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Preliminary Conceptual design of FCC-hh cryoplants: Linde evaluation

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Abstract. In the framework of an international collaboration, a 100 TeV hadron collider in a 100-km long tunnel is under study as a future circular collider beyond LHC at CERN. Its design is based on 16-T superconducting magnets cooled at 1.9 K by 10 cryoplants 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 cooled between 40 and 60 K. This non-conventional thermal load distribution is an additional challenge for the cryogenic system. An engineering study on FCC-hh cryoplants is ~~undergoing~~ in progress with world-leader industries to define the preliminary conceptual design of industrial solutions and to confirm innovative technologies. The paper recalls the FCC-hh cryogenic requirements, presents the main results of Linde Kryotechnik study and highlights some identified R&D efforts.

1. Introduction

The Future Circular Collider (FCC) study elaborates the design of the next generation of high-energy particle physics instruments being hosted at CERN in the framework of an international collaboration to nurture the next European Strategy for high energy particle physics. Different scenarios of circular colliders are currently examined and a 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 infrastructure for the on-going FCC study. Building such a FCC-hh machine requires key technology R&D program to select the most advanced superconducting magnet, cryogenic and accelerator technologies. Among them, the development of large-scale cryogenic infrastructures to cool down superconducting accelerator components is identified to design a reliable and sustainable solution.

Preliminary studies performed at CERN, CEA, TUD and WrUT are summarized in [1] and propose a baseline solution for the FCC cryogenic system. The overall cryogenic layout is defined taking into account both the FCC infrastructure constraints (access points, surface/underground installations) and the non-conventional thermal load distribution. The cryogenic heat loads along the 100-km long accelerator are unusual with helium refrigeration capacity larger than the present state-of-the-art (25 kW at 4.5 K) and with non-conventional thermal load distribution showing large entropic refrigeration loads above 40 K as detailed in figure 1. At maximum, the cooling heat loads to be extracted at 1.9 K for the superconducting magnets is estimated at 120 kW. The synchrotron radiation emitted by the high-energy proton beams is intercepted in beam screens operating between 40 and

60 K. The total power to be extracted in this range of temperature is about 6 MW including thermal shielding cooled at the same temperatures. Finally the high temperature superconducting (HTS) current leads are cooled between 40 and 290 K using a total mass-flow of 850 g/s.

For the production of the refrigeration capacity above 40 K, the preliminary design [1] is based on an innovative Turbo-Brayton cycle using a mixture of neon and helium and centrifugal compressors [2]. A pure helium forced flow cooling loop distributes this cooling capacity in the heavy-loaded beam screens and thermal shields along the sector in the FCC tunnel. Below 40 K, the helium refrigeration cycle is based on a conventional Claude cycle associated with a train of cold compressors in series with warm volumetric compressors to provide the 1.8 K refrigeration for the high-field superconducting magnets as successfully demonstrated in LHC. The total FCC-hh cryogenic refrigeration capacity is equivalent to 1 MW at 4.5 K distributed around the ring circumference in 10 cryoplants as shown in figure 1. Large unit-capacity cryogenic plants of 100 kW equivalent at 4.5 K are required to cool the superconducting magnets below 1.9 K and to supply the refrigeration capacities above 40 K for the beam screens, the thermal shields and the HTS current leads.

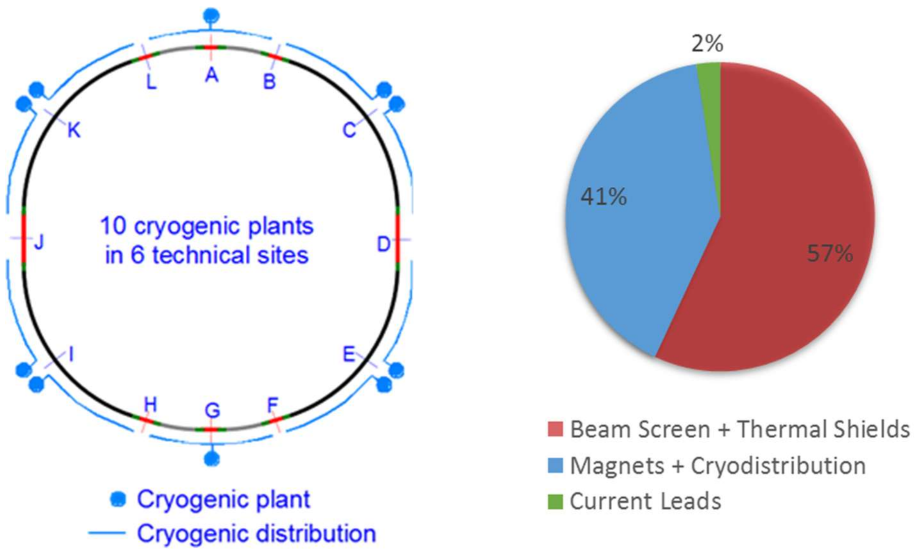

Figure 1 – FCC-hh cryogenic infrastructure overview with 10 cryoplants in 6 technical sites (left) and total exergetic load distribution among the main cryogenic users (right)

