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PARAMETRIC STUDIES ON FCC-ee CRYOGENIC DESIGN

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On behalf of the CERN cryogenics group

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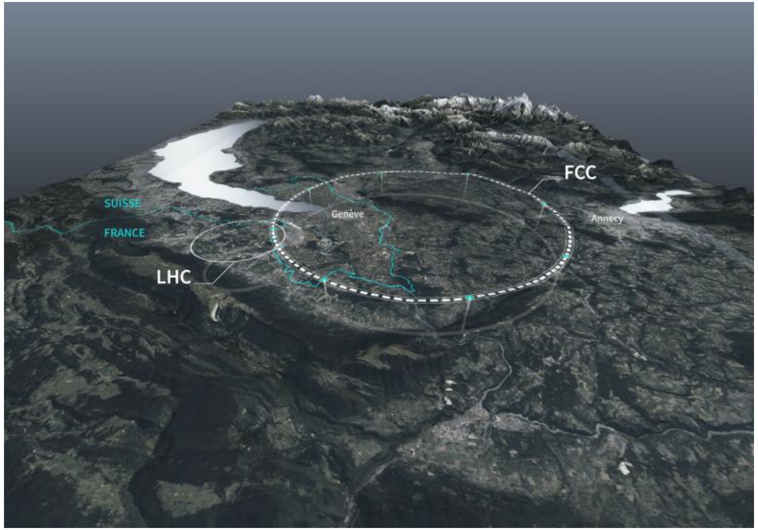
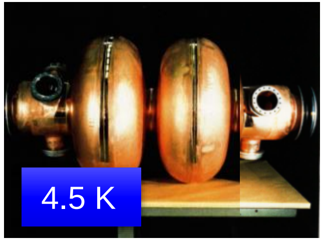
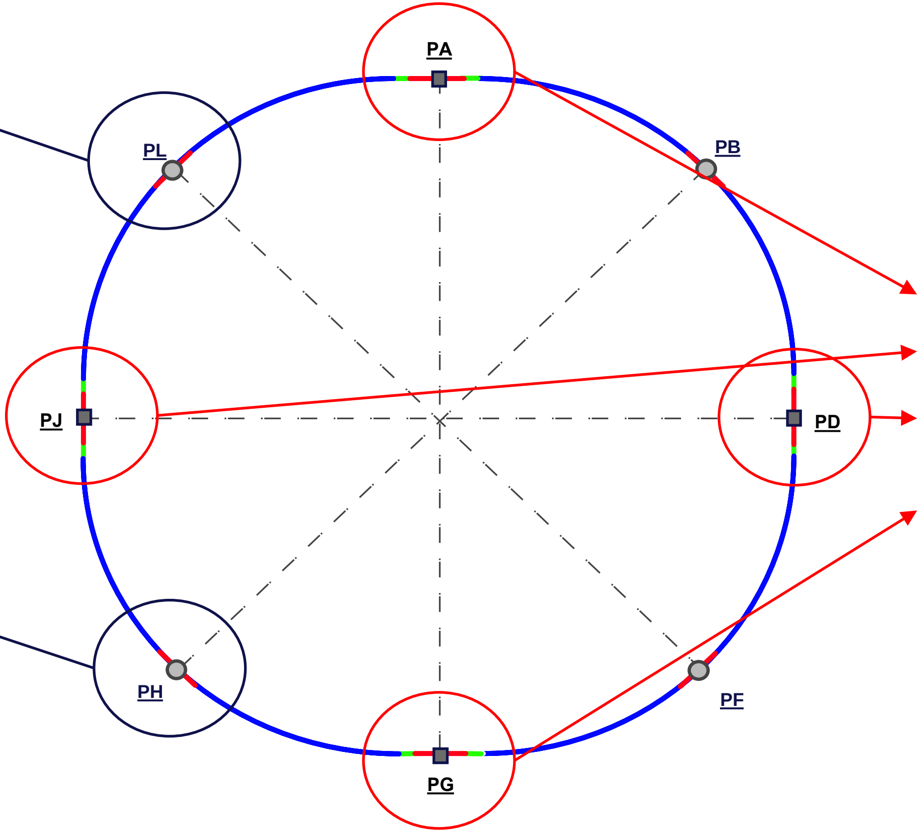


FCC-ee cryogenic cooling users

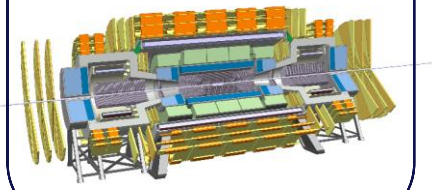
RF **booster** cavities



RF **collider** cavities



Detector solenoids and MDI magnets



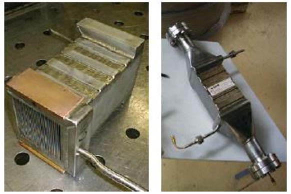
FCC-ee 2 K cooling – The system components

