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2 K system exergetic optimisation and helium recovery system for FCC-ee

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Abstract. At its ttbar stage, FCC-ee is expected to require over 200 cryomodules housing 800 MHz bulk niobium superconducting radio frequency cavities at 2 K, and more than 60 cryomodules housing 400 MHz niobium-sputtered copper cavities at 4.5 K. The complexity, energy intensity, and scale of the associated cryogenic system requires a holistic design approach. Topics such as sustainability or resilience against prolonged electrical grid perturbations become integral to this process. Thus, helium preservation, energy efficiency, and integration constraints are considered in the current conceptual design phase.

This paper details the design of the very low-pressure system used to maintain the cavities at 2 K. The operational variables of its distribution line have been addressed in a parametric manner using a combination of numerical simulations and exergetic analyses. The results enable the comparison of various implementation options, directly linking them to the energy consumption of the refrigerator. Subsequent sensitivity analyses reveal that while a central heat exchanger architecture is preferred for integration aspects, it is overall less energy-efficient than a distributed one at lower heat exchanger effectiveness values. Finally, we propose a helium recovery system based on diesel-powered compressors of up to 1 MW to preserve the cryogen inventory during incidents. Initial sizing allowed to extract the additional space, cooling water and electricity requirements needed for its implementation.

1 Introduction

FCC-ee is a proposed circular lepton collider set to become part of the CERN accelerator complex and come in operation after HL-LHC, in the midst of the 21st century. It consists of a 91 km circumference tunnel and 8 access points. The tunnel, with a diameter of 5.5 m, shall contain both the booster and collider.

One of the main systems of FCC-ee is the superconducting radio frequency (SRF) system tasked with accelerating the leptons and compensating for the synchrotron radiation losses. The collider SRF system is located at point H and is composed of cavities at 800 MHz and at 400 MHz, requiring operation at 2 K [1] and at 4.5 K respectively. The booster SRF system, located at point L, is composed of only 800 MHz cavities requiring operation at 2 K. Such cavities are housed in dedicated cryomodules (CMs) which provide the necessary local conditions and interface with the cryogenic system. The SRF system evolves with the different stages of the FCC-ee, that is, Z, W, H and ttbar. The evolution of the associated cryogenic needs and system layout is detailed in [2]. As the ttbar stage provides the driving heat loads for the sizing of the various circuits, it is taken as a design point for the cryogenics distribution line.

The paper focuses first on the 2 K system and its distribution circuit, following an exergetic optimisation aimed at reducing the power needs of the system, whilst addressing integration constraints. It then proposes a helium recovery system concept, aiming to preserve helium inventory in the occurrence of an operational issue.

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2 2 K system optimisation

2.1 System constraints and components

Refrigeration of the RF cavities in a 2 K saturated bath involves low density helium (He) with process pressures in the 30 mbar range. A series of compressors are required to achieve these pressure levels. Whenever high mass flow rates of helium need to be treated, performing a large fraction of the compression at low temperatures allows to operate with a higher density, effectively limiting the size of the compressors. During FCC-ee@ttbar, about 550 g/s or 250 g/s [2] per train will need to be pumped, at point H and L, respectively. In both cases a cold compressor system (CCS), composed of a series of centrifugal compressors, will be required to provide the compression back to semi-atmospheric levels (≈ 400 mbar). From previous studies, it is considered that a CCS of 12 kW @ 1.8 K is feasible [3][4]. This translates into a mass flow rate of about 500 g/s with one train of 4 compressors, at a suction pressure of 16 mbar. Adressing FCC-ee needs, the suction pressure of such CCS can be increased as the desired saturation temperature is of 2 K. This leads to higher densities and, hence, allows for an operation with larger than 500 g/s mass flow rates.

The lower the design suction pressure of a CCS is, the more compressors stages may be required to reach semi-atmospheric levels, increasing the complexity of the system further. Since the cavities are cooled by a saturated He-II bath [5], the furthermost 2 K cryomodule will need to be at the saturation pressure of He at 2 K, that is, at 31 mbar. The pressure drop along the distribution line to that cryomodule needs to account for this and shall be minimised so that the suction pressure at the inlet of the CCS is kept as high as possible. The design goal is to limit the total pressure losses such that the suction pressure of the CCS stays above 22 mbar. Out of the 9 mbar of avaialble pressure drop, 7 mbar is left as a margin for heat exchangers, elbows and valves, and 2 mbar are set as a design criteria for sizing the Very Low Pressure (VLP) return line or line B in Fig. 1. The choice of 2 mbar is providing a good compromise for the CCS suction pressure and the overall size of the VLP line. Limiting the pressure drop furhter could hinder the already difficult distribution line integration in the 5.5 m diameter tunnel, where the space is very limited due to the presence of both booster and collider machines.

