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Towards the conceptual design of the cryogenic system of the Future Circular Collider (FCC)

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Abstract. Following the update of the European strategy in particle physics, CERN has undertaken an international study of possible future circular colliders beyond the LHC. The study considers several options for very high-energy hadron-hadron, electron-positron and hadron-electron colliders. From the cryogenics point of view, the most challenging option is the hadron-hadron collider (FCC-hh) for which the conceptual design of the cryogenic system is progressing. The FCC-hh cryogenic system will have to produce up to 120 kW at 1.8 K for the superconducting magnet cooling, 6 MW between 40 and 60 K for the beam-screen and thermal-shield cooling as well as 850 g/s between 40 and 290 K for the HTS current-lead cooling. The corresponding total entropic load represents about 1 MW equivalent at 4.5 K and this cryogenic system will be by far the largest ever designed. In addition, the total mass to be cooled down is about 250’000 t and an innovative cool-down process must be proposed. This paper will present the proposed cryogenic layout and architecture, the cooling principles of the main components, the corresponding cooling schemes, as well as the cryogenic plant arrangement and proposed process cycles. The corresponding required development plan for such challenging cryogenic system will be highlighted.

1. Introduction

The Future Circular Collider is the next high-energy particle physics instrument being studied at CERN in the framework of an international collaboration. The study considers several options for very high-energy hadron-hadron (FCC-hh), electron-positron (FCC-ee) and hadron-electron (FCC-he) colliders as well as an upgrade in energy of the existing LHC accelerator (HE-LHC). As concerns cryogenics, the most challenging option is the FCC-hh machine. This machine is basically a proton collider with a centre-of-mass energy of 100 TeV and will be installed in a tunnel with a circumference close to 100 km. The FCC-hh will use the most advanced superconducting magnet, cryogenic and accelerator technologies ever employed.

The FCC-hh will employ 16-T twin-aperture superconducting magnets based on Nb_3Sn technology and operating in static baths of pressurized superfluid helium below 1.9 K. This operating temperature of 1.9 K is based on a technical-economical optimization study showing that the extra cost (capital and operation) of a cryogenic system operating at 1.9 K is largely compensated by the saving of the superconducting material quantity required for the magnet system. The technology of pressurized superfluid helium chosen for the FCC-hh is largely used in the LHC machine. The total power to be extracted at 1.9 K is about 120 kW.

The synchrotron radiation emitted by the high-energy proton beams will dissipate about 5 MW in cryogenic environment. Before reaching the magnet cold masses, this power has to be intercepted at a higher temperature using beam screens operating between 40 and 60 K. This operating temperature of the beam screens is a compromise between vacuum and wall-impedance considerations as well as the thermodynamic optimization [1]. As the thermal shielding will be performed at the same temperature level, the total power to be extracted between 40 and 60 K is about 6 MW.

Another refrigeration load concerns the HTS current leads which will be cooled between 40 and 290 K using a total mass-flow of 850 g/s.

The total FCC-hh refrigeration capacity is equivalent to about 1 MW at 4.5 K distributed around the ring circumference.

2. General layout and architecture

The general layout of the FCC-hh cryogenic system is based on 10 cryogenic plants distributed over 6 technical sites. Figure 1 shows the general layout of the cryogenic system. Each cryogenic plant has to serve a 10-km long sector (at Points C, E, I and K) or two adjacent 5-km long sectors (at Point A and G). In 4 technical sites the presence of two cryogenic plants will allow for partial redundancy.

Figure 2 shows the cryogenic architecture of one cryogenic plant. As the refrigeration to be produced above 40 K represents about 50 % of the total entropic load, special efforts have to be done to elaborate an efficient and reliable cycle based on a mixture of neon and helium. To limit the effect of the gravity (hydrostatic head and relative enthalpy variation) in the deep access shafts (up to 400 m), the cold part of the helium cycle below 40 K, including cold compressors, must be located in underground caverns.

