EFATS 2024, 4th International Workshop on Emissions Free Air Transport Through Superconductivity
16 – 17 October 2024, University of Twente, Enschede, The Netherlands

Lessons Learned About Helium Cooling of Large Cryogenic Systems

Antonio Perin, CERN, TE-CRG

IEEE CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 58, Feb. 2025.
Invited presentation was given at EFATS 2024, Oct. 17, 2024.

Outline

- Brief Introduction to CERN
- Cryogenics at CERN
- Helium cryogenic facilities at CERN
- Cooling superconductors
- The availability challenge
- Managing helium
- Summary

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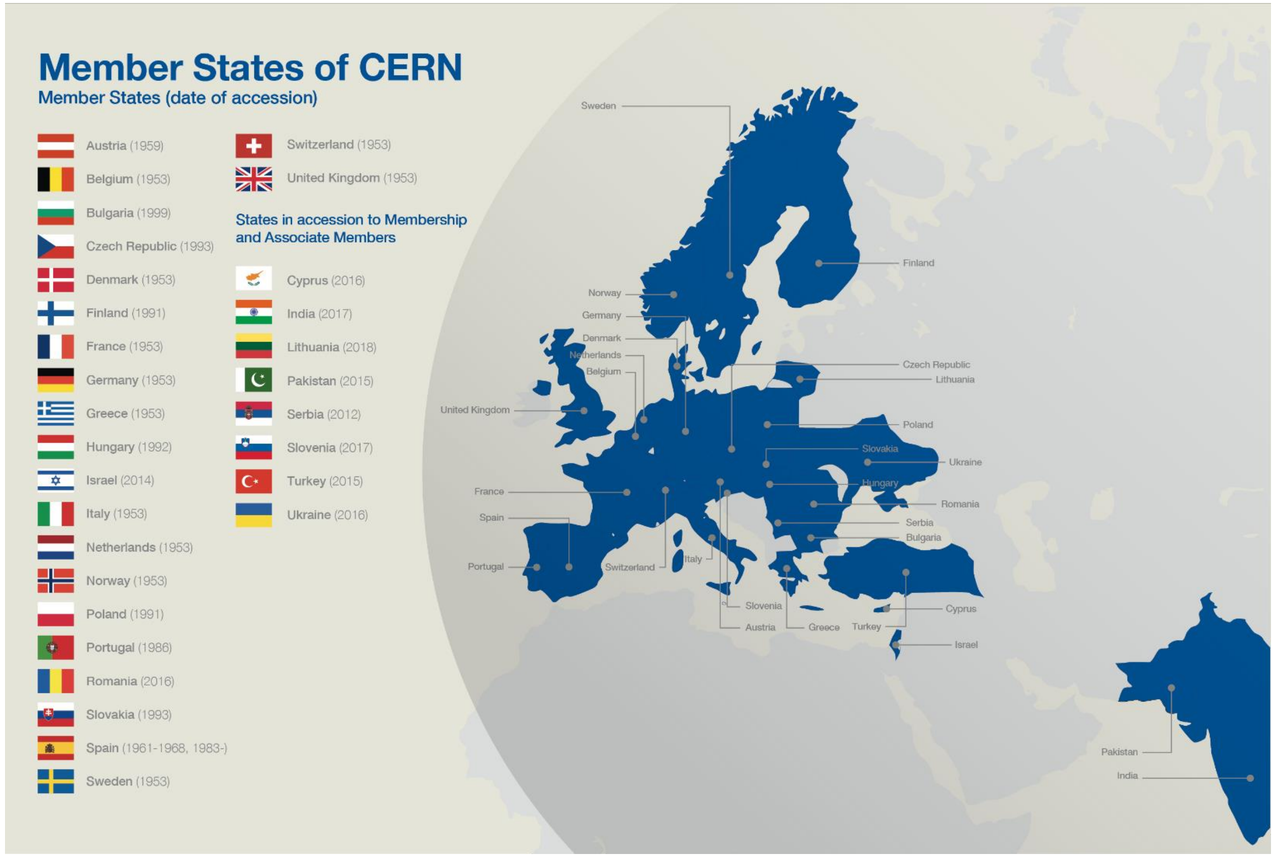
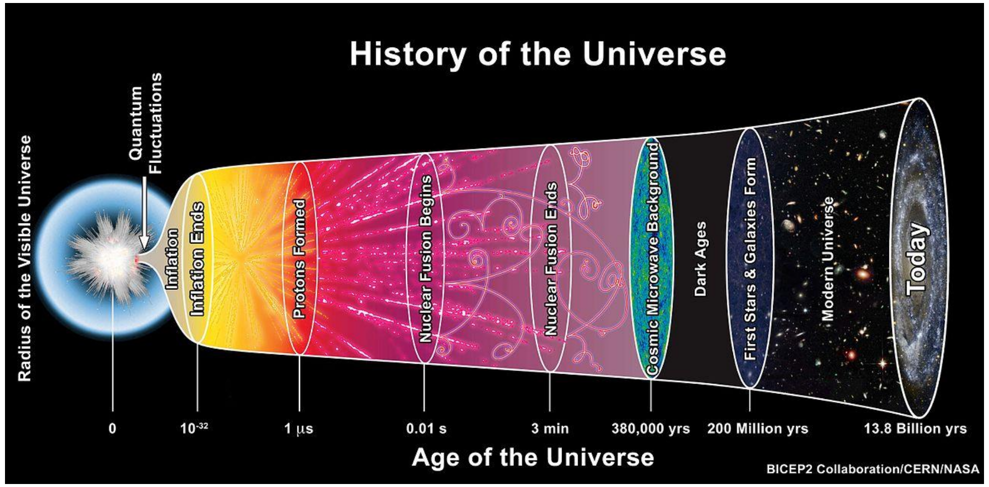
CERN in brief





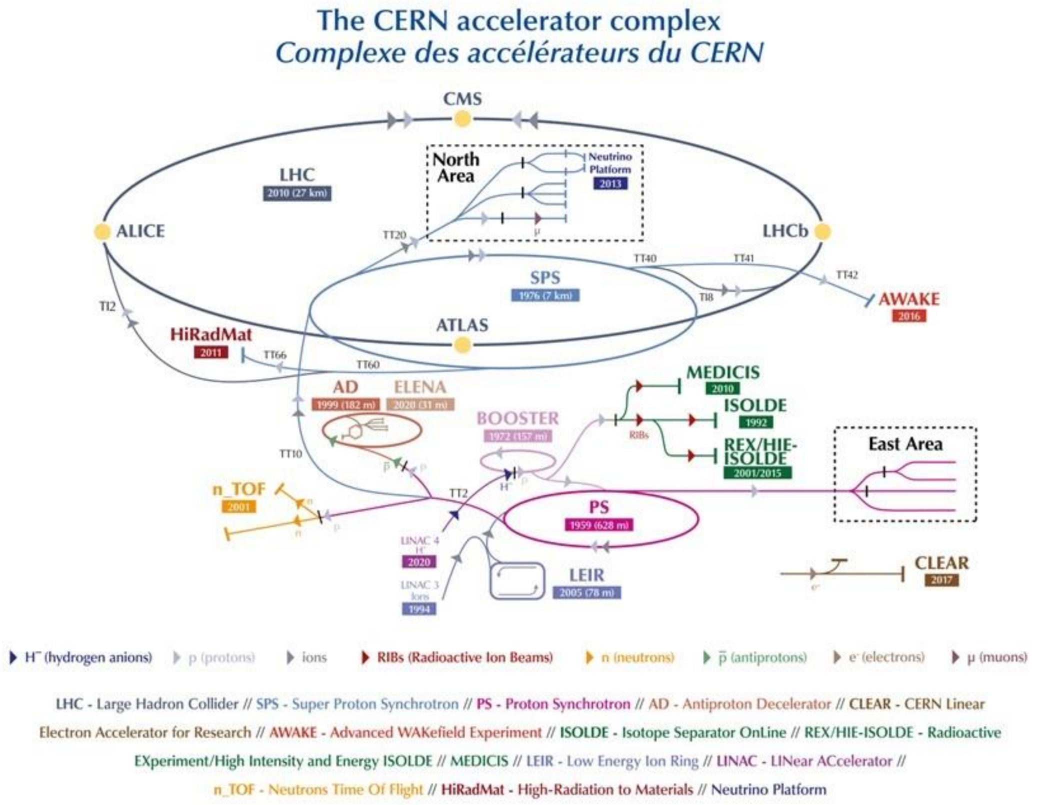
Created in 1954 in Geneva (CH) as "Science for Peace"

