Preliminary conceptual design of FCC-hh cryo-refrigerators: Air Liquide Study

L Tavian¹, F Millet², M Roig³, G Zick¹ and JM Bernhardt³

¹ CERN, CH-1211 Geneva 23, Switzerland
² Univ. Grenoble Alpes, CEA IRIG-SBT, F-38000 Grenoble, France
³ AIR LIQUIDE Advanced Technologies, BP15, 38360 Sassenage, France

Abstract. In the framework of a world-wide international collaboration, the FCC-hh, a 100 TeV hadron collider in a 100-km long tunnel, is proposed as a future circular collider beyond LHC at CERN offering the broadest discovery potential at the energy frontier. For such high performance hadron collider, the cryogenic system has to distribute very large cooling capacities all along the 100-km tunnel for the superconducting magnets continuously cooled at 1.9 K and for the beam screens operated between 40 and 60 K. The required total cooling power will be produced in 10 refrigeration plants with a unit equivalent capacity of 100 kW at 4.5 K, up to 4 times larger than the present state-of-the-art. Half of the entropic refrigeration load is due to the synchrotron radiation produced by the high-energy proton beams and deposited on beam screens actively cooled around 50 K. This non-conventional thermal load distribution is an additional challenge for the FCC-hh cryogenic system. Furthermore, the cryogenic system has to cool down the cold mass of the FCC-hh machine in less than 20 days with controlled thermal gradients in the cryo-magnets and beam screens. Based on preliminary design works from research institutes, an engineering study was performed with world-leader industries to assess a preliminary conceptual design for the FCC-hh cryogenic plants with industrial solutions and innovative technologies. The present paper recalls the FCC-hh cryogenic requirements and presents the main results of Air Liquide study confirming the novel precooling refrigeration option down to 40 K.

1. Introduction
The Conceptual Design Reports of the Future Circular Collider (FCC) have been published in 2019 to nurture the next European Strategy for high energy particle physics. This conceptual study elaborates the design of next generation of high-energy particle physics instruments being hosted at CERN in the framework of an international collaboration with different scenarios of circular colliders. The hadron-hadron collider (FCC-hh) with a centre-of-mass energy of 100 TeV in a 100-km long tunnel is the baseline of the overall technical infrastructure for the FCC study and is detailed in [1]. To achieve the scientific objectives of the FCC-hh machine, key technologies have to be developed, such as advanced 16 T superconducting magnets, cryogenic and accelerator technologies. Among them, the development of large-scale cryogenic infrastructures to cool down superconducting accelerator components is undergoing to define a reliable and sustainable solution. For that purpose, an engineering study was performed with the implication of the main world-leader cryogenic companies. The present paper describes the main outcomes of the Air Liquide study.

2. Preliminary design studies
Preliminary studies were performed in the framework of an international collaboration and the baseline solution for the FCC-hh cryogenic system was summarized in [3]. The cryogenic architecture was selected taking into account both the FCC infrastructure constraints (access points, surface/underground...
installations) and the specific thermal load distribution. On the one hand, the cryogenic heat loads are deposited along the 100-km long accelerator in an underground tunnel and the cooling capacity is produced in 10 cryogenic plants in different technical sites as illustrated in Figure 1.

Figure 1. FCC-hh cryogenic infrastructure layout with 10 cryogenic plants in 6 technical sites (left) and simplified cryogenic plant architecture (right) with localization of the main subsystems. WCS refers to warm compression station, UCB to upper cold box and LCB to lower cold box.

On the other hand, the estimated refrigeration capacity is larger than any existing cryogenic plants using helium as working fluid. And the required capacity presents a non-conventional thermal load distribution with large entropic refrigeration loads above 40 K as detailed in Figure 2.

Figure 2. Total exergetic load distribution among the main cryogenic FCC-hh users (left) and FCC-hh cryogenic plant units compared to the State of the Art of existing He plants (right). LHC unit refers to one of the eight 18-kW-at-4.5 K refrigerators in operation at CERN, Ras Laffan to one helium liquefier installed in Qatar and ITER unit to one of the three 4.5 K modules working in parallel.

