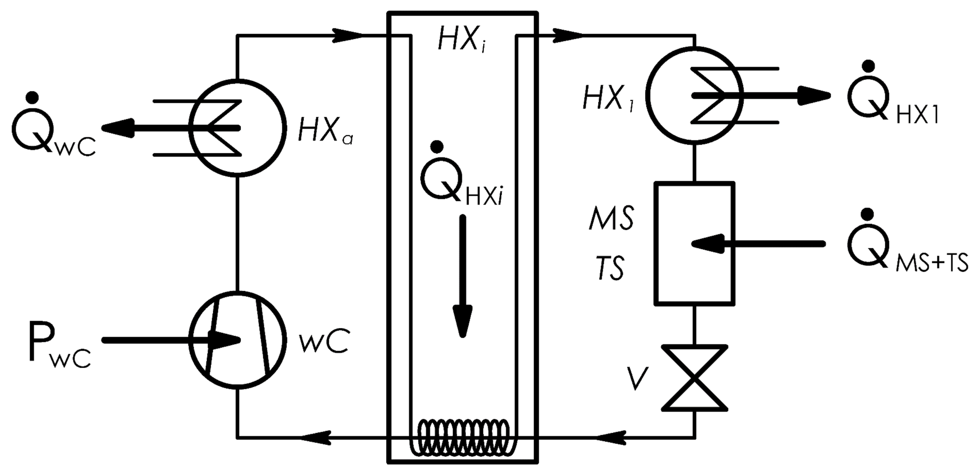


Figure. Schematic of the warm circulation cycle

$$\dot{Q}_{HX1} = P_{wC} - \dot{Q}_{wC} + \dot{Q}_{TTD} + \dot{Q}_{MS+TS}$$

cC ... cold circulator **MS** ... magnet strings **HX1** ... Nelium HX #1 **HXi** ... internal HX **TS** ... thermal shielding
wC ... warm circulator **V** ... control valves **HX2** ... Nelium HX #2 **HXa** ... ambient HX **TTD** ... terminal temperature difference

Warm Circulation scheme

2. The major part of the power of a circulator working at ambient temperature can be extracted at a much "cheaper" temperature level. The terminal temperature difference of the internal heat exchanger though allows a certain energy to "pass" – this heat has to be extracted by the Nelium cycle.

4. Main technical parametres to reduce the pressure losses in the beam screen cooling system are

   - Diameter of the headers
   - Number of magnets per magnet string

Exergy consumption

The total exergy consumption corresponds to the need of electrical power for a successful cooling and constitutes the major part of the operational costs.

$$\dot{X}_{tot} = P_C + \frac{\dot{X}_{NeHe}}{\eta_{NeHe}}$$

The exergetic efficiency of the beam screen cooling system (without Nelium cycle) is the ratio of the exergetic benefit (exergy of the extracted heat) and the exergy input .

$$\zeta = \frac{\dot{A}_{MS+TS}}{P_C + \dot{X}_{NeHe}}$$

$\dot{X}$ ... exergetic effort $\dot{A}$ ... exergetic benefit ζ ... exergetic efficiency

Cold circulation:

$$\dot{X}_{NeHe} = \left(P_{cC} + \dot{Q}_{MS+TS}\right) \cdot \left(\frac{T_{amb}}{T_{BSC}} - 1\right)$$

Warm circulation:

$$\dot{X}_{NeHe} = \left(P_{wC} - \dot{Q}_C + \dot{Q}_{MS+TS} + \dot{Q}_{TTD}\right) \cdot \left(\frac{T_{amb}}{T_{BSC}} - 1\right)$$

For the two schemes the exergy of the extracted heat loads is the same. Depending on the performances of the circulator and of the internal heat exchanger, the total pressure loss is the main influence quantity for the cycle efficiency.

