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

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Abstract. Following recommendations of the recent update of the European strategy in particle physics, CERN has undertaken an international study of possible future circular colliders beyond the LHC. This study considers an option for a very high energy (100 TeV) hadron-hadron collider located in a quasi-circular underground tunnel having a circumference of 80 to 100 km. The synchrotron radiation emitted by the high-energy hadron beam increases by more than two orders of magnitude compared to the LHC. To reduce the entropic load on the superconducting magnets’ refrigeration system, beam screens are indispensable to extract the heat load at a higher temperature level. After illustrating the decisive constraints of the beam screen’s refrigeration design, this paper presents a preliminary design of the length of a continuous cooling loop comparing helium and neon, for different cooling channel geometries with emphasis on the cooling length limitations and the exergetic efficiency.

1. Introduction
The Future Circular Collider (FCC) under conceptual study at CERN will have a circumference of 80 to 100 km. The high energy proton beams accelerated will reach energies up to 50 TeV per aperture. These beams will continuously circulate in the accelerator, emitting synchrotron radiation. Depending on the circumference of the accelerator ring, the specific heat load to be extracted in the beam bending sections (arcs) will reach up to 44.3 W/m per beam giving an integrated power of up to 5 GW for the whole accelerator. The direct impact of this heat load on the superconducting magnets operating at a temperature between 1.9 and 4.5 K is technically and economically unacceptable. Consequently, the synchrotron radiation must be intercepted by a beam screen which will be actively cooled at a higher temperature and will protect the magnets. The design of the beam screen and its cooling channels are constrained externally by the geometrical dimensions of the cold bore of the magnets and internally by the minimum geometrical aperture required by the beam.

The current state of the FCC design is based on a half-cell length of about 107 m, consisting of six dipoles, one quadrupole (15 m of length each) and drift spaces of 30 cm between adjacent magnets. To keep a reasonable number of cooling loops with associated control valves and instrumentation and to be compatible with the optical periodicity of the machine, the length of a beam screen cooling loop must correspond to an integer number of half-cells.

As cooling medium, two cryogens were considered, helium and neon. Whereas the properties of helium in cryogenic applications are well-known, neon is a new refrigerant, which first has to be established as an appropriate refrigerant for accelerators.

2. Preliminary beam-screen and half-cell designs of the FCC
The performed calculations have been based on assumptions made in the first phase of the FCC feasibility studies, on extrapolated data of the LHC design report [1] and on the experience gained during the first operation of the LHC.

2.1. Constraints and boundary conditions
Several constraints for the beam screen design and the operating state of the cryogen have to be considered.
1) To preserve a good vacuum condition and an acceptable electrical impedance of the beam screen to conduct the image current, its temperature is determined to be between 40 K and 60 K [2].

2) To reduce the risk of mechanical damages due to the dynamic fatigue of vibrations, an arbitrary velocity limit for the cryogen in the cooling channels was chosen; it should not exceed 10 % of the sound velocity.

3) To guarantee the possibility of controlling the mass flow of the cryogen by valves at the end of each half-cell, the maximal pressure drop in a continuous cooling section (i.e. one half-cell) was set to be 80 % of the supply pressure.

4) The geometrical constraints of the beam screen are mainly imposed by the magnet design and the required beam aperture, additionally some requirements regarding its electrical and mechanical properties and the restrictions due to the manufacturing process have to be taken into account.

2.2. Beam screen geometry

The decisive parameter for the total space available for the beam screen is the diameter of the magnet inner bore, which was determined to be 40 mm (“small CB”) or 48 mm (“big CB”). Regardless of this value a cold bore tube of a thickness of 1.5 mm is necessary to “close” the inner bore as well as a minimal distance of 1 mm between the outermost part of the beam screen and the cold bore tube itself to avoid contact.

The basic shape of the beam screen is circular and it consists out of two layers as shown in Figure 1. The main body is made out of stainless steel with a thickness of 1.75 mm to withstand the mechanical stresses during a quench. The inside is covered with copper of 0.3 mm of thickness to conduct the image current of the beam with low resistivity. Dependent on the diameter of the inner bore, two beam screen sizes were assumed, one with an inner diameter of 25.9 mm (small CB) and the other with an inner diameter of 30 mm (big CB). In both designs an annular space is available to place the cooling channels (2.5 mm for the small CB and 4.5 mm for the big CB as illustrated in Figure 2).

Figure 1. Metal Layers of the beam screen

Figure 2. Available annular space for two different diameters of the cold bore

The limited annular space has to be used reasonably. Two different channel designs were taken into account. On the one hand channels with a circular shaped cross section (“C”), which are cheaper to produce and optimized regarding the mechanical stresses due to the pressure of the containing cryogen, but with disadvantages in the exploitation of the available space. On the other hand channels
with an “oval” shaped cross section (“O”) were considered, which are more expensive, more difficult to mount and more critical containing fluids at high pressure, but with a big advantage regarding the possible utilisation of the available annular space.

