Preliminary design of the beam screen cooling for the Future Circular Collider of hadron beams

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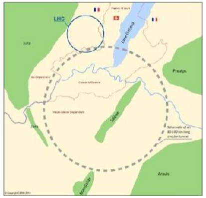
Introduction

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 80 - 100 km.

In course of the planned upgrades the proton beams shall reach energies up to 50 TeV per aperture emitting synchrotron radiation of about 28.4 – 44.3 W / (m·beam). The heat load's impact on the superconducting magnets at a temperature close to absolute zero would call for a disproportionally large cooling capacity. Therefore the installation of a so-called beam screen is planned; a cooled tube containing the beams, taking the role of a thermal shield to protect the magnets.



Schematic illustration of a possible location for the FCC

The design of the beam screen and its cooling is constrained by geometrical, technical and physical conditions:

1. The temperature of the beam screen must be kept between 40 K and 60 K
2. The velocity of the cryogen in the cooling channels must not exceed 10 % of the sound velocity
3. The pressure drop in a continuously cooled loop must not exceed 80 % of the supply pressure
4. The beam screen and its cooling must fit into the inner bore of the magnets

Two cryogens have been considered. On the one hand helium, which is a well-known refrigerant in cryogenic applications for particle physics, on the other hand neon, which has advantages regarding the possible margins in the beam screen design and the operational costs.

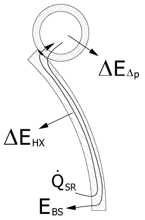
Aim of the investigations was the comparison of the feasibility and the exergetic efficiency of the beam screen cooling with different beam screen designs using helium or neon.

Exergetic analysis

The exergetic efficiency is a good parameter to assess the quality of a cryogenic process, it is the ratio of the exergetic benefit to the exergetic costs. The exergetic benefit was defined as the exergy E_{BS} of the extracted heat Q_{SR} at beam screen temperature level. The exergetic costs were defined as the exergy difference of the cryogen at the half-cell inlet and the half-cell outlet.

The exergetic losses of the half-cell cooling were divided into four parts:

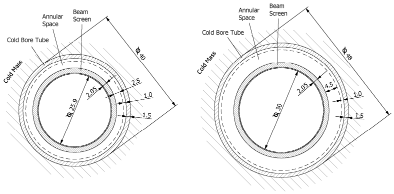
1. The heat exchanger losses (HX) due to the necessary temperature difference to conduct the extracted heat from the inside of the beam screen to the cooling channels
2. The pressure drop losses (Δp) in the cooling channels due to the viscosity of the cryogen
3. The mixing losses due to the mixing of several cryogen flows in different states in the mixing chambers
4. The valve losses due to the isenthalpic expansion in the control valve at the half-cell outlet



Exergy and heat flows in the beam screen

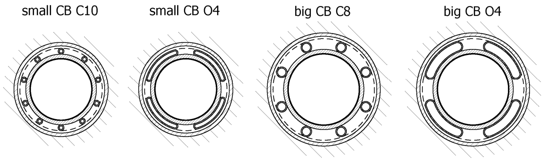
Beam screen design

The main geometrical constraint of the beam screen design is the inner diameter of the of the superconducting magnets. It was determined to be 40 mm or 48 mm. Depending on this dimensions two basic beam screen designs were developped.



The two basic beam screen designs dependent on the size of the cold bore

The little annular space available for mounting the cooling channels has to be used reasonably. Two different channel shapes have been considered (circular and oval). The optimal number of cooling channels arise from a certain combination of their size and the number of parallel heat bridges (welds) for the thermal conduction in the beam screen. The possible number of cooling channels is restricted by the production process. Four beam screen designs have been examined.

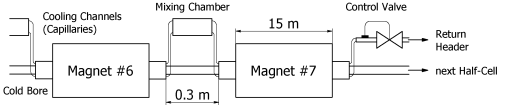


small CB C10 small CB O4 big CB C8 big CB O4

The four examined beam screen designs

Half-cell in the FCC

One continuously cooled loop corresponds to the length of a half-cell in the FCC. One half-cell consists out of seven magnets in series (15 m each). Between the magnets the different cooling channels will be united in mixing chambers unifying the different cryogen flows to avoid large temperature and mass flow differences between the single channels. At the half-cell outlet a control valve is installed to regulate the mass flow of the cryogen.

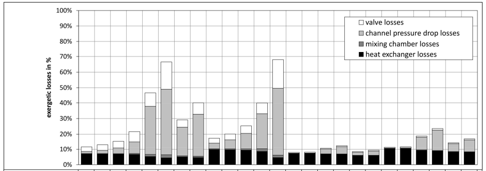


Interconnection between magnets and warm end of a half-cell

Results

By combining different beam screen designs, boundary conditions and initial states 48 different arrangements for the beam screen cooling have been generated. Out of these 48 combinations, with 25 it was possible to cool one half-cell continuously satisfying all the determined limits and constraints.

In the diagram beneath the percental distribution of the single exergy losses for each of the 25 combinations is shown. The overall exergetic efficiency is the difference of the sum of all exergy losses to 100 % and can be found in the first row below the bars.



exergetic efficiency [%]	88.5	87.2	84.6	78.4	53.3	33.5	70.9	60.0	82.6	79.9	74.7	60.1	32.0	92.1	91.8	89.3	87.7	91.5	90.6	88.7	88.4	81.2	76.4	85.5	83.0
exergetic costs [kW]	16.6	16.8	17.3	18.6	27.8	44.2	20.7	24.4	27.2	28.0	29.9	37.3	70.4	15.6	16.0	16.3	16.9	15.8	16.3	24.7	25.1	27.2	29.6	26.0	27.3
supply pressure [bar]	50	40	30	20	50	40	50	40	50	40	30	20	50	50	40	50	40	50	40	50	40	50	40	50	40
channel configuration	O4				C8		O4		O4				C8	O4		C8		O4		O4		C8		O4	
cold bore size	big						small		big				small	big				small		big				small	
Q_{SR} [W / (m · beam)]	28.4								44.3					28.4						44.3					
Cryogen	Helium													Neon											

Distribution of the exergy losses for the 25 "successful" combinations of the beam screen cooling

Conclusions

Using helium as cryogen the restricting factor for the beam screen cooling is the large generated pressure drop in the cooling channels due to its low density. Efficient cooling with helium is only possible with big cooling channels.

Despite of the more efficient cooling with neon, it has some disadvantages, which have to be taken into account:

- In the necessary temperature and pressure ranges neon is very close to its two-phase region
- In case of a power cut during nominal operation the heat stored in the neon would be transferred to the superconducting magnets and the temperature of neon could decrease under its solidification temperature
- There only exists little experience with neon in cryogenic applications in accelerator physics and its possible radio-activation due to the unavoidable bombardment with high energy particles
- Due to the high density the necessary mass of neon is about 15 times higher than the necessary mass of helium

Despite of its lower exergetic efficiency, these considerations make helium the better choice for the beam screen cooling.

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