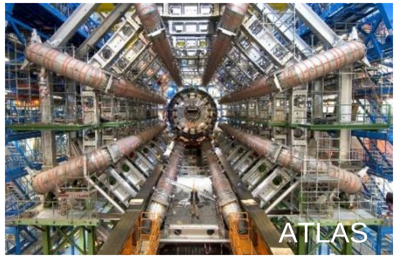
24 member states, 10 associate member states

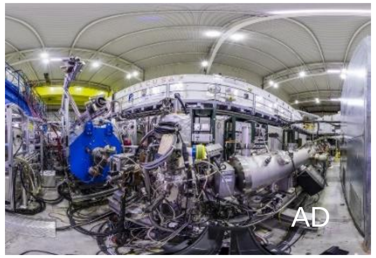
2'600 staff, 1'600 others & 12'500 users

1'300 MCHF annual budget (pro GDP)

CERN in brief







A very large technical site with a unique series of accelerators, detectors and computing serving particle physics towards high energies and diversity

The Large Hadron Collider and its experiments

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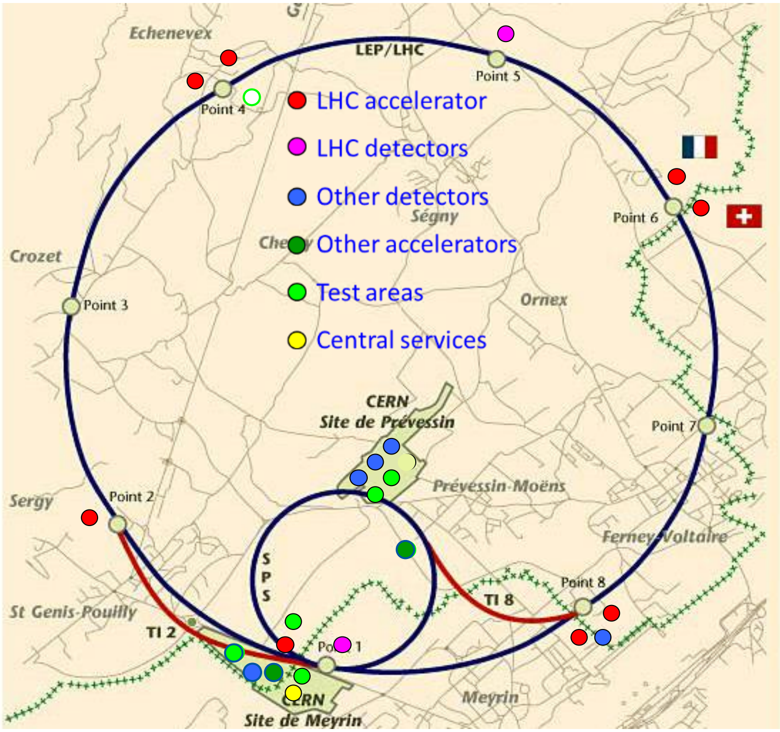
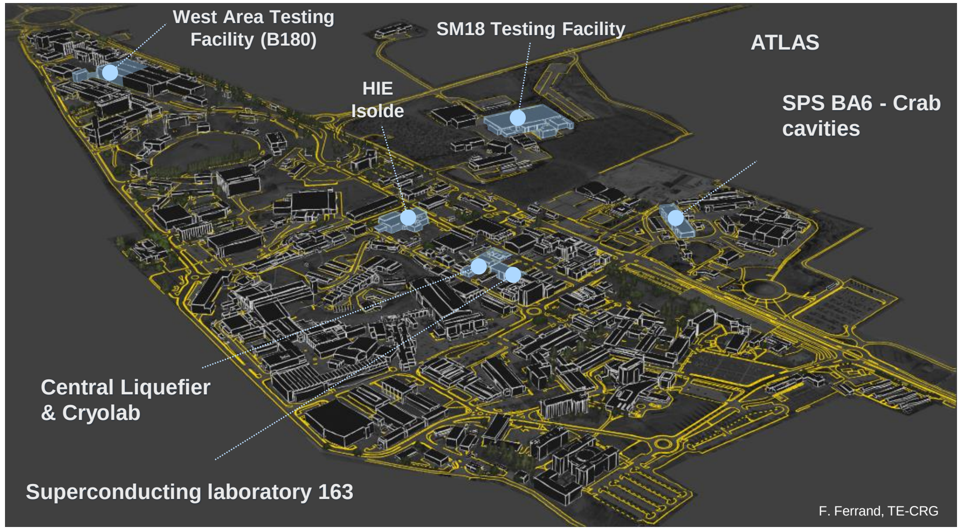
Cryogenics at CERN

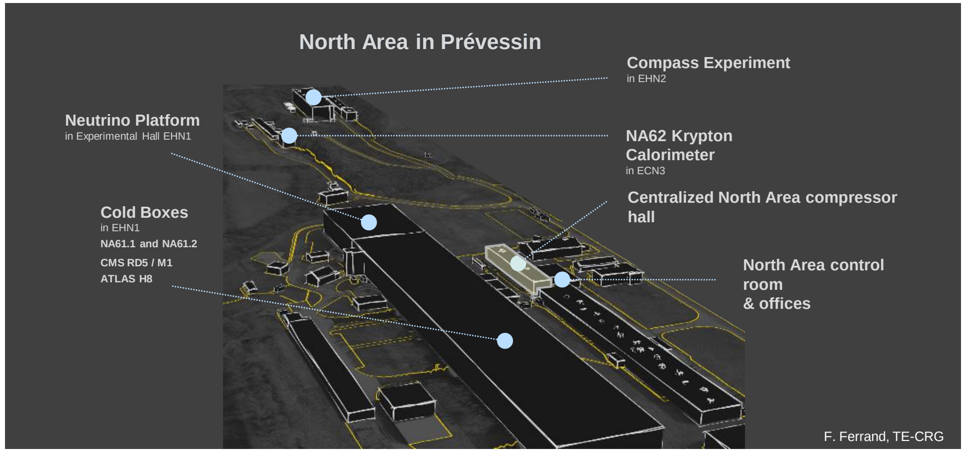
Cryogenics is a key enabling technology for CERN mission

- LHC
  - 8 cryoplants including 8 cold compression systems
  - 8 Cryogenic sectors
  - 56 DFBs , 5 SC links
- LHC detectors
  - ATLAS SR + MR, PCS, ANRS, cryogenic circulators
  - CMS
- SM18
  - 2 refrigerators/liquefiers
  - 2 cooldown-warmup units
  - Magnet test benches
  - RF test benches
  - HL-LHC IT String
- Meyrin
  - Central liquefier B165, Cryolab
  - Central purifier B253
  - B163
  - HIE ISOLDE
  - WAT/B180 (FAIR S-FRS tests)
- North Area
  - Vertex NA61.1, NA61.2
  - NA62
  - COMPASS/AMBER
  - ATLAS H8
  - CMS RD5
- SPS
  - BA6 (CC), BA4 (Coldex)



