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“Development of the neon-helium Turbo-Brayton cryogenic refrigerator for the FCC-hh”

Student workshop on superconductivity and applications, Genoa // 08.10.2020

EASITrain – European Advanced Superconductivity Innovation and Training. This Marie Sklodowska-Curie Action (MSCA) Innovative Training Networks (ITN) has received funding from the European Union’s H2020 Framework Programme under Grant Agreement no. 764879

Outline

Cryogenics for the FCC

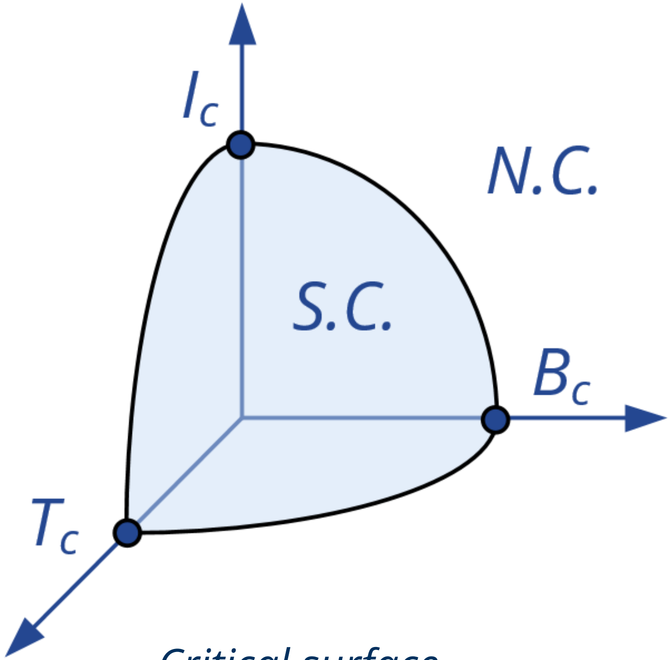
Beam screen cooling requirements

Improved cryogenic refrigerator for the *beam screen* and *thermal shield* cooling

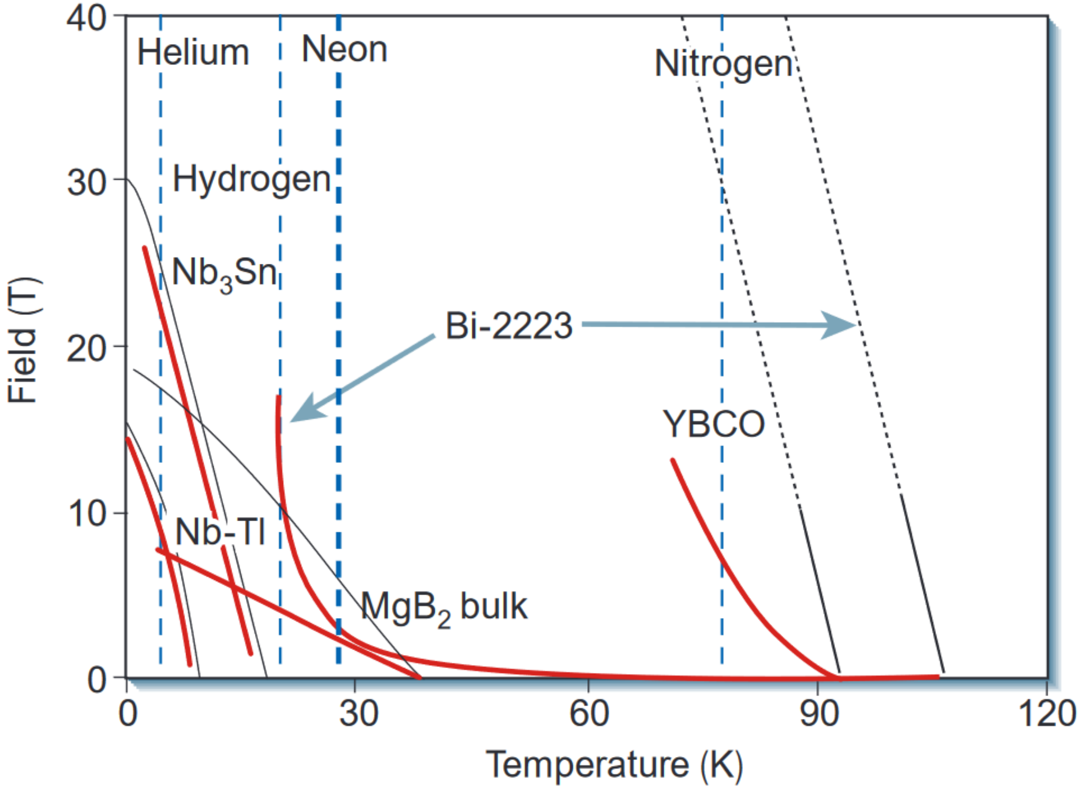
Cryogenics for superconductivity

Critical parameters for the superconducting state: temperature, current density, magnetic flux