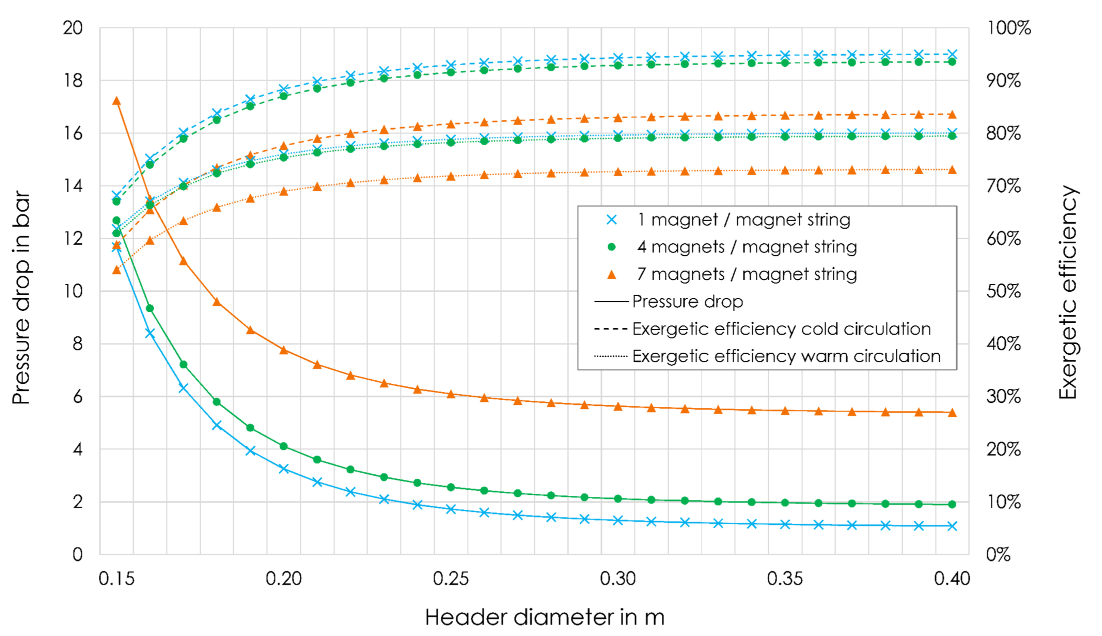
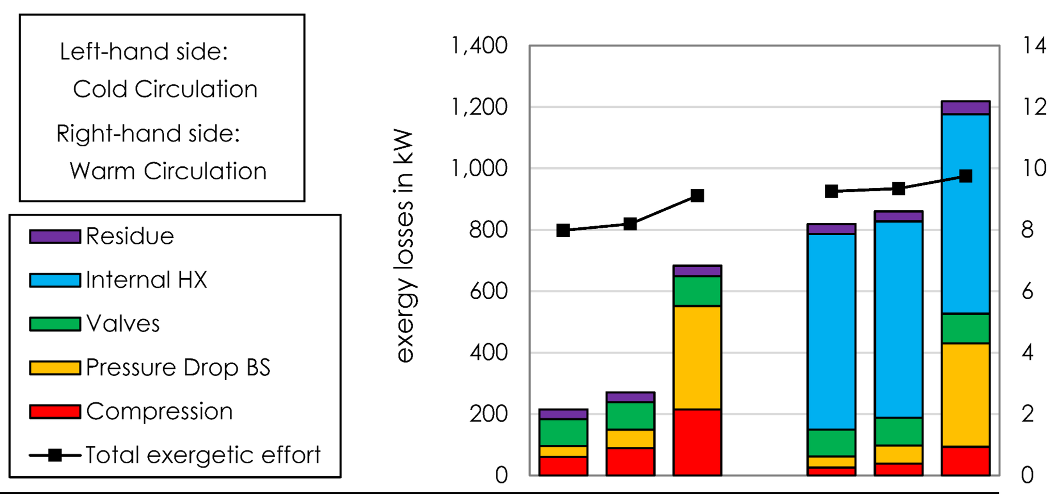


Figure. Progresses of overall pressure loss and exergetic efficiency of the beam screen cooling cycle vs. the header diameter for three different lengths of magnet strings. With increasing header diameter the overall pressure loss approaches asymptotically the pressure drop in the last magnet string.

