LARGE-SCALE HELIUM REFRIGERATION CRYOGENIC SYSTEMS COSTING FOR SUPERCONDUCTING PARTICLE ACCELERATORS SUCH AS THE FCC-ee

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Abstract

Large-scale helium refrigeration cryogenic systems are a key element, essential to the safe and reliable operation of particle accelerators using superconducting devices such as radio-frequency cavities or magnets. The long-term success of the LHC operation with an outstanding physics production to date paves the way towards the High-Luminosity LHC (HL-LHC) upgrade to be operated until the early 2040s, after which it could be followed by the Future Circular Collider (FCC). Such large-scale projects, requiring a significant amount of cryogenic cooling capacity to be installed, pose the question of the cost estimation methodology to be employed, as the cryogenic system represents a non-negligible fraction of the total capital, operation & maintenance cost of the facility. Capitalizing on the experience of the LHC project, then on its recent HL-LHC upgrade, the existing CERN methodology was updated with the latest available industrial indexation, thus allowing the cost of the FCC cryogenic system to be assessed. This paper reports on the approach used to estimate the cost of the FCC cryogenics, refining the method adopted at the time of the LHC project. It considers the evolution of material and labour costs over the past two decades, studies the updated economics of 4.5 K and 1.8 K helium refrigeration, and presents the strong impact of the cryogenic distribution system. It also identifies and proposes ways for improving the capital, operation & maintenance expenditure.

INTRODUCTION

The design maturity of the Future Circular Collider (FCC) cryogenic system has progressed significantly from the initial 2018 concept to the 2025 feasibility report, triggering the need for an update of the cost estimate for the FCC-ee machine. The first exercise was performed along with the release of the FCC Conceptual Design Report (CDR) in 2018, with the feasibility report of 2025 the opportunity to update and complete the methodology that was proposed by S. Claudet et al in July 1999 in their Economics of large helium cryogenic systems publication in the context of the LHC project [1].

CRYOGENICS FOR FCC-ee

The latest FCC baseline layout (PA31-3.0) is a 91-km long circular tunnel consisting of eight sectors, each of which is 11.35-km in length. It hosts four experimental points, and four technical points, out of which two (points PH for the collider and PL for the booster) are associated with the superconducting radiofrequency (SRF) system. These need to be operated at both 2 K (800 MHz cavities) and 4.5 K (400 MHz cavities) to accelerate the particles to the required energies. Detailed information about the cryogenic architecture associated with the FCC-ee machine and its SRF system at its ttbar stage are to be found in the FCC Feasibility Report [2] published in March 2025. Figure 1 gives a general overview of the cryogenic system associated with the FCC-ee machine in its ttbar stage.

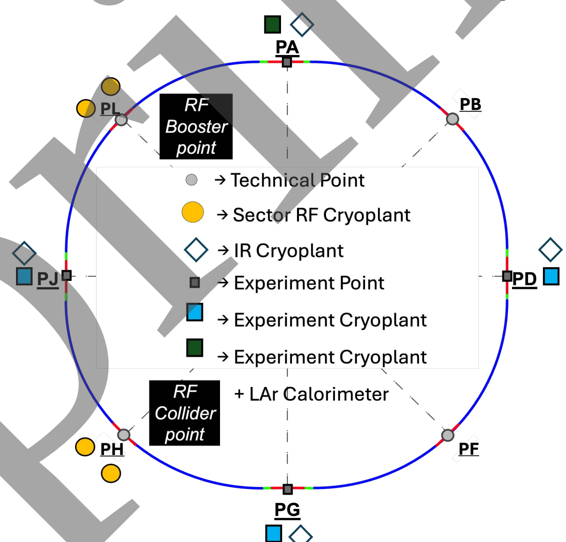

Figure 1: FCC-ee cryogenic system layout for ttbar operation.

METHODOLOGY

The cryogenic system for particle accelerators is usually composed of five main types of components: the cryoplants, the cryogenic distribution, the cryogen inventory and storage, the control and instrumentation, and the warm piping. Those items are used as high-level categories to create the Product Breakdown Structure (PBS) necessary to evaluate the cost of FCC-ee cryogenics.

EVALUATING THE COST: THE INDEX

The costing methodology is mainly based on an analogous technique, where LHC and HL-LHC data are used as a main reference to create a scaling law and to verify its accuracy. Extensive cost data is available from 1998 when the LHC project was being finalised [1]. To scale this data to 2023 figures, the date at which this exercise was performed, an index was compiled and used with the support of the CERN Procurement Group.

