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Report

Beyond the Large Hadron Collider: a first look at cryogenics for CERN future circular colliders

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Abstract

Following the first experimental discoveries at the Large Hadron Collider (LHC) and the recent update of the European strategy in particle physics, CERN has undertaken an international study of possible future circular colliders beyond the LHC. The study, conducted with the collaborative participation of interested institutes world-wide, considers several options for very high energy hadron-hadron, electron-positron and hadron-electron colliders to be installed in a quasi-circular underground tunnel in the Geneva basin, with a circumference of 80 km to 100 km. All these machines would make intensive use of advanced superconducting devices, i.e. high-field bending and focusing magnets and/or accelerating RF cavities, thus requiring large helium cryogenic systems operating at 4.5 K or below. Based on preliminary sets of parameters and layouts for the particle colliders under study, we discuss the main challenges of their cryogenic systems and present first estimates of the cryogenic refrigeration capacities required, with emphasis on the qualitative and quantitative steps to be accomplished with respect to the present state-of-the-art.

1. Introduction

The flagship instrument of the world's particle physics community today is the Large Hadron Collider (LHC) in operation at CERN, the European Organization for Nuclear research in Geneva, Switzerland [Brüning et al. (2004)].

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Following the discovery of the Higgs boson at the LHC in 2013, the first priority of CERN for the next two decades is to study the properties of the new particle and look for physics beyond the Standard Model, by exploiting the full potential of the machine, first with nominal parameters up to 2023 and then with its high-luminosity upgrade until around 2035. This approach is also that which maximizes the scientific return on investment.

In parallel with this base program, and given the long lead times of such big projects – the first LHC studies started in the early 1980s – CERN has launched the study of Future Circular Colliders (FCC) beyond the LHC, based on a new 80 km to 100 km circumference tunnel infrastructure in the Geneva basin (Fig. 1). The FCC study, that is being organized as a world-wide international collaboration, comprises an energy-frontier 100 TeV proton and heavy-ion collider, a high-luminosity electron-positron collider as potential intermediate step, and also the analysis of options for a hadron-lepton collider which would be installed in the large tunnel [Benedikt et al. (2014)]. The goal of the study is to deliver a conceptual design report, together with a cost estimate, in time for the next update of the European strategy in particle physics due to take place in 2018.

Superconductivity and helium cryogenics will be present in all machine options. Key technologies are high-field superconducting magnets for the hadron collider, and an efficient high-power RF system, based on superconducting cavities for the lepton collider. In all cases, large-capacity helium refrigeration down to 4.5 K and possibly 1.8 K will be required, together with the corresponding distribution, recovery and inventory storage systems. Technological goals for the study include the development of short 16 T dipole models by 2018, investigation of 20 T magnet technology based on combination of low- and high-temperature superconductors, superconducting RF developments aiming at overall system optimization, as well as further progress in large unit-size cryogenic plants producing efficient refrigeration down to 4.5 K and 1.8 K.

In the following, we first present the parameters of the hadron and electron-positron colliders which impact the cryogenic systems, discuss the main design challenges based on first estimates of heat loads at the different temperature levels of interest, and identify the lines of specific developments in cryogenic cycles, cooling schemes and machinery.