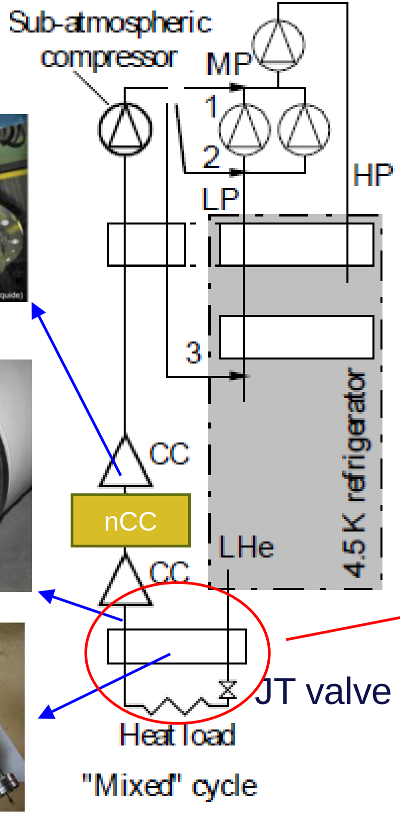
LHC-like approach

Cold compressors

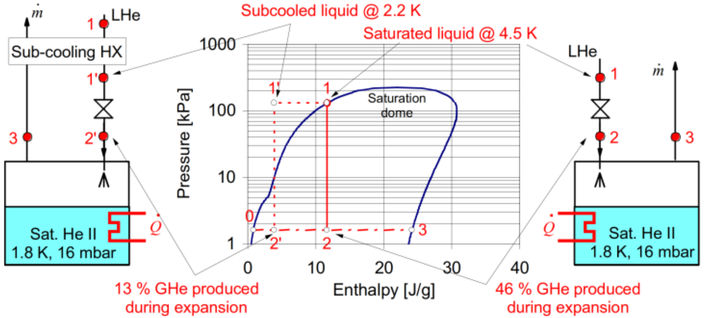
Compound cryogenic distribution line (incl. ScHe supply and VLP return)

Subcooling heat exchanger



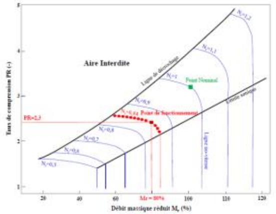


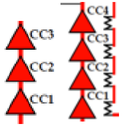
4.5 K refrigerator

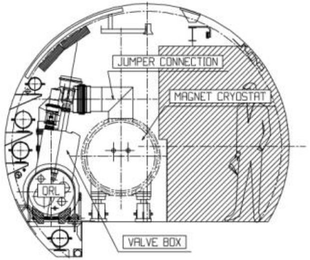


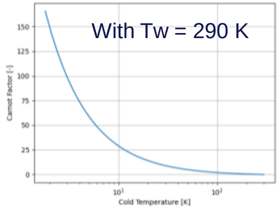
FCC-ee 2 K cooling – The system constraints

- **Usage of a cold compressor**
  - Compression from kPa to bar ⬄ Rotation speeds of the compressors
  - Need for dense gas compression
- **Mass flow limits**
  - Choke limit at high mass flows (local sonic flows) => operation of compressors in parallel?
  - ρ_{GHe} = 0.41 kg/m3 @ (1.8K/15mbara) vs 0.76 kg/m3 @ (2K/30mbara)
  - FCC-hh CDR cryo studies: 12 kW @ 1.8 K deemed feasible (~550g/s)
- **Low pressure side limit**
  - CCs low inlet pressure is driving complexity and operability of the system
- **Pressure drop along the return**
  - ΔP to be carefully addressed
    - VLP line sizing ⬄ integration constraint
    - Subcooling heat exchangers needed to decrease flash through JT ⬄ current state-of-the-art @ 250 g/s while ~500 g/s expected for FCC-ee
- **High thermodynamic cost**
  - Typical COP_2K is about 900 Wel/W ⬄ 230 Wel/W at 4.5 K (LHC refrigerators)



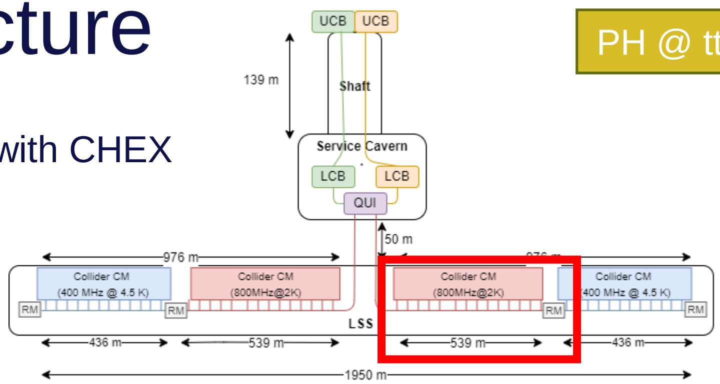




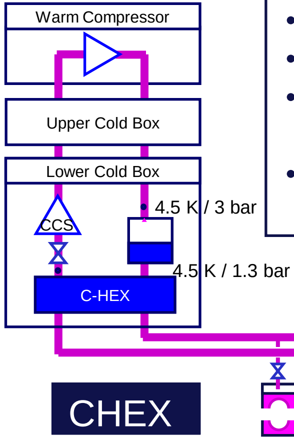


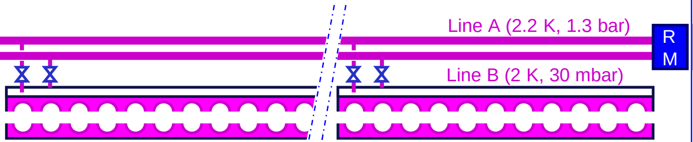
FCC-ee 2 K cooling – Architecture

PH @ ttbar



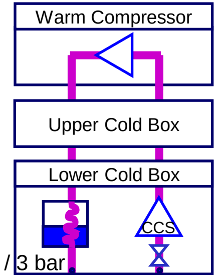
- FCCee @ ttbar current design = +250 CM @ 2 K on 2300 m with CHEX
- Parametric study scope = challenge the CHEX choice
  - With smaller distributed HEX (DHEX)
  - LHC-like approach

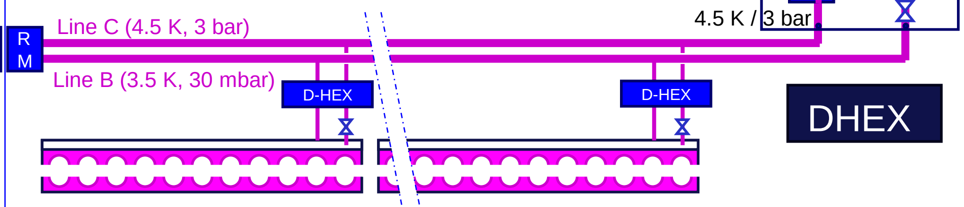




- Fewer elements (**+**)
- Feasibility at 550 g/s to be confirmed (**-**)
- Challenging design and tighter qualification requirements (**-**)
- Better compatibility with an integrated distribution line (**+**)

- As many HEX as cryo-cells (**-**)
- Harder integration (**-**)
- Feasible (HL-LHC HEX is 7.5 g/s to 25 g/s) (**+**)
- Easier design and qualification (**+**)
- No single point of failure (**+**)





FCC-ee 2 K cooling – Exergetic analysis principles

- Exergetic analysis to determine the most efficient architecture.
  - Heat inleaks and fluid friction
  - Discrepancies in temperature between cooling scheme & cooling requirement.