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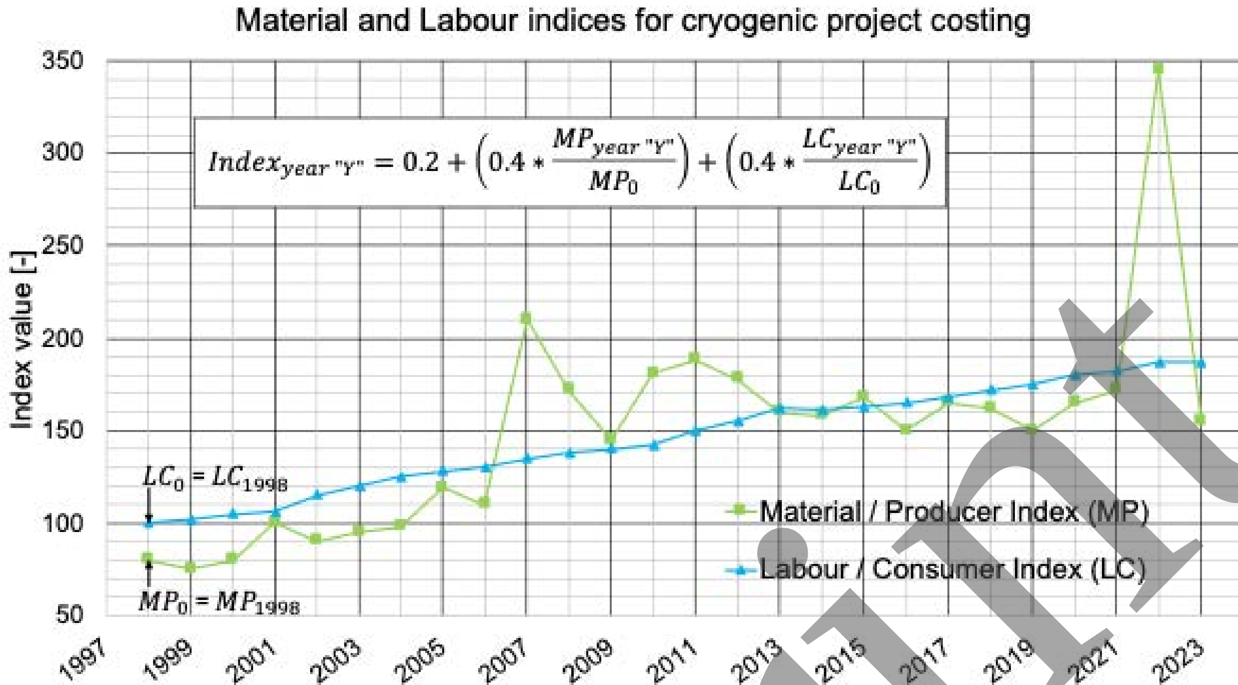

Figure 2: Cost index used to scale cost data from 1998, as initially compiled for the HL-LHC project.

It is composed of a fixed term (20%), a term reflecting the evolution of the material costs MP (40%), and a term reflecting the evolution of the labour costs LC (40%), as illustrated in Figure 2.

Two factors were then obtained. A "full_index", appropriate for items such as cryoplants or cryogenic distribution lines, which have a significant engineering component, and corresponds to a 3% annual increase over 25 years. A "reduced_index" (set to 75% of the "full_index"), appropriate for items such as storage tanks and warm piping, that are mostly driven by their material cost. This is justified as in the last 25 years, industry partners have optimized and streamlined their internal processes, making the production more efficient and thus partly compensating for the increase in the material cost.

When applying the cost index evolution of Figure 2 between 1998 (LHC project era reference) and 2023, it leads to the following:

$$I_{2023} = 0.2 + \left(0.4 * \frac{MP_{2023}}{MP_0}\right) + \left(0.4 * \frac{LC_{2023}}{LC_0}\right), \quad (1)$$

where I_{2023} is the change of the index between the reference year and the year of the cost exercise (here 2023), with MP (material prices) and LC (labour cost). Index "0" refers to the reference year (here 1998), ensuring validity of the initial cost as given in [1].

Considering the strong impact on prices provoked by the Ukrainian war from 2021, and the fact that we arelooking for a long-term cost estimate, it was agreed with the FCC study management team and the CERN Purchasing Department to stabilize the MP_{2023} value at 50% of the MP_{2022} value, while the LC value is assumed constant between 2022 and 2023.

With these assumptions, formula (1) gives a factor of 1.72 to be used as the "full_index" and 1.3 to be used as the "reduced_index".

COST ESTIMATE BY ITEMS

The cost estimates of FCC-ee cryogenics by item, as proposed in the PBS, can be calculated by applying the full and reduced index values.

Cryoplants

A costing for the 4.5 K refrigerator is extracted from [1] and adjusted to 2023 prices using the full index that was presented above. This leads to:

$$Cost\ 4.5\ K\ refrigerator[\ MCHF_{2023}] = 2.2 * full\_index * (Capacity[kWeq@4.5K])^{0.6}. \quad (2)$$

This refrigerator must account for the 2 K refrigeration unit as a non-isothermal load. Therefore, the equivalent capacity at 4.5 K is obtained considering the heat loads of the cavities at 2 K and at 4.5 K, as well as the heat loads from the shields between 50 and 75 K.