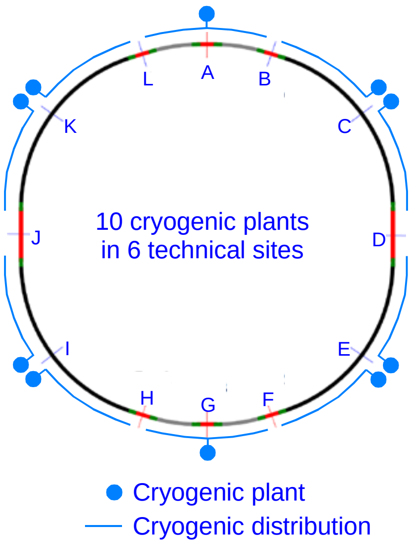

Figure 1. General layout

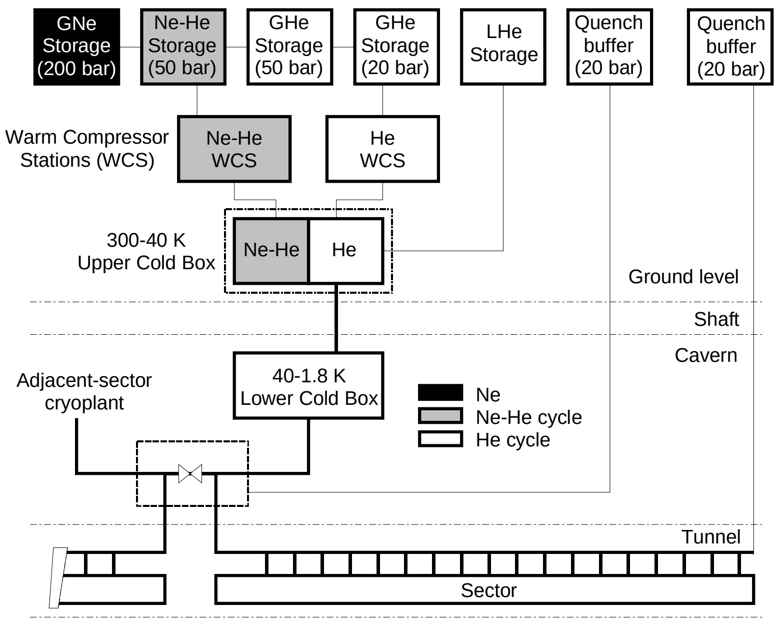

Figure 2. Cryogenic plant architecture

3. Ring operation and heat loads

The cross section of the FCC tunnel and the integration of the main equipment are shown in Figure 3. The tunnel will have an internal diameter of 6 m. The two main components are the cryo-magnet string and the cryogenic distribution line containing all the lines needed for the transport of the refrigeration capacity. The weak point of conventional cryogenic distribution lines, using stainless steel tubes, is their compensation units based on bellows and their inherent risks of leaks and buckling. For the FCC-hh, the conceptual design will be based on Invar® tubes [2]. Invar®, an iron-nickel alloy, exhibits a very low thermal contraction coefficient and the corresponding cool-down stresses can be handled without compensation units. Moreover, to transport the huge refrigeration capacity between 40 and 60 K for the beam-screen and thermal-shield cooling (~600 kW per sector), an efficient distribution (low pressure drop) combined with the need of a limited size of the supply and return lines (lines E and F) has required to choose an operating pressure of 50 bar [3], which complicates the design of reliable bellows-based compensation units.