- Useful exergy ΔE_u: needed to keep the system at 2 K with saturated He II without considering any losses (pressure drop, flash, etc.).

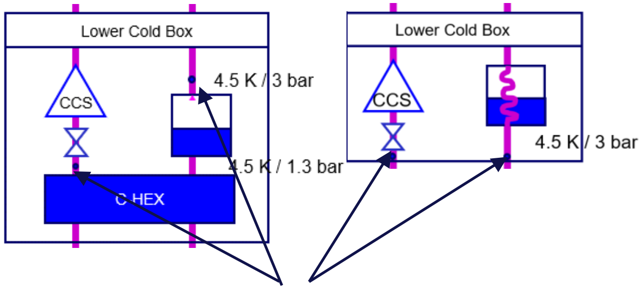
$$\Delta E_u = \Delta H_{vap} - To \times \Delta S_{vap} = L - To \times \Delta S_{vap} = \sim 1640\ kW$$ equivalent to $$\Delta E_u = W = \dot{Q} \times \left(1 - \frac{T_0}{T}\right)$$

- Real exergy ΔE_r: actual increase of exergy experienced by the fluid through a given system, including its losses. To compare all systems (simulated or measured):
- Inlet always taken at 3 bar abs / 4.5 K ScHe conditions.
  - Outlet always measured at CCs inlet.
- Exergetic efficiency: $\xi = \frac{\Delta E_u}{\Delta E_r} \times 100$

To = 290 K

Input data for simulations:

- 60 CM operating at 2 K of 540 m length. Slope (0.25%) - neglected so far.
- Static + Dynamic heat loads per CM @ 2 K + margins = 190 W / CM800.
- Heat load on distribution lines: 0.09 W/m2 (extracted from LHC).
- Fully segmented architecture: each CM has its own jumper.
- 2 mbar allowable pressure drop in the return VLP line



Real exergy calculation points

FCC-ee 2 K cooling – Exergetic analysis outcome

	Option 1: C-HEX	**Option 2: D-HEX**
ξ_{max} [%]	85.7%	83.8%
$VLP\ return\ line\ D_{B_{min}}$ [mm]	**330**	**375**
$\dot{m}$ per HEX [g/s]	544	10
$\Delta p_{HEX_{LP}}$ [mbar]	2	2
Absolute increase in exergy w.r.t. min. consumption (Option 1)	+0	+170 kW (all FCC-ee SRF @ ttbar)
Increase in 4.5 Keq needs w.r.t min.	+0	+2.7 kW
Increase in electrical consumption w.r.t min.	+0	+600 kW (**1.3%** of total power)

- **Exergetically, it can be concluded that both options are equivalent** (assuming maximum heat exchanger effectiveness limited by T_{λ} at the HEX HP outlet).
- The main gain of the CHEX option is the size of the VLP return line and the lower number of components (cost and reliability). It implies an overall easier integration at the cost of more complex HEX design and qualification.

FCC-ee 2 K cooling – Exergetic analysis outcome

- Losses per component (for one half-LSS at point H)

C-HEX exergetic losses	
Phase separator	17.6 % (48.4 kW)
HEX	**48.1 % (132.5 kW)**
Supply line	2.4 % (6.5 kW)
JT valves	**22.4 % (61.8 kW)**
Return line	9.6 % (26.4 kW)
Total losses	275.6 kW

Pressure head losses not included (lower for D-HEX as lower density)

D-HEX exergetic losses	
HEX	**42.4 % (135 kW)**
Supply line	1.2 % (3.8 kW)
JT valves	**49.3 % (156.9 kW)**
Return line	7.1 % (22.6 kW)
Total losses	318 kW

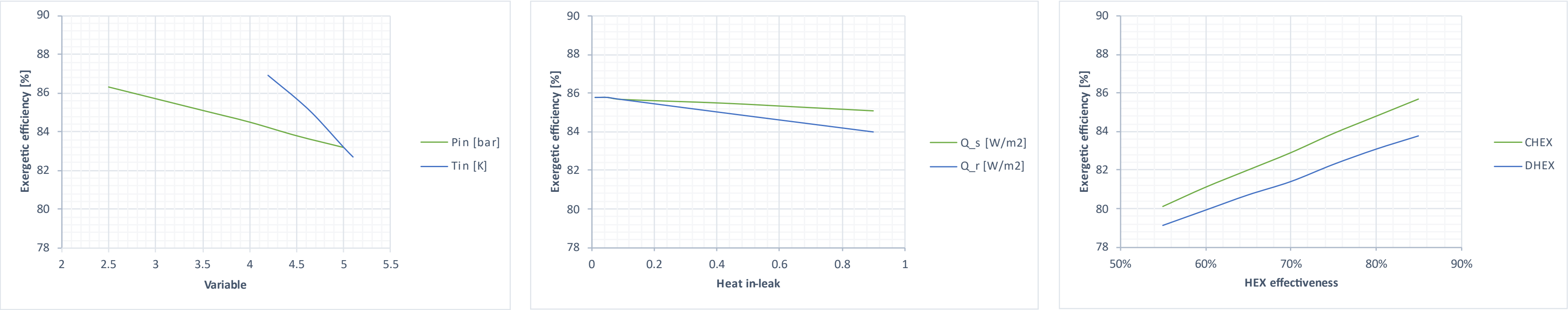
For both options, the biggest losses come from the HEX and the JT expansion

Splitting the HEX in two and adding an expansion in between, such that the JT expansion is done at a lower pressure has been previously proposed.