Finally, ensuring a thermodynamically well-adapted architecture is essential to reduce the high-cost coming from cooling at 2 K. To fill the cryomodule bath with liquid He, a JT expansion is used. A subcooling heat exchanger (HEX) placed before this expansion helps reducing the flash, significantly lowering the mass flow rate needs and hence the energy consumption. This heat exchanger shall be of high effectiveness and with a very low pressure drop for the reasons evoked above. Its location options define different architecture possibilities, which are compared below through an exergetic analysis. In any case, a reduction of the total mass flow rate helps in all aspects, that is, with integration, with the CCS complexity and, most importantly, with the overall energy consumption of the system.

2.2 Architecture

The arrangement of the components described above can be done in different ways. Figure 1 shows the two main, yet not exhaustive, options that are being considered at this phase of the study. Fig. 1 a)

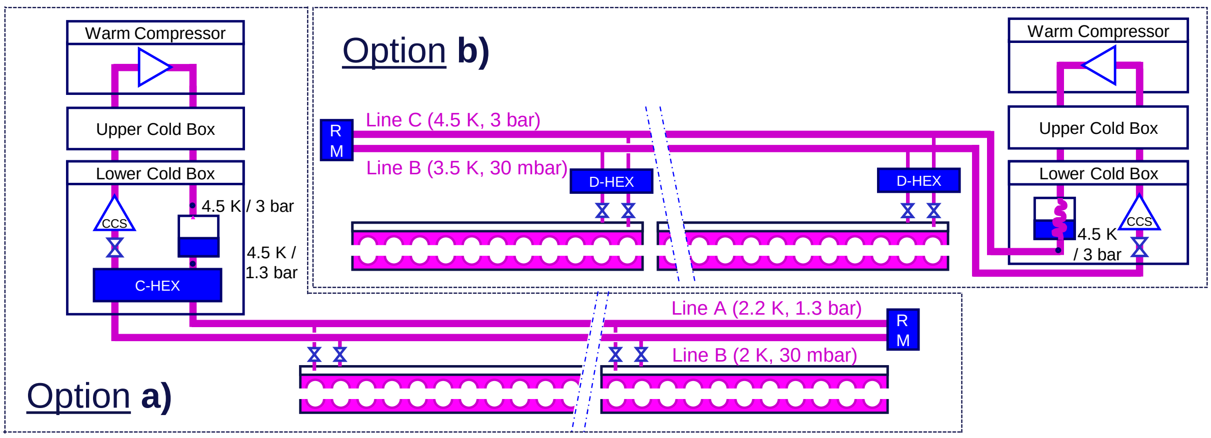

Figure 1: FCC-ee 2 K system distribution architecture studied options. CCS being the Cold Compressor System, RM the Return Module, C-HEX the Centralised Heat Exchanger and D-HEX the Distributed Heat Exchanger.

shows the centralised heat-exchanger (CHEX) architecture whilst Fig. 1 b) shows the distributed heat-exchangers (DHEX) architecture. Other options not addressed here include a CHEX option distributing at 3 bar, instead of at 1.3 bar, or even at sub-atmospheric pressures, after introducing two-stages CHEXs.

2.3 Exergetic analysis and comparison

Exergy (E) is a measure of the maximum useful work that can be extracted from a system as it reaches equilibrium with its environment by an ideal process [6]. For a cooling process, exergy gives the minimum work that needs to be added to a system in order to extract heat and reach a certain temperature. Any irreversibility, such as friction or heat in-leaks, as well as a mismatch between the refrigerator and the client, translate into an exergy loss which can be quantified. It is defined as:

$$\Delta E = \dot{m} \times (\Delta h - T_0 \times \Delta s) \tag{1}$$

Where $\dot{m}$ is the mass flow rate, T_0 is the reference temperature here set to 290 K, and Δh and Δs are the specific enthalpy and entropy differences between the reference state and the final state.

The exergetic analysis that was performed follows the principles described in [7]. In short, a useful exergy ΔE_u is defined as the minimum to be provided to cover for the user needs, in this case, to the SRF cryomodules. Then the real exergy ΔE_r, which is the one that the refrigerator sees, includes any thermodynamic mismatch and/or loss. The ratio of the two gives the exergetic efficiency ζ.

