# CERN(LHC acc.) *vs ILC Japan*
# Cryogenic Systems

**CFS Workshop at CERN**

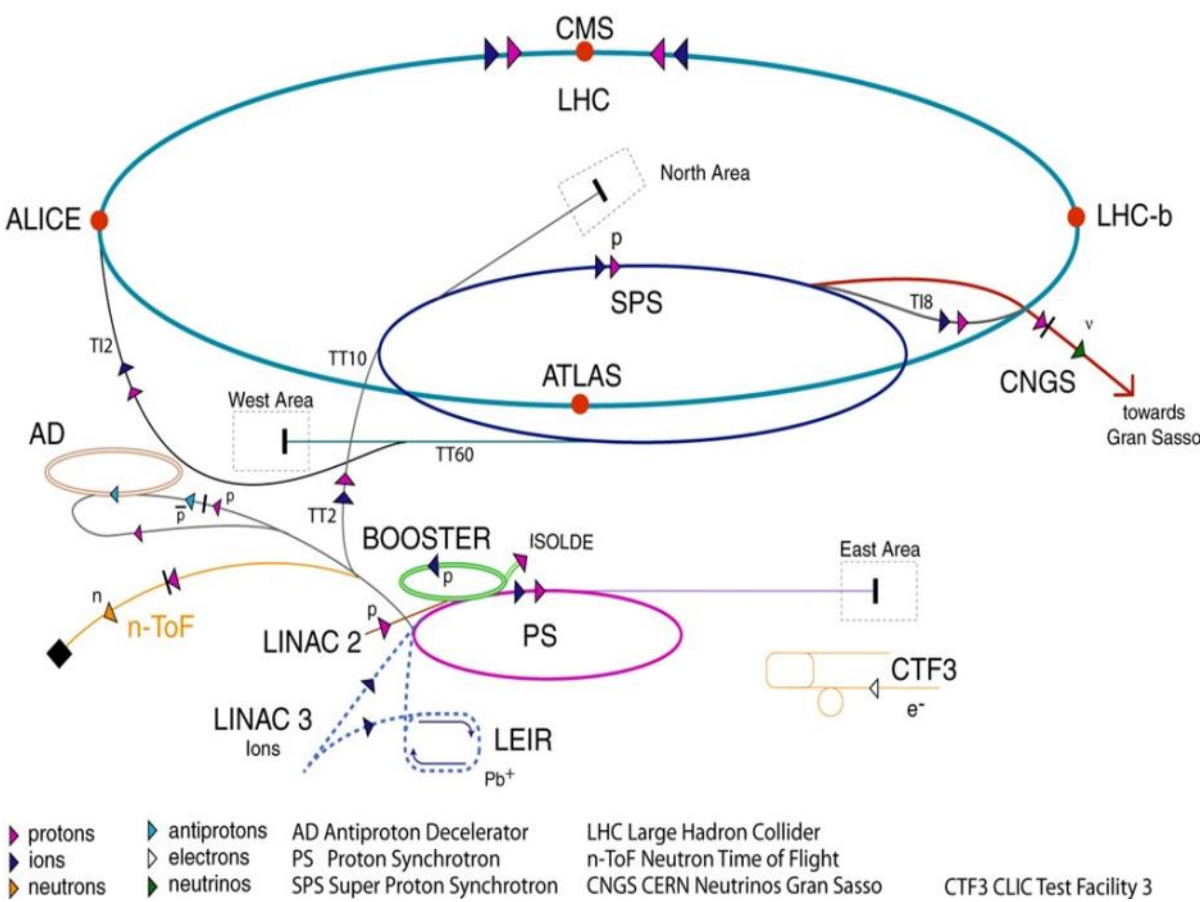
27-28 August 2015

D. Delikaris
Technology Department, Cryogenics Group
CERN

# Agenda

- The CERN Accelerators Complex
- Helium Refrigeration Capacity at CERN
- Main Use of Helium Cryogenics
- The CERN LHC Accelerator Cryogenics
  - Cryogenic system layout, Constraints, Architecture, Cooling principle, Cryogen Distribution Lines & Measured Heat Loads, 4.5 K and 1.8 K Cryogenic Plants
- Management of Cryogen at CERN
  - Storage, Distribution
- Brief report from the first 3-years LHC Physics Run
  - Operation, Cryogen Inventory Management
- Conclusions (Summary) High objective: attempt to be useful to ILC strategic decisions on cryogenic system & cryogen storage implementation