FCC-ee 2 K cooling – Sensitivity analysis example

- Exergetic analysis used to determine the dependency of overall efficiency on different parameters

- For CHEX case, low impact on efficiency for the:
  - Pressure drop along the lines – but impact on the size of the lines, i.e., integration.
  - Number of cryomodules per cell – but strong impact on the local cooling loops not accounted in this analysis.
  - Length of each cryomodule – but clear impact on integration within the LSS.



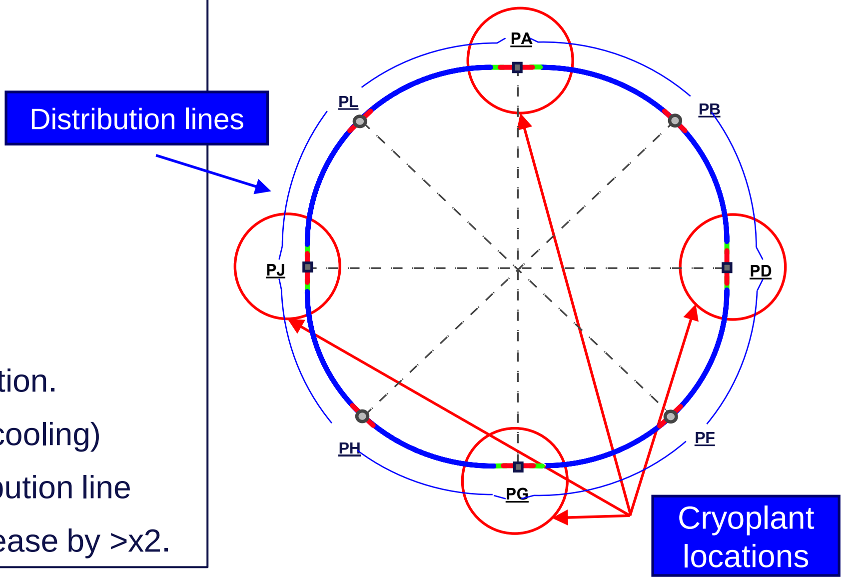
Impact of varying inlet pressure (**Pin**), inlet temperature (**Tin**), heat inleaks on the supply (**Q_s**) and return (**Q_r**) lines, and on the effectiveness of the CHEX and DHEX case. All the calculations refer to the CHEX architecture, except the DHEX effectiveness case.

Alternative concepts – HTS4

FCC-ee baseline consists of only warm magnets in the arc. This is an alternative assessment.

- HTS4 proposes to exchange the baseline FCC-ee Short Straight Section (SSS) room temp magnets with superconducting ones => 363 cryostats per sector, 3 m each, located every 27.9 m in the arc.
- A request from the HTS4 team led to assess a centralized cryoplant-based solution.
- Following heat loads were provided per magnet: 4 W @ 40 K and 25 W @ 80 K.

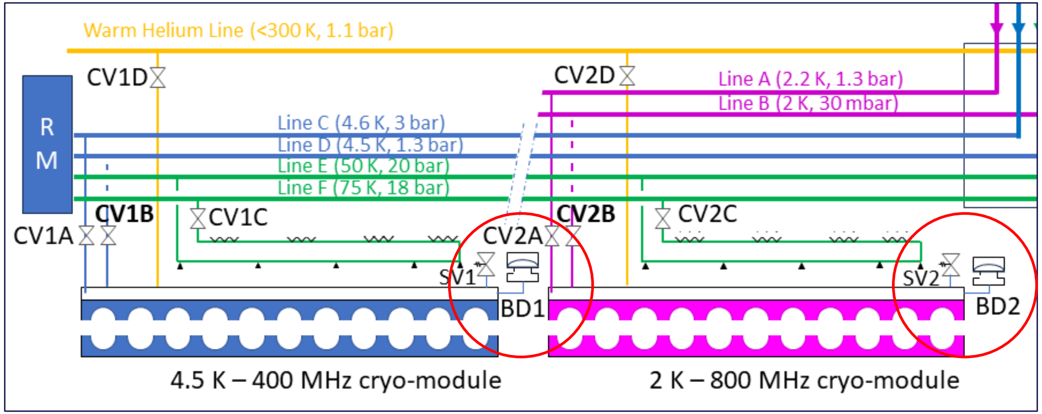
- Outcome of the assessment:
  - 4 cryoplant locations: PA, PD, PG and PJ – distributing points.
  - Proposed distribution avoids busy RF points PH / PL.
  - Points coincide with Detector and MDI cryoplants.
  - 1 cryoplant per point or per two sectors (4 in total) each of:
    - **5.3 kW @ 4.5 Keq** or 120 kW @ 77 Keq.
  - Total electrical consumption between **3.4 and 5 MWe**.
  - ~DN550 distribution line in the arcs, considering a two-circuit solution.
  - Low Exergetic efficiency of the distribution line <30% (point-wise cooling)
  - 2900 interconnections (distribution line – magnet) make the distribution line very expensive. Cryogenic system cost estimate expected to increase by >x2.



Helium Recovery System for FCC-ee SRF

The He inventory for the cryomodules is
- 55 kg of He @ 2 K per 800 MHz cryomodule
- 116 kg of He @ 4.5 K per 400 MHz cryomodule

The total inventory of the cryomodules and their distribution line, excluding the inventory present in the cryoplants is:
- At point H: **11 ton of LHe at 4.5 K and 7 ton of LHe at 2 K**.
- At point L: **9.7 ton of LHe at 2 K**.



- Cryomodules = low-pressure rated devices ⇔ high risk of inventory loss in case of a non-nominal scenario:
  - **S1** – Isolated cryomodule(s) from the cryoplant due to a malfunctioning valve.
  - **S2** – Loss of full sector cooling capacity (for example, due to power outage).
  - S3 – Beam vacuum break.
  - S4 – Insulation vacuum break.
- Target for He Recovery System: S1 or S2
- S3 and S4 are not covered by this system due to the extremely high mass flow rates.