Due to probable production process (electron beam welding), the possible number of attached channels is limited (see Figure 3). Two parameters are crucial for increasing the continuously cooled length and decreasing the flow velocity and therefore the pressure losses with respect to the determined limits: First of all the summed up cross section areas of all channels and secondly the number of weld contacts. Bigger channels can carry larger mass flows producing the same pressure drop. An increasing number of weld contacts decreases the necessary temperature difference between the cryogen and the beam screen working as parallel heat conductors. Based on a design with consistently distributed channels around the beam screen, an optimal number of channels could be found. Combining the two beam screen sizes (big CB and small CB) with the two channel designs (C and O) yield four beam screen designs which have been examined.

2.3. Heat transition in the beam screen
The decisive heat load on the beam screen is caused by the synchrotron radiation of the bended beam (28.4 – 44.3 W/(m·beam) depending on the circumference of the FCC). At high particle energies the dispersion angle of the synchrotron radiation is supposed to be very small and the beam emits radiation only in the opposite direction of the accelerator centre, hence all the heating power of the synchrotron radiation will impact a small area and has to be conducted through the beam screen to the channels as indicated in Figure 4. The temperature difference between this impact area and the cryogen should be kept as small as possible, as it reduces the temperature range available. For all four designs a numerical simulation has been performed to establish their thermal resistances based on the method of finite differences. Using a grid independency analysis a satisfying compromise between accuracy and computing time was found benefiting from the symmetry of the designs. As the materials aren’t determined yet, constant but pessimistic material properties have been assumed. This not only reduces the computing time, it also gives the possibility to make the thermal resistance of each channel dependent only on the heat transfer number of the cryogen. Therefore a simple connectedness between the cryogen state and the heat absorbed by each channel in the steady state mode could be established and used in further calculations.

In Figure 5 the results for the total thermal resistance of each beam screen design are shown. At small heat transfer coefficients, the thermal resistance between the channel and the cryogen is crucial for the total resistance – designs with smaller channels have larger resistances. With increasing heat transfer number the heat conduction in the main body of the beam screen becomes more and more important – the curves are getting flatter. As with parallel heat bridges the total resistance is smaller than the smallest one, the distance from the impact area to the first weld contact and the number of weld contacts become decisive for the total resistance.
2.4. Half-Cell cooling

One FCC half-cell consists of seven magnets in series. Each magnet has a length of 15 m and the gap between two adjacent magnets is assumed to be 0.3 m long. This yields a half-cell length of about 107 m, which should be cooled continuously. In between the magnets all channels are detached from the beam screen and the different mass flows are gathered in a mixing chamber to unify temperature and pressure on a regular basis to avoid large temperature differences between the fluids in the different channels, which would lead to large different pressure drops and mass flows.

The properties of the cryogen were determined by the initial values at the first magnet inlet, defined by temperature and supply pressure. Starting with a small initial mass flow, the cryogen was iteratively increased, until the cooled length of 107 m was reached. When the outlet of a magnet was reached, the distribution of the cryogen to the channels was varied until the pressure ratios between each pair of channels was $1 \pm 0.00001$. If the velocity limited the iteration an increase of the cooled length couldn’t be achieved by incrementing the mass flow, because the velocity limit was reached even earlier in the next step – in these cases the half-cell couldn’t be cooled. In no case the pressure drop limit was reached. Depending on the chosen limits a certain length could be found for each
combination of beam screen geometry and cryogen, which at least has to be cooled to reach the pressure drop limit before the velocity limit – these lengths exceed the length of a half-cell in any case.

For calculating the pressure drop $\Delta p$ in the channels the Darcy–Weisbach equation (1) was used, obtaining the Darcy friction factor $f$ from the explicit formula of Swamee-Jain (equation (2)) [3]. The pipe roughness $\varepsilon$ of the channels was assumed to be about twice the roughness of the beam screen channels in the LHC [4] ($1.5 \times 10^{-6}$ m). The Nusselt number $Nu$ (and in further consequence the heat transfer coefficient $h$ (equation (4))) was determined by equation (3) [5].

$$\Delta p = f \cdot \frac{L \cdot \varepsilon^2}{d_o \cdot 2 \cdot \rho \cdot A^2}$$  \hspace{1cm} (1)

$$f = 0.25 \left[ \log \left( \frac{D}{\varepsilon} + \frac{5.74}{Re^{0.8}} \right) \right]$$  \hspace{1cm} (2)

$$Nu = \frac{f^{(1/8)} \cdot Re \cdot Pr}{1 + 12.7 \cdot f^{(1/8)} \cdot \left( Pr^{1/3} - 1 \right) \cdot \left[ 1 + \left( \frac{d_o}{L} \right)^{1/2} \right]}$$  \hspace{1cm} (3)

$$h = \frac{Nu}{L} \cdot k$$  \hspace{1cm} (4)

For calculating the pressure drop in the mixing chamber an arbitrary and constant pressure loss coefficient was considered. The mixing process in the chamber was assumed to be ideal. The pressure drop in the control valve was determined to be 20% of the pressure drop in the magnet string, but at least one bar.