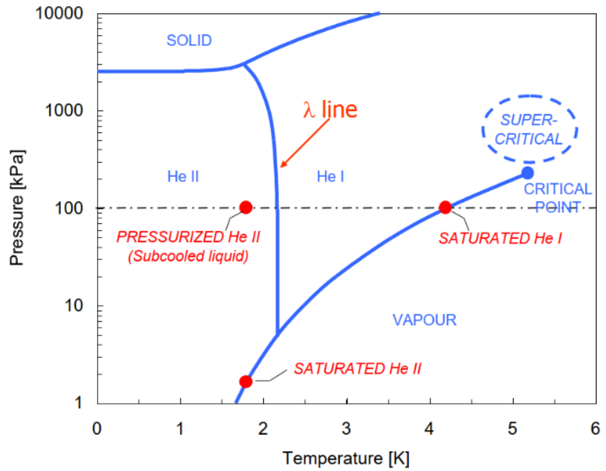
26 Helium cryoplants





Cryogenic fluids (helium, nitrogen, argon, krypton)

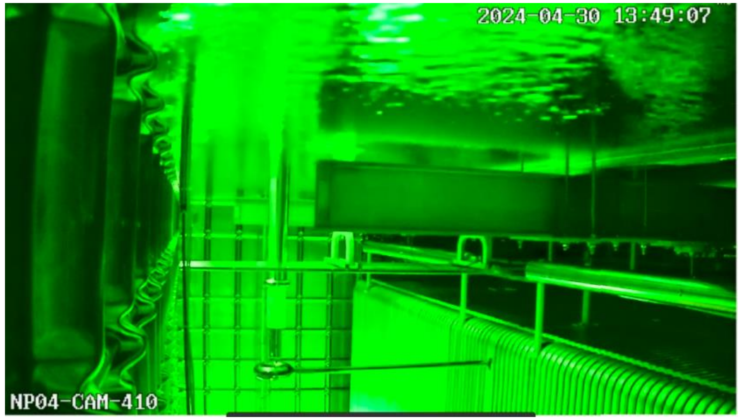
- **Helium inventory at CERN: 170 t (today) : needs to be managed !**
  - LHC (accelerator & detectors) helium full inventory: 136 t
  - Strategic permanent storage : 20 t
- Nitrogen liquid for LHC (accelerator & detectors) full cool down: 11’500 t
  (equivalent to 500 ISO-transportable containers delivered), normal consumption CERN wide about 6’000 t/year.
- Argon liquid for Neutrino platform and ATLAS calorimeter: up to 1’800 t
- Krypton liquid for NA62 calorimeter: 24 t (detector cryostat 30 years in continuou operation)
- Hydrogen small amount in targets



Phase diagram of helium < 6 K

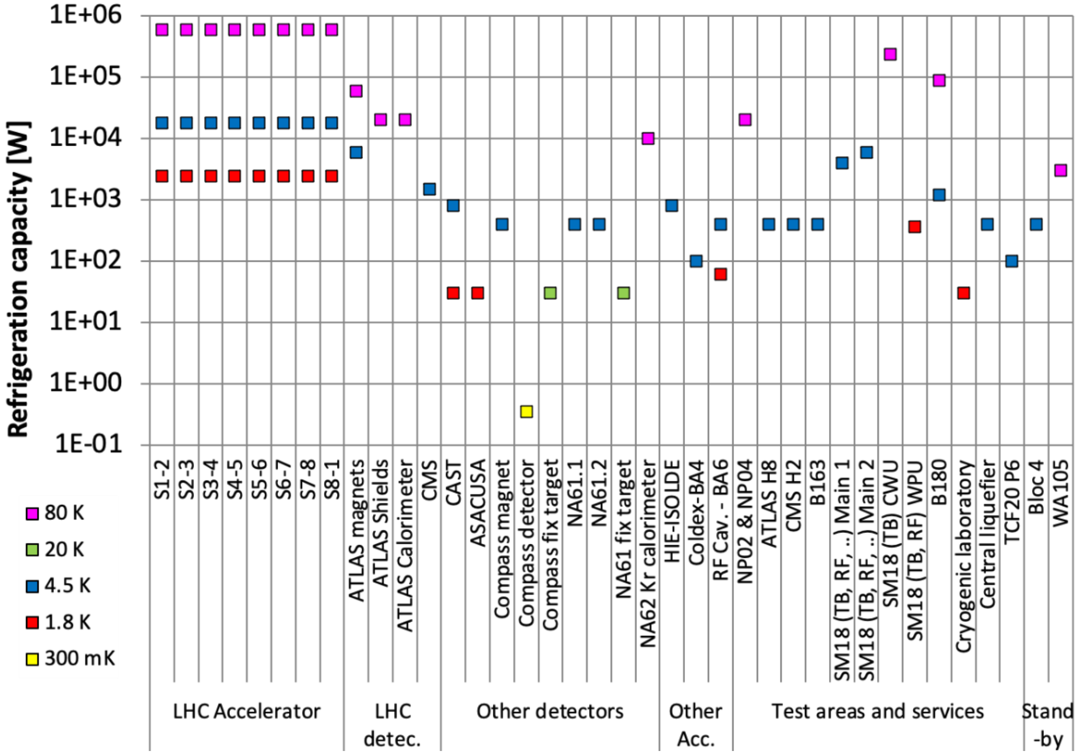
Characteristic temperatures of cryogenic fluids [K]

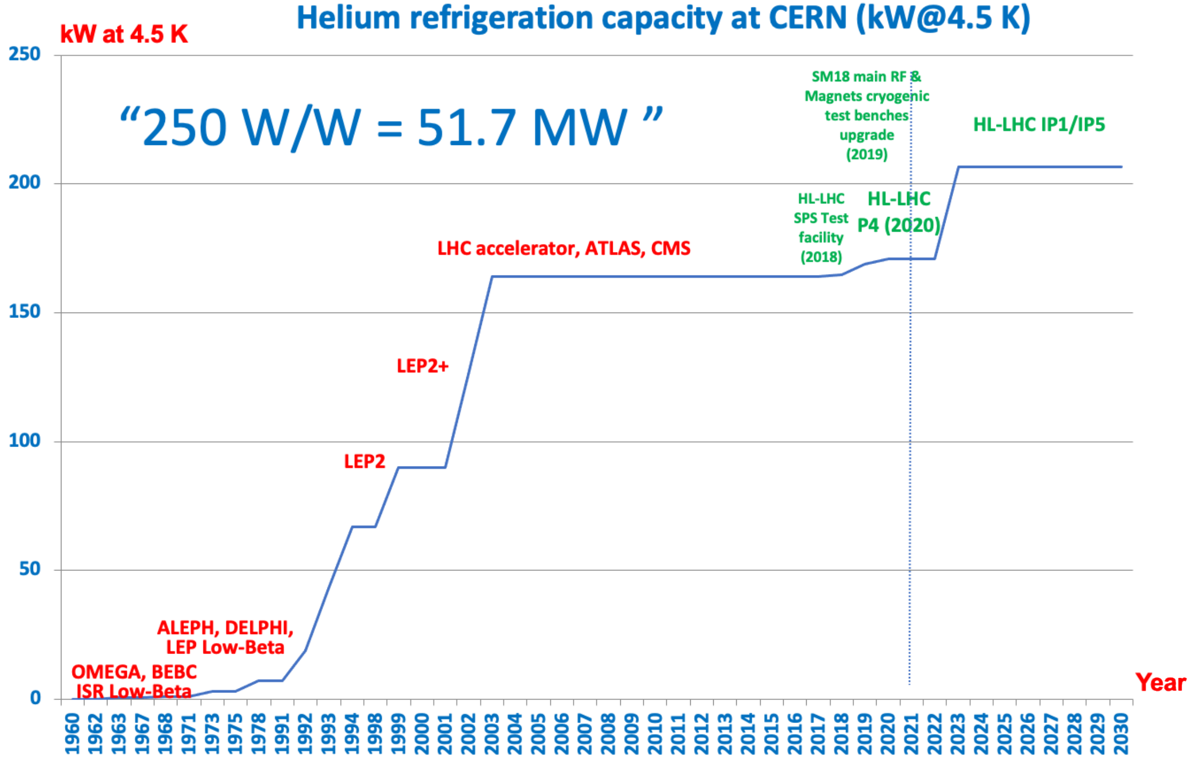
Fluid	Triple point	Normal boiling point	Critical point
Methane	90.7	111.6	190.5
Oxygen	54.4	90.2	154.6
Argon	83.8	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	2.2 (λ point)	4.2	5.2