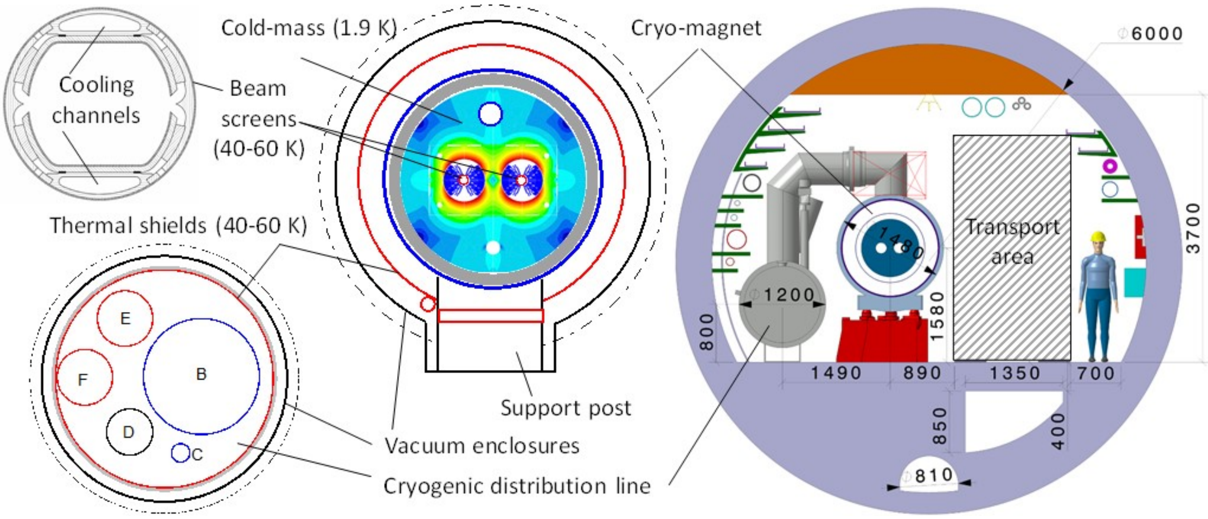

Figure 3. Cross section of the FCC tunnel and main FCC-hh cryogenic components

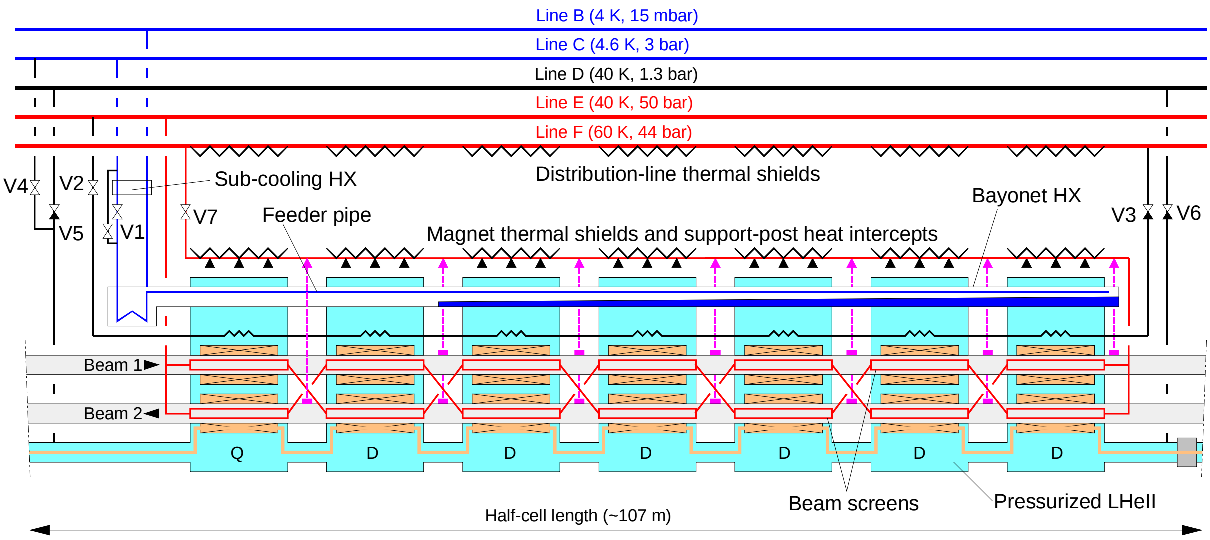

Figure 4. Cryogenic flow-scheme of a FCC-hh half-cell

The cryogenic flow scheme of a FCC-hh half-cell (string of one quadrupole and 6 dipole cryo-magnets) is shown in Figure 4. The pressurized superfluid helium bath at 1.9 K in which the superconducting magnets are immersed, is cooled by saturated two-phase helium flowing in a bayonet heat exchanger (HX) tube extending along the string of magnets and supplied by line C through expansion valve V1 and a sub-cooling heat exchanger [4]. The low saturation pressure is maintained by pumping the vapour through line B. Table 1 gives the main superfluid helium cooling loop parameters (LHC parameters are also given for comparison). Cool-down and warm-up are achieved by forced circulation of high-pressure gaseous helium supplied at variable temperature by line E, tapped through valve V2 and returned to the cryogenic plant by valve V3 and line F. At the end of the cool-down, the liquid helium filling is done by valve V4. In case of magnet resistive transitions, the resulting pressure rise is contained below the 2 MPa design pressure by discharging the liquid helium inventory of a half-cell into line D through the V5 & V6 safety relief valves; the low hydraulic impedance of this 200 mm diameter pipe, normally maintained at 40 K, is very helpful in containing the helium discharge and buffering the gas storage vessels. The beam screens are cooled by forced circulation of high-pressure helium, tapped from line E and returned to line F by valve V7 after cooling the magnet thermal shields and support-post heat-intercepts [5]. Table 2 gives the main beam-screen cooling loop parameters (LHC parameters are also given for comparison).