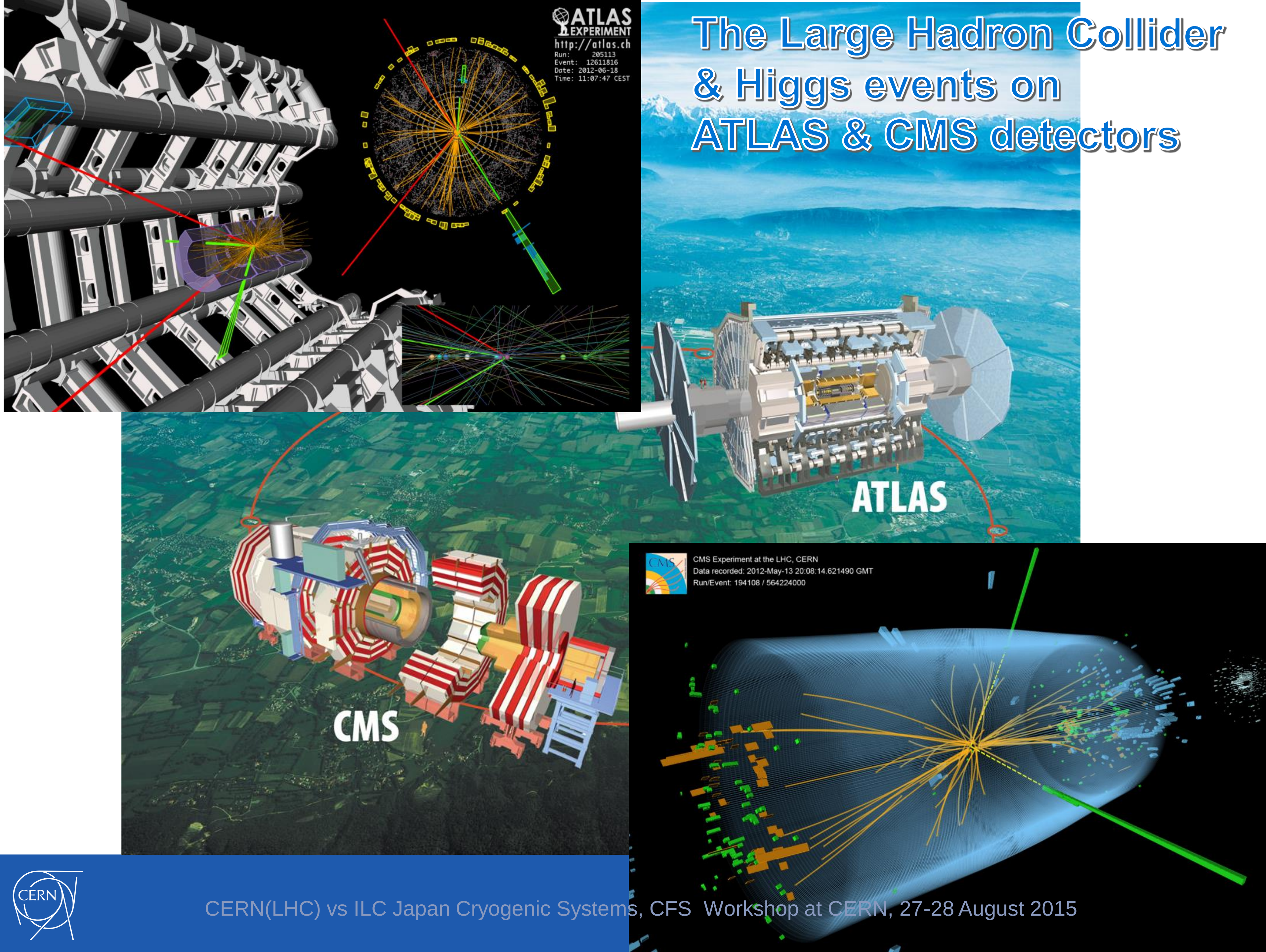
# CERN: Accelerators Complex





CERN AC - F116

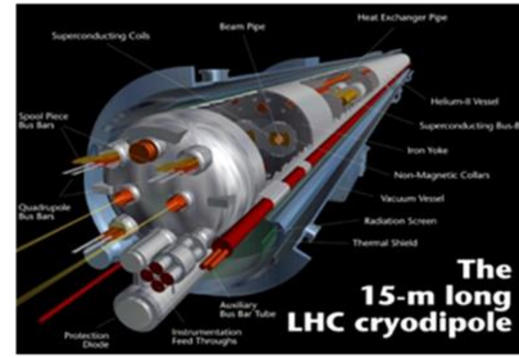
# The Large Hadron Collider & Higgs events on ATLAS & CMS detectors



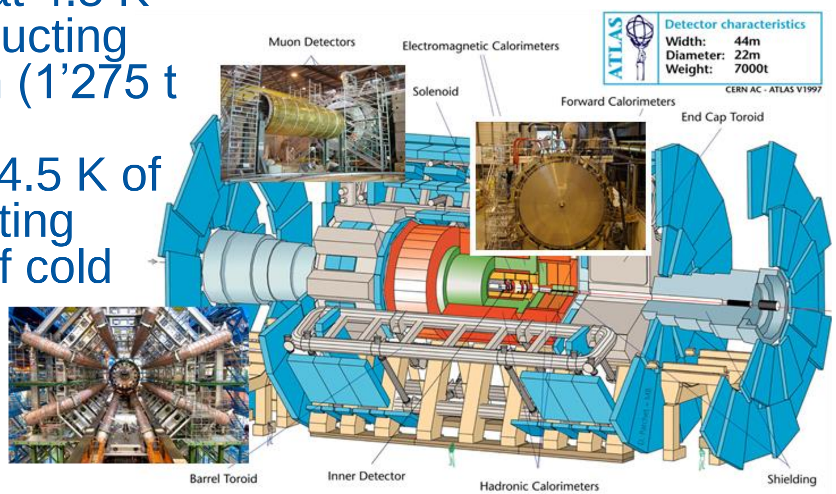
# The Long Shutdown 1(2013-2014) for Accelerator & Detectors Consolidation & Maintenance was successfully completed;
# The LHC in now at 1.9 K and in Operation for Physics Run 2 period (2015-2018)