A costing for the 2 K refrigerator unit can also be extracted from [1]. However, this unit referred to a 1.8 K refrigerator, so dealing with heat loads at 2 K while using this formula introduces a bias (a factor of 1.67 difference between the density of saturated helium vapour at 1.8 K and 2 K) and subsequently an overestimation of the required size of such machines when considering the necessary volumetric flow. This overestimate of the machine size introduces an over cost of a few percent and therefore well below the level of accuracy required in such a study (class 3 cost estimate as defined by the Association for the Advancement of Cost Engineering – AACE [3]). The same costing model is therefore used here for a cold compressor operating at 2 K. To adjust the cost to 2023, the full index is once again used, leading to the Eq. (3):

$$Cost\ 2\ K\ refrigeration\ unit[MCHF_{2023}] = 2.6 * full\_index * (Capacity[kW@1.8K])^{0.55}. \quad (3)$$

For the remaining components (dryer, vertical transfer lines, valves, and vacuum vessels), the experience from HL-LHC has been used and adapted to FCC shaft lengths. After combining all three parts, the total cost of a cryoplant is obtained, including its design, fabrication, installation, and commissioning. The methodology was benchmarked against the HL-LHC cryogenic system to verify its accuracy.

Cryogenic Distribution

The LHC distribution line is used as a reference to obtain a scaling law, with HL-LHC as a benchmark. Several factors needed to be considered:

- The number of headers within the line;
- The lengths of the line's inter-service modules;
- The number / size / complexity of service modules.

Two factors are thus obtained:

- Distribution Line Cost per meter = full_index * 5 $kCHF_{1998}$/m.
- Service Module (SM) unit cost = full_index * 250 $kCHF_{1998}$/SM.

An additional factor is then multiplied to both above-mentioned costs, to take into account the complexity of these items (with LHC as reference) by considering the number of headers in the Distribution line (30% of the weight) and in the Service Modules (70% of the weight), to reflect the difference between 4.5 K and 2 K units.

With that and the knowledge of the SRF system architecture [2], the overall cost of the cryogenic distribution can be directly derived.

Cryogen Inventory and Storage

Costing of the initial inventories and storage for the nitrogen and helium necessary for the operation of FCC-ee was derived from recent experience with the HL-LHC project, allowing a direct estimate in $MCHF_{2023}$.

Control and Instrumentation

A thorough assessment of the control hardware required to operate the FCC-ee cryogenic system was performed by control experts from the CERN cryogenics group, identifying the needs for specific equipment such as data servers, Programmable Logic Controllers, Front-End Computers, and signal acquisition electronics using LHC and HL-LHC experience. The final cost was derived by scaling the unit cost of each item in the control hardware inventory.

For the instrumentation specific to the distribution lines, the approach followed a standard practice based on experience from previous projects, where a share of 5% of the total capital cost covers this specific item.

Warm Piping

This accounts for any non-cryogenic pipes and the helium ring line used between the RF points PH and PL to manage the helium inventory. Following the general approach of this paper, LHC prices from [1] are used and scaled to 2023, then benchmarked against HL-LHC.

The cost of stainless-steel piping in 1998 was of 7.5 CHF/kg. A material cost multiplier for ambient temperature pipework is used as indicated by [1] and the price adjusted to 2023 prices using the reduced index.

Overall Cost Estimate Breakdown

The overall cost estimate breakdown of the FCC-ee cryogenic system is derived by combining all the individually costed items. The refrigeration represents 60% of the cost, while 28% is for the distribution. Instrumentation comes third with 6%, followed by storage and inventory with 4%, and warm piping at 2%.

CONCLUSION

This paper presented the methodology used to estimate the capital cost of FCC-ee cryogenics based on its 2023 mid-term review and further refined for the Feasibility Report published in early 2025. The need for a credible cryogenic cost estimate was directly driven by the expectations of the FCC Study, that required a Class 3 level of uncertainty (-20 to +30%) [3] by the end of the Feasibility Phase in early 2025. The methodology presented in this paper, based on historical data derived from the LHC project and consolidated with recent HL-LHC developments, has also been benchmarked with recent EU (ITER) [4] and non-EU (LCLS-II) [5] projects, with excellent results. It makes it an easy tool to be used to evaluate the cost of a large-scale helium refrigeration cryogenic system during a project's study phase, to assess its capital cost before involving industry with a detailed design and specification.

Considering the volatility of the index that was built to trace the evolution of the material and labour costs between 1998 and 2023, it would be beneficial to update these with the latest available data, including the evolution of the major currencies used in such large-scale projects (namely USD, EUR and CHF).

As the cryoplants and the distribution system account for more than 80% of the total cost of cryogenic facilities, they should be considered as priority targets for improvement. The possibility of using warm helium centrifugal compression or even bringing a cryogenic distribution system based on a low-thermal expansion material to industrial production grade through a focused R&D activity and a co-innovation approach with industrial partners could be assessed. With a yearly OPEX evaluated at around 3% of the cryogenic capital cost (considering yearly costs for operation, maintenance and cryogen usage scaled up from LHC cryogenics experience), such advances could result in a significant reduction in both the operational cost and future total cost of such facilities.

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