In FCC-hh nominal operation, the total cooling capacity of 120 kW at 1.8 K has to be provided to keep the superconducting magnets at 1.9 K and the total cooling capacity of about 6 MW between 40 and 60 K has to be produced not only to cool the thermal shields but mainly to cool the beam screens intercepting high synchrotron radiation emitted by the high-energy proton beams (30 W/m). These
unusually large heat loads for the thermal shields and beam screens represent 57% of the total exergetic load. To complete the magnet and beam screen loads, the high temperature superconducting (HTS) current leads have to be cooled to temperatures between 40 and 290 K using a total mass-flow of 850 g/s. The total FCC-hh cryogenic refrigeration capacity is equivalent to 1 MW at 4.5 K supplied by 10 cryogenic plants around the ring circumference as shown in Figure 1. Large unit-capacity cryogenic plants of 100 kW equivalent at 4.5 K will cool the superconducting magnets below 1.9 K and supply the refrigeration capacities above 40 K for the beam screens, the thermal shields and the HTS current leads. The FCC-hh cryogenic plants are therefore larger than the present state-of-the-art of He plants (25 kW at 4.5 K) as illustrated in Figure 2. The FCC-hh preliminary design [1], [2] was based on two coupled cryogenic plants. Below 40 K, one helium refrigeration cycle provides 1.8 K refrigeration for the 16 T high-field superconducting magnets in a conventional Claude cycle associated with a train of cold compressors in series with warm volumetric compressors as successfully demonstrated in LHC [3]. Above 40 K, a mixed refrigerant (MR) plant using a mixture of neon and helium and centrifugal compressors provides the refrigeration capacity in a Turbo-Brayton cycle. Finally, a pure gaseous helium forced flow cooling loop distributes this MR cooling capacity in the heavy-loaded beam screens and thermal shields along the sector in the FCC tunnel as illustrated in Figure 3.

![Figure 3. Process Flow Diagrams for the FCC-hh cryogenic plants: international-collaboration preliminary design with helium-neon precooling [1]. T refers to turbine and C to compressors.](image-url)
3. Objectives of the industrial engineering study

The industrial engineering study performed by Air Liquide has to assess the preliminary conceptual design with industrial solutions to fulfill the FCC-hh baseline with 10 cryogenic plants distributed along the ring as illustrated in Figure 1 as well as the steady-state operating requirements summarised in Table 1. The performed study is divided in two phases. First, different process cycle options are compared using the “High” mode loads to select the preferred industrial solution. Then the selected process cycle is studied in more details to estimate its performance and equipment in different steady-state and transient operating modes such as the “Low” mode, turndown capability, the cool-down and filling to 1.9 K.

Table 1. Main cooling requirements for one FCC-hh sector (= one cryogenic plant) in the steady-state modes. “High” and “Low” correspond respectively to the maximum and minimum cooling needs. Qcm = heat loads on superconducting-magnet cold masses, Qbs+Qts = heat loads on beam screens and thermal shields, Qcl = mass flowrates for HTS current leads

| Loads       | Cooling circuit        | Temperature range | “High” mode | “Low” mode |
|-------------|------------------------|-------------------|-------------|------------|
| Qcm [kW]    | Superconducting Magnets| 1.9 K             | 12          | 4          |
| Qbs+Qts [kW]| Beam screens & shields | 40-60 K          | 620         | 90         |
| Qcl [g/s]   | HTS Current leads      | 40-290 K         | 85          | 43         |

In addition to the steady-state performances listed in Table 1, transient modes have to be studied. Thus, the turndown capability up to a factor 6 for the beam screen heat loads has to be confirmed when running from Injection Standby to Normal Operation modes. Similarly, a dynamic range of cooling operations up to a factor 3 is required for the magnet cooling. Finally, the cool-down of one 10 km-long sector of around 24’000 metric tons has to be performed in less than 15 days using only the cryogenic plant turbines (no external LN2 supply) and therefore requiring cool-down capacities up to 2.5 MW down to 80 K.