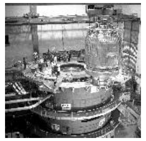


ProtoDUNE (NP04), liquid Argon submerged camera

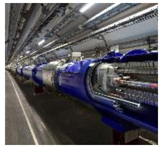
Cryogenic temperature levels and cooling power



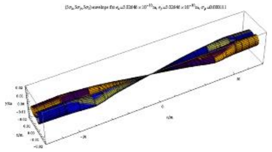



BEBC


LEP2


LHC


SM18


HL-LHC

HL-LHC P4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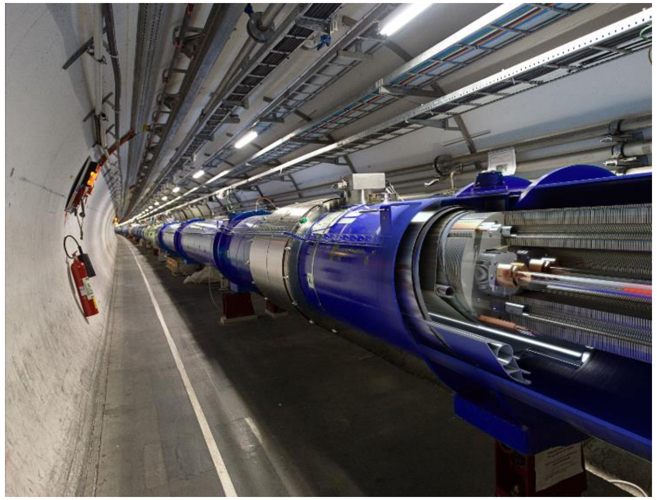
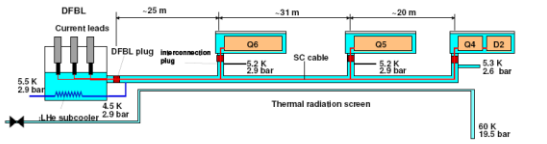
Helium Cryogenics at CERN (1/2) the LHC and its experiments

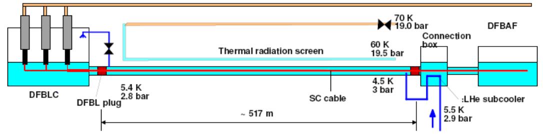
- LHC
  - 8 cryoplants
  - 8 Cryogenic sectors
  - 56 DFBs, 1200 CLs (with HTS), 5 SC links
- LHC detectors
  - ATLAS SR + MR, PCS, ANRS
  - CMS
- Instrumentation and control
  - > 30 000 I/O
  - > 5000 control loops



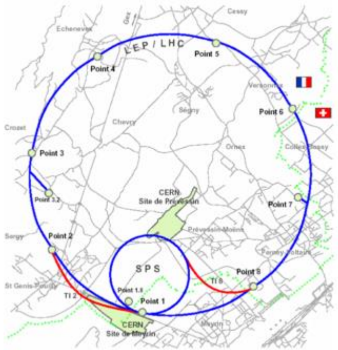
24 km of superconducting magnets (8.33T) @ 1.9K, 140t Helium

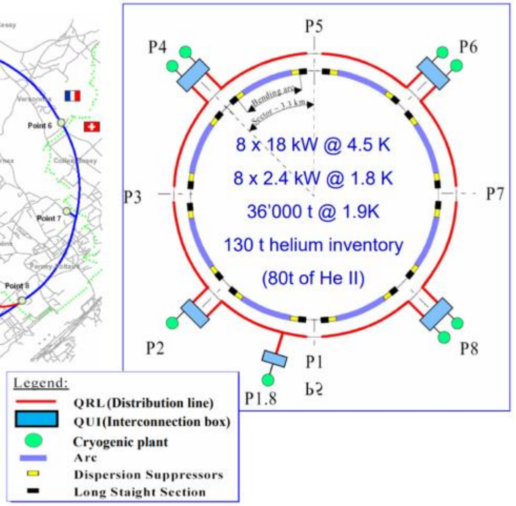
56 electrical feedboxes, 1200 current leads
120 A – 13 kA, > 3 MA total . Bi2223 HTS

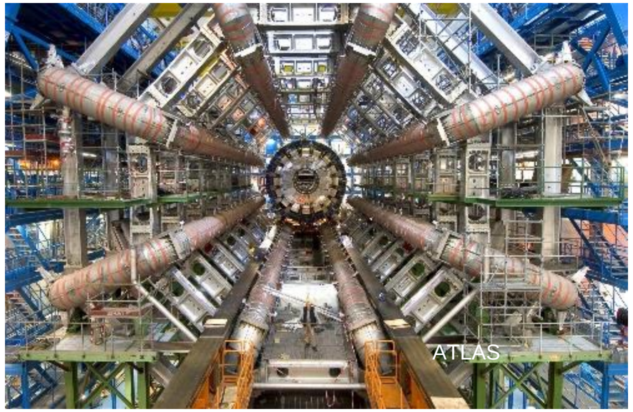




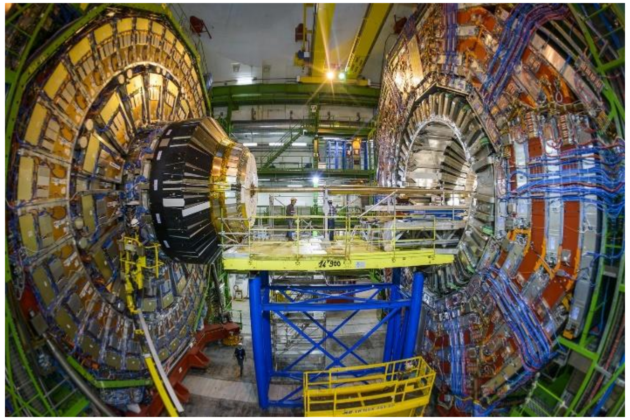
5 Superconducting Links : 4x 66 kA (60 m), (44x600A)
450 m (4.5 K – 5.5 K)







ATLAS, cooling at 4.5 K of the superconducting magnetic system (1'275 t of cold mass) and at 80 K to cool 90 m3 of liquid argon



CMS, cooling at 4.5 K of the superconducting solenoid (225 t of cold mass)

Helium Cryogenics at CERN (2/2)

CERN wide helium cryogenic systems for:

- Test benches for accelerator magnets, cables and wires, RF cavities
- Detectors' components tests (magnets and sub-detectors)
- Large magnetic spectrometers for fixed target physics experiments
- Cryogenic laboratory test bench facilities
- In situ helium liquefaction for users without dedicated cryogenic plant
- Wide temperature range and powers