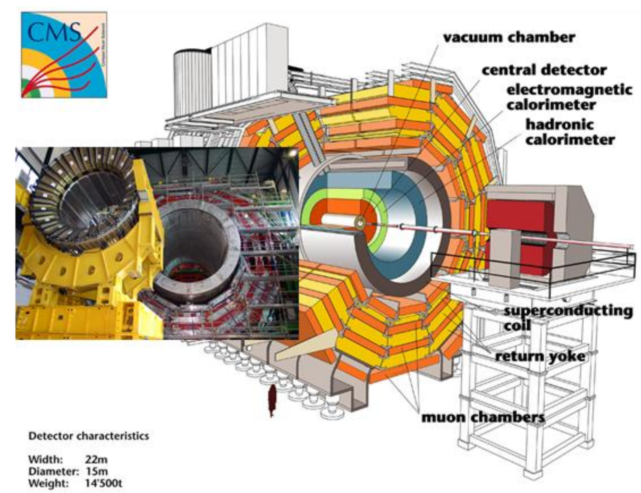
# Use of Helium Cryogenics (1/1)

**LHC accelerator**
Cooling at 1.9 K of the superconducting magnets (36'000 t of cold mass) distributed over the 26.7 km underground accelerator




**LHC physics detectors**
ATLAS, cooling at 4.5 K of the superconducting magnetic system (1'275 t of cold mass)
CMS, cooling at 4.5 K of the superconducting solenoid (225 t of cold mass)



# Use of Helium Cryogenics (2/2)

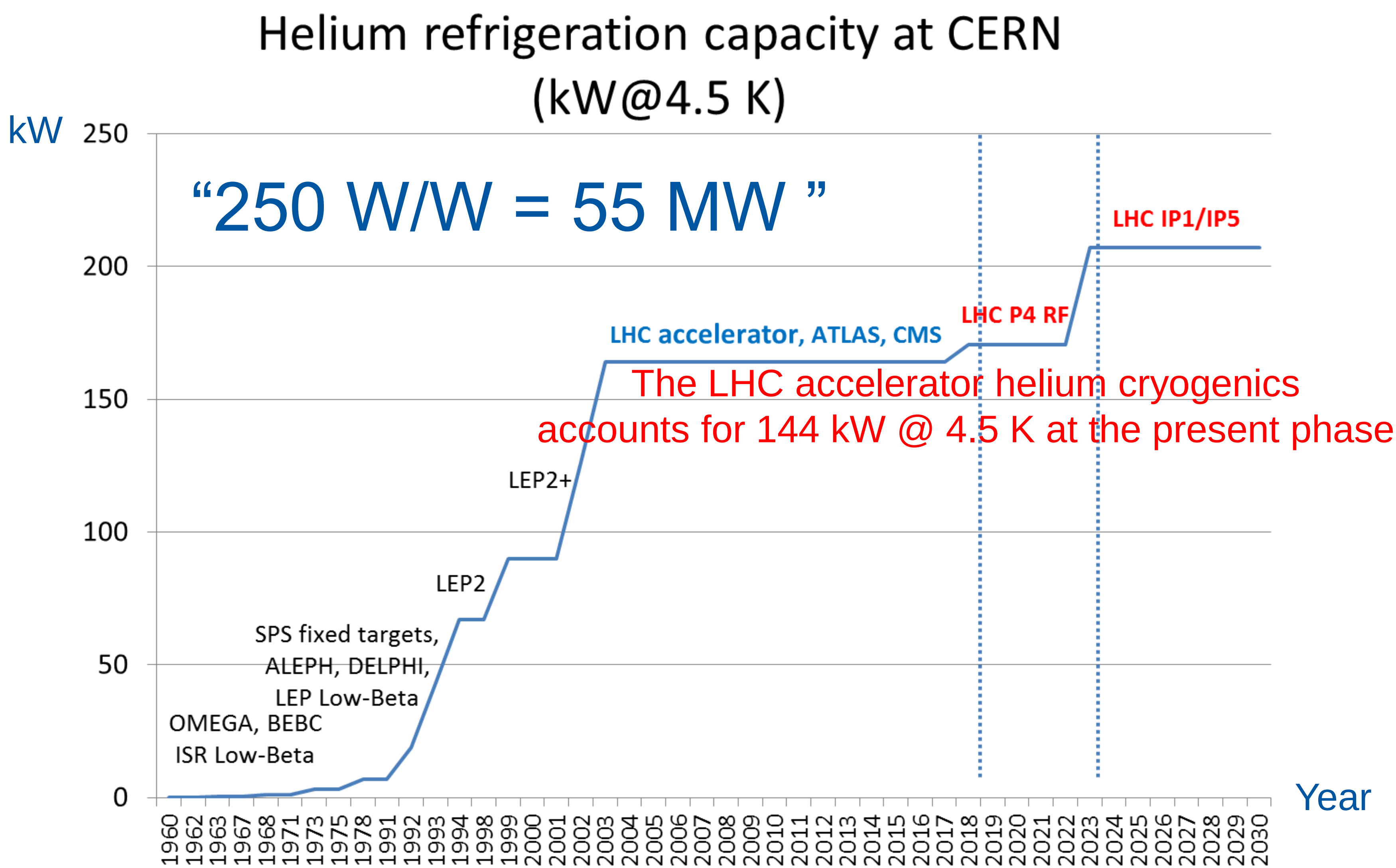
CERN wide helium refrigeration systems for:

- ✓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

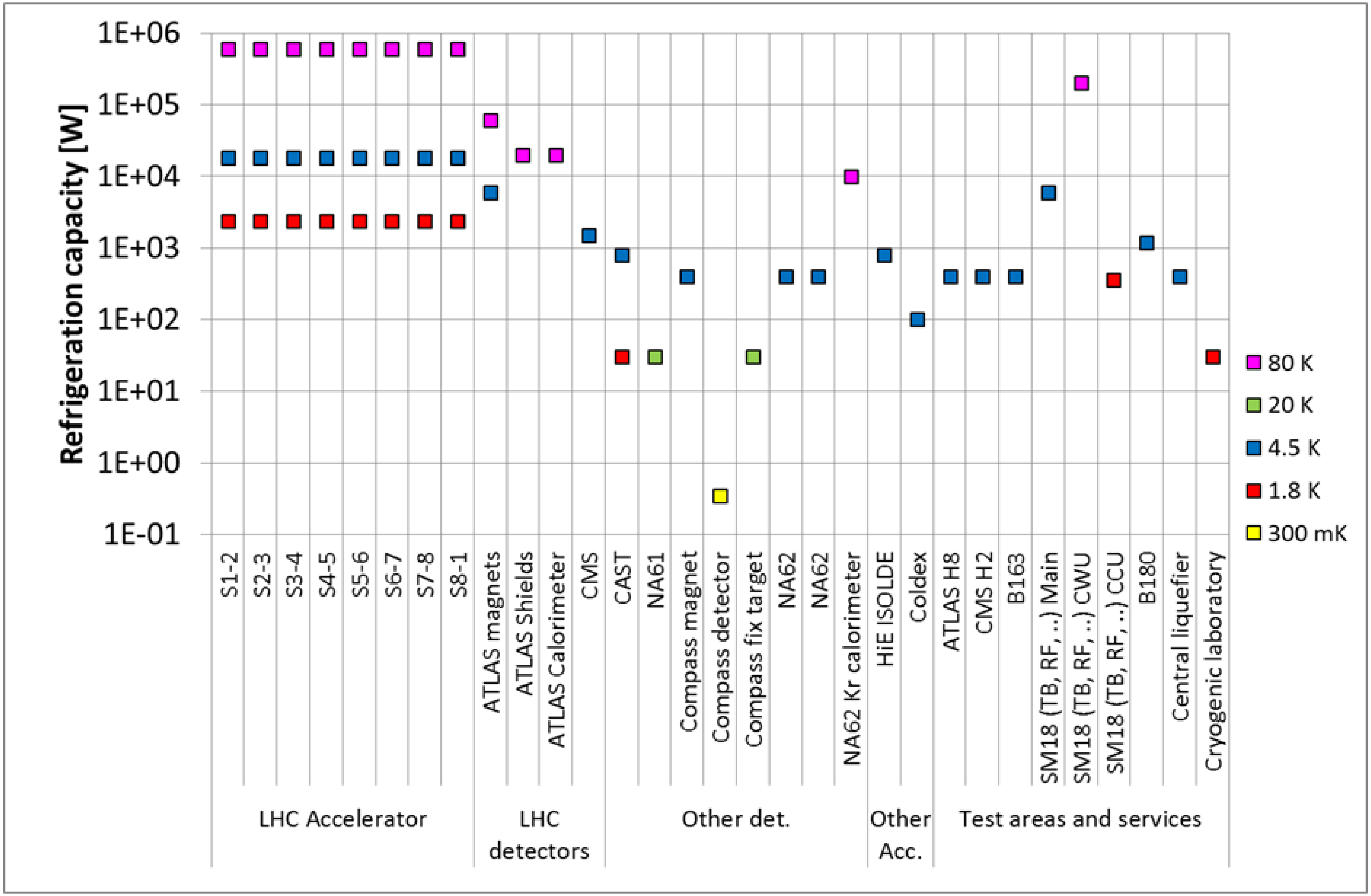




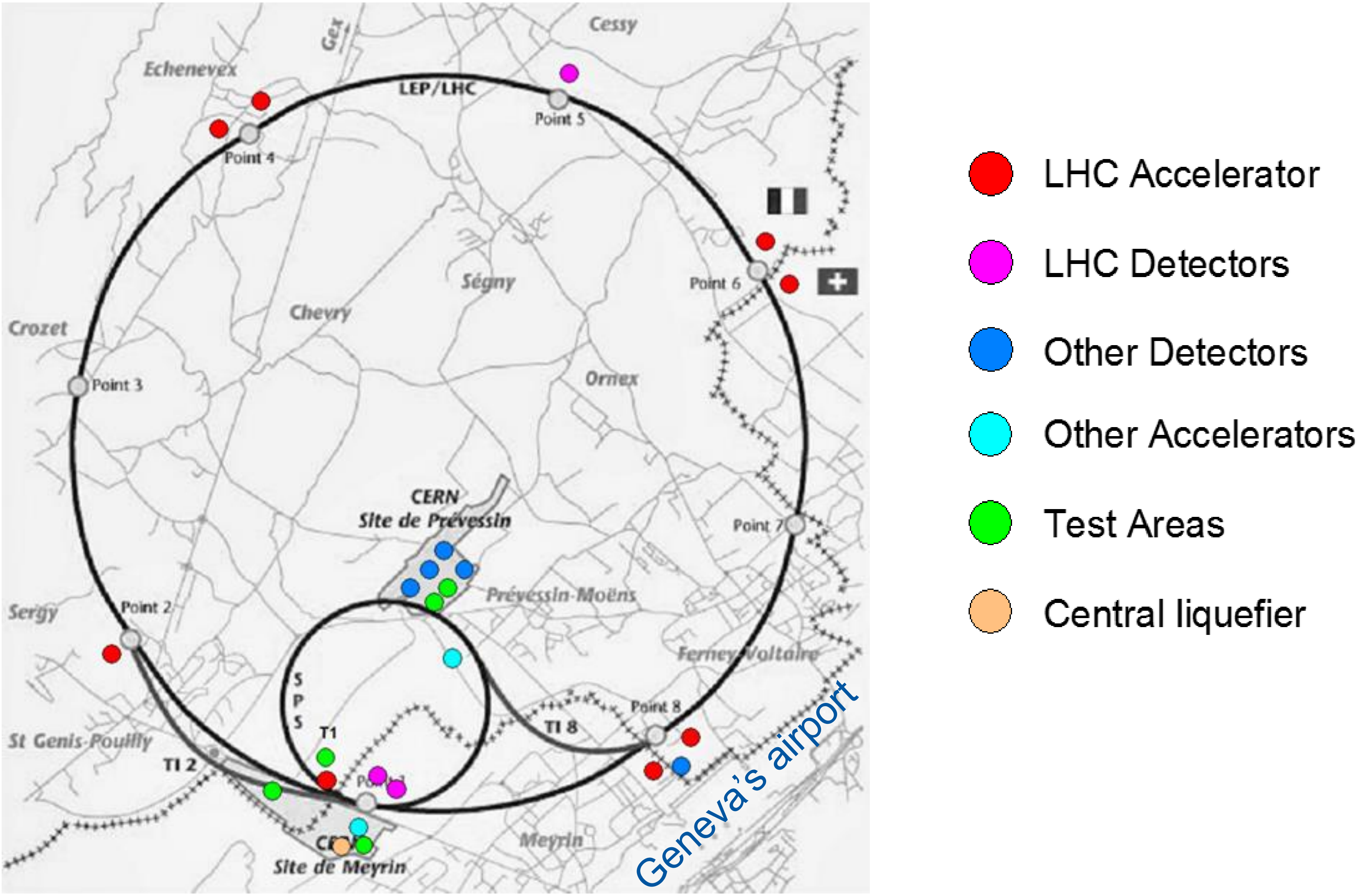