4. Process cycle comparison and selection

In all calculations and analysis, the cryogenic plant interfaces with the FCC-hh sector and the specified heat loads are identical. Consequently, similar cold ends below 40 K is selected in the lower cold box. Supercritical helium (SHe) at 4.5 K is produced in the lower cold box through a set of conventional heat exchangers and expansion turbines. Then, the SHe flow is distributed along the sector and expanded in the 1.8 K saturated helium bath of the superconducting magnets. A train of three large cold compressors in series pumps this 1.8 K saturated helium baths where the magnet heat loads are deposited. Additionally, fixed equipment efficiencies scaled from similar equipment are applied for calculations with isentropic efficiencies at 80% for the turbines, between 70 to 80% for the centrifugal compressors.

As a consequence, the main difference in the evaluated process solutions concerns the upper cold box devoted to cool the beam screens, thermal shields and the HTS current leads as well as to precool the helium flow before the lower cold box as shown in Figure 4. The following process cycles have been evaluated:

- Solution A = Helium plant with MR precooling similar to the preliminary design,
- Solution B = Helium plant without a separate precooling cycle similar to the LHC design,
- Solution C = Helium plant with a nitrogen precooling cycle similar to the ITER design.

Solution A, a cryogenic plant with MR precooling, is based on the existing Turbo-Brayton cryogenic systems developed by Air Liquide for HTS cooling and LNG boil-off gases re-liquefaction, an innovative solution with high efficiency and reduced maintenance [4]. This MR precooling solution is similar to the international collaboration preliminary design shown in Figure 3 and selected as baseline solution in [1]. The MR plant uses two large turbines in series for the precooling of the helium circuits down to 40 K. A gas mixture of neon and helium with a neon fraction of 30% is considered as a good...
balance between reducing the number of compression stages in the warm compression station due to the neon mixture impact and increasing the mass flowrates in the cold box due to the neon inferior heat transfer properties compared to pure helium.

Solution B is a pure helium refrigerator without separate precooling and is similar to the LHC refrigerators in nominal operation at CERN. Large helium turbines replace the MR precooling cycle down to 40 K in the upper cold box of the cryogenic plant and consequently, larger helium mass flowrates circulate in the upper cold box and have to be compressed in the warm compression station. Solution B is the simplest one without precooling unit and mixed heat exchanger between different refrigerants but such large heat exchangers as well as efficient helium compression are still challenges nowadays.

Solution C, a cryogenic plant with LN2 precooling proposes a closed-loop nitrogen refrigerator providing the precooling down to 80 K with two turbines and a phase separator. In addition, a large helium turbine is required for the cool-down to 40 K. Nitrogen precooling cycles are the selected option for the ITER cryogenic plant as they offer several advantages such as a cheaper refrigerant and mature technologies from the air separation units (ASU) [5].

The three solutions are qualitatively and quantitatively evaluated with different technical-economic criteria such as the process and equipment design, performances and operation costs, as well as the technology availability and maturity. Table 2 summarizes the estimated total electrical power consumption for the three studied solutions with two technology options in the helium warm compression station.

The screw compressors are existing components in helium plants and give conservative electrical consumptions above 20 MW. In the opposite, the centrifugal compressors are a promising technology for helium and achieve significantly lower consumptions around 17 MW. One has to note that the turbine energy recovery of the largest turbines (shaft powers larger than 100 kW) are systematically subtracted from the calculated compression power consumptions. The performance ranking of the compared solutions listed in Table 2 are fully dependent of the warm compression station options. The cryogenic plant with MR precooling is the more efficient solution using helium screw compressors (33% Carnot efficiency), whereas the cryogenic plant without separate precooling (only pure helium) is the best one assuming the availability of helium centrifugal compressors (39% Carnot efficiency).
Table 2. Electrical power consumptions for one FCC-hh cryogenic plant in “High” mode with three precooling options (MR, He, LN2) and two warm helium compressor technologies (screw, centrifugal)