Table 1. Main superfluid helium cooling loop parameters
(value in brackets are for a maximum cold-mass temperature of 2 K requiring a smaller pumping line diameter but reducing the magnet operating temperature margin)

Parameter	Unit	LHC	FCC-hh
Unit cooling length	m	106.9	107.1
Sector cooling length	m	2900	8400
Number of parallel cooling loops (total)	-	216	790
Average nominal heat load	W/m	0.40	1.4
Bayonet heat exchanger inner diameter	mm	53.4	83.1
Feeder pipe inner diameter	mm	10.0	15.0
Wall thickness of bayonet heat exchanger	mm	2.3	5.0
Joule-Thomson valve inlet temperature	K	2.18	2.18
Free longitudinal cross-section area	cm^2	60	156
ΔT max pressurized-saturated HeII	mK	50	50
Cold mass operating pressure	bar	1.3	1.3
Pumping line diameter	mm	270	630 (500)
Heat load on pumping line	W/m	0.11	0.24
Pumping pressure at cryogenic plant interface	mbar	15	15
Maximum cold-mass helium temperature	K	1.9	1.9 (2.0)

Table 2. Main beam-screen cooling loop parameters

Parameter	Unit	LHC	FCC-hh
Unit cooling length	m	53.4	107.1
Sector cooling length	m	2900	8400
Number of parallel cooling loops (total)	-	432	790
Average beam-screen nominal heat load	W/m	1.6	60
Supply pressure	bar	3	50
Supply helium temperature	K	5	40
Max. allowed BS temperature	K	20	60
BS helium outlet temperature (nominal)	K	20	57
Minimum BS temperature (nominal)	K	5	43
BS pressure drop (nominal)	bar	0.5	4.3
ΔP control valve (nominal)	bar	0.8	1
ΔP supply and return line (nominal)	bar	0.4	0.5
Total cooling loop pressure drop	bar	1.7	5.8
Supply/return header diameter	mm	100/150	250/250
Exergetic efficiency (distribution only)	%	76	86
Total exergetic efficiency (with cold circulator)	%	N/A	82
Total exergetic efficiency (with warm circulator)	%	?	71

Specific heat loads at different temperature levels are given in Table 3. In addition to the static heat in-leaks, dynamic heat loads due to beam-induced heating and resistive heating in SC cable splices will create dynamic ranges which require an efficient turn-down capability of the cryogenic plants.

Table 3. Specific heat loads at different temperature levels

Temperature level		40-60 K	1.9 K	4 K VLP
Static heat in-leaks [W/m]	CM supporting system	2	0.13	
	Radiative insulation		0.13	
	Thermal shield	3.1		
	Feedthrough & vacuum barrier	0.2	0.1	
	Beam screen		0.12	
	Distribution	4	0.1	0.24
	Total static	**9.3**	**0.58**	**0.24**
Dynamic heat loads [W/m]	Synchrotron radiation	57	0.08	
	Image current	3.4		
	Resistive heating in splices		0.3	
	Beam-gas scattering		0.45	
	Total dynamic	**60**	**0.83**	
	Total [W/m]	**70**	**1.4**	**0.24**
	Dynamic range [-]	8	2.5	1

4. Refrigeration process cycle

Figure 6 shows the conceptual design of the refrigeration process cycle, which is proposed for the FCC-hh. For the production of the refrigeration capacity above 40 K, the conceptual design is based on a turbo-Brayton cycle using a mixture of neon and helium which allows to use centrifugal compressors in the warm compressor station [6]. These warm centrifugal compressors have oil-free active magnetic bearings and do not need gear-boxes and shaft-seals (see Figure 5). The Carnot efficiency of such a cycle is expected to be higher than 40 %. This cycle will also be used for the precooling at 40 K of the pure helium cycle required for the production of the refrigeration capacity at 1.8 K for cooling the superconducting magnets. Below 40 K, the helium refrigeration cycle is based on a Claude cycle with a Carnot efficiency of 28.8 % (LHC cryogenic plant value). Refrigeration at 1.8 K is provided by a cold compressor train in series with warm volumetric compressors (C3) allowing efficient turn-down capability. Table 4 gives the main tunnel user heat loads per sector. The electrical power to the cryogenic plant is 20 MW per cryogenic plant, i.e. 200 MW in total for the FCC-hh machine.