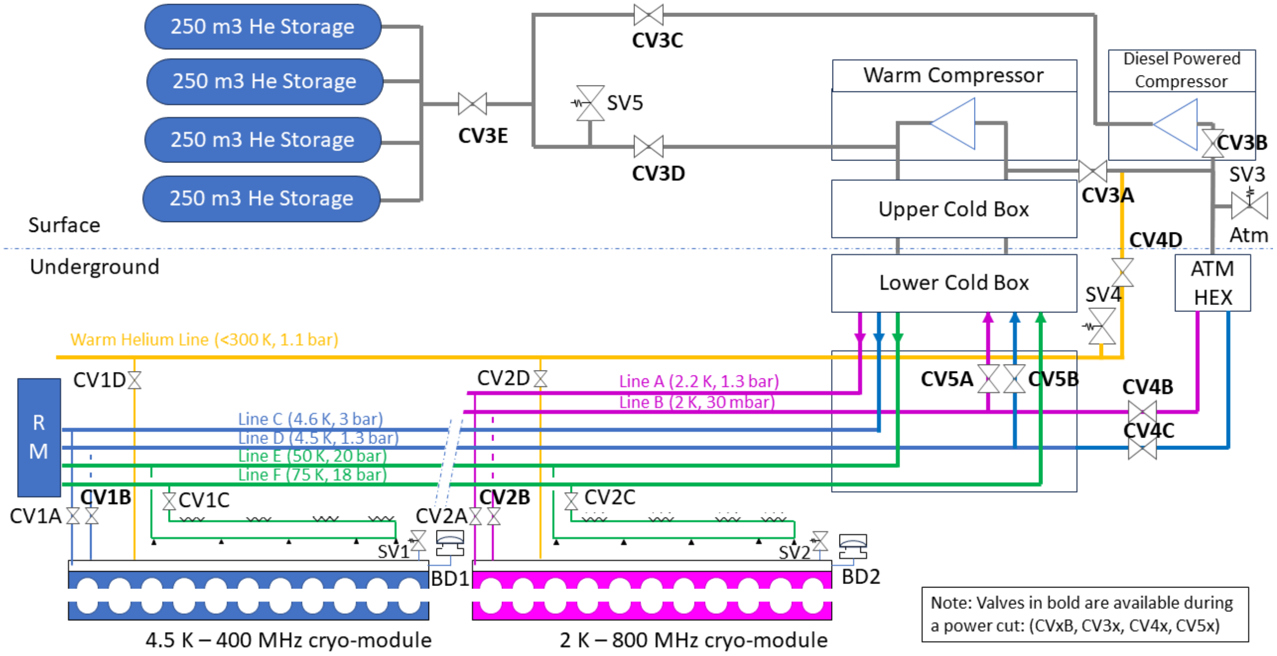
The cryomodules start building up in pressure due to the heat inleaks. They are equipped with a pressure relief valve and a burst disc usually rated at around 1.7 bara and 2.1 bara. Those devices release the helium into the tunnel to protect the integrity of the device.

Usual behavior without a He recovery system

Proposed concept

- Focus on point H as point L is simpler (only 2 K cryomodules)
- 2 K and 4.5 K cryomodules share the distribution line

Main components:
- UPS powered valves (in bold)
- Atmospheric HEX
- Diesel Generator to power a compressor station.
- HP compressor.
- 20 bar 250 m3 tanks storage.



Scenario S1

S1 compliance – Single or several cryomodules isolation

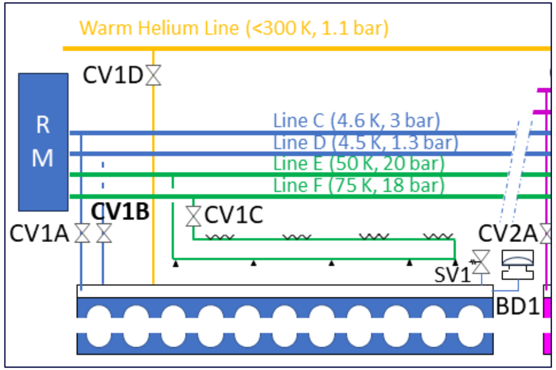
- Cause: return valve (CV1B) blockage that could appear due to:
  1. Electronic failure in the valve positioner, crate or common computer.
  2. Electrical network failure.
  3. Compressed air supply failure.
  4. Mechanical issue blocking the valve: jamming or debris.

- Mitigation measures:
  - 1-3 issues can be addressed by installing a Fail Open (FO) valve.
  - Debris blockage (4) is addressed with purification systems (dryers, adsorbers and filters) installed online within the cryoplant.
  - If mechanical jamming (4) occurs during normal operation, the valve will just stay opened.

- No mitigation provided: Mechanical jamming of the valve in a closed position.

- Risk assessment – with mitigation measures, it is deemed that a failure in the return line leading to the loss of the cryomodule(s) Helium inventory is **very unlikely**, and the **severity is contained** to the inventory of one cryomodule.

If the return valve is open and the refrigerator is working nominally, the cold line B or D can well recover all the inventory of the cryomodule.



Likelihood \ Impact	Negligible	Minor	Moderate	Significant	Severe
Very Likely	Low Med	Medium	Med Hi	High	High
Likely	Low	Low Med	Medium	Med Hi	High
Possible	Low	Low Med	Medium	Med Hi	Med Hi
Unlikely	Low	Low Med	Low Med	Medium	Med Hi
Very Unlikely	Low	Low	Low Med	Medium	Medium

The mitigation measures are provided by:
- Fail-open valves.
- A purification system.