HIE Isolde Cryo Modules


SPS BA4 COLDEX


SPS BA6 Crab Cavities

Central Liquefier

North Area


Vertical magnet tests in SM18


Horizontal magnet tests in SM18

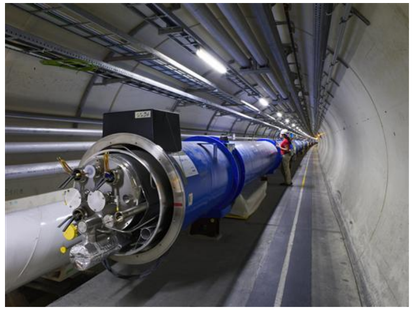

Cryogenic infrastructure in B180

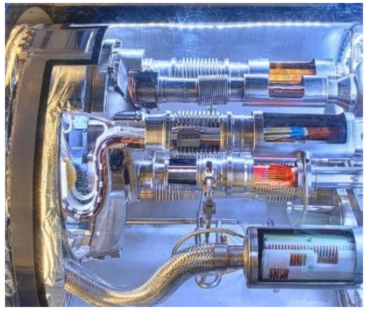
HL-LHC SC link tests in 2024 (courtesy A. Ballarino)

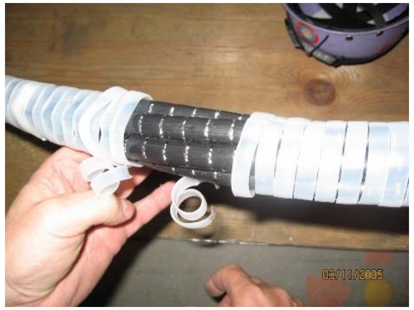

HL-LHC String: SC link and cryogenic distribution line

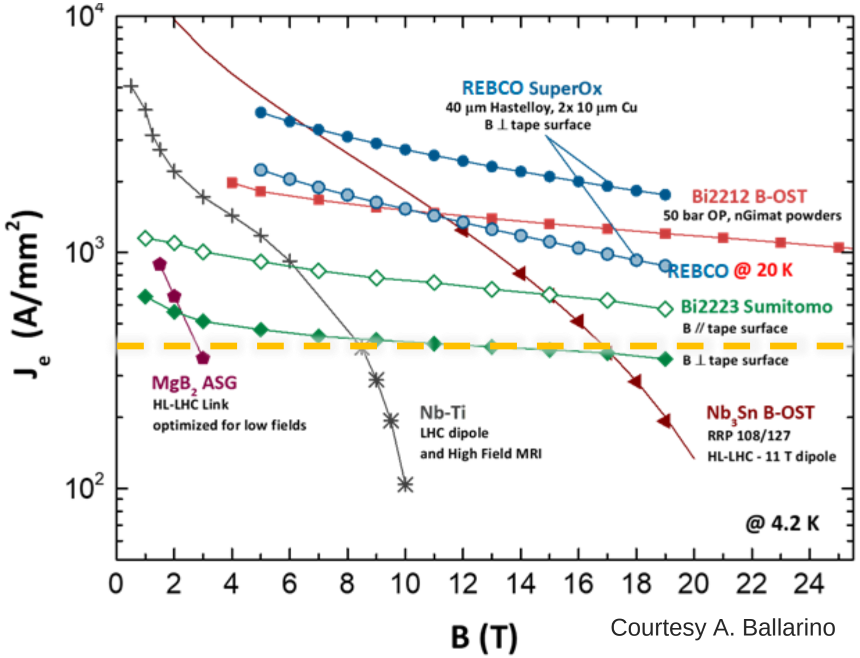
Helium cryogenics and superconductors

- LT superconductors cooling at 1.9 K (HeII) / 4.5 K (LHe) / 4.5 – 5.5 K (supercritical, LHC SC links)
- LHC HTS current leads in the range 4.5 K – 50 K
- Superconducting links for HL-LHC: MgB_2 4.5 – 20 K and REBCO 20 K – 60 K
- MgB_2 superferric magnet operating at 20 K


LHC dipole

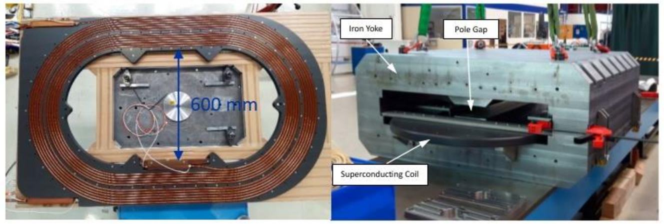

LHC magnet interconnection


NbTi cable of LHC SC link



Courtesy A. Ballarino

Nb3Sn magnet for HL-LHC (1.9 K)

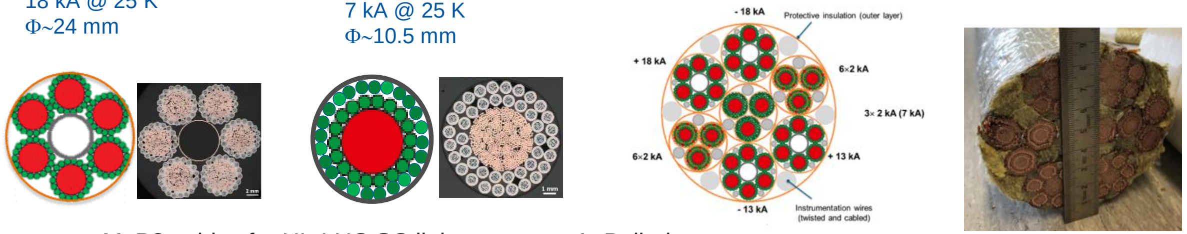


MgB_2 Superferric magnets operating at 20 K, courtesy A. Ballarino

18 kA @ 25 K
Φ~24 mm

7 kA @ 25 K
Φ~10.5 mm

120 kA @ 25 K, Φ~90 mm



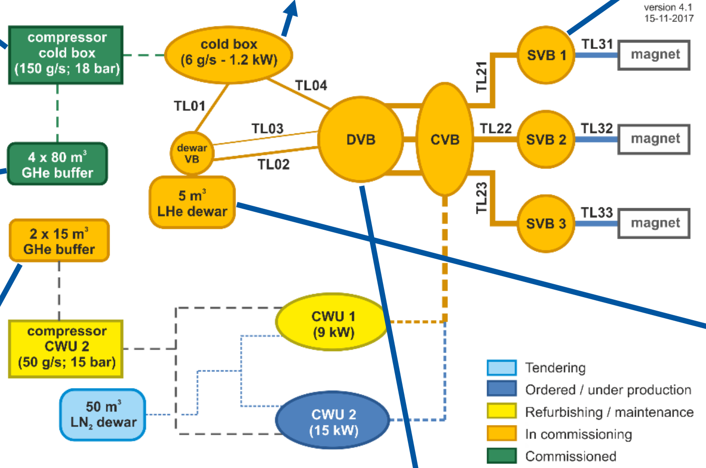
MgB2 cables for HL-LHC SC links, courtesy A. Ballarino


REBCO cable 2 kA @ 77 K

Systems of a cryogenic facility (WAT facility at CERN)

A cryogenic facility is made of many systems.

They must all operate together !



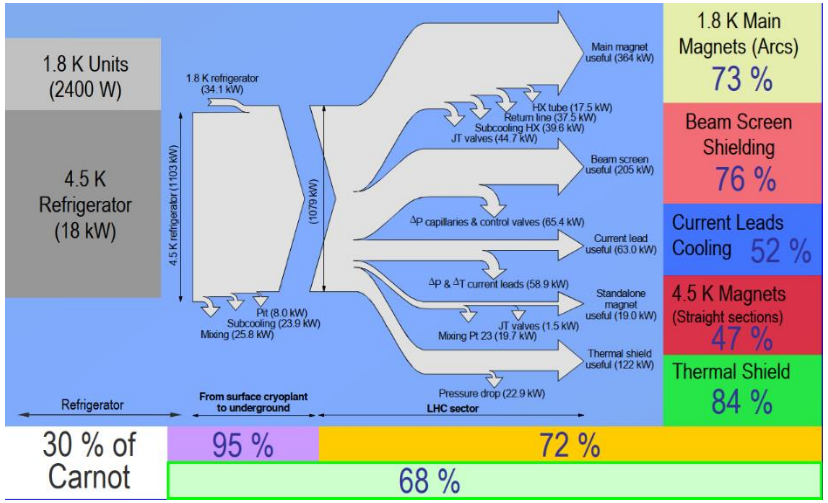
System design for cooling superconducting systems (1/2)

- A thorough <u>integrated system analysis </u>of the requirements and functionalities is mandatory. Design the superconducting system together with cryogenics.
- Selection of operating temperature, shielding and cooling technology is essential.
- Keep design of specific systems in-house. Careful identification of critical components.
- Include margins. But not margins on margins: manage the margins.
- Essential to study and design for nominal case <u>and non-nominal cases</u>. What happens if … ?