→ cryogenics is required



Critical surface of a superconductor



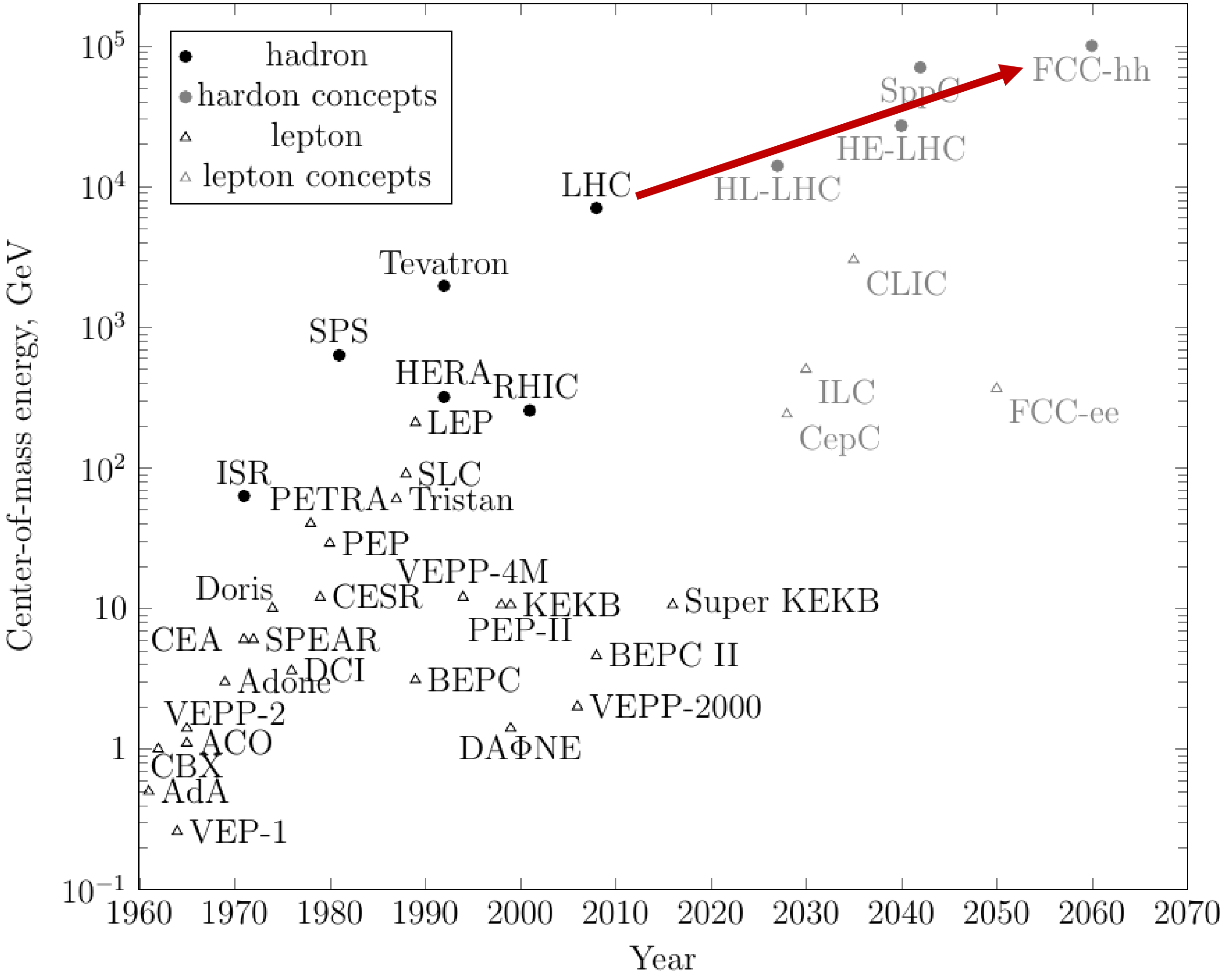
Courtesy: D. Larbalestier et al., "High-Tc Superconducting Materials for Electric Power Applications," Nature 141, 368 (2001).

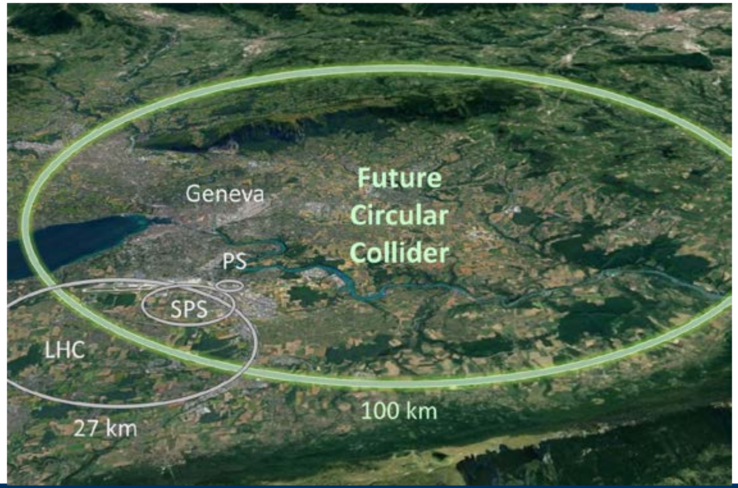
$T<T_c$ ↓ B, I ↑

Cryogenics:

T < 120 K

FCC background



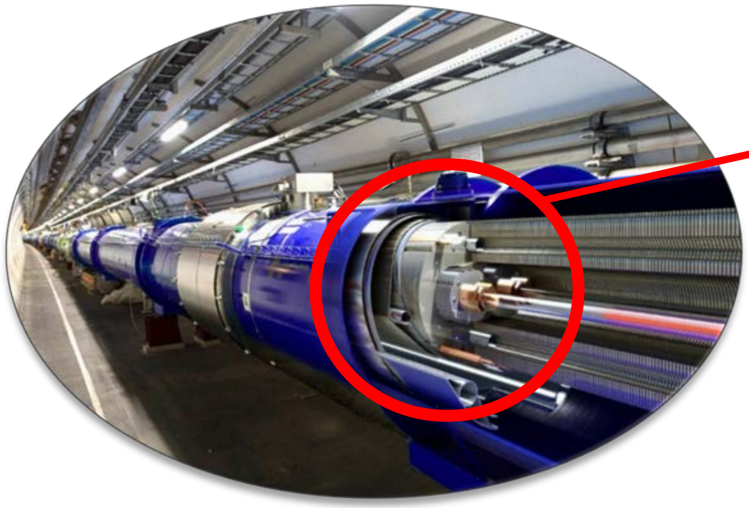


	LHC	FCC
Centre-of-mass energy, TeV	14	100
Circumference, km	27	100
Equivalent cooling power @ 4.5 K	**140 kW**	**~1 MW**
Input power for cryogenics	**40 MW**	**~200 MW**