Figure. Exergy loss fluxes in the beam screen cooling cycle (bars) and total exergy consumption of the entire cooling system (solid lines) for three different lengths of magnet strings, a header diameter of 0.25 m and an isothermal efficiency of the Nelium cycle of 42 %.

Isentropic efficiencies:
Cold circulator 70 %
Warm circulator 83 %



number of magnets per magnet string	1	4	7		1	4	7
exergetic efficiency [%]	92.9	91.5	81.8		78.8	78.2	71.9
exergy consumption BSC cycle [MW]	3.3	3.4	3.9		4.0	4.1	4.4
exergetic effort Nelium cycle [MW]	8.0	8.2	9.0		9.1	9.1	9.2
total exergetic effort [MW]	8.0	8.2	9.1		9.2	9.3	9.7

The pressure losses in the beam screen cooling system using a cold circulation scheme have a siginificantly larger impact on the overall exergetic consumption compared to a beam screen cooling system using a warm circulation scheme.

Summary and discussion of results

1) The sector dimensions, the beam screen design and the heat loads are determined and define the basic exergetic effort to keep the beam screen cooling cycle at the necessary temperature level.
2) Increasing pressure drop in the hydraulic scheme calls for additional circulation power. Although the circulation power of a cold circulator is smaller compared to a warm circulator, in the cold circulation scheme the power has to be extracted at cryogenic temperature level.
3) In the warm circulation scheme the major part of the compression power can be extracted very cheaply at ambient temperature level. The necessary internal heat exchanger though cannot transfer the entire heat and allows a certain heat energy to pass to low temperature.
4) If the sum of the cold circulation power and its extraction at low temperature level is a larger effort than the sum of the warm circulation power and the exergetic effort to extract the heat energy slipped through the internal heat exchanger due to the terminal temperature difference, the warm circulation cycle becomes exergetically cheaper.
5) With increasing length of magnet strings, the exergy losses due to the pressure loss in the beam screen increases with the power of three.
6) The compression losses are higher for the cold circulator, because of the cryogenic temperature level, the compression heat is deposited on. The main exergy loss of the warm circulation cycle is caused by the terminal temperature difference of the internal heat exchanger. The exergetic losses of the beam screen cooling cycle are much lower if a cold circulator is used.
7) Also the total exergy consumption including the Nelium cycle is larger for the warm circulation cycle for the given pressure drop. From the progress of the total exergetic effort curves, the stronger dependency of the cold circulation scheme on the pressure drop can be recognized.

Conclusions

The exergetic advantage of large headers and short magnet strings is accompagnied by an increasing effort of capital costs, controlling effort and possible downtime due to component failure.

- Larger headers require more space increasing the necessary size of the distribution line, the amount of needed material, the heat loads and the civil engineering costs.
- A larger amount of auxiliary equipment (e.g. control valves, sensors, ...) complicates the controlling and increases the error proneness and therefore the downtime of the entire cryogenic system.

Other applications and cryogenic infrastructure already are supposed to follow the pattern of half-cells of a length corresponding to seven magnets in series (~ 107 m). Adjusting the beam screen cycle units to this pattern simplifies the assembly, the maintenance and the organisation, paying for these conveniences with increased operational costs.

Based on the current beam screen design, sector dimensions and expected heat loads, the cold circulator scheme seems to be the more economic solution. Modifications of any of these parametres could increase the generated pressure drop in the beam screen cooling system leading to an improved exergetic performance of the warm circulation scheme, due to the pressure drop sensitivity of the cold circulator.

Technical advantages of the warm circulator, for example easier handling, less error proneness and the possibility of multipurpose use (e.g. during cool down and warm up) and a possible better performance during transient modes could make it a better choice, despite of the higher operational costs.

The investigation of the performances of different circulator concepts including the impact on the Nelium cycle is the next step in the development of a reliable and efficient BSC system.

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