Energetic cost for heat loads and current leads

	Temp. Level	Equ. @4.5 [W]	Elec.power [W]*	Description
Heat loads "cost / Watt"	50 - 75 K	0.058	17.4	Heating of GHe from 50 K to 75 K (screen cooling, 18.5 bar)
	4.5 - 20 K	0.48	144	Heating of supercritical helium (3 bar)
	20 - 25 k	0.18	54	Typical MgB2 SC link
	4.5 K	1	300	Isothermal heating (T= 4.5 K) of saturated LHe (boiling)
	1.8 K	2.51	753	Isothermal heating (T= 4.5 K) of saturated LHeII
Current leads "cost" / kA	4.5 - 290 K	5.6	1680	Normal conducting current lead feeding in LHe (per kA)
	20 - 290 K	2.3	690	Current lead with feed at 20 K(value per kA)
	50 - 290 K	1.2	360	Current lead with feed at 50 K(value per kA)

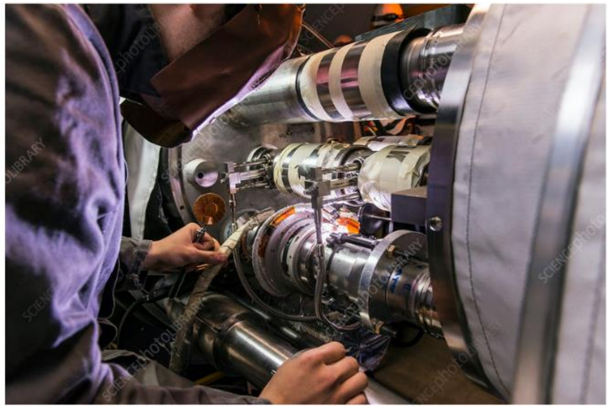
* assuming 250 W electric per watt isothermal @4.5 K



Exergy flow diagram for an LHC sector, courtesy S. Claudet, CERN

System design for cooling superconducting systems (2/2)

- Cryogenic and superconducting systems are complex and difficult to repair !
- Plan a robust design, capable to withstand any operational error or contamination (they do happen !)
- Identify critical components and where possible provide redundancy or replaceability
- Take into account cycling (thermal, electrical and mechanical)
- The energy needed to create a hole in cryostat is small (electrical arc).
- Maintainability / repairability shall be included as a core design requirement. Access to critical systems (splices, etc.), sectorization, maintenance of cryoplants, etc.
- And more …

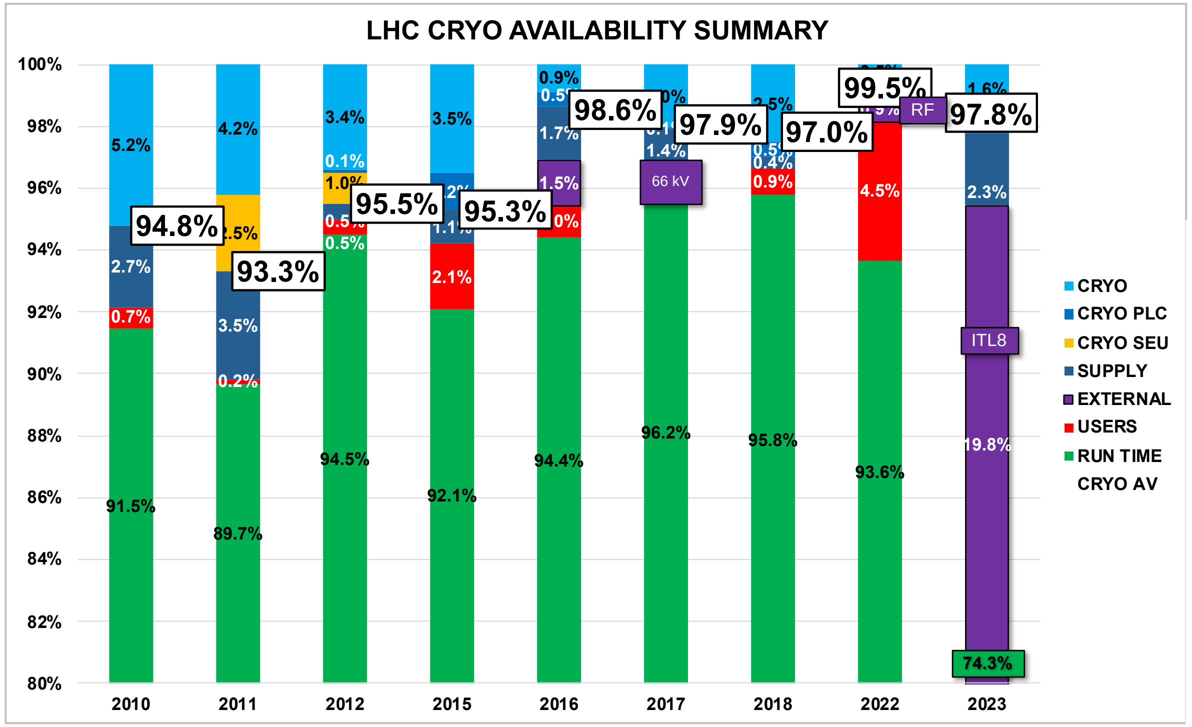


Consolidation of LHC splices during LS1

Repair of metallic compensator in the LHC cryogenic distribution line during LS2 (2020)

The availability challenge

- Complex Helium cryogenic facilities can operate with availability > 98% for a year !
- Cryogenic systems and machinery (cryoplants) need maintenance! Yearly technical stops and long shutdown approx. every 40’000 hours. Typical 26’000 hrs (for LS2).
- Spare parts analysis, planning and monitoring are essential!



LHC availability

Maintenance of LHC compressors

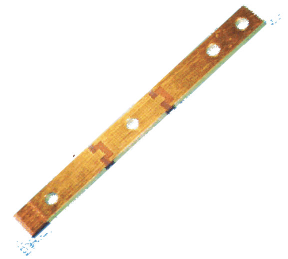
Replacing a cold compressor impeller in LHC

			July 2016 - June 2017		July 2017 - June 2018		July 2018 - June 2019	
			RUN	Availability	RUN	Availability	RUN	Availability
Meyrin	Central Liquefier 165	LHe Liquefier	7,715 h	99.5%	7,574 h	100.0%	6,023 h	98.8%
	Cryolab 163	LHe Liquefier	7,886 h	99.9%	7,308 h	96.2%	8,239 h	99.8%
SM18	Testing Facility	LHe Liquefier	7,630 h	99.4%	6,969 h	99.3%	5,793 h	99.6%
North Area	NA61.1	LHe Refrigerator	4,524 h	97.9%	4,115 h	99.5%	1,772 h	91.9%
	NA61.2	LHe Refrigerator	4,657 h	99.7%	4,166 h	99.6%	1,888 h	96.4%
	ATLAS H8	LHe Refrigerator			2,154 h	99.9%	1,716 h	93.8%
	COMPASS	LHe Refrigerator			2,652 h	100.0%	3,739 h	99.3%
	CMS RD5	LHe Refrigerator	4,559 h	98.8%	3,735 h	92.8%		
	NA62	LKr Calorimiter	8,760 h	99.9%	8,760 h	100.0%	8,760 h	100.0%
Isolde accelerator	HIE-Isolde	LHe Refrigerator			6,207 h	99.6%	3,825 h	97.9%
SPS accelerator	BA4 Coldex	LHe Refrigerator	1,680 h		4,488 h		3,720 h	
	BA6 RF Cavity test	LHe Refrigerator					2,952 h	
LHC Point 8	CAST	LHe Refrigerator			3,755 h	97.3%	2,275 h	95.1%
Neutrino	NP04	LAr Calorimiter					6,168 h	
	NP02	LAr Calorimiter						
Total cumulated running hours			47,411 h		61,883 h		56,870 h	