F. Lebrun, L. Tavian

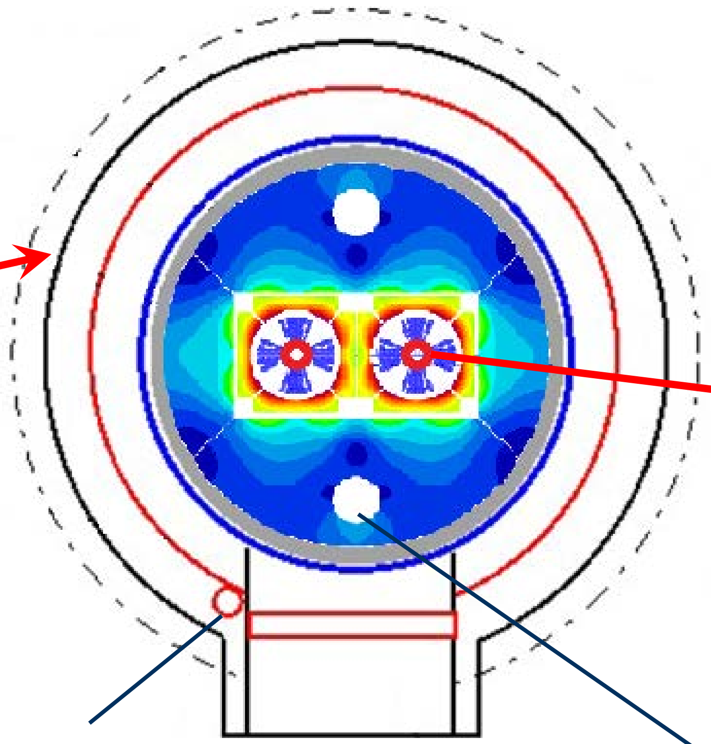
Beam screen cooling requirements

Accelerator tunnel

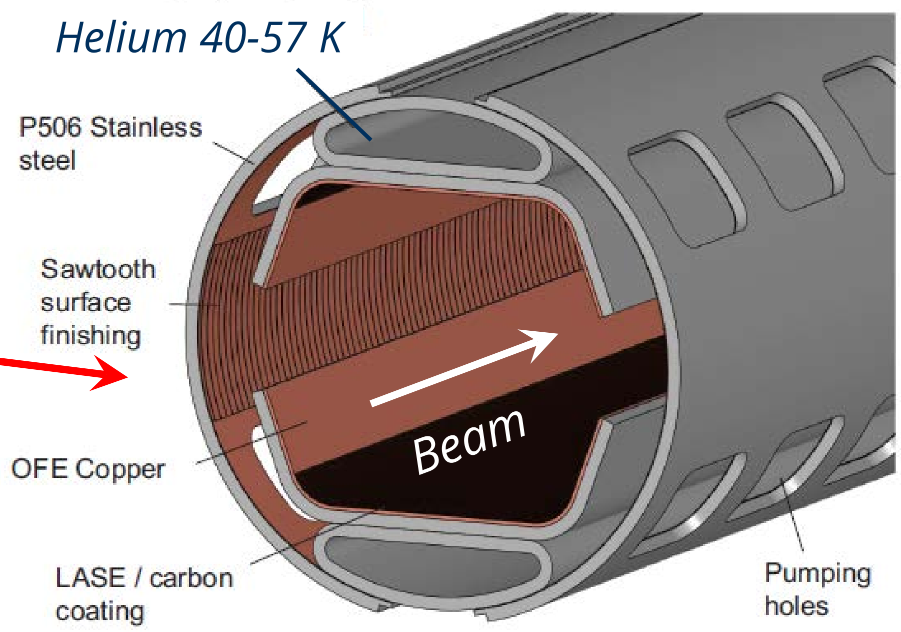


Courtesy: CERN

Magnet cross-section

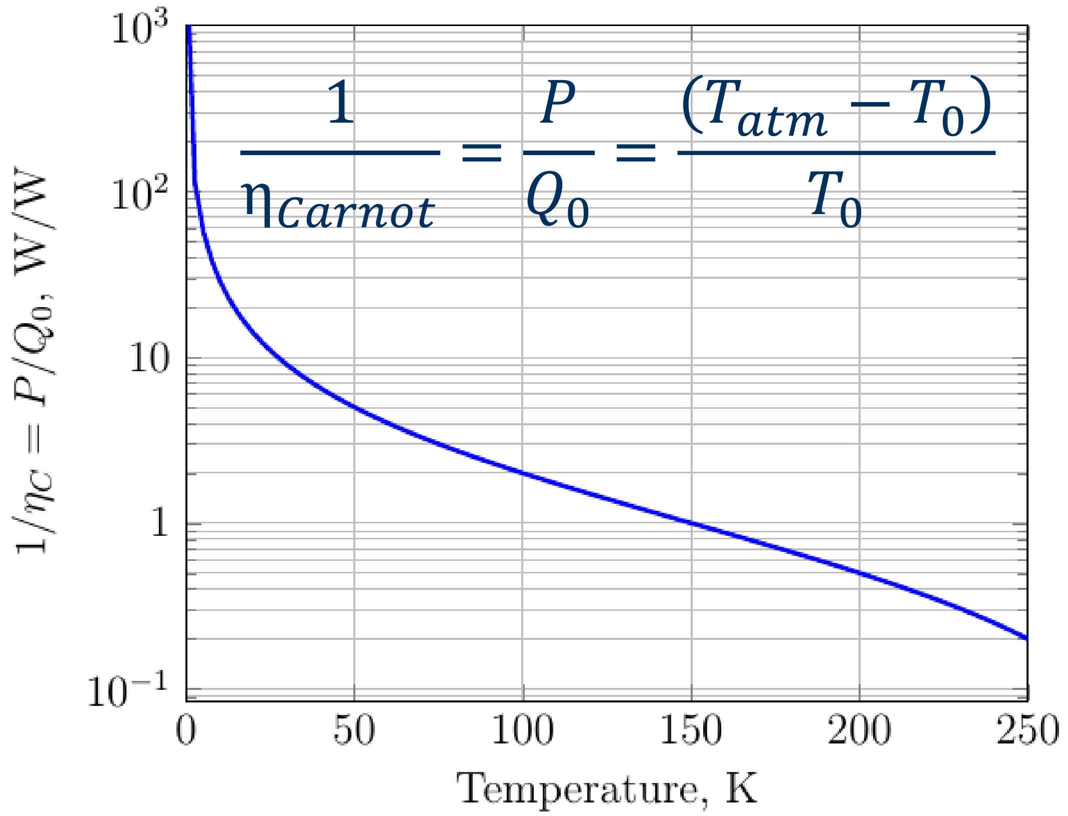


Beam screen



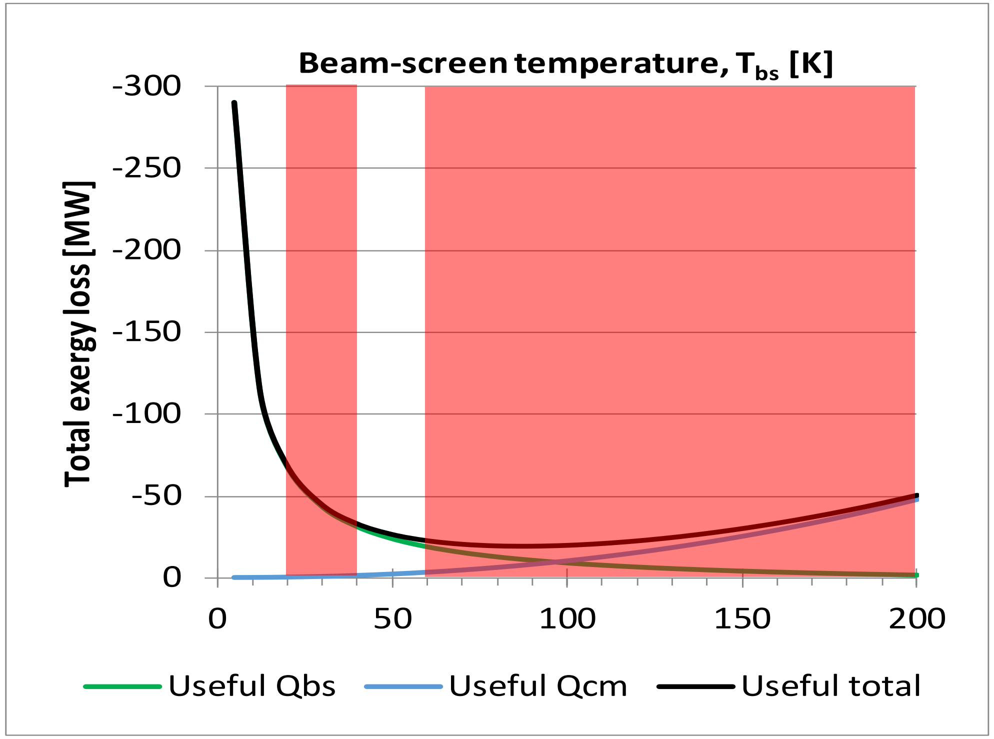
Courtesy: I. Bellafont et al. Summary of modelling studies on the beam induced vacuum effects in the FCC-hh. 2019.