# Cryogenic power at CERN (1/2)



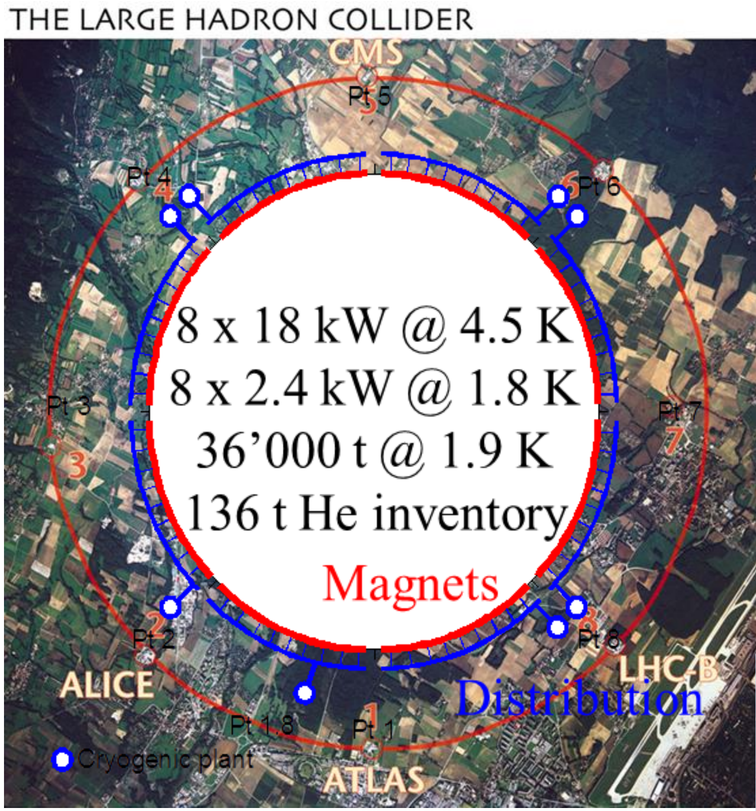
# Cryogenic power at CERN (2/2)