2.5. Cryogens

The fluid properties were taken from the databases “HePak” of the company Cryodata Inc. (helium) and “RefProp” of the American NIST (neon). The temperature at the inlet of the first magnet was determined to be the lowest allowed (40 K). For helium four different supply pressures have been considered (20 bar, 30 bar, 40 bar and 50 bar), whereas for neon only two values were taken into account (40 bar and 50 bar) to avoid entering the two-phase region or even getting too close to it.

The helium heat capacity is roughly twice as high as the heat capacity of neon in the considered pressure and temperature ranges, which leads to about half the necessary mass flow, if cooled with helium. The density of neon though is about ten to twenty times higher. The volumetric flow, which is crucial for the pressure losses, is clearly smaller, if cooled with neon.

2.6. Exergetic efficiency

The exergetic efficiency is a good indicator to validate the costs of a thermodynamic process. The amount of exergy $E$ of heat depends on the condition of the ambiance (index $a$) – for temperatures lower than the ambiance’s it can be calculated with equation (5). The specific exergy $e$ contained in a mass flow can be calculated with its specific enthalpy $h$ and entropy $s$ (equation (6)).

$$E = Q \left( \frac{T_a}{T} - 1 \right)$$  \hspace{1cm} (5)

$$e = h - h_a - T_a \cdot (s - s_a)$$  \hspace{1cm} (6)

The exergetic efficiency $\zeta$ of a half-cell cooling loop (equation (7)) was defined as the ratio of the exergy (index BS) of the extracted heat of the synchrotron radiation (index SR) at the temperature level of the impact area (i.e. exergetic benefit) divided by the exergy difference of the total mass flow at the half-cell inlet and the half-cell outlet (i.e. exergetic costs).
Every heat exchanger (index HX) produces exergy losses due to the necessary temperature difference to exchange the heat. The beam screen can be considered as a heat exchanger, with different amounts of heat exchanged and different driving temperature differences between the cryogen in each channel and the impact area of the synchrotron radiation. The HX exergy losses for each channel (index Ch) can be calculated with equation (8).

\[
\Delta E_{HX} = Q_{SR} \cdot T_a \left( \frac{1}{T_{Ch}} - \frac{1}{T_{BS}} \right)
\]

The mixing of two or more mass flows in different states also creates exergy losses (index mix). By calculating the difference of the sum of the exergy fluxes of the single channels before and after the mixing chamber, the exergy losses can be calculated for each mixing process (equation (9)), containing also the losses due to the pressure drop in the mixing chamber.

\[
\Delta E_{mix} = \sum (\dot{m}_{Ch} \cdot e_{Ch}) - \dot{m}_{tot} \cdot e_{tot}
\]

The remaining exergy losses are caused by the pressure losses in the channels and in the valve. The exergy loss in the valve is the difference of the exergy fluxes before and after the valve (equation (10)). As indicated in Figure 7 the heat exchanger loss and the exergy transferred in the cooling process have to be subtracted from the total exergy losses to obtain the losses due to the friction for each channel and magnet (equation (11)).

\[
\Delta E_{valve} = \dot{m}_{tot} (e_{in, Valve} - e_{out, Valve})
\]

\[
\Delta E_{SP} = \dot{m}_{Ch} (e_{in, Ch} - e_{out, Ch}) - \Delta E_{valve} - \Delta E_{HX}
\]

3. Results and discussion

By combining different designs and boundary conditions 48 possible arrangements have been generated for the half-cell cooling. Out of these 48 combinations, 25 were able to cool the half-cell satisfying all the limits determined. With the beam screen design with the smallest accumulated channel cross section area (small CB C10) it isn’t possible to cool the length of a half-cell; with the beam screen design with the largest accumulated cross section area (big CB O4) the half-cell could be cooled regardless of the other boundary conditions.

Comparing the temperatures and mass flows of the different channels to obtain their imbalances, it could be found that the ratios for both quantities don’t exceed 1 ± 0.05. These imbalances are larger for neon than for helium (due to the smaller heat capacity), they are larger for beam screen designs with a high number of channels (circular shaped channels) and they are larger for a higher heat load.