Beam screen cooling requirements



→ ***Energetically cheaper to extract energy at higher temperature level,***
but the heat load to the magnets increases with T↑

Forbidden operating temperature (vacuum and/or beam impedance restrictions)



Courtesy: L.Tavian

→ ***40-60 K*** *is an optimum for the FCC beam screen incl. restrictions*

Beam screen cooling requirements

FCC cryogenics: 10 cryogenic plants within **100 km**

Cooling power per plant:

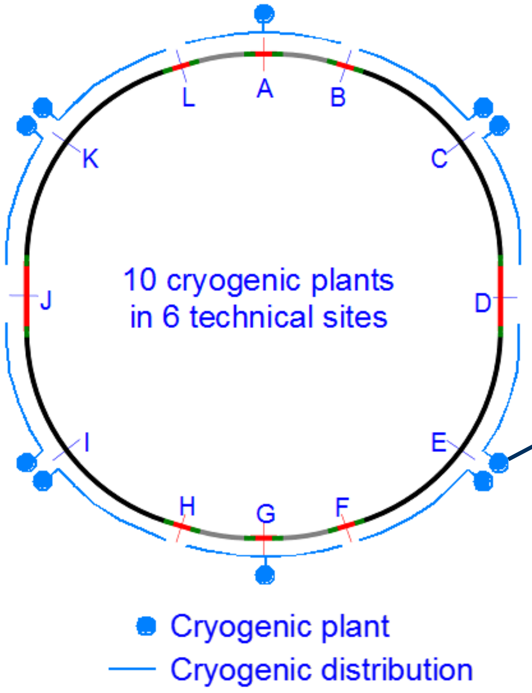
	T, K	Q, kW
Magnets	1.9 K	12
Beam screen & thermal shield	40-60 K	620
HTS Current leads	40-300 K	85

Turndown ratio: $Q_{BS+TS} \rightarrow 3.5$

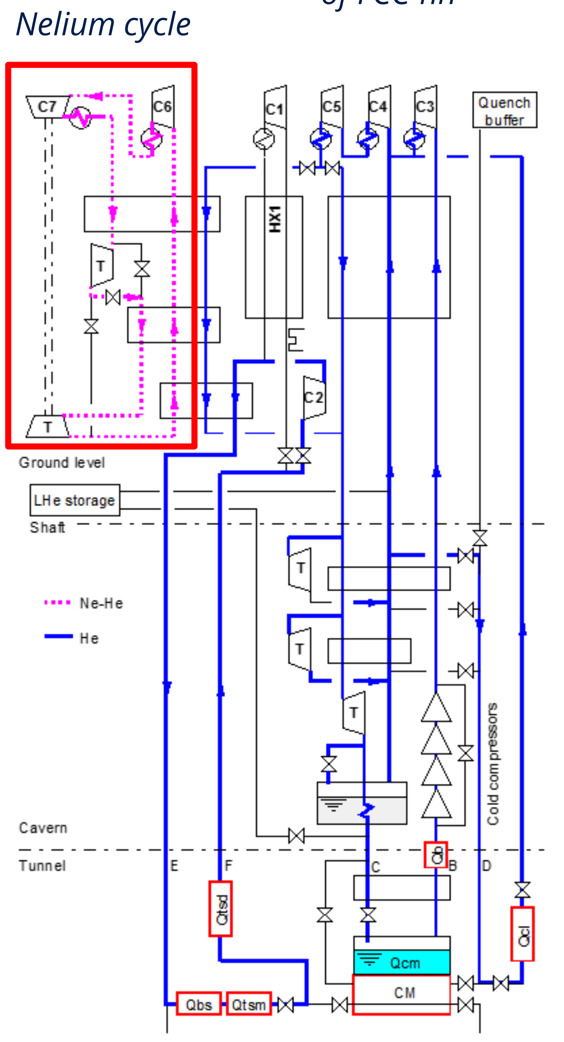
→ **Separate refrigerator** optimised for the beam screen and thermal shield cooling can be more efficient

Project objective: improvement of the Turbo-Brayton cryogenic refrigerator concept *(H. Quack, TUD)* for the *beam screens* and *thermal shields* cooling fitting requirements at all operational modes

FCC-hh cryogenic facilities layout



Cryogenic system layout of FCC-hh



Courtesy: L. Tavian, CERN

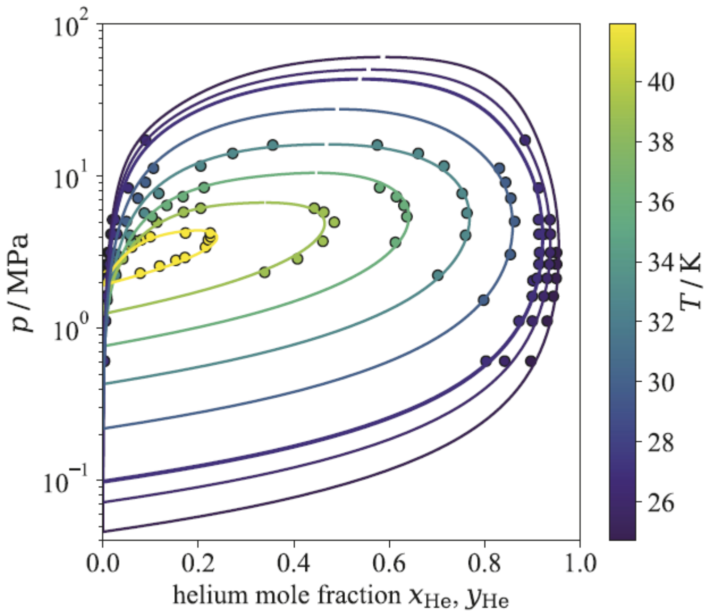
Working fluids

→ **Neon-helium mixture** *(Nelium)* is used to balance between good heat transfer properties and the number of the turbocompressor stages

→ **Equations of state** of the neon-helium mixture: model of ***J. Tkaczuk et al. (2020) Equations of State for the Thermodynamic Properties of Binary Mixtures for Helium-4, Neon and Argon***

	NEON	HELIUM	HYDROGEN
Molar mass *(g/mol)*	20,179	4,003	2,016
Critical T / P *(K / bar)*	44,5 / 26,8	5,2 / 2,3	33,1 / 13,0
Triple point T / P *(K / bar)*	24,6 / 0,43	2,17 / 0,05*	13,8 / 0,07
Density @ 300 K, 1 bar *(kg/m³)*	0,808	0,160	0,081
Isobaric heat capacity @ 300 K, 1 bar *(kJ/kg·K)*	1,03	5,19	14,31
Thermal conductivity @ 300 K, 1 bar *(W/m·K)*	0,048	0,156	0,187

**Lambda point*

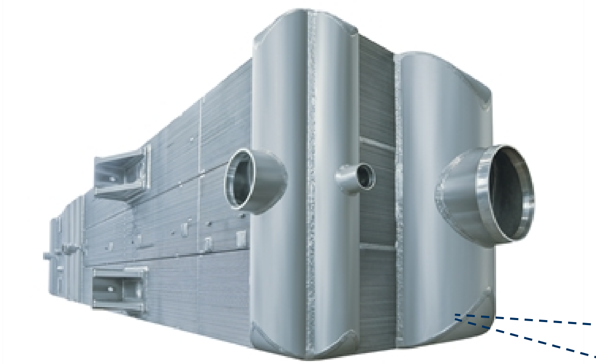


Courtesy: J. Tkaczuk et al.