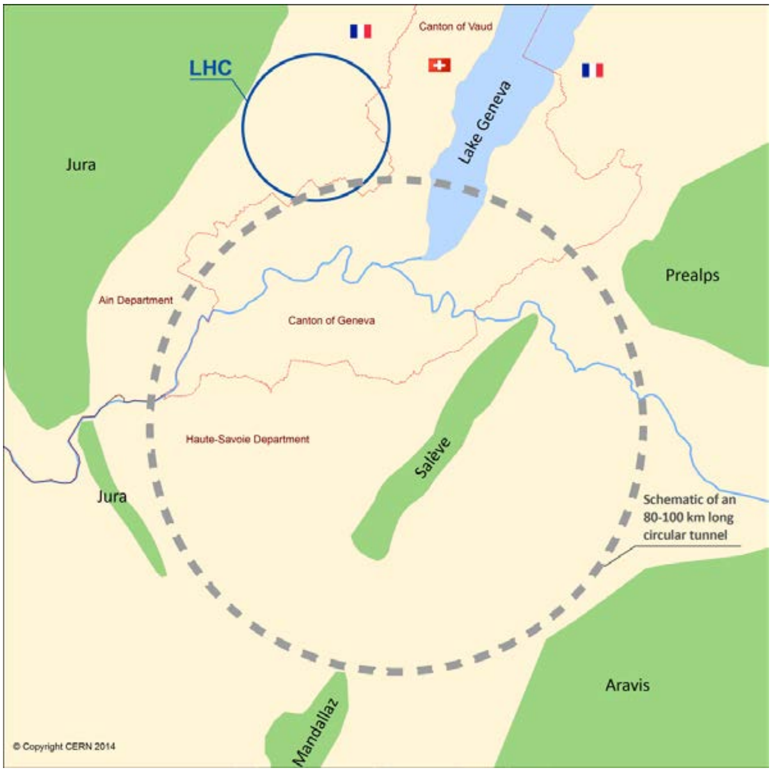


Fig. 1. Footprint of the 100-km FCC accelerator in the Geneva basin.

2. The hadron collider

The main technological challenge of the hadron collider is the high-field superconducting magnet system, requiring to cool most of the machine circumference at liquid helium temperature; the option is still open between normal helium at 4.5 K and superfluid helium at 1.9 K, depending on the choice of magnet technology and on the cryo-pumping requirements for the beam vacuum. A look at Table 1 which compares machine parameters of the FCC hadron collider with those of the LHC, immediately shows the important steps to be accomplished with respect to the present state-of-the-art:

- The larger circumference reflects in longer sectors (8 to 10 km) with impact on the magnet cooling scheme, cryogenic distribution, unit size of the sector cryogenic plants and overall helium inventory,
- The much higher energy stored in the circulating beams increases the risk of major helium release in the tunnel and corresponding safety issue,
- Synchrotron radiation from the beams is both “harder” (X-rays) and more intense; beam screens are therefore mandatory to absorb the synchrotron radiation at higher temperature than that of the superconducting magnets – whether 4.5 K or 1.9 K (not yet defined) – and thus reduce the entropic load on the refrigeration system.

Table 1. Machine parameters of the 100-km FCC hadron collider (value for 83-km FCC in brackets).

Parameter	LHC	FCC-hadron collider
c.m. Energy [TeV]	14	100
Circumference [km]	26.7	100 (83)
Dipole field [T]	8.33	16 (20)
Number of straight sections	8	12
Sector length [km]	3.3	8.3 (6.9)
Arc length [km]	2.8	7 (5.5)
Number of IPs	4	2 + 2
Peak luminosity [10^{34} cm-2s-1]	1	5
Beam current [A]	0.584	0.5
RMS bunch length [cm]	7.55	8 (7.55)
Stored beam energy [GJ]	0.392	8.4 (7.0)
SR power per ring [MW]	0.0036	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	28.4 (44.3)
Dipole coil aperture [mm]	56	40
Beam aperture [mm]	~40	26

2.1. Beam screen

Consider the generic beam screen shown in Fig. 2: subject to synchrotron radiation heat load Q_{sr}, it evacuates Q_{bs} to its cooling capillaries, and leaks the residual Q_{cm} to the magnet cold bore through radiation and conduction along its supports. The corresponding thermodynamic optimization [Baglin et al. (2013)] can be made for minimizing the total exergetic load ΔE (see Equation 1), or else – folding in the real efficiency η with respect to the Carnot cycle – the electrical power to the refrigerator P_{ref} (see Equation 2), thus leading to an optimum temperature for the beam screen.