Figure 5. Warm centrifugal compressor (Courtesy of MAN Diesel & Turbo)

Table 4. Main tunnel user heat loads per 10-km long sector

Temperature level	40-60 K [kW]	1.9 K [kW]	4 K VLP [kW]	40-290 K [g/s]
Cold-mass load, Qcm		12		
Beam screen load, Qbs	504			
Magnet thermal shield load, Qtsm	44.5			
Distribution thermal shield load, Qtsd	33.5			
Pumping line (line B) load, Qb			2	
Current leads cooling, Qcl				85
Total	580	12	2	85

4.1. Cool-down of sectors

One characteristic of a turbo-Brayton cycle is that the refrigeration power is proportional to its operating temperature, i.e. if the cryogenic plant is producing 500 kW at 50 K, it will be able to produce up to 2.25 MW at 225 K. Consequently, this turbo-Brayton cycle can be used also to produce the cooling capacity for the cool-down of the 23-kt sector cold-mass. A warm circulator (C1) is required to supply the cool-down mass-flow. Considering a cool-down temperature difference of 75 K per half-cell (giving less than 50-K temperature difference per magnet), the required mass-flow to distribute the cooling capacity is 5.8 kg/s and the maximum pressure drop during the cool-down operation with a supply pressure of 50 bar is about 6 bar. The cool-down time from 300 to 40 K using the turbo-Brayton refrigeration cycle is about 15 days. The cool-down operation cost which corresponds to the electrical consumption of the turbo-Brayton cycle and of the warm circulator is about 2.3 MCHF for the entire machine. This cost has to be compared with a cool-down using liquid nitrogen pre-coolers which will require 45’000 t of liquid nitrogen (~4 MCHF per cool-down), large LN2 storage reservoirs (56’000 m^3 equivalent to 10 spherical reservoirs with a unit diameter of 27 m), which will be empty most of the time and challenging delivery logistics to get the LN2 inventory at the right time.