Cryogenic cycle design

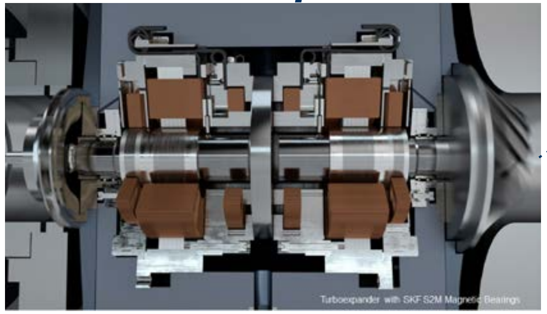
Simple reverse Brayton cycle

Heat exchanger

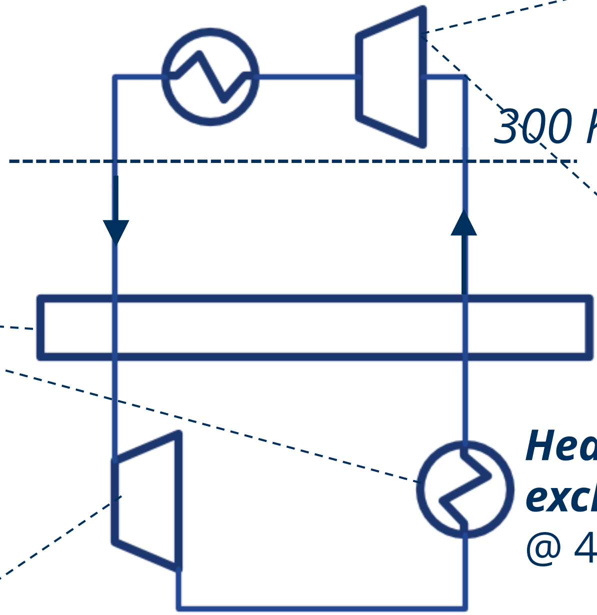


Courtesy: Linde Engineering

Turbo-expander



Courtesy: SKF



Screw Compressor

Courtesy: MAN

→ Standard for helium refrigerators

Low initial cost

Low efficiency (ηT~0.5...0.55)

Oil removal system (pressure losses)

Oil-free turbocompressor

Courtesy: MAN

➡ ***Ne+He***

High efficiency: (ηs~0.75...0.9)

High reliability

Efficient part-load control

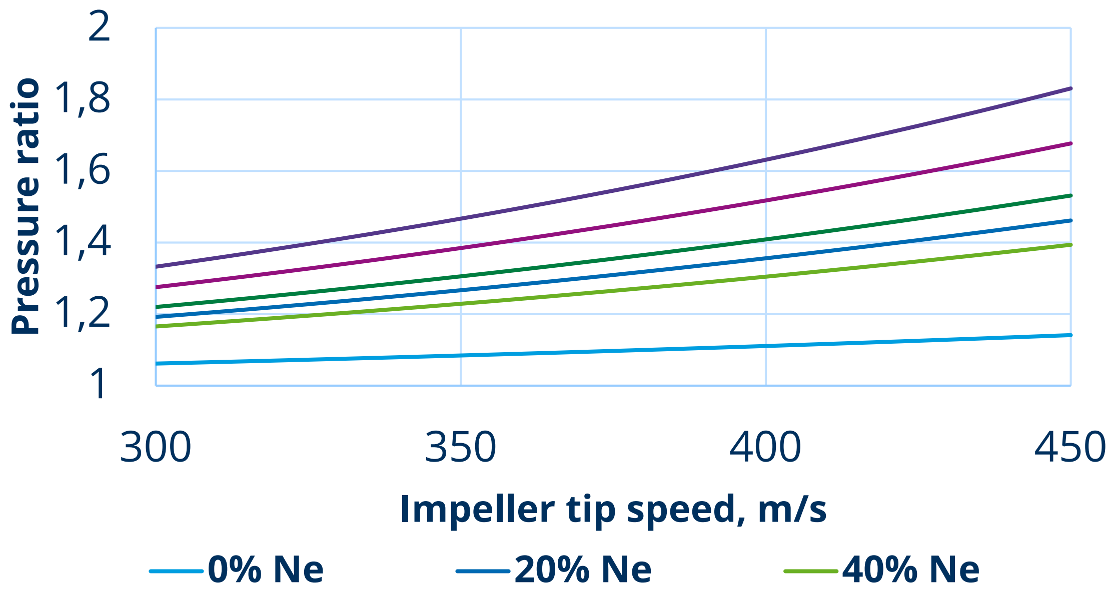
High initial cost

High number of compressor stages for light gases

Cryogenic cycle design: limitations

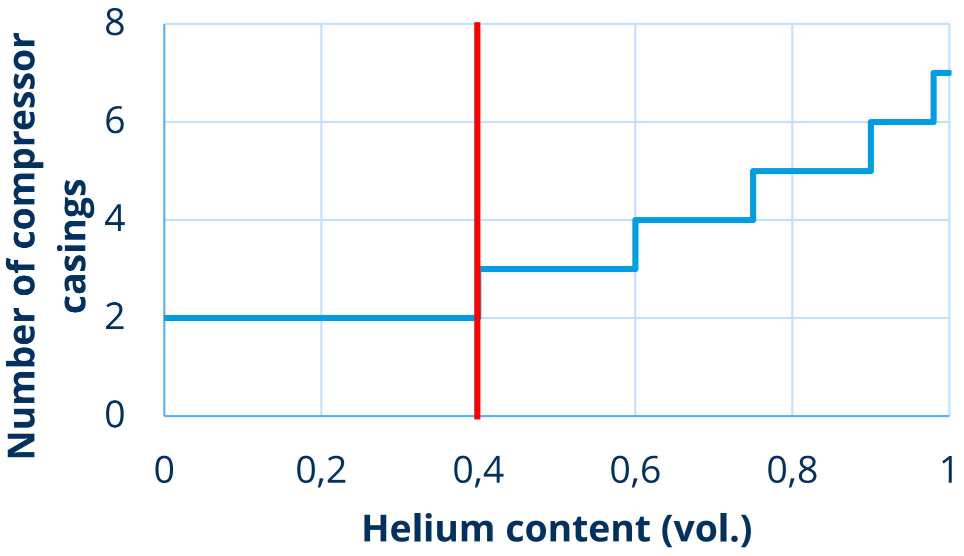
1. Turbo-compressor design

Maximum pressure ratio of 1 compressor stage



→ Required pressure ratio ~ **6-7**

Number of required compressor casings depending on the helium content
(M. Podeur, University of Stuttgart; MAN)