The scenario of a mechanical valve blockage is not covered as it is very unlikely, and its **impact is limited to 116 kg of He.**

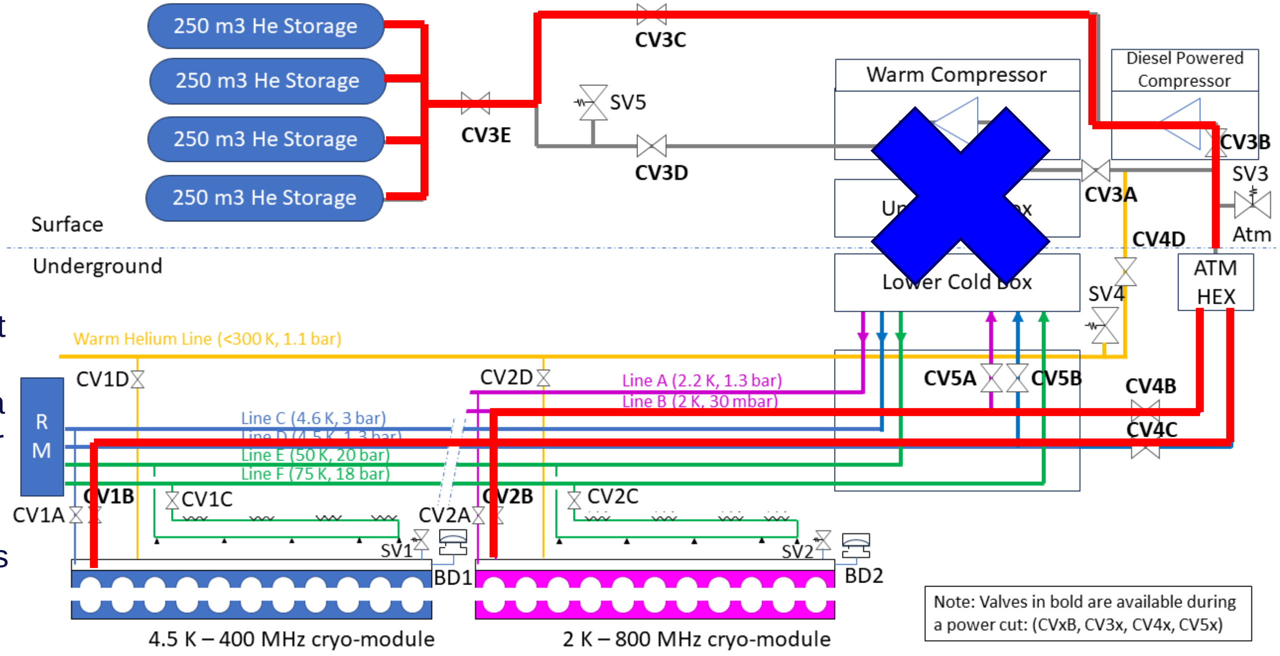
Scenario S2

S2 compliance – Loss of full sector cooling capacity

- Cause: lack of refrigeration capacity that could appear due to:
  1. A problem in the compression station.
  2. A problem with the cold box.
  3. A full power cut.

- Mitigation measures:
  - UPS-powered critical valves.
  - Installation of an atmospheric heat exchanger / evaporator.
  - Installation of a diesel generator, a supply of diesel and a compressor that is powered by this generator.

- Strategy: it is awaited until cryomodules reach 1.5 bar before starting the recovery (~30 min for 4.5 K CM, and ~ 100 min for 2 K CM).



Allows for a small operational margin.

Helium Recovery System study outcome

Preliminarily concept sizing:

Separate compressor, or reusing part of the stage compressors?

	Point H	Point L
Mass flow rate	530 g/s	315 g/s
Isothermal compression power	1 MW	600 kW
Electrical Power needs	1.35 MW	970 kW
Diesel generator rating	2.5 MW	1.4 MW
Autonomy	24 h	13 h
Diesel tank	12500 L	4000 L
Cooling water needs	~100 m3/h	~60-100 m3/h
Atmospheric heat exchanger	810 kW	500 kW
Cavern volume needs	16 m2 x 8 m	10 m2 x 8 m

Source: Linde

All the helium storage is provided by the usual He gas tanks installed at each point.

The diesel could be supplied a-posteriori thanks to the operational margin of >30 min.

Is the concept compatible with CV and HSE constraints in the cavern?

Further study needed to assess if ATM HEX can be located on the surface/shaft instead.

Conclusions

Flaticon.com

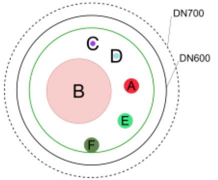
- **Efficiency** is addressed from the beginning of the design, especially for the 2 K cooling system, through **exergetic analysis**.
- **CHEX and DHEX solutions are similar efficiency-wise**. CHEX solution is preferred as fewer components leading to easier integration (smaller QRL too). However, no existing CHEX reaching 500 g/s today. Its development and its technological validation is not straightforward. CHEX stays the baseline, but a potential integration of DHEX along the SRF string is worth studying.
- A centralized cryoplant-based solution for **HTS4 superconducting magnets was assessed** and its consumption is limited to 5 MWe. Its distribution along the machine implies a poor distribution exergetic efficiency due to a point-wise cooling style. The cost of such solution would, at least, double the cryogenic system cost estimate for FCC-ee.
- A **Helium Recovery System concept has been presented** ensuring that all SRF cryomodules inventory can be recovered following the identified scenarios:
  - A CAPEX/OPEX assessment should follow to decide on its implementation.
  - A more thorough assessment of the risk scenarios could be performed.
  - The location of the ATM HEX to be validated with involved teams (SCE, CV, HSE and integration).