2. Technical specifications for an industrial engineering study

The industrial engineering study performed in the last twelve months by Linde Kryotechnik has to assess the preliminary conceptual design with industrial solutions and to confirm the innovative technologies which have to be developed to build more-efficient and more-reliable FCC-hh cryoplants. The present study has to deal with the FCC-hh baseline solution with 10 cryoplants distributed along the ring as illustrated in figure 1 and has to fulfil the following performance requirements specified at the end of 2016:

- The refrigeration capacities for the steady-state “High” and “Low” modes depending on the machine operations respectively the maximum and minimum cooling needs,
- The turndown capability of 6 for the beam screen heat loads when running from Injection Standby to Normal Operation modes and the dynamic range of 3 for the magnet heat loads,
- The cool-down of one 10 km-long sector of around 24’000 metric tons in less than 15 days without LN2 trailers requiring cryoplant cool-down capacities larger than 2.5 MW down to 80 K.

This industrial study covers the process concept evaluation in the “High” mode to select the preferred industrial solution, then the performance calculations and equipment definition in all operating modes. Finally a roadmap study for the development of novel technologies as detailed in the following chapters is presented.

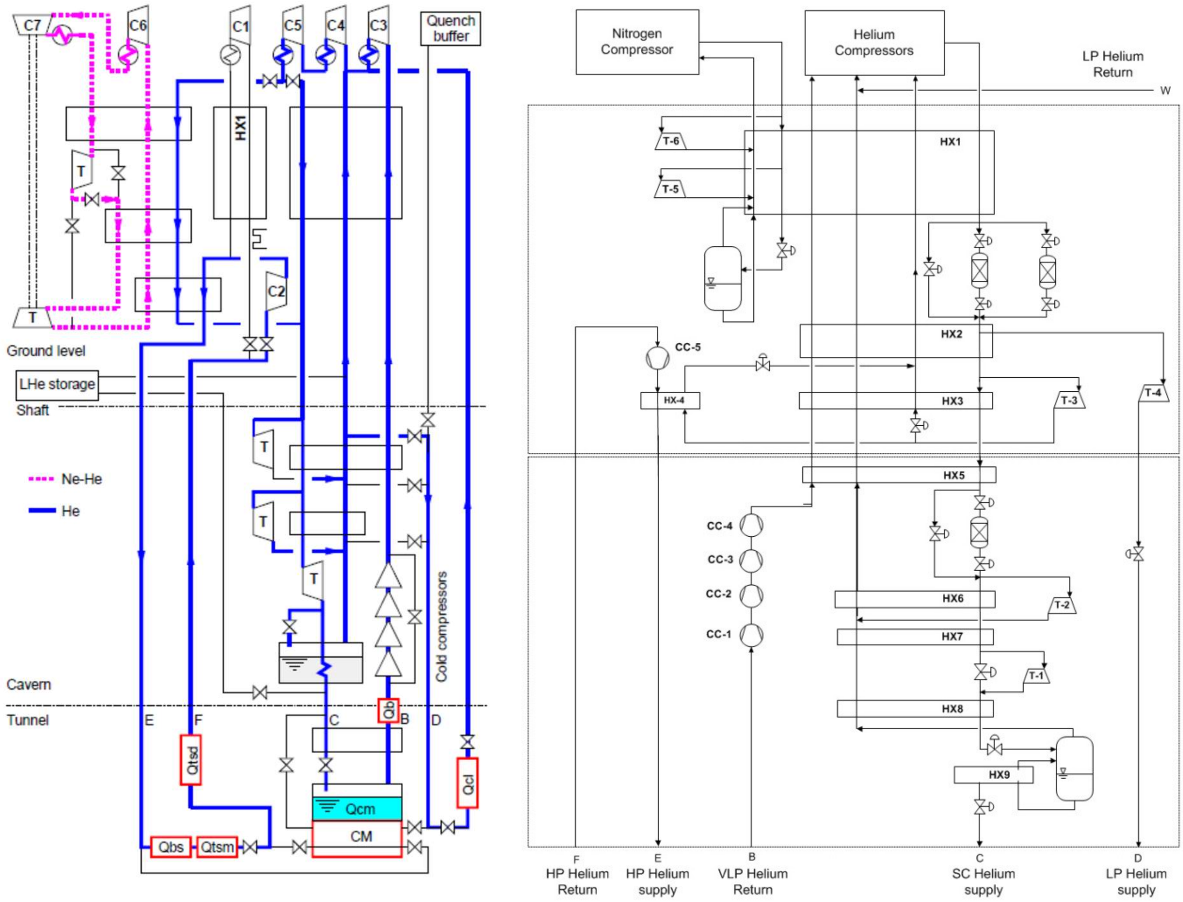

Figure 2 – Process Flow Diagrams for the FCC-hh cryoplants: CERN preliminary design with helium-neon precooling [1] (left) and Linde preferred design with nitrogen precooling (right)

3. Process concept evaluation and performances

Three different process concepts are calculated and evaluated by Linde Kryotechnik based on the state-of-the-art and the know-how on novel technologies:

a) A Helium plant with helium-neon precooling similar to the CERN preliminary design,
b) A Helium plant without a separate precooling cycle,
c) A Helium plant with a nitrogen precooling cycle.

The assumptions and the boundary conditions are identical for all calculations and evaluations of the three studied concepts. The process of the lower cold box below 40 K is identical in all of the three concepts and contains a set of conventional heat exchangers and expansion turbines to cool down to 4.5 K the supplied supercritical helium flow towards the superconducting magnets. A train of four large-scale cold compressors in series is implemented to pump the 1.8 K heat loads. The major difference between the three evaluated concepts concerns the precooling stage devoted to the beam screens and thermal shields. For the estimation of the power consumption, calculations are performed using initially fixed equipment efficiencies scaled from existing equipment [3]. The cold compressors and circulators are assumed in the process