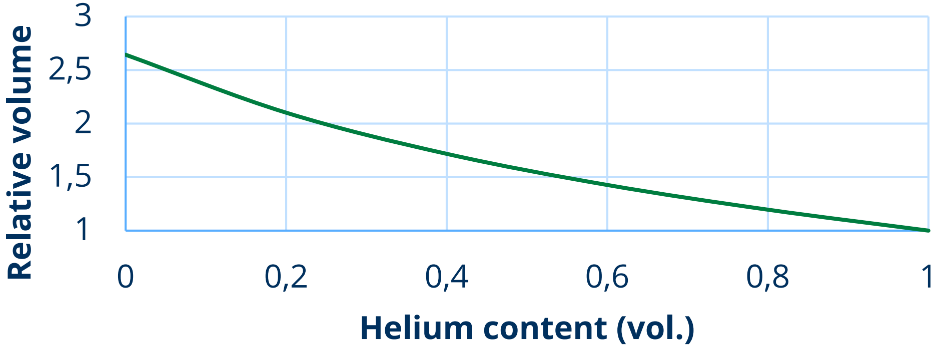
→ ***For the compressor design refer to the talk of M. Podeur (University of Stuttgart)***

→ **One tandem compressor** (with 2 casings) is economically feasible

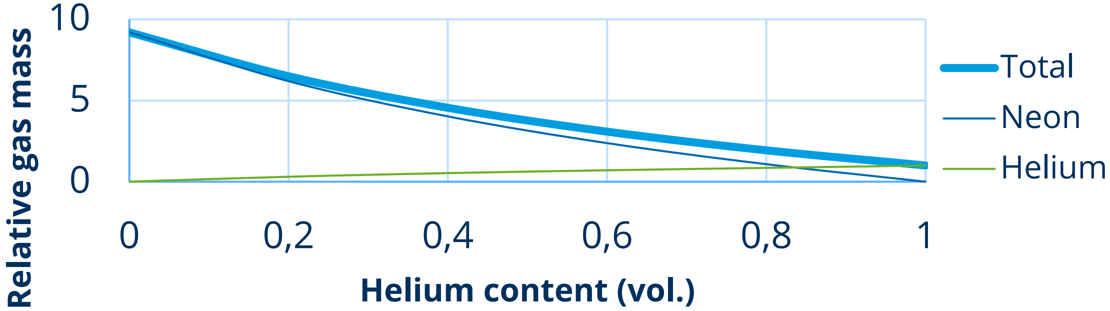
Cryogenic cycle design: limitations

2. System size and gas mass

Relative heat exchanger sizes



Relative gas mass compared to a pure helium cycle (excluding the buffer)



Coldbox of the 4.5 LHC refrigerator

Courtesy: CERN

→ Different cycle architectures were compared:

- to reduce the cycle ***pressure ratio***
- to keep the ***coldbox size*** feasible
- to increase the helium content for ***higher efficiency***

→ *Python library developed for cycle simulation („CryoSolver“)*

Cryogenic cycle design: proposed architecture

Specification of designed system:

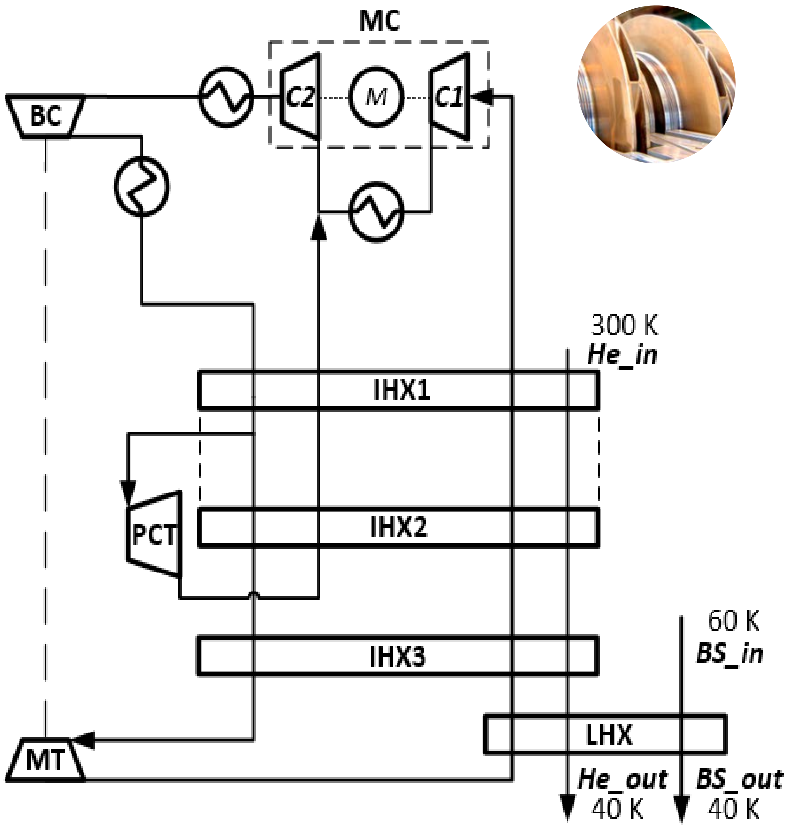
→ Reverse **Turbo-Brayton** cycle

→ **Neon-helium** mixture (Nelium) as a working fluid instead of a conventional helium cycle with LN_2 pre-cooling

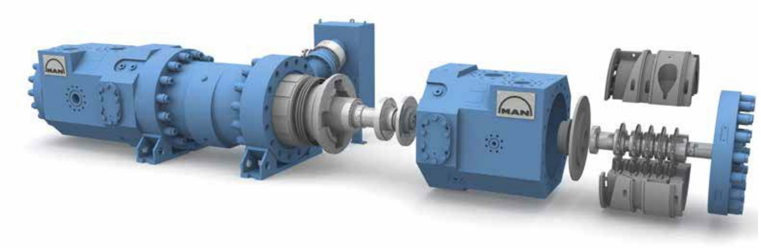
→ Multi-stage **turbocompressor** (η_s~0.75…0.9) instead of a screw compressor (η_T~0.5…0.55) and without oil removing