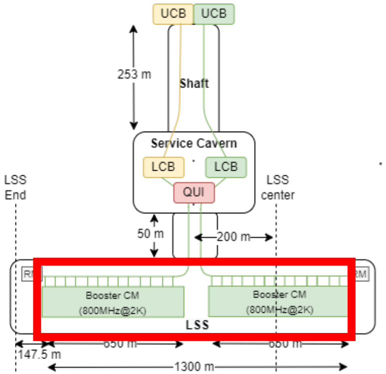
FCC

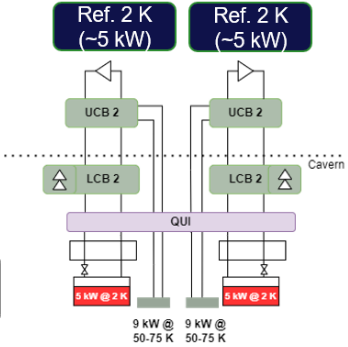
THANK YOU FOR YOUR ATTENTION

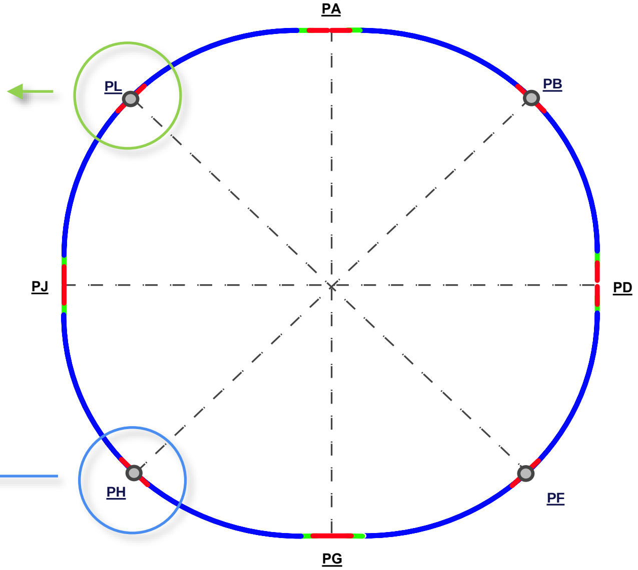
FCC-ee SRF cryogenic system layout summary @ ttbar

Layout addressed in detail in L. Delprat presentation.