The goal of the analysis is to compare the two architectures presented in Fig. 1 and define which one is more adapted to FCC-ee SRF cryomodules, considering the constraints presented in Section 2.1. To calculate the useful exergy, the heat loads from the current cryomodule design have been used [5]. As for the real exergy, the two systems have been simulated with iterative numerical models. Focusing on the 2 K SRF section of one half of point H, the following inputs were used:

- 60 CM operating at 2 K, with a distribution line of 540 m length, neglecting the slope of 0.25%.
- Static and dynamic heat loads per CM @ 2 K, including margins, set at 190 W.
- Heat load on supply and return lines set at 0.23 W/m2 .
- Fully segmented architecture considered, that is, one jumper connection per cryomodule.
- 2 mbar pressure drop imposed in the return VLP line, and 2 mbar on the HEX low-pressure side.
- Maximum subcooling HEX efficiency assumed, i.e., limited by T_λ at the HP outlet.

For both cases, the initial state is considered to be at 4.5 K and at 3 bar, and the final is given by whatever state the simulations reach at the inlet of the CCS, given the previous inputs.

Table 1: Exergetic analysis results and comparison of 2 K system architectures valid for one side of FCC-ee point H heat loads [2]. Reference temperature To of 290 K.

	C-HEX	D-HEX
ζ [%]	85.7%	83.8%
VLP return line B diameter [mm]	330	375
$\dot{m}$ per HEX [g/s]	544	10
Total exergy losses [kW]	275	318

Several conclusions can be extracted from the results shown in Table 1. The difference in total losses can be converted to equivalent refrigeration capacity at 4.5 K, which leads to a total increase if the DHEX is chosen, including both sides of point H and point L, of 2.7 kW @ 4.5 Keq. Considering the total cryoplant sizes presented in [2], this represents only a 1.3% increase in both cryoplant sizes and energy consumption. It is therefore concluded that the two solutions are, practically, exergetically equivalent. The main gain of the CHEX option is the smaller size of the VLP return line, as well as the central location of one single HEX, reducing the number of components in the tunnel, and easing the overall integration. The exergetic analysis also allows a decomposition of the losses per component, as shown in Fig. 2, which eases pinpointing or studying points for improvement whenever possible.

A sensitivity analysis is also performed, running the simulations by changing one parameter at a time in order to understand how that variation impacts the overall system exergetic efficiency. Fig. 3 shows some of the obtained results. Both Fig. 3 a) and Fig. 3 b) refer to the CHEX case, showing that minor variations of the inlet pressure or temperature for the former, and of the supply or return lines heat in-leaks for the latter, have a weak impact on the overall efficiency. Fig. 3 c) shows the variations of

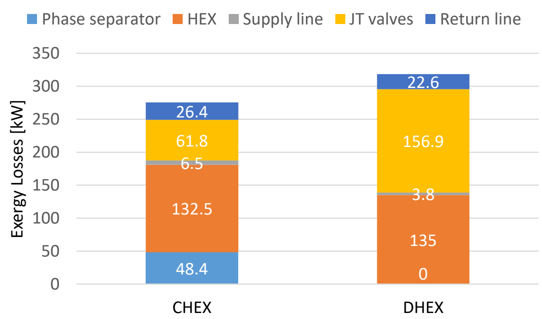

Figure 2: FCC-ee 2 K system distribution architecture exergetic losses comparison. Phase separator losses include flash before the CHEX. Supply and return lines include friction losses and heat in-leaks.