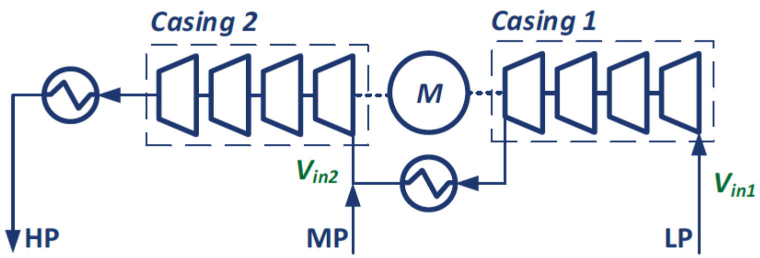
→ Turbine power recovery

Flow diagram of the Nelium Turbo-Brayton cycle



≈38 % of Carnot efficiency with 10.3 MW power (instead of 30 % for the helium cycle)

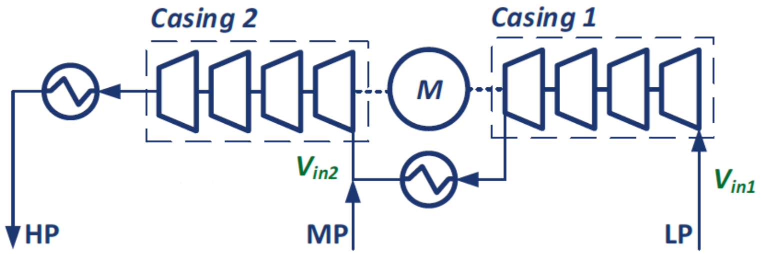




Turbocompressor developed at University of Stuttgart (M. Podeur) and at MAN

Courtesy: MAN Energy Solutions

Part-load operation

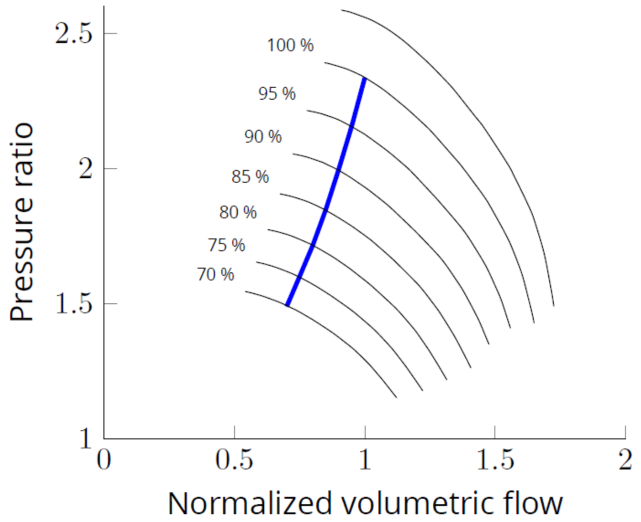


Part-load strategy: variation of rotational speed & removing the gas (buffer)

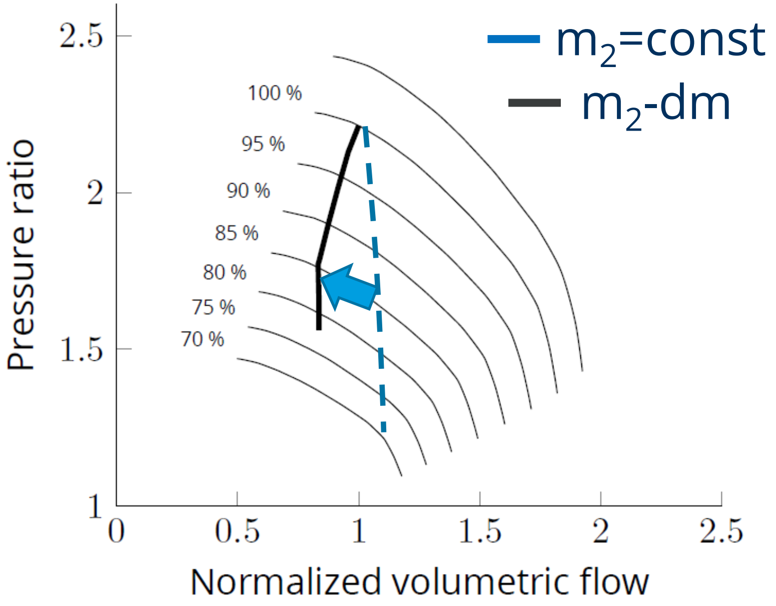
→ Turbocompressor control – best efficiency line operation (φ_{in}=const) of the 1st casing

Estimated buffer volume: 15.6 m^3, dead mass: 64 kg (~11 % of the total mass) → acceptable

$$\varphi = \frac{4 \cdot V_{in}}{D^3 \pi^2 n} \qquad V_{MC2in} = \frac{m}{\rho(p)}$$



Casing 1



Casing 2

→ **Reduction of the massflow** through the ***pre-cooling* turbine** compared to the designed massflow helps to stay on the best efficiency line of the casing 2

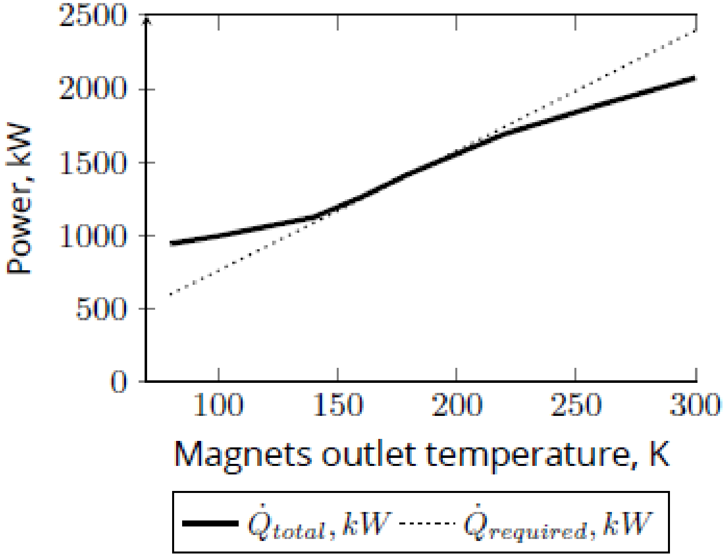
Compressor map based on data of MAN, M. Podeur