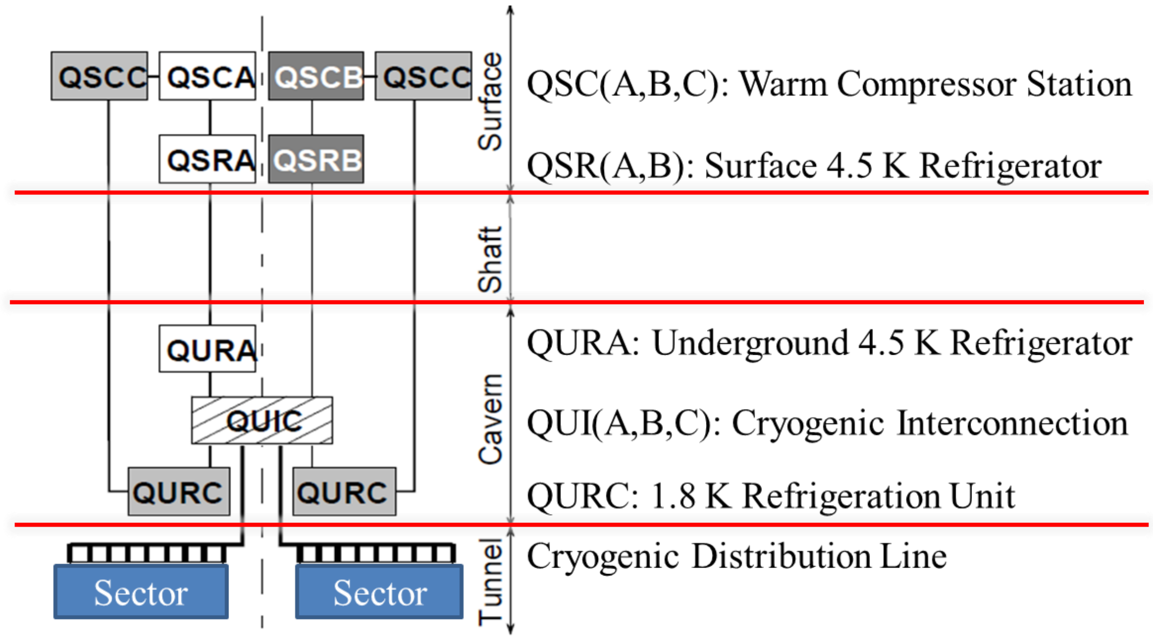


# Cryogenic Installations at CERN



# The LHC Cryogenic System



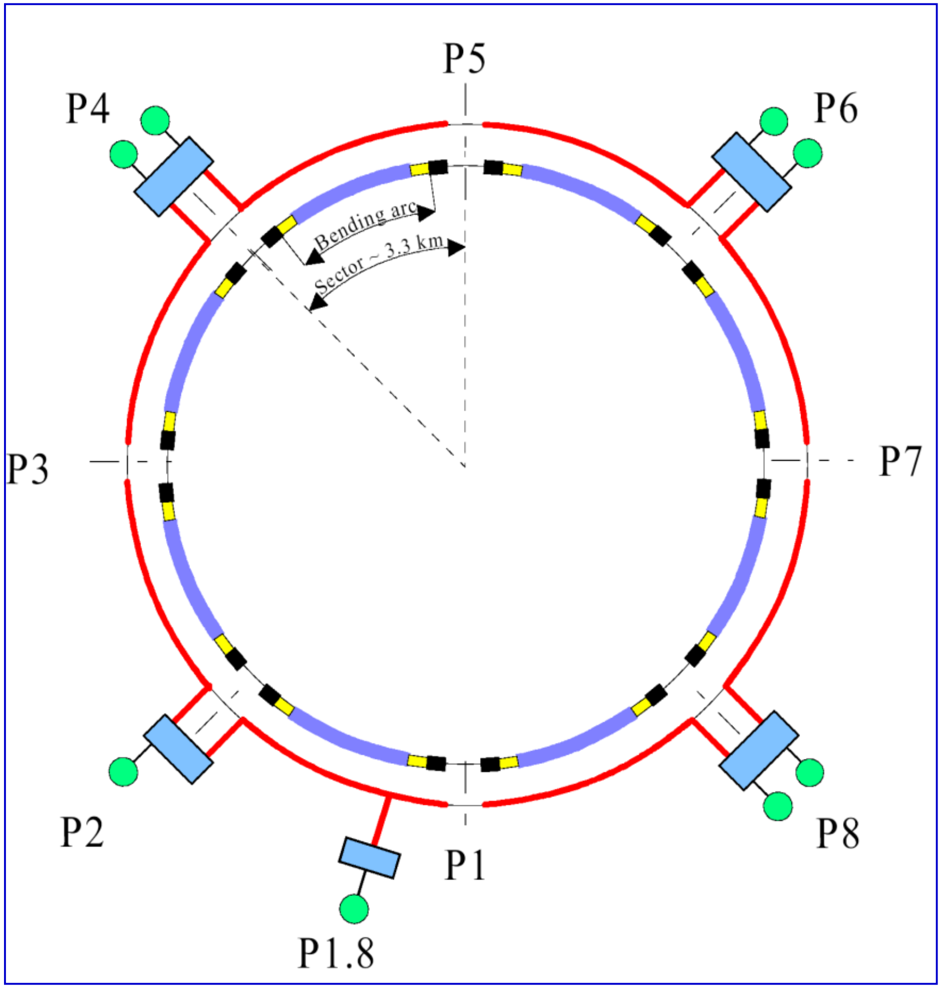




The LHC cryogenic system consists of 8 cryogenically independent sectors, each 3.3 km long, all cooled and operated at 1.9 K

| Main cryogenic components | Inventory |
|---|---|
| Helium screw compressors | 64 |
| Cold compressors | 28 |
| Expansion turbines | 74 |
| I/O signals | 60’000 |