$$\Delta E = Q_{cm} \cdot \left(\frac{T_a}{T_{cm}} - 1 \right) + Q_{bs} \cdot \left(\frac{T_a}{T_{bs}} - 1 \right) \quad \text{with } T_a \text{ the ambient temperature (290 K)} \qquad (1)$$

$$P_{ref} = Q_{cm} \cdot \left(\frac{T_a}{T_{cm}} - 1 \right) \cdot \frac{1}{\eta(T_{cm})} + Q_{bs} \cdot \left(\frac{T_a}{T_{bs}} - 1 \right) \cdot \frac{1}{\eta(T_{bs})} \qquad (2)$$

Considering a beam screen similar to that of the LHC and refrigerator efficiencies identical to those of the LHC [Gruehagen et al. (2004) and Claudet et al. (2004)], the results are shown in Fig. 3 for magnet operating temperatures of 4.5 K and 1.9 K. The much higher values of synchrotron power at FCC push the optimum beam screen temperature to a higher range, from 80 K to 120 K. As these temperatures are forbidden by considerations of vacuum and wall impedance, the beam screen of the FCC hadron rings should be operated in the highest allowed window, i.e. 40-60 K. In this temperature range, the beam screens can be cooled by circulation of gaseous helium at 20 bar, available in the refrigeration plant.

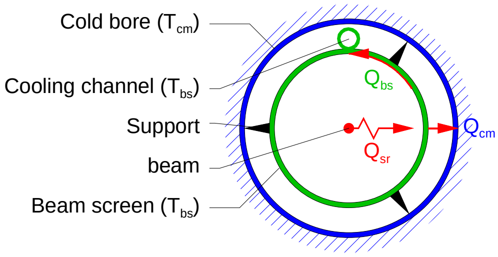


Fig. 2. Generic scheme of beam screen, with heat loads used for thermodynamic optimization.

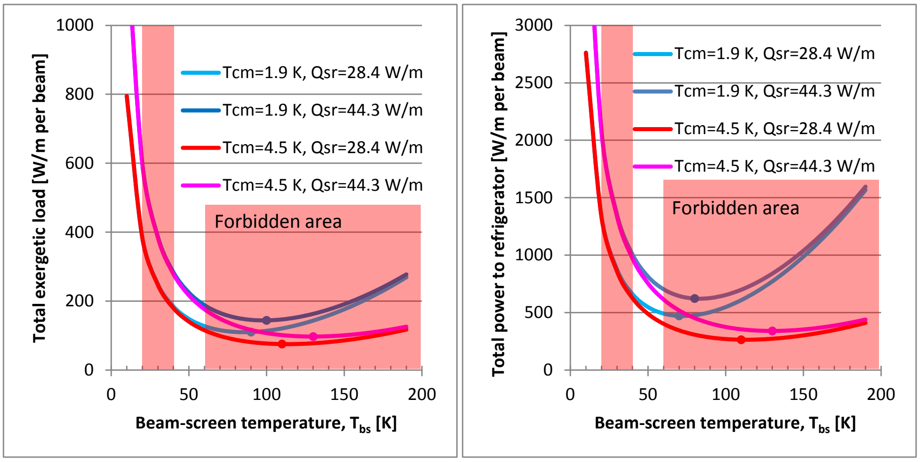
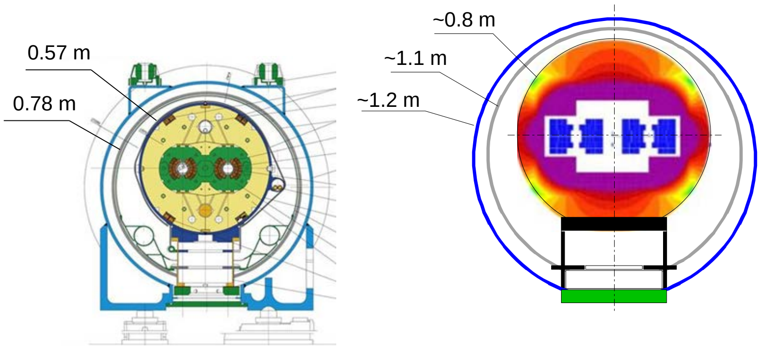


Fig. 3. Exergetic load and electrical power to (real) refrigerator for beam screen cooling.