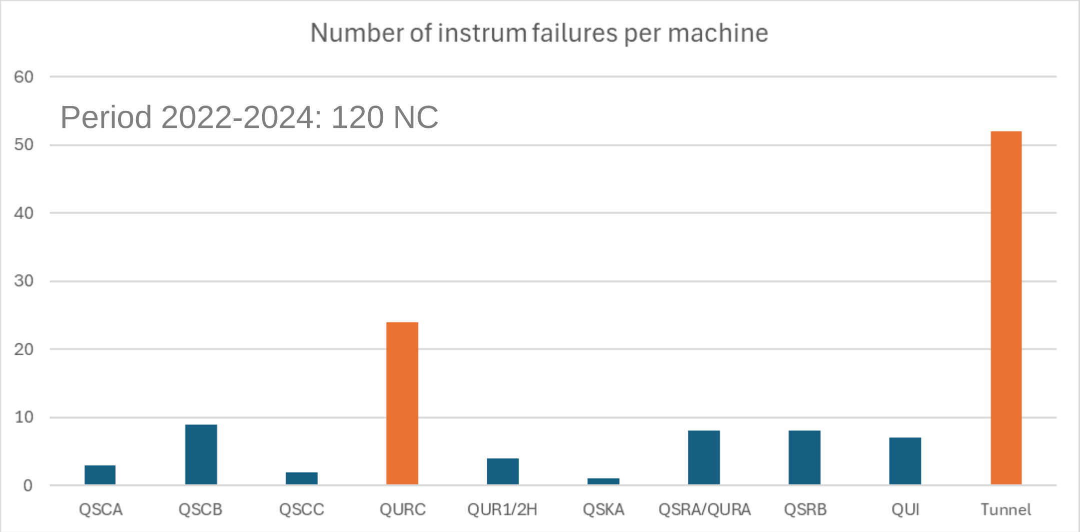
Non-LHC facilities availability

Instrumentation and control

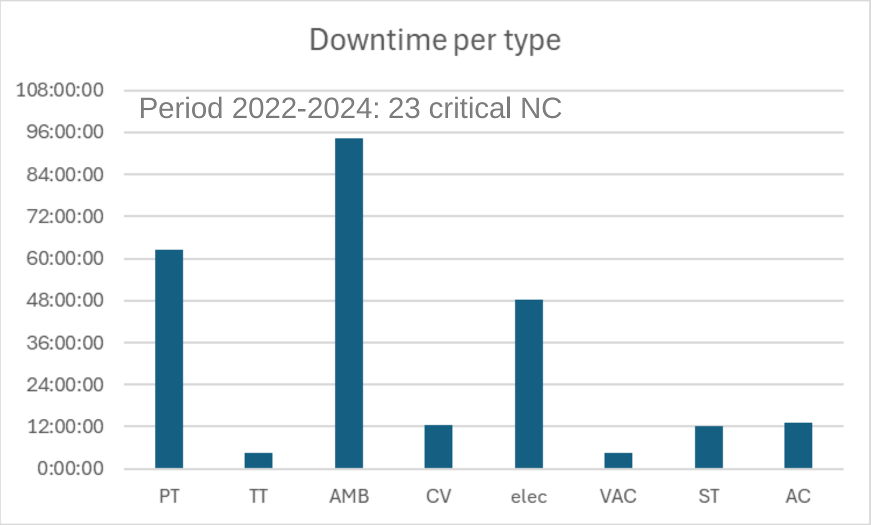
- The total system availability depends on the weakest and sometime simplest components (not valid only for cryogenics!)
- Redundancy and replaceability for most critical components is highly desirable!
- Validation program necessary for non-replaceable (of very difficult to repair) sensors (e.f. Temp sensors)
- It is possible to achieve >98 % availability with > 30’000 I/O, thousands of valves, >5000 control loops, 100 PLCs, etc.
- For long operation (>10 years), aging and obsolescence need to be taken into account. For example: control PLC “EoL” = 15/20y, electrical cabinet “EoL”= 25y



CERN developed mounting plate for vacuum side T sensors



Instrumentation failure per LHC system 2022-2024, courtesy B. Bradu, CERN



Critical NC causing LHC machine downtime per type, courtesy B. Bradu, CERN

Availability: the warm side

Don’t underestimate the impact of more «conventional» components

38 Cryo plants: Capacity@4.5K from 100W to 18kW, Total capacity: 171kW @4.5 K;

94 Helium Screw Compressors: from 110kW to 1876kW;

14 Helium Piston Compressors: from 14bar to 250bar;

107 Oil pumps in operation

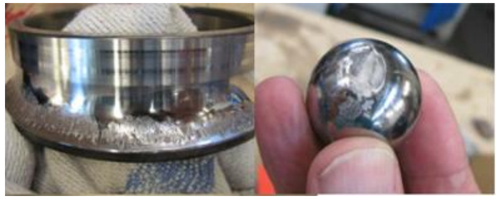
133 Gas Helium Pressure Vessels: From 15 m^3 to 250 m^3 ;

54 High Pressure Gas Cylinders: from 0.8 m^3 to 3 m^3 ;

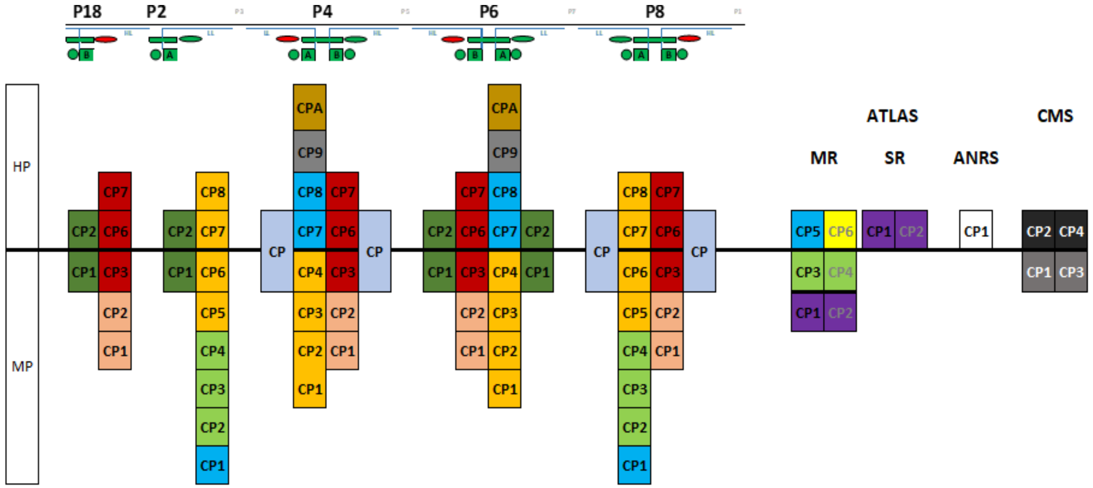
- Rotating room temperature machinery can be a significant cause of non-availability.
- Identify and take the necessary measures for “cold “ or “hot” spares.
- Preventive maintenance and monitoring!