cycle with isentropic efficiencies between 70 to 80% and the turbines with efficiencies ≥ 85% [3]. The warm compression technologies are the proven screw compressors with a typical isothermal efficiency ≤ 55% and centrifugal compressors with an isentropic stage efficiency between 70 to 80% [3]. Centrifugal compressors are a promising technology to reduce the total electrical power consumption with better achieved efficiencies than the currently used volumetric screw compressors in helium refrigerators. Furthermore, the turbine energy recovery up to 1.2 MW are included for the largest turbines with turbine shaft powers larger than 100 kW [3].

The first concept a) shown in figure 2 is based on the CERN preliminary design [1] using a Turbo-Brayton cycle circulating a mixture of neon and helium for the precooling of the helium circuits down to 40 K with two turbines. The neon fraction (25%) used in [1] increases the maximum pressure ratio achievable in one centrifugal compression stage compared to pure helium. However neon has inferior heat transfer properties compared to helium resulting in either larger heat exchangers or larger temperature differences in heat exchangers and thus larger mass flowrates [2]. Within the industrial engineering study the power consumption of one FCC-hh helium cryoplant with helium-neon mixture precooling (concept a) is estimated to 19 MW for the “High” mode, about 200 MW in total.

The second concept b) is designed as a conventional helium refrigerator without a separate precooling cycle. At least three large-scale helium turbines are added in the upper cold box of the helium cryoplant to replace the mixture precooling cycle down to 40 K. This leads to larger helium refrigerant mass flowrates in the helium warm compression station and to a slightly higher estimated total power consumption (19.5 MW) even if pure helium offers higher heat transfer properties and reduces the number of channels in the 300-40 K heat exchangers. Compared to the concept a) the additional equipment and expensive neon refrigerant required for the separate precooling cycle is avoided with the simple concept b).

In the third concept c) shown in figure 2, a closed-loop nitrogen refrigerator with two turbines and a phase separator provides the precooling down to 80 K and a large-scale helium turbine (≈ 1MW – similar to the pure helium concept) is required for the cooling down to 40 K. Nitrogen precooling cycles as selected for ITER offer several advantages for FCC cryoplant: it is a cheaper refrigerant using mature technologies from the air separation units (ASU). Additionally LN2 precooling offers a stable operating temperature at 80 K and leads to lower compression works due to the lower nitrogen isentropic exponent (κ=1.4) than the helium and neon ones (κ=1.66). The total power consumption estimated for concept c) is the lowest with 18.5 MW.