2.2. Cryomagnet heat loads

A possible cross-section of the dipole magnet cryostat for the FCC hadron ring is sketched in Fig. 4, compared to the existing LHC cryostat. The cryostat heat in-leaks can thus be scaled from those of the LHC: solid conduction along the supporting system is assumed to scale with the magnet cold mass, while radiation and residual gas conduction to the cold mass and the thermal shield are assumed to scale with their respective surface areas. As concerns dynamic heat loads, synchrotron radiation and beam image current dissipation are mostly taken by the beam screen, still with a residual of 0.2 W/m falling on the cold mass. Joule heating due to dissipation in the resistive splices of the superconductors, scaling with the number and resistance of splices and the current squared, are estimated to another 0.3 W/m in the cold mass. The results are given in Table 2, compared to those of the LHC. It appears that the total heat load to the cold mass cannot be made lower than 1 W/m, which amounts to more than twice the LHC value.



a b

Fig. 4. Schematic cross-sections of collider cryomagnets, (a) LHC (b) FCC.

Table 2. Preliminary heat load estimate for 100-km and 83-km (in brackets).

		LHC [W/m]			FCC hadron collider [W/m]	
	Temperature level	50-75 K	4.6-20 K	1.9 K	40-60 K	1.9 or 4.5 K
Static heat in-leaks	CM supporting system	1.5	-	0.1	2.9	0.2
	Radiative insulation	-	-	0.11	-	0.15
	Thermal shield	2.7	-		3.8	-
	Feedthrough & vac. barrier	0.2	-	0.1	0.2	0.1
	Total static	**4.4**	**-**	**0.3**	**6.9**	**0.45**
Dynamic heat loads	Synchrotron radiation		0.33	ε	57 (88)	0.2
	Image current		0.36	-	2.7 (2.9)	-
	Resistive heating		-	0.1	-	0.3 (0.4)
	Total dynamic		**0.7**	**0.1**	**60 (91)**	**0.5 (0.6)**
	Total	**4.4**	**0.7**	**0.4**	**67 (98)**	**1.0 (1.1)**

2.3. Current leads

In line with the solution implemented in the LHC, the different powering circuits of the FCC hadron collider will most likely use high-temperature superconductor (HTS) current leads to reduce the corresponding refrigeration load. With the conservative assumption that HTS technology is similar to the present state-of-the-art, i.e. the upper part of the HTS section of the current leads being cooled at 40 K, this refrigeration load scaling proportional to the current and to the number of circuits, would amount to 3.6 kW at 4.5 K equivalent.

2.4. Cryoplants, layout and availability

Concatenating the previous estimates of distributed and localized heat in-leaks and power dissipation, leads to a preliminary sizing of the cryogenic plants serving each 8 km sector, for both options of magnet operating temperature (4.5 K and 1.9 K). The results are shown in graphical form in Fig. 5, not including thermal loads due to cryogenic distribution, nor overcapacity margins for safe operation. The equivalent refrigeration capacity at 4.5 K of each of the 12 sector cryogenic plants ranges from 51 kW (magnets at 4.5 K, 100 km) to 75 kW (magnets at 1.9 K, 83 km). This largely exceeds the 18 kW at 4.5 K of the LHC cryogenic plants, procured at the turn of the millennium, as well as the present state-of-the-art of 25 kW at 4.5 K represented by the ITER refrigerators. A first challenge is therefore to understand where the practical limit on the refrigeration capacity of a single cryogenic plant lies, and to find out how this limit can be extended to the 50 to 100 kW at 4.5 K range. A second challenge derives from the fact that beam screen heat loads at 40 K to 60 K represent the single largest fraction of the total capacity: hence the cryogenic plants of the FCC hadron collider will no longer be primarily producing liquid helium. This opens the way to alternative refrigeration cycles, in particular Brayton cycles using turbo-machinery and helium-neon mixtures as process fluids such as being developed for hydrogen liquefaction [Seemann et al. (2013)], with the promise of significant improvements in thermodynamic efficiency.