| PLC | 120 |
| PID control loops | 4’000 |

| CAMMS data | LHC Cryogenic System |
|---|---|
| Referenced equipment | 21’000 |
| Referenced spare parts | 4’200 |
| Stored references | 3’100 |
| Individual materials | 62’000 |
| Maintenance tasks | 320 |

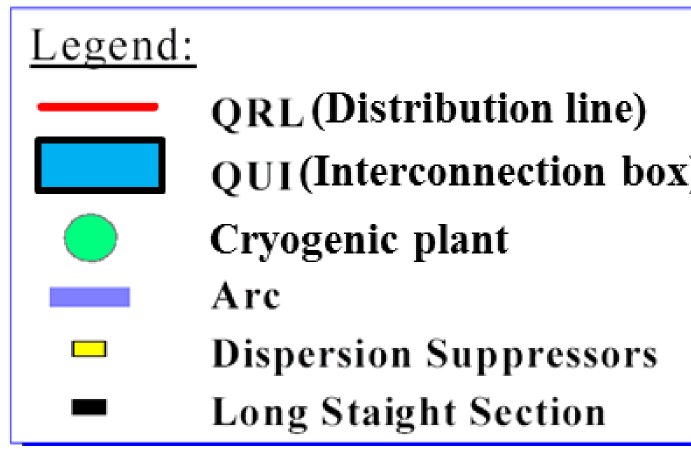
# LHC cryogenic system layout




5 cryogenic islands

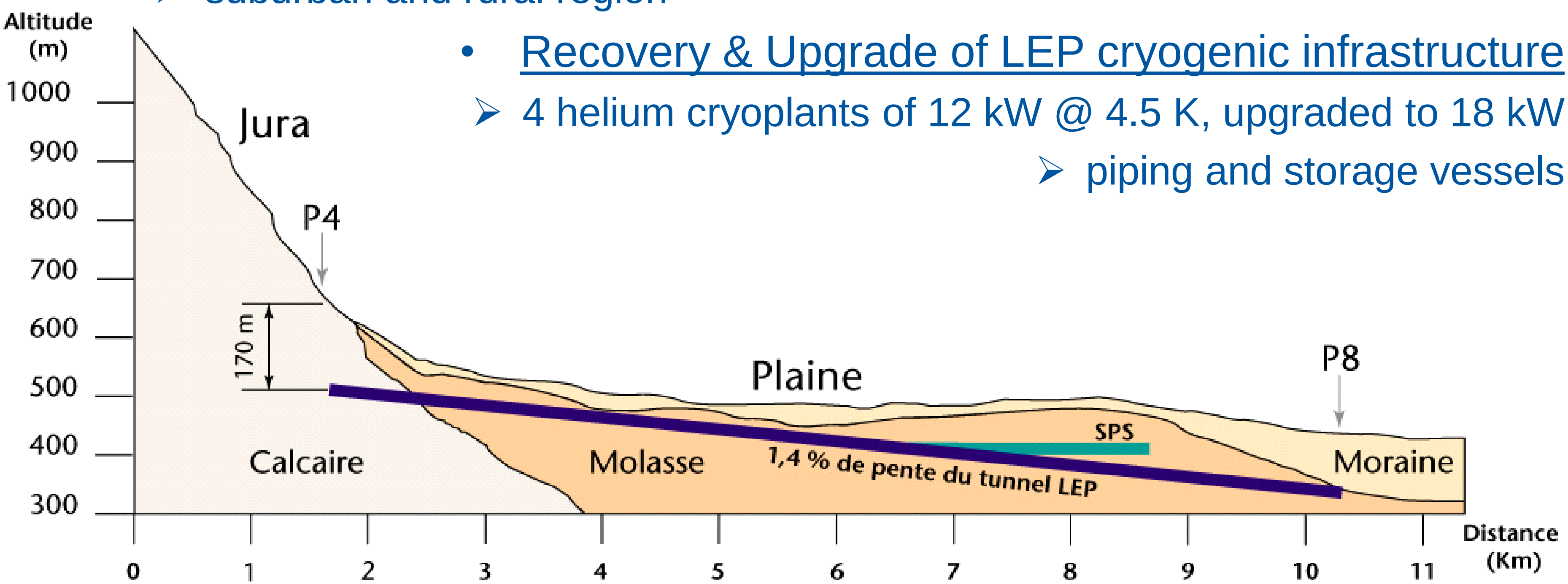
8 helium cryogenic plants:
1 cryoplant plant serves 1 sector