Acoustic emission requalification of pressure vessels

LHC compressor hall



Damaged ball bearing



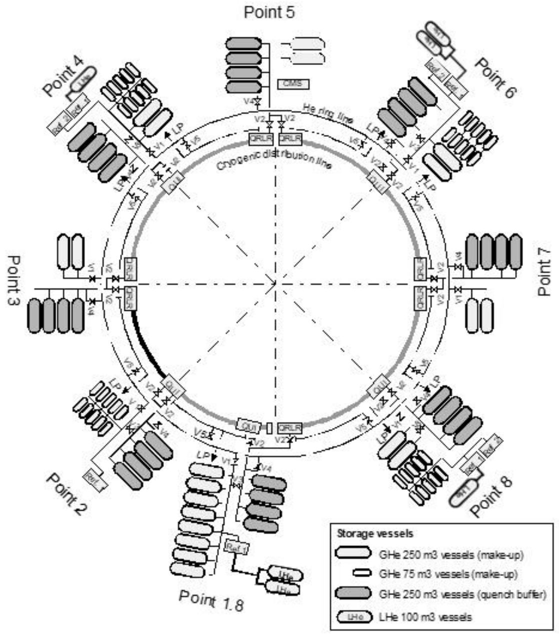
Type of compessors for the LHC (each color is a different model)

Managing helium

- Helium is non-renewable. Losses happen !
- Helium is mandatory for cryogenics below 20 K
- Annual production (2023) approx. 28’000 T but recent supply crisis with large price variation. Demand is expected to increase.
- Save, plan, manage when needed

For **LHC machine** constant effort to reduce losses showed significant results over the past 15 years

LHC Inventory 140 to 150 T
<10% of losses for the LHC machine



Gaseous helium storage 250m^3

Liquid helium storage 250m^3

→ Gaseous storage **15’200 m^3 = 44 tons**

→ Liquid storage **720 m^3 = 90 tons**

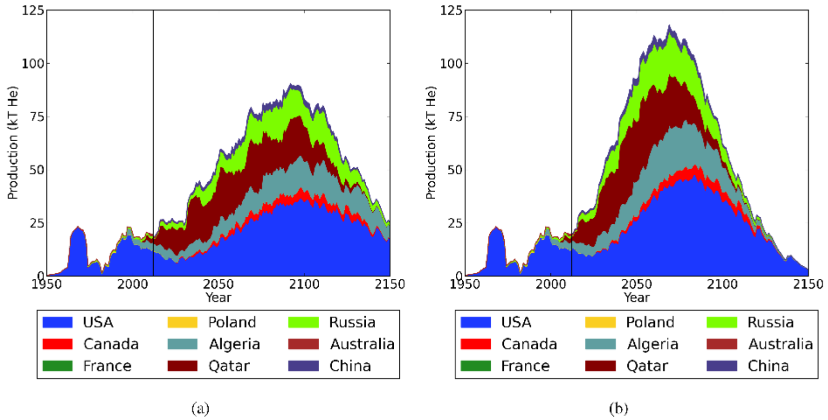
Courtesy F. Ferrand, CERN

Helium: tentative forecast for the next century ?

Theoretical exercise with high level of uncertainty

Long term projections are risky, but some models are published based on exponential decrease model:

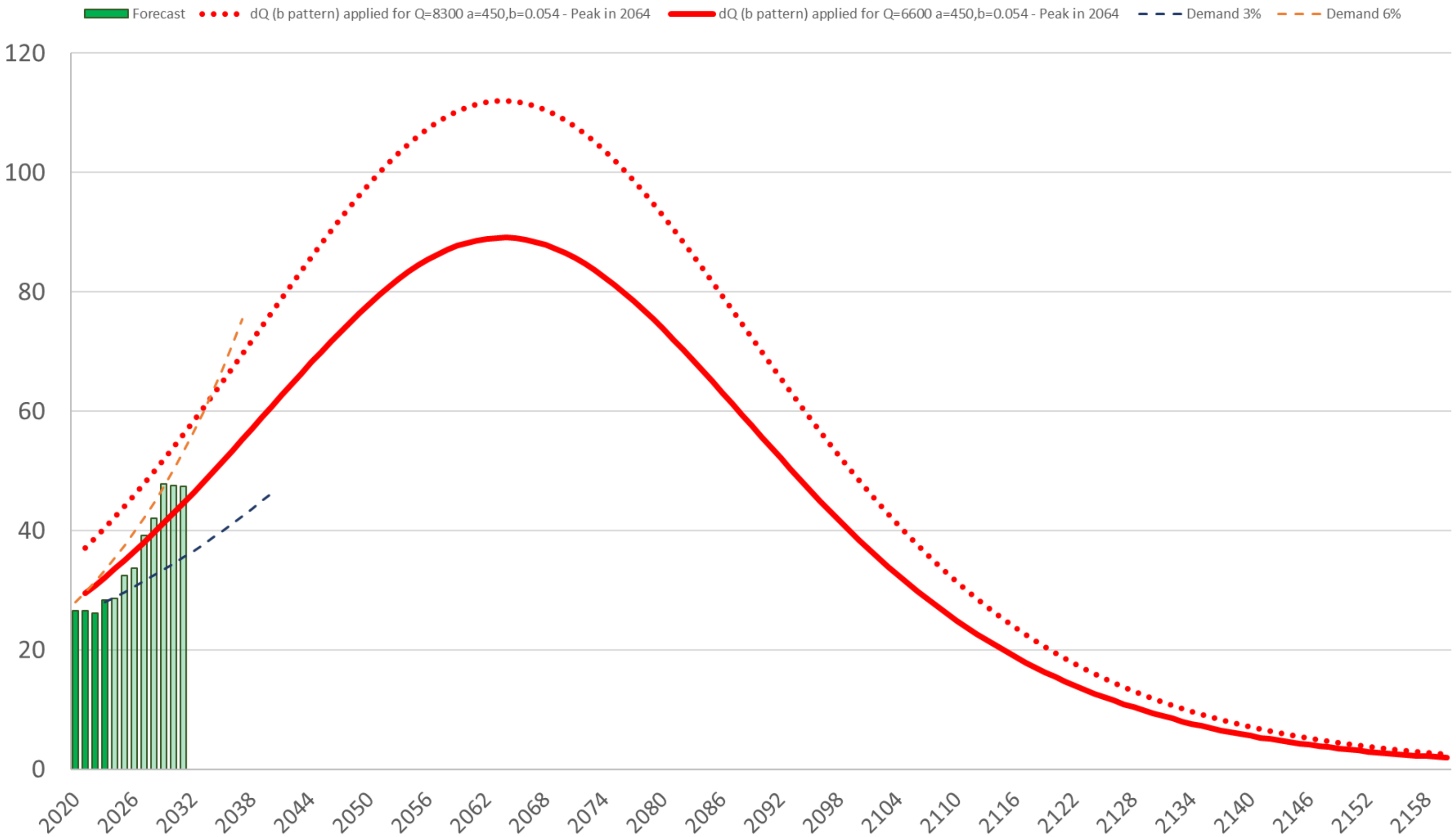
$$Q(t) = \frac{Q_{\max}}{1 + ae^{-bt}}$$



Source Minerals 2014 by Steve Mohr and James Ward
based on WW estimated reserve of 8'300 Kt

"The elephants" behind the figures:

- To obtain helium as a by-product, LNG must be extracted from the relevant sources. How does this align with the current fossil fuel trajectory?
- Without a business model that justifies investment in helium liquefaction at the source, there is a high risk of losing the molecules anyway.



Exponential decrease model (b) compared to production capacity forecast

Slide Courtesy F. Ferrand, CERN

Summary

- CERN has designed, installed and operates a large number of helium cryogenic systems for superconducting devices
- Very diverse superconducting systems are operated at CERN in temperatures ranging from 1.9 K to 50 K
- Very complex cryogenic superconducting systems can achieve availability > 98 %
- High performance and availability requires considering all the aspects of a system at design time and then very organized operation and maintenance
- Performance and availability improvements are fed back the design of new systems