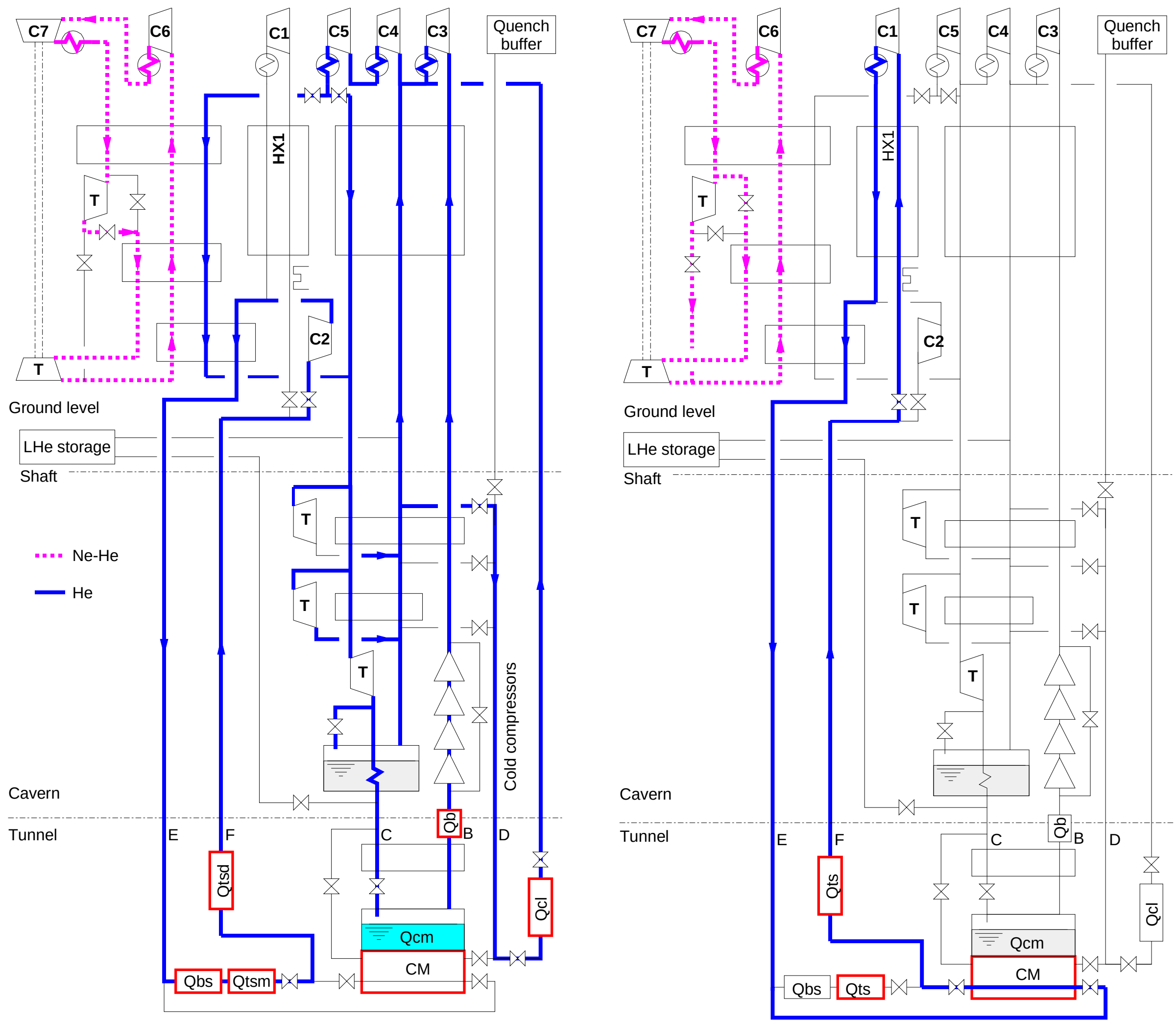

Figure 6. Conceptual design of the refrigeration process cycle for nominal (left) and cool-down (right) operation modes showing the main tunnel user loads.

4.2. Beam-screen cooling

Concerning the beam-screen and thermal-shield cooling a cold circulator (C2) will supply a mass-flow of 5.6 kg/s at 50 bar with a pressure ratio of 1.13 for compensating the 5.8 bar of pressure drop in the cooling loop. A compression power of 130 kW consumed by this cold circulator, with an assumed isentropic efficiency of 70 %, has to be extracted at cryogenic temperature. The total exergetic efficiency of this cooling loop is 82 % (see Table 2). As the cold circulator C2 requires about same characteristics (mass-flow, operating pressure and pressure ratio) than the warm circulator C1, this warm circulator can also be used as redundant machine for the beam-screen and thermal shield cooling loop. In this case, the total exergetic efficiency will be reduced to 71 % (see Table 2) taking into account a warm circulator isentropic efficiency of 83 % and a NTU of 40 for the heat exchanger HX1. The difference of 11 points in the exergetic efficiency using cold or warm circulators will give an operation cost saving of about 2.8 MCHF per sector over 10 years of operation. This cost saving should compensate the capital cost of the cold circulator by far.

Another challenge of the cryogenic system is the dynamic range of 8 (see Table 3) mainly due to the large synchrotron radiation deposited on the beam screen which increases with the power of 4 of the beam energy or of the dipole magnet current. The corresponding heat load transient is very severe, since the synchrotron radiation reaches its maximum value in less than 30 minutes. This transient has to be handled by the local cooling loops which do not allow temperature excursion of the beam screens above 60 K, and by the cryogenic plants which have an inherent time constant for the capacity adaptation. Concerning the local cooling loop, the strategy is to keep in each loop a constant mass-flow corresponding to the expected nominal value. Without beams, the temperature gradient along the beam-screen length is about zero. With beam, when the synchrotron radiation reaches its nominal value, the temperature gradient will obviously appear without demanding large changes in the control configuration. Working at constant supply pressure at the outlet of the beam-screen circulator would impose to discharge and refill a large quantity of helium, when the return line F (~400 m^3 per sector) has its temperature varying alternately from 40 to 60 K. The corresponding density variation of 15 kg/m^3 would yield a mass variation of about 6 t per sector. To avoid this large inventory variation, it is proposed to work at a constant helium inventory in the beam-screen and thermal shield cooling loop. Consequently, the pressures in line E and F will be reduced without beam and will progressively increase to their nominal value in steady-state with beam. In addition, due to the large thermal inertia of the two distribution lines of 250 mm, the capacity at the cryogenic plant interface increases with a time constant of about 4 hours, compatible with the capacity adaptation of such large cryogenic plant [7]. Figures 7 and 8 show the evolution of the different parameters during a typical low-luminosity physics run with a stable beam plateau of about 10 hours. In the case of high-luminosity physics runs, the stable beam plateau duration will be about 4 hours, i.e. the cryogenic plant will never operate in steady-state.