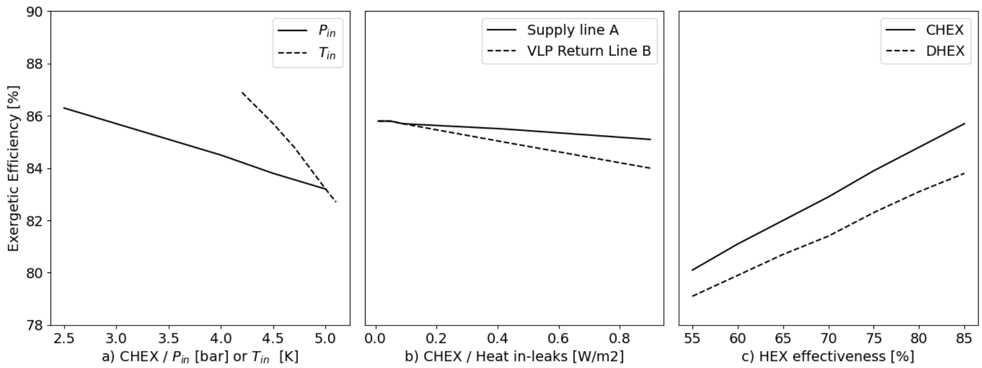

Figure 3: FCC-ee 2 K system distribution architecture sensitivity analysis

the HEX effectivenness for both CHEX and DHEX architectures. Here the variation is more important, and, in fact, it shows that the most efficient HEX architecture depends on the achievable CHEX and DHEX effectiveness. As shown in Table 1, the mass flow rate of the DHEX is of 10 g/s. Small plate heat exchangers used for LHC [8] reach this perfromances for up to 4.5 g/s. Presently a scaled design is being validated for HL-LHC reaching up to 25 g/s whilst keeping the performances. The highest mass flow rate subcooling heat exchanger known today is used in LCLS-II [9] reaching values of up to 215 g/s. R&D is needed to go for larger flows and the choice of architecture will depend on the reached performances.

3 Helium recovery system

3.1 Covered scenarios

The latest available cryomodule inventory values are of 55 kg of LHe at 2 K per 800 MHz cryomodule, and of 116 kg of LHe at 4.5 K per 450 MHz cryomodule [5]. Unlike magnet cryostats, as the SRF cavities do not withstand more than 2.1 bar abs, the cryomodules are low-pressure rated devices. Therefore, the risk of inventory loss in case of a non-nominal scenario is high. Without a recovery system, in the case of non-nominal operation, pressure inside the helium tank of the cryomodules would start building up, eventually reaching the set pressure of the pressure relief valve first, then ultimately the burst disc as the main safety component preventing the cavity to suffer from any mechanical damage. By doing so, helium would be lost in the atmosphere. The scenarios that could lead to such situation are:

- **Scenario 1:** Isolated cryomodule(s) from the cryoplant due to a malfunctioning valve.
- **Scenario 2:** Loss of the full sector cooling capacity (e.g. due to a power outage).
- **Scenario 3:** Beam vacuum break.
- **Scenario 4:** Insulation vacuum break.

Scenario 3 and 4 generate very high mass flow rates due to the large heat load that appears after a vacuum break. Therefore, these are to be addressed with the pressure relief devices alone. The Helium Recovery System (HRS) shall cover for Scenario 1 and 2, which consist of only design static heat loads.

3.2 Proposed concept

After performing a preliminary risk assessment of scenario 1, it has been concluded that the only situation in which a cryomodule can get isolated is when the return valve gets blocked in a closed position. This could occur essentially due to three reasons, the first being an electrical, an electronic or a pneumatic problem in the valve positioner. This is quickly addressed by using a Fail-Open (FO) valve, which imposes that the return lines can never exceed 2.1 bar. The second cause of failure could be if the valve gets mechanically blocked. Debris blockage is mitigated by the usage of purification systems in the cryoplant. The case of mechanical jamming of the valve in a fully closed state is deemed to be very unlikely as it is not a normal operating state of the valve. Its impact is limited to the inventory of one CM. Finally, the third identified cause is a wrong control system order. It is considered that this situation can be quickly mitigated by the manual intervention of the operations team.

Regarding scenario 2, several additional components are required in order to be able to recover the full sector inventory in case of a refrigerator problem, a compressor station loss or even in case of an extended full power cut. Fig. 4 shows a schematic with the concept proposal. It is composed of uninterrupted power supplied (UPS) valves shown in bold, an atmospheric heat exchanger (ATM HEX) or evaporator, a diesel generator to power a compression station, an available 20 bar isothermal compressor, fuel to cover for the full recovery of the sector, a back-up supply of cooling water, and several 250 m3 20 bar storage tanks. The compressor could be reused from the cryoplant main compressor station. The system would also benefit from a UPS-powered independent programmable logic controller (PLC) tasked with performing the recovery even when a generalised control system failure occurs.

The recovery strategy consists in first waiting until the cryomodules raise in pressure up to 1.5 bar. Preliminary dynamic simulations show that the 400 MHz shall reach this point in about 30 min, whilst the 800 MHz in some 100 min. From that point onwards, the CVxB valves, which shall always stay available, start regulating and releasing the helium in the return lines D and B. Then, the cold box is bypassed closing CV5x and opening CV4x and the helium is directed to the ATM HEX where it is warmed up before reaching the diesel-powered compressor on the surface. It then gets compressed up to 20 bar and stored in the tanks. The ATM HEX current location proposal is in the cavern but, due to its expected large size, it could also be located along the shaft connecting the tunnel to the surface.