The three concepts are compared for different technical-economic criteria including the process and equipment design, the technical risks, the technology readiness level (TRL), the operation costs (OPEX) and the capital costs (CAPEX). Based on this technical-economic analysis, it appears that the helium cryoplant with nitrogen precooling achieves the lowest total cost ownership (TCO = OPEX + CAPEX) at low technological risks. The concept b) without precooling is ranked as second best choice.

The nitrogen precooling concept is chosen as preferred industrial design for the FCC-hh cryoplants and is elaborated. Its performances in steady-state and transient operation modes are then estimated with an iterative method between the equipment pre-design and the process calculations. The preferred solution is revised with “actual” equipment performances from potential suppliers and the process is consolidated with additional equipment to fulfil the required cool-down capacity. The technical feasibility of the helium cryoplant with LN2 precooling is finally confirmed with the following achieved performances:

- The power consumption in “High” mode with 100 kW equivalent load at 4.5 K is calculated just below 16 MW with helium centrifugal compressors (Carnot eff. > 40%) and at 20 MW with screw compressors. The “Low” mode with 23 kW equivalent load at 4.5 K is estimated at about 7MW for both helium compressor options.
- The turndown capability of factor 6 for the beam screen loads is obtained with throttling of dedicated turbines and adaptation of the pressure levels. A gas management system with external medium pressure storage buffers are required to manage such controls.
- The already qualified LHC-like strategy (a train of cold compressors in series with volumetric warm compressors) is applied for the magnet load adaptation up to a dynamic range of factor 3.
- Up to 3.5 MW of turbine powers are available for the cooldown between the room temperature to 80 K and about 1.5 MW down to 40 K. These cool-down capacities are larger than required.

4. Identified technical adaptation and novel developments

In parallel with the process and equipment pre-designs, a technical feasibility checking is performed with technical risk assessment (TRA) matrixes to identify the needs of R&D developments for the main equipment of the studied FCC-hh cryoplants:

- Warm compressors: due to the large helium volumetric flows (> 20 000 m^3/h) at the compressor inlet, the industrial conceptual design proposes an advanced technology for oil-free helium compression with high-speed turbo-centrifugal compressors. Potential compressor suppliers confirmed the feasibility of this alternative option to the screw compressors. This advanced technology is already commercially available and currently used in other applications and offers larger flow capacities and better efficiencies than the screw compression reducing the overall FCC-hh cryoplant power consumption by about 20%. Advanced high-speed centrifugal compressors with wheel tip speeds >600 m/s and with reduced sealing losses are currently in development for hydrogen and helium. This technology will have to be experimentally qualified in the coming years [3].
- Turbines: the pre-designed helium dynamic gas bearing turbines below 40 K and the nitrogen turbines are mature products with the power within the existing range for helium refrigerators and in ASUs [6]. In the opposite, large-scale helium turbines (up to 1 MW) with active magnetic bearings have to be qualified with minor adaptation of existing technologies for other applications [3]. Furthermore, the helium turbine energy recovery via electrical generators or turbine-compressors has to be implemented for turbine shaft powers larger than 0.1 MW. This offers an effective way to improve the overall FCC-hh cryoplant exergy efficiency up to 6%.
- Heat exchangers: a special attention is required for the detailed design of the required multi-stream counter-current aluminum brazed plate-fine heat exchangers (PFHX). Some of them will be at the limits of the maximum PFHX dimensions that can be manufactured in a single unit [3].
- Cold compressors: no technology modification is identified. However a substantial up-scaling in sizing is necessary for the unconventional FCC flows with a factor 5 compared to the state-of-the-art. This concerns particularly the large motor and rotor-dynamics.
- Cold circulators: only moderate short-time technical adjustments of existing cold circulator products are identified for the helium cold circulator with minor casing adaptation to higher design pressure (5.0 MPa) and lower temperature operation (60 K).

5. Conclusion and perspectives

The Linde Kryotechnik engineering study has confirmed the CERN preliminary conceptual design studies and its expected performances, dimensions and costs for the FCC-hh cryoplants. The helium cryoplant with nitrogen precooling is the preferred industrial conceptual design and achieves a high level of technical maturity. It uses state-of-the-art technologies or technologies that can be slightly modified from other industrial applications with short to medium term technical developments. A significant increase of 25% in the overall cryoplant Carnot efficiency is achievable using the advanced centrifugal compressors instead of the state-of-the-art screw compressors (respectively 40% and 30% of Carnot efficiency and 160 MW and 200 MW of total electrical power consumption). Such operation cost reduction justifies the proposed detailed studies and equipment development roadmaps to build future more-efficient and more-reliable large-scale helium cryoplants.

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