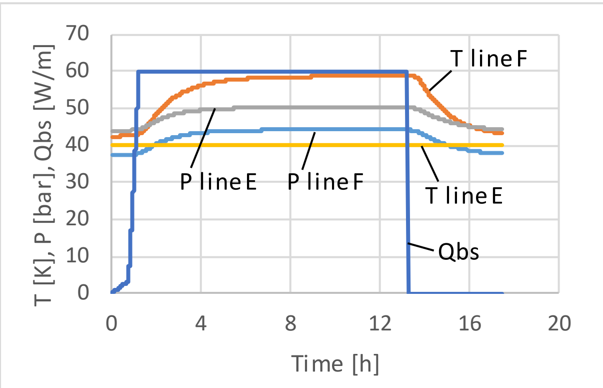

Figure 7. Evolution of the pressure and temperature of lines E and F at the cryogenic plant interface during a typical physics run

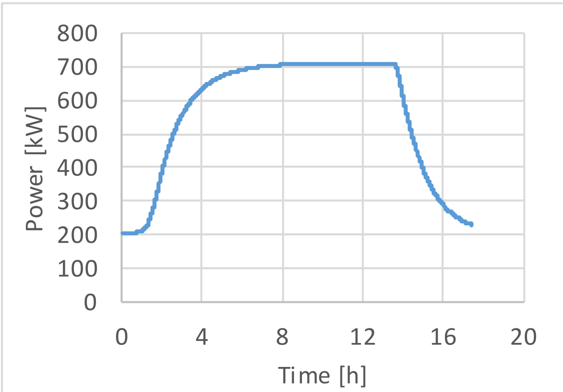

Figure 8. Evolution of the refrigeration capacity during a typical physics run

4.3. 1.8 K refrigeration

The cooling of the superconducting magnets of the FCC-hh requires a refrigeration capacity of 12 kW at 1.8 K per cryogenic plant, a capacity 5 times larger than the state-of-the-art cryogenic plants presently in operation on the LHC. Specific studies and developments will be required on the design of larger cold compressors and/or on the operation of cold compressor trains in parallel. The dynamic range of 2.5 will be not an issue for the proposed mixed-compression scheme as demonstrated on the LHC. Moreover additional studies are expected to improve the overall efficiency of the helium plant such as the introduction of centrifugal compressors in the warm compression station and the precooling capacity of the Claude cycle down to 40 K usefully provided by the turbo-Brayton cycle as shown in Figure 6.

5. Cryogen inventory and storage

The FCC-hh cryogenics system will require neon, helium and nitrogen.

Nitrogen will be required only for the regeneration of adsorbers and dryer beds; consequently, one standard 50-m^3 LN2 reservoir is foreseen on each technical site (6 in total).

Concerning the neon, the proposed mixing rate of the Ne-He cycle is 25 % of neon and 75 % of helium. As this cycle remains localized at the ground level, the neon inventory can be kept at about 500 kg per cryogenic plant. It is proposed to store the neon inventory in 5 x 2-m^3 cylinders at 200 bar per cryogenic plant corresponding to a storage capacity of about 1.5 t per cryogenic plant.

The helium inventory is mainly driven by the cold-mass void fraction (33 l/m scaled from LHC cold-mass inventory) and by the lines E and F (250-mm diameter) which contain high-density helium. The total helium inventory is about 880 t, equally shared between the cold-mass and the distribution system. 20 % of the inventory will be stored in standard 250-m^3 medium-pressure reservoirs (216 reservoirs in total). The remaining part (80 %) will be stored in 120-m^3 liquid reservoirs (50 reservoirs in total). Boil-off liquefiers (one per technical site) must be foreseen to preserve the liquid helium inventory during long shut-down periods, dedicated to the major-overhauling of the main cryogenic plants.

6. Conclusion

The conceptual design of the cryogenic systems for a Future Circular Collider is in progress in the framework of an international collaboration. The final Conceptual Design Report (CDR) will be issued by 2018 and then examined by the next European Strategy for high energy particle physics. In the case of a positive feedback, the next step will be the studies and developments of the new concepts with the construction of demonstrators and/or prototypes.

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