| Precooling solution | He WCs option | Electrical power consumption [MW] (Carnot efficiency [%]) |
|---------------------|---------------|--------------------------------------------------------|
| MR plant            | Screw         | 20.0 (33 %)                                            |
|                     | Centrifugal   | 17.5 (38 %)                                            |
| Pure Helium         | Screw         | 24.0 (28 %)                                            |
|                     | Centrifugal   | 16.9 (39 %)                                            |
| LN2 plant           | Screw         | 23.0 (29 %)                                            |
|                     | Centrifugal   | 17.0 (39 %)                                            |

Consequently, other parameters such as sizing and maturity of the components are also evaluated. Based on the global technical-economic analysis and recent success with Turbo-Brayton cryogenic systems, Air Liquide selects the solution A with MR precooling offering the most efficient solution in screw compression option, the lowest number of large turbines (2 in the MR cycle) and the smallest “UA-value” for the heat exchangers.

5. Performance and design analysis

Solution A, the cryogenic plant with MR precooling, is then studied in more details to consolidate the process cycle with new arrangements or additional equipment when needed in steady-state and transient operation modes. As an example, the position of the high-pressure helium circulator (CC5 in Figure 4) is evaluated according to the pressure losses along the cooling loop, to the pinch value (6 K) of the HX10 heat exchanger and to the isentropic efficiency $\eta_i$ of the circulators. Figure 5 presents this circulator position evaluation indicating that in nominal operation, the cold circulator option is no longer the best efficient solution for pressure drops larger than 4.5 bar (presently the specified one is 6 bar). Such result in nominal operation associated with the cool-down study invite designers to select the warm circulator option.

![Figure 5](image-url)

**Figure 5.** Electrical power consumption required for the beam-screen and shield cooling versus pressure losses in cooling loops for two different localizations of GHe circulator with 40% Carnot efficiency in the MR cycle.

The industrial analysis has confirmed the technical feasibility of the FCC-hh cryogenic plants with MR precooling as preliminary elaborated by the international collaboration. The total electrical power
consumption in the “High” mode is calculated to reach 20 MW with the existing helium screw compressors and significantly drops to about 17 MW with the challenging helium centrifugal compressors. Such consumption reduction induces Carnot efficiency increase from 33% to about 38%. The required heat load variation up to factor 6 for the beam screens is obtained by controlling the turbine cooling powers and the pressure levels in the warm compression station. Similarly, the turndown capability up to factor 3 for the magnets is provided thanks to the proven LHC-like strategy (a train of cold compressors in series with volumetric warm compressors). Finally, the cool-down analysis has introduced some process and equipment adaptation to fulfill cooling capacity up to 2 to 3 MW down to 80 K.

6. Conclusion and perspectives
The Air Liquide engineering study has confirmed the baseline design of the international collaboration with MR precooling and its expected performances and dimensions for the FCC-hh cryogenic plants reported in [1]. The cryogenic plant with MR precooling is therefore the preferred industrial solution taking benefit from the recent Air Liquide experiences in Turbo-Brayton developments. With respect to conventional refrigeration systems (Pure He and LN2 precooling), this solution has a better Carnot efficiency (33%) giving a reduction of the electrical power consumption of 13%, i.e. a saving of about 10 MCHF per year of operation of the FCC-hh cryogenics. In addition to the confirmation of the FCC-hh baseline design, the present industrial study demonstrates that the selection of the warm circulator option for beam screens and thermal shields simplifies the cool-down management without impacting the performances in nominal operation. Similarly, the warm centrifugal compressors for helium is identified as a challenging industrial option for the coming years and would further increase significantly the overall Carnot efficiency of the cryogenic plant and further reduce the total electrical power consumption by 13%. Such improvements will offer more-efficient and more-reliable large-scale helium cryogenic plants in the future.

7. References
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