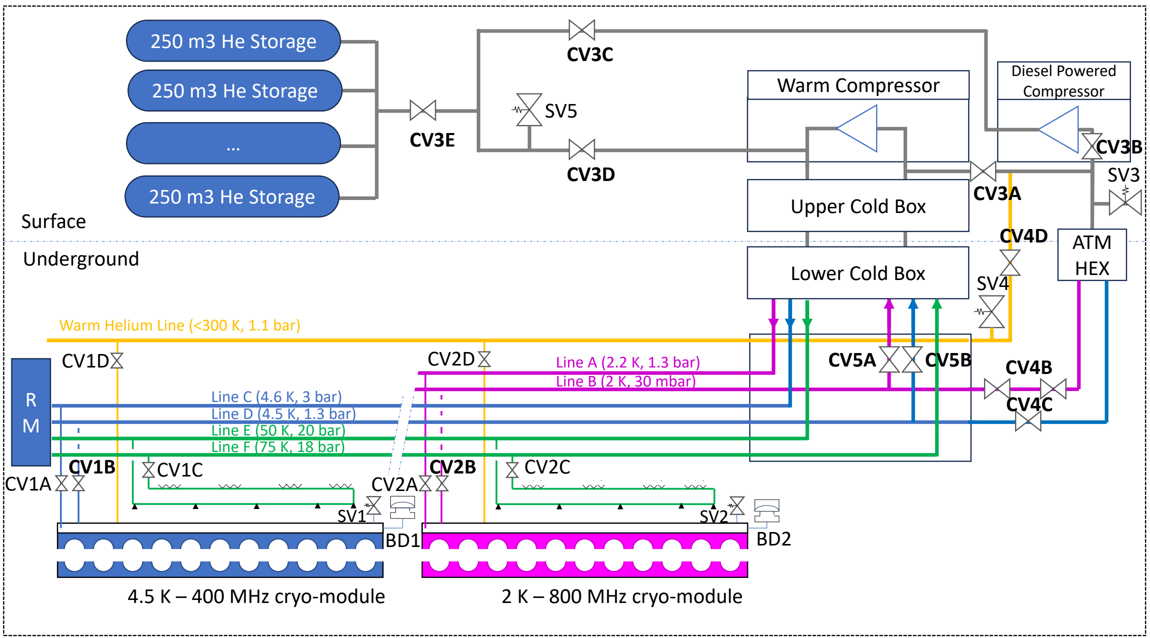

Figure 4: FCC-ee proposed Helium Recovery System (HRS) concept

With the current inventory and static heat loads assumptions, the sizing of the system per point, considering all the CMs and the distribution inventory, is presented in Table 2. The results where obtained assuming a screw compressor efficiency of 50%, an electrical motor efficiency of 95%, and a conversion efficiency of the fuel into electricity of 30%. If a conventional atmospheric heat exchanger is used, its size could exceed the 100 m^3.

Table 2: FCC-ee Helium Recovery System preliminary sizing summary

	Point H	Point L
Total inventory	18 t	10 t
Mass flow rate	530 g/s	315 g/s
Isothermal compression power	1 MW	600 kW
Electrical Power needs	2 MW	1.2 kW
Autonomy	24 h	13 h
Diesel tank	15000 L	4900 L
Cooling water needs	100 m3/h	60-100 m3/h
Atmospheric heat exchanger	810 kW	500 kW

4 Conclusion

The size and complexity of the FCC-ee SRF cryogenic system, together with the important requirements of sustainability, efficient energy usage and resilience against an unstable energy supply, set the context of this work. With that in mind, a multifactor optimisation of one of the most energy intensive parts, i.e. the 2 K system, has been performed following an exergetic comparison of its two main architecture options. It was concluded that the CHEX and the DHEX approaches are similar efficiency-wise. The CHEX option is preferred as it offers advantages in terms of integration thanks to a smaller distribution line and a lower amount of components. However, it also implies a more complicated and less proven HEX design requiring further R&D. If high-effectiveness CHEX values can not be reached for the needed mass flow rates, an industry ready high-effectiveness DHEX based architecture could outweigh the integration benefits of the CHEX option. Lastly, a preliminary risk assessment of the cryomodule non-nominal scenarios has been performed and, based on the latest static heat loads and helium inventories estimation, a first concept of a Helium Recovery System was proposed. Whilst it requires space for the installation of a large atmospheric evaporator, the system would allow both increasing the system availability after incidents, and reducing the impact of the helium markets volatility, without any additional lines in the tunnel.

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