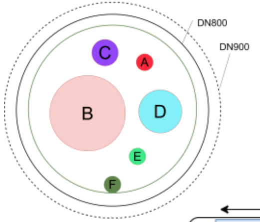


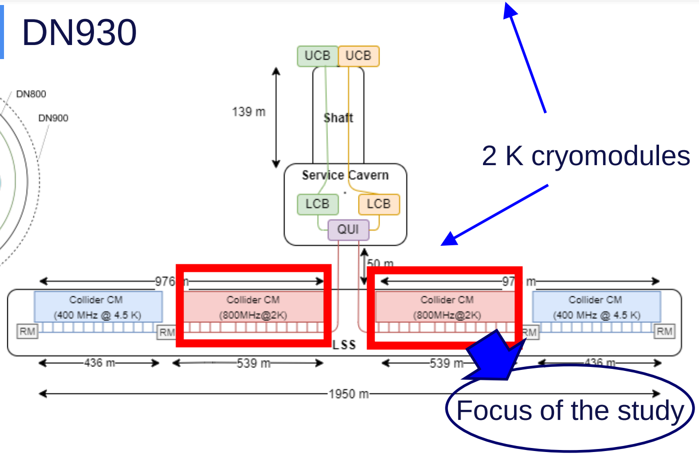


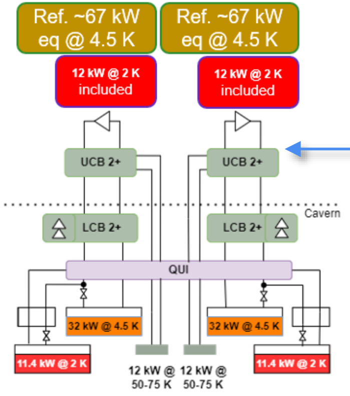


Point L DN700

Point H DN930

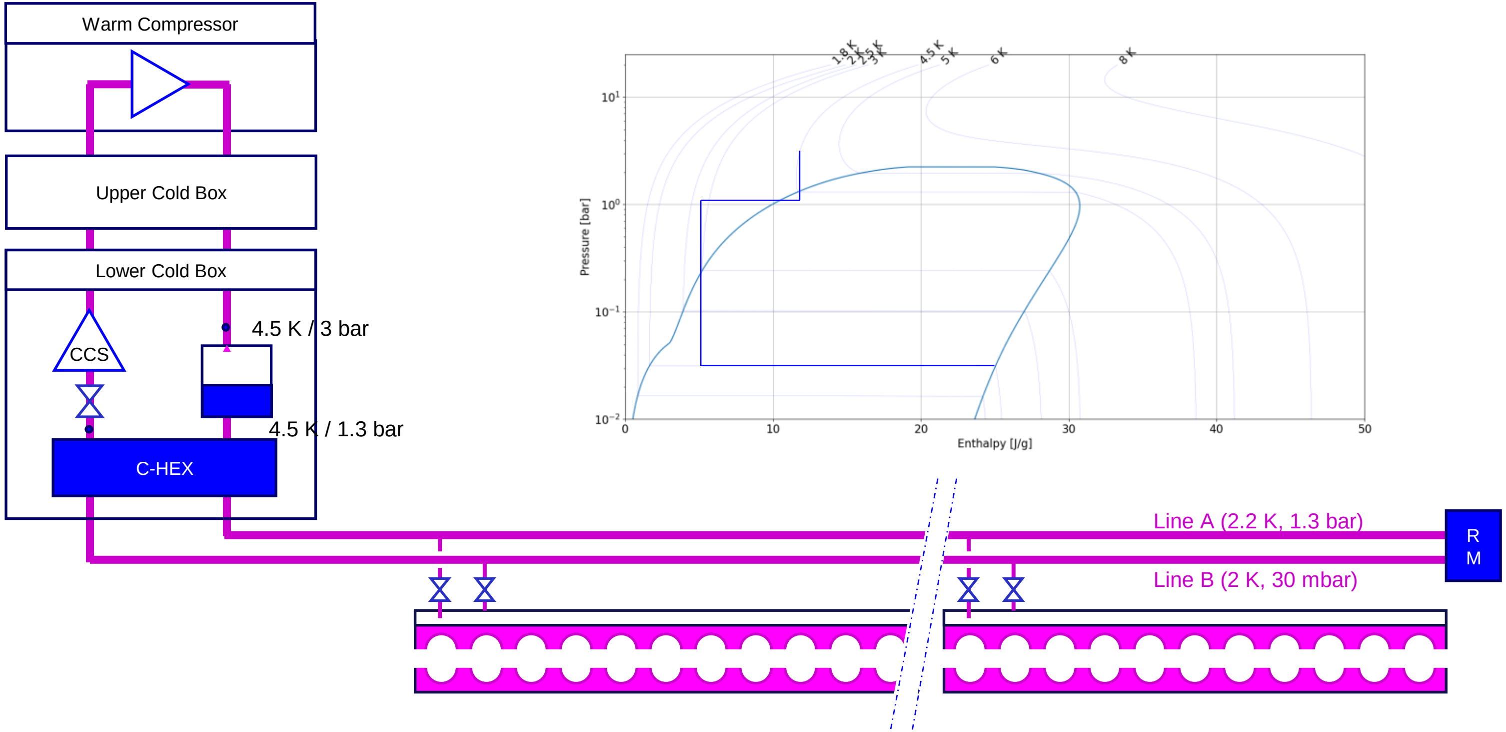




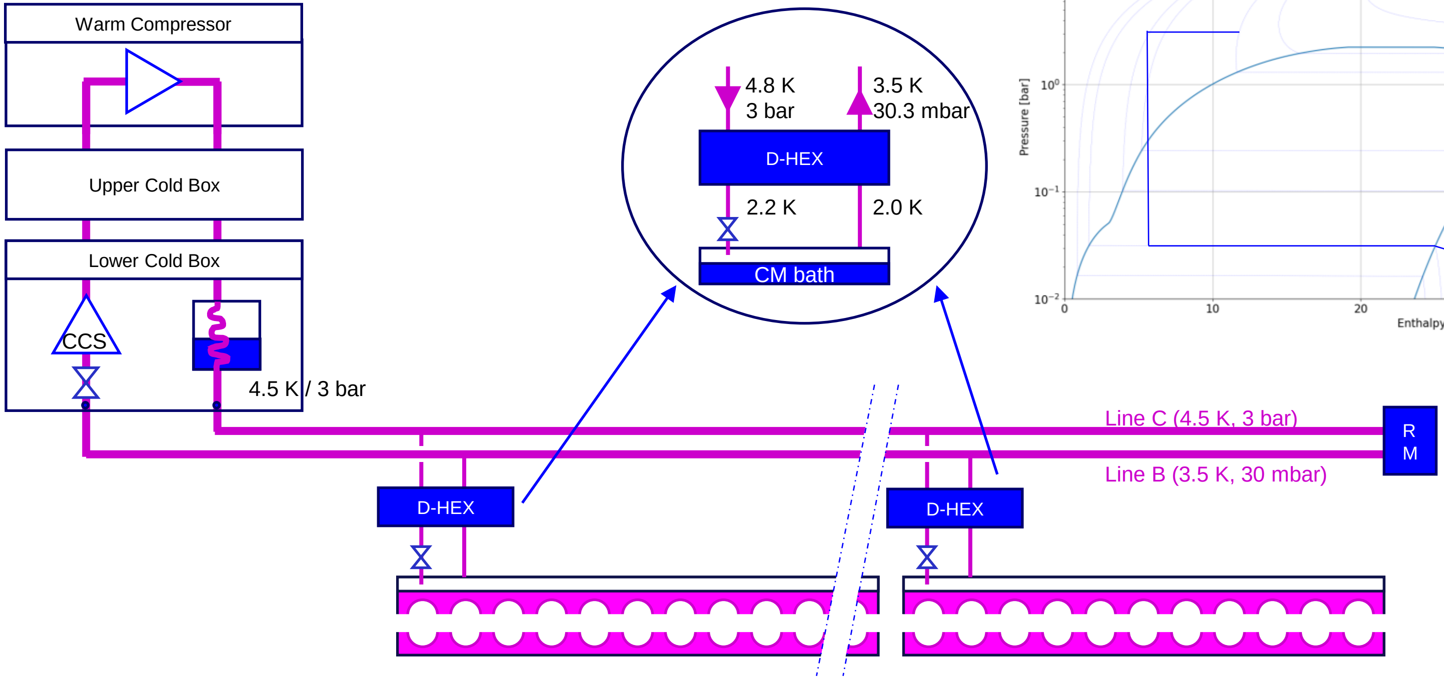


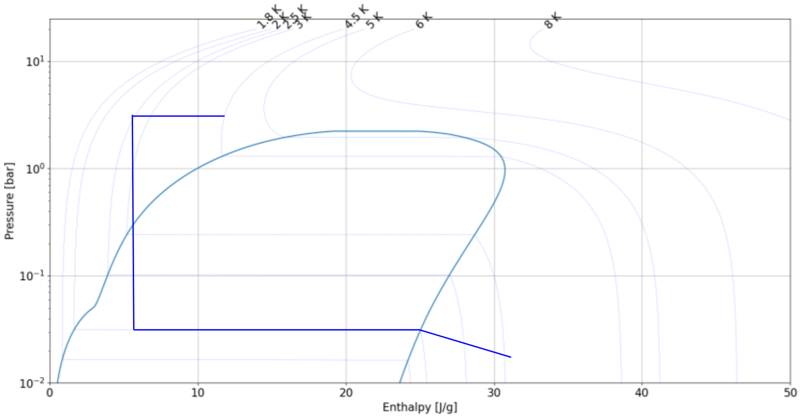
- 47 MW electrical power
- 35 ton Helium inventory
- > 10000 m2 of surface

2 K cooling – Architecture / CHEX



2 K cooling – Architecture / DHEXs





2 K cooling – Architecture / Split CHEX