The difference of the exergy contained in the cryogen at the half-cell inlet and the half-cell outlet can be divided into two parts: First of all the exergy used to extract the heat load of the synchrotron radiation at the temperature level of the impact area (which remains exergy by definition) and secondly the exergy converted into anergy due to pressure losses, mixing and the non-ideal heat transition in the beam screen. In Figure 8 the distribution of the used exergy during the cooling of a half-cell is shown. Every bar in the diagram represents the sum of the exergy losses of the cryogen.
between the half-cell inlet and the half-cell outlet, hence the smaller the bar, the higher the exergetic efficiency. The exergetic efficiency of each half-cell cooling is the difference of the exergy losses and the exergy decrease of the cryogen during the cooling process (which corresponds to 100 %).

![Figure 8. Distribution of the exergy losses of the different beam screen designs](image)

The order of the accumulated exergy losses in every bar is the same. Starting with the bottommost, the black part represents the exergy losses due to the temperature difference for the heat transition. These losses increase with a higher synchrotron radiation (due to the larger necessary temperature difference) and a higher thermal resistance of the beam screen. Although the thermal resistance of the beam screen design with the channel configuration C8 is the highest, the relative HX exergy loss compared to the one caused by the pressure drop in the channels is smaller.

The second, dark grey part of the bar represents the exergy losses in the mixing chamber due to the mixing process itself and the pressure loss.

The third, light grey part of the bar represents the exergy losses due to the pressure losses in the cooling channels. These losses exceed all the others in beam screen designs with small cooling channels, especially if cooled with helium. Due to small density of helium, the exergetic efficiency is significantly smaller than the one of neon, especially with decreasing channel sizes. Efficient cooling with helium is only possible with large channels.

The fourth, white part of the bar represents the exergy losses due the isenthalpic expansion in the control valve at the warm end of the half-cell. If the pressure drop before the valve inlet is smaller than one bar (possible with large cooling channels), the pressure losses in the valve exceed the pressure losses in the cooling channels as it was determined to be at least one bar; hence the exergy losses in the valve exceed the exergy losses (caused by the pressure drop) in the channels. With increasing pressure drop in the channels, the exergy losses in the channels start to outweigh the exergy losses in the valve. If the pressure drop in the channels exceeds five bar, the exergy losses in the valve increase too, as they are determined to be 20% of the pressure drop in the cooling channels.

The main influences on the exergetic efficiency can be summarized:

- Smaller heat loads lead to higher exergetic efficiencies, because of a smaller driving temperature difference necessary for the heat transition
- Smaller thermal resistances of the beam screen lead to higher exergetic efficiencies, because of a smaller driving temperature difference necessary for the heat transition
Larger capillaries lead to higher exergetic efficiencies, because smaller velocities cause less pressure losses
Larger supply pressures lead to higher exergetic efficiencies, because the smaller volumetric flow causes less pressure losses
Using neon as cryogen leads to higher exergetic efficiencies, because the smaller volumetric flow causes less pressure losses

4. Summary and outlook
With the necessary mass flows to cool one half-cell, the pressure drop generated in the channels is the constraining factor for an efficient and reliable cooling. Beam screen designs with a large accumulated cross section area of its channels are preferable compared to designs with a smaller thermal resistance.

Regarding the exergetic efficiency neon is the better choice for cooling applications in the temperature range from 40 K to 60 K. Due to its high density, the pressure losses can be kept small, which allows it to cool a half-cell efficiently in a larger range of operating conditions and enables beam screen designs with smaller channels. However using neon as cooling medium has the following drawbacks:

- The thermodynamic state of neon in the necessary temperature range is very close to its two-phase region, which restricts the choice of the supply pressure and - even if a high supply pressure is chosen - can cause instabilities and unpredicted behaviour due to the massive changes of its properties
- In case of a power cut, when no beam is circulating but the superconducting magnets are at their nominal temperature, the heat stored in the neon in the cooling channels would be transferred to the magnets and the temperature of the cryogen could decrease below its solidification temperature
- Bombardment with high energy particles of the beam screen will create radio-activation of the neon and the corresponding inventory will have to be managed as radioactive storage with stringent traceability
- The availability of a large quantity of neon is not consolidated yet

Therefore, the cooling of the beam screen with helium, a well-established fluid in cryogenic applications, is recommended for FCC. With respect to neon, at identical operating pressure, working with helium will provide a lower exergetic efficiency. For beam screen designs with the big cold bore diameter and oval capillaries and a specific synchrotron radiation of 28.4 W/m per beam, the exergetic efficiency will be about four points lower, but still close to 90 % which remains acceptable.

Based on the findings the connection of several half-cells in parallel within a FCC sector are the target of the next investigations and the mutual influence of the beam screen cooling and its distribution system has to be examined.

References