(18 kW @ 4.5 K, 2.4 kW @ 1.8 K and 600 kW LN2 precooler)

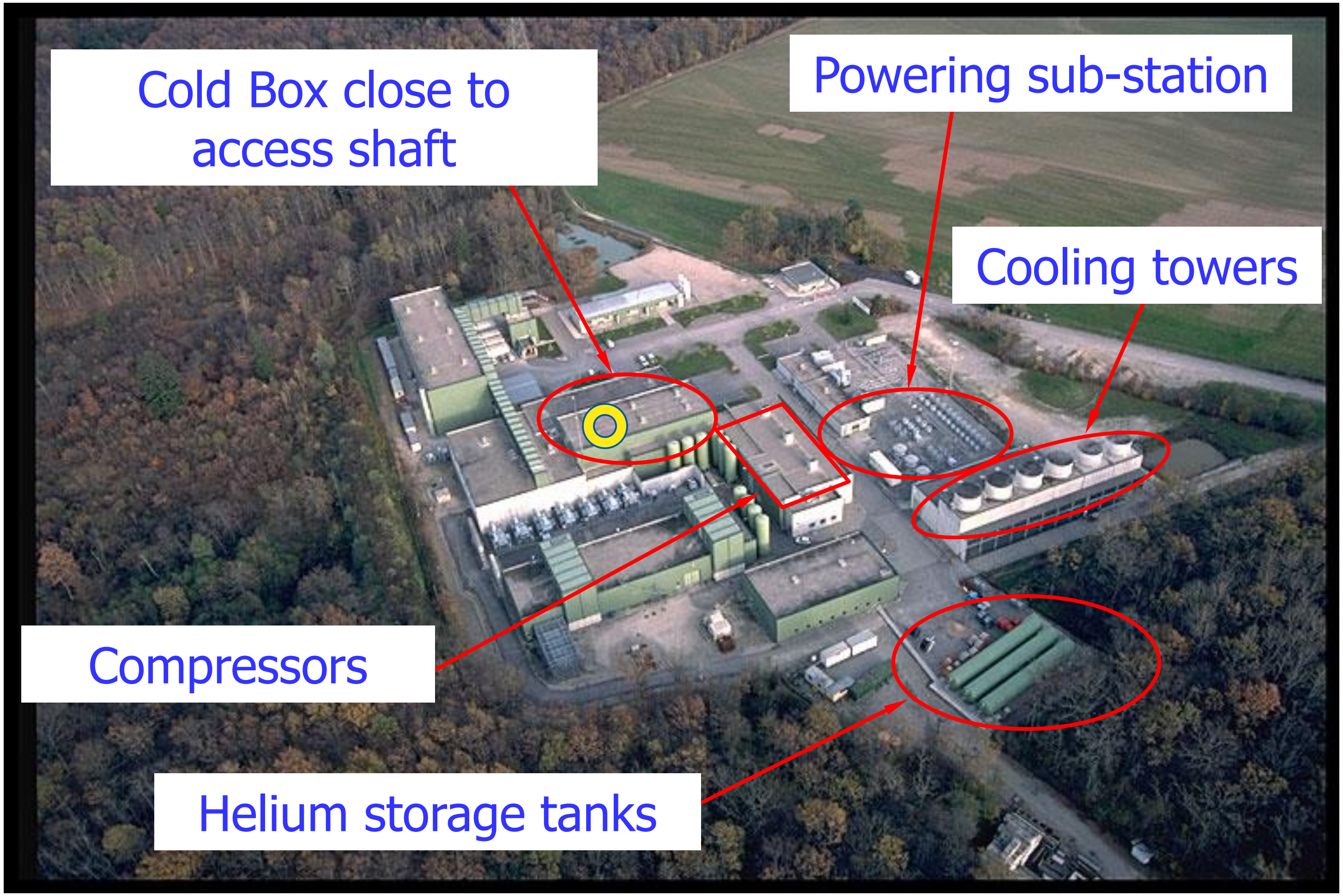


# Constraints of the LHC cryogenic system

- Use of the existing LEP accelerator tunnel
  - 3.8 m diameter (in arcs)
  - 3.3 km-long sectors
  - deep underground with limited access shafts and technical service areas
  - 1.4 % slope and elevation differences (hydrostatic heads)
  - suburban and rural region
- Recovery & Upgrade of LEP cryogenic infrastructure
  - 4 helium cryoplants of 12 kW @ 4.5 K, upgraded to 18 kW
  - piping and storage vessels