Fig. 5 also shows possible cryogenic plants layouts. The first layout corresponds to sector cooling with two large cryogenic plants located at each odd point, serving a full sector. The second layout corresponds to half-sector cooling with one large or two smaller cryogenic plants at each point, serving two adjacent half-sectors.

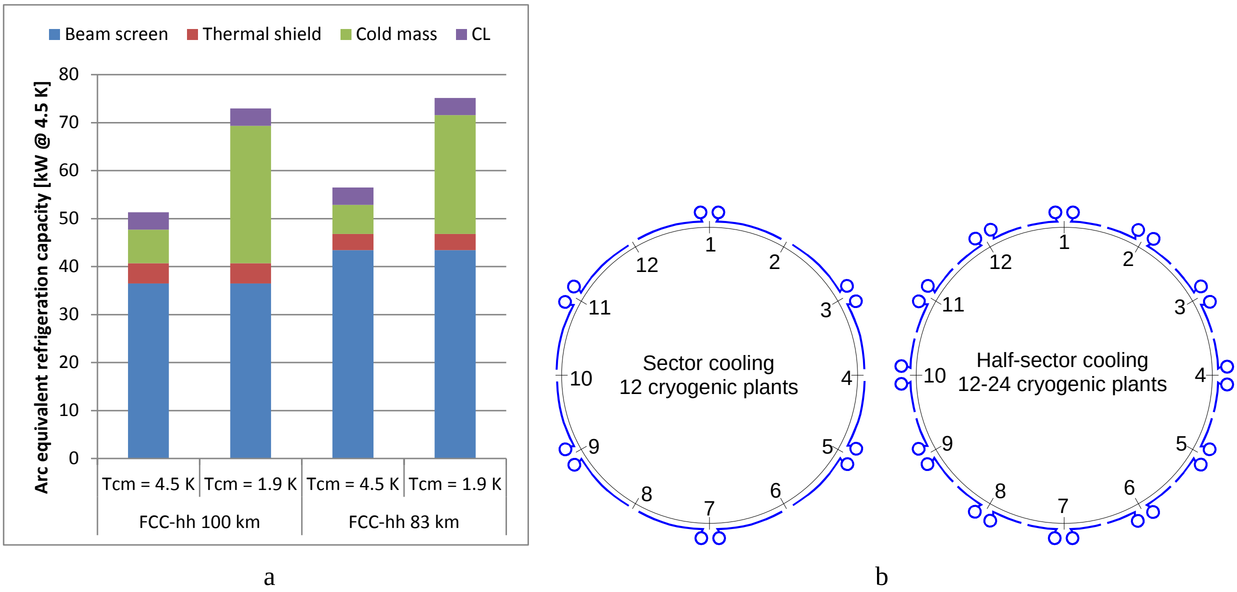


Fig. 5. (a) Preliminary size of sector cryogenic plants and (b) possible cryogenic layouts of the FCC hadron ring.

Reliability and availability of the cryogenic system, much larger than that of the LHC in terms of capacity, number of components and geographical extent, raise specific concerns. Achieving an overall reliability of 0.95, comparable to that observed during the first run of the LHC with an individual cryogenic plant availability of 0.994 [Delikaris et al. (2013)], would require bringing up this number to 0.998 in the case of 24 cryogenic plants around the FCC ring. Considering 200 days of operation for physics per year, this is equivalent to a maximum allowance of 10 hour/year down-time per cryogenic plant. This issue needs to be analysed in detail to understand the critical failure paths and develop mitigation measures, based on both the reliability of single components and on the plant architecture.

2.5. Superfluid helium refrigeration

In the case of a magnet system operating at 1.9 K, the previous estimates of distributed heat loads yield an integrated refrigeration capacity of up to 7 kW at 1.8 K per sector, not including overcapacity margins for safe operation. This also largely exceeds the 2.4 kW at 1.8 K of the LHC cryogenic plants which correspond to the present state-of-the-art. One should therefore analyse where the practical capacity limit of the 1.8 K stages is, and find out how this limit can be extended to the 10-kW range. The development of larger cold compressors and the operation with parallel cold compressor trains have to be investigated.