Cooldown operation

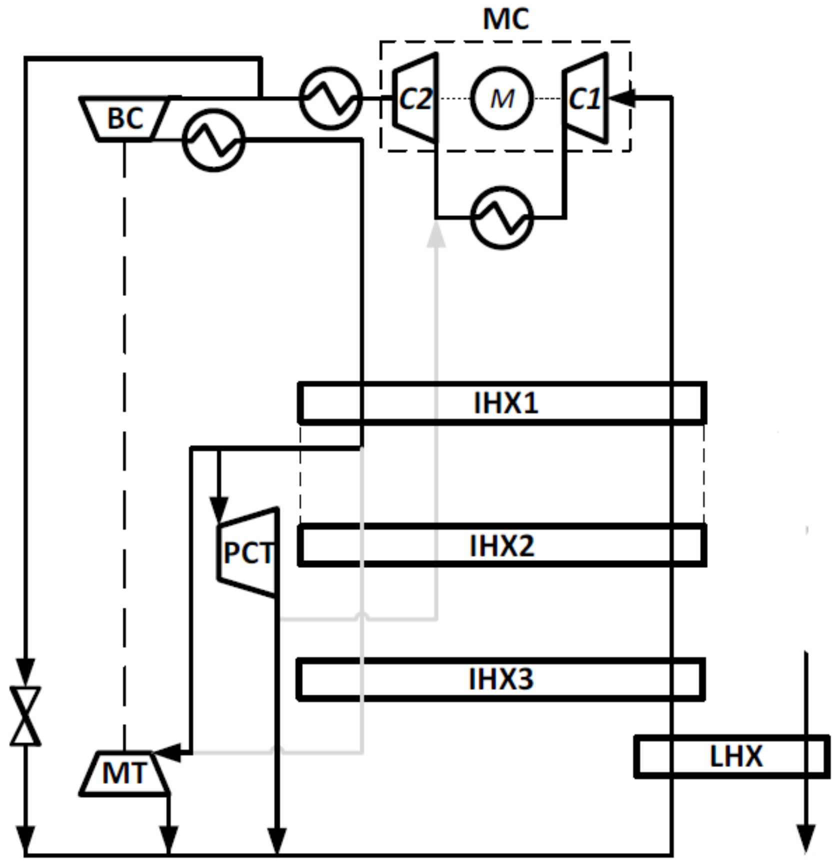
Possibility of the refrigerator usage for the initial magnet cooldown from **300 to 40 K** was studied

→ turbines power availability checked from the preliminary design

→ cycle operation in parallel turbine switch mode evaluated



Maximum cooling power provided by the turbines

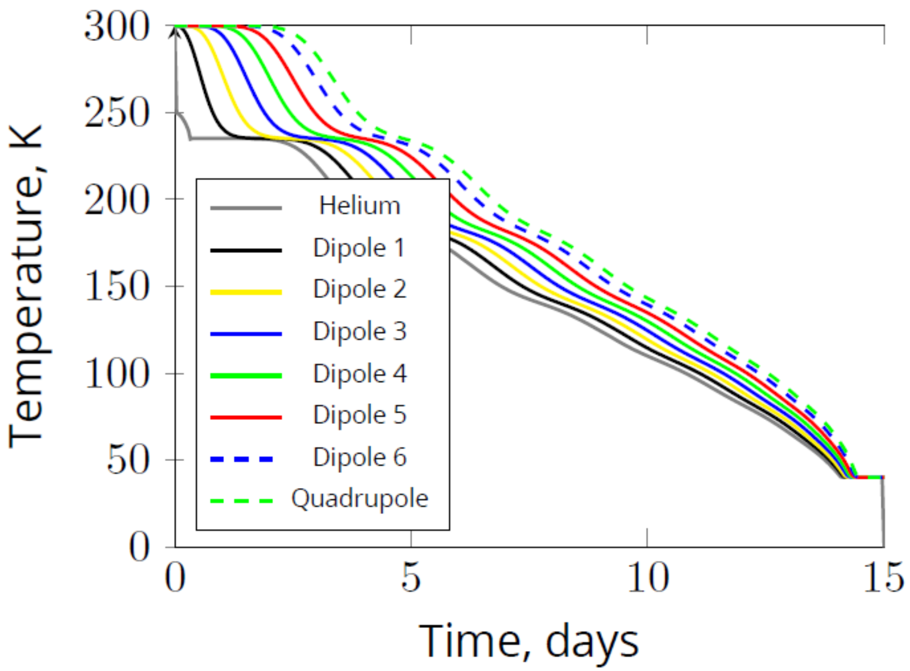


Parallel turbine switch for the cooldown mode

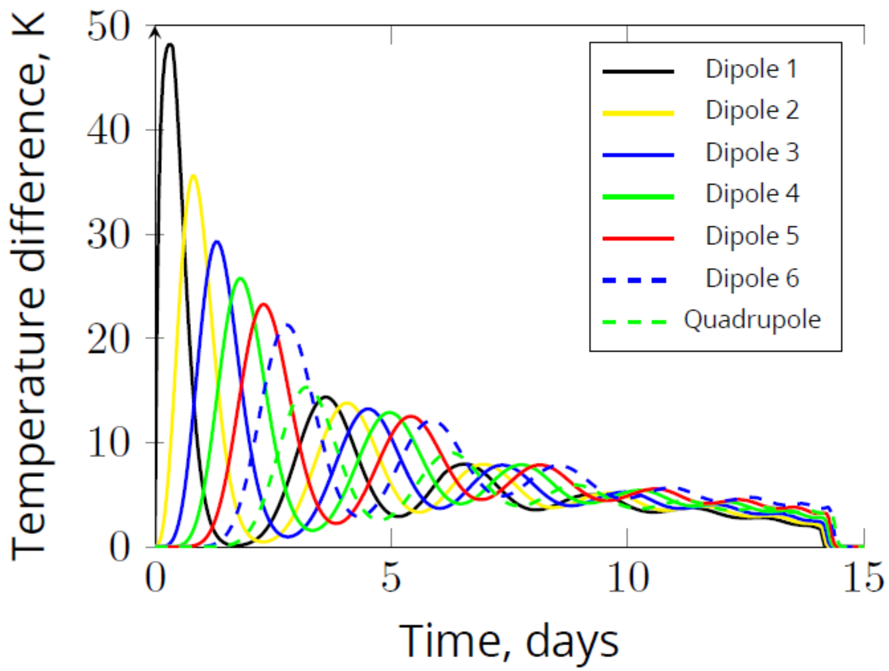
Cooldown operation

Co-simulation of the refrigerator operation at maximum turbine power and the magnet half-cell cooling realised in Python

→ Cooldown from **300 to 40 K** can be done within **15 days** (ideal value, but fitting the requirements)



Magnet half-cell cooldown time to 40 K



Temperature difference within magnets during cooldown

Conclusion

Work done:

- Analysis of different cryogenic system architectires for the FCC BS & TS cooling at 40-60 K
- Improved design of the Nelium Turbo-Brayton cryogenic refrigerator for the FCC
- Efficient part-load operation with the turndown ratio of 3.5 is expected
- Cooldown of accelerator magnets down to 40 K is possible within the required time

Additionally studied:

- Natural neon-helium mixture production from the air (Ne:He ~ 3:1)
- Downscaling possibilities for industrial HTS applications

PhD Thesis in progress…

Thank you

for your attention…
&
for the amazing 3 year-long journey with EASITrain!

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