2.6. Cooldown

The cold mass diameter of the FCC superconducting magnets has been preliminary estimated to 0.8 m (see Fig. 4). A scaling from LHC gives a specific mass to be cooled of about 3.3 t/m, i.e. a total mass per sector of 280 kt (100 km) or 220 kt (83 km). A cool-down time of 2 weeks from 300 to 80 K thus requires pre-cooling capacity per sector of 3000 kW (100 km) or 2400 kW (83 km). As for the LHC, these numbers are incommensurable with steady-state refrigeration capacities of the cryogenic plants, so that precooling requires vaporization of liquid nitrogen: 75000 t (100 km) or 59000 t (83 km) of liquid nitrogen are needed for the whole accelerator. If the delivery by semi-trailers is retained, up to 75 (100 km) to 60 (83 km) semi-trailers per day and per sector will be required, i.e. one semi-trailer every ~20 minutes per sector, a severe logistics issue which has to be addressed.

2.7. Cryogen inventory

Assuming the FCC cold-mass has the same filling factor as the LHC (~10 %), a content of 50 l/m of liquid helium is expected. In total, 525 t of helium would be required to fill the FCC magnet cold mass. Taking into account 25 % of additional inventory for the cryogenic distribution and cryogenic plants, a total helium inventory of 700 t is estimated. This corresponds to 12 % of the present European annual market and to 2.5 % of the world annual market. Filling the FCC hadron ring with helium therefore constitutes a strategic technical and commercial issue.

3. The electron-positron collider

Given their much lower energy, the beams of the FCC electron-positron collider have a lower magnetic rigidity and can thus be handled by a normal-conducting system of magnets with maximum bending field of only 0.05 T. The electron-positron ring is therefore at room temperature over most of its circumference, with the exception of the long straight sections housing the superconducting acceleration cavities. Cooling these cavities constitutes the main cryogenic challenge of the electron-positron ring. Table 3 gives the machine parameters of the FCC electron-positron collider. Cryogenics for the FCC electron-positron collider is less demanding than for the FCC hadron collider. As on all high-gradient superconducting RF systems, a particular challenge will be the large dynamic range (RF on/off) that has to be handled by the 1.9 K refrigeration stages. In addition, concerning the operating temperature, progress in cavity materials and surface quality could reduce the residual wall resistance, with the consequence of displacing the optimum operating temperature down to 1.6 K. At this temperature, the helium saturation pressure is only 7.5 mbar, so that the cold compression system would require 5 to 6 stages in series, raising serious control issues. Experience at CERN with trains having 3 and 4 stages in series shows a strong impact of cold compressor trips on the cryogenic-plant downtime: typically 3 hours with 3 cold compressors in series and 7 hours with 4 cold compressors in series. The impact of the increase in the cold-compressor number on the overall availability must therefore be carefully addressed.

Table 3. Machine parameters of the 100-km FCC electron-positron collider.

Parameter	FCC-electron-positron collider
Cavity type	704 MHz 5-cell cavity
Gradient [MV/m]	20
Active length [m]	1.06
Voltage per cavity [mV]	21.2
Number of cavities	568
Number of cryomodules	71
Total length of cryomodules [m per beam]	902
Q0	2.0×10^{10}
Dynamic heat load per cavity @ 1.9 K [W]	44.4
Total dynamic heat load [kW per beam]	25.2

4. Outlook

We have identified the main cryogenic challenges raised by the study of very large Future Circular Colliders at CERN, in a qualitative and partly quantitative manner. This approach has already permitted to define specific topics for further study and development. As the technical definition and implantation studies of the possible colliders proceed in the coming years, the cryogenic analysis will be refined, with the aim of exploring promising technological alternatives and producing a conceptual design report with technically consistent and economically viable, if not fully optimized solutions. Towards this goal, collaborations with expert partner institutes are being developed on an international basis, and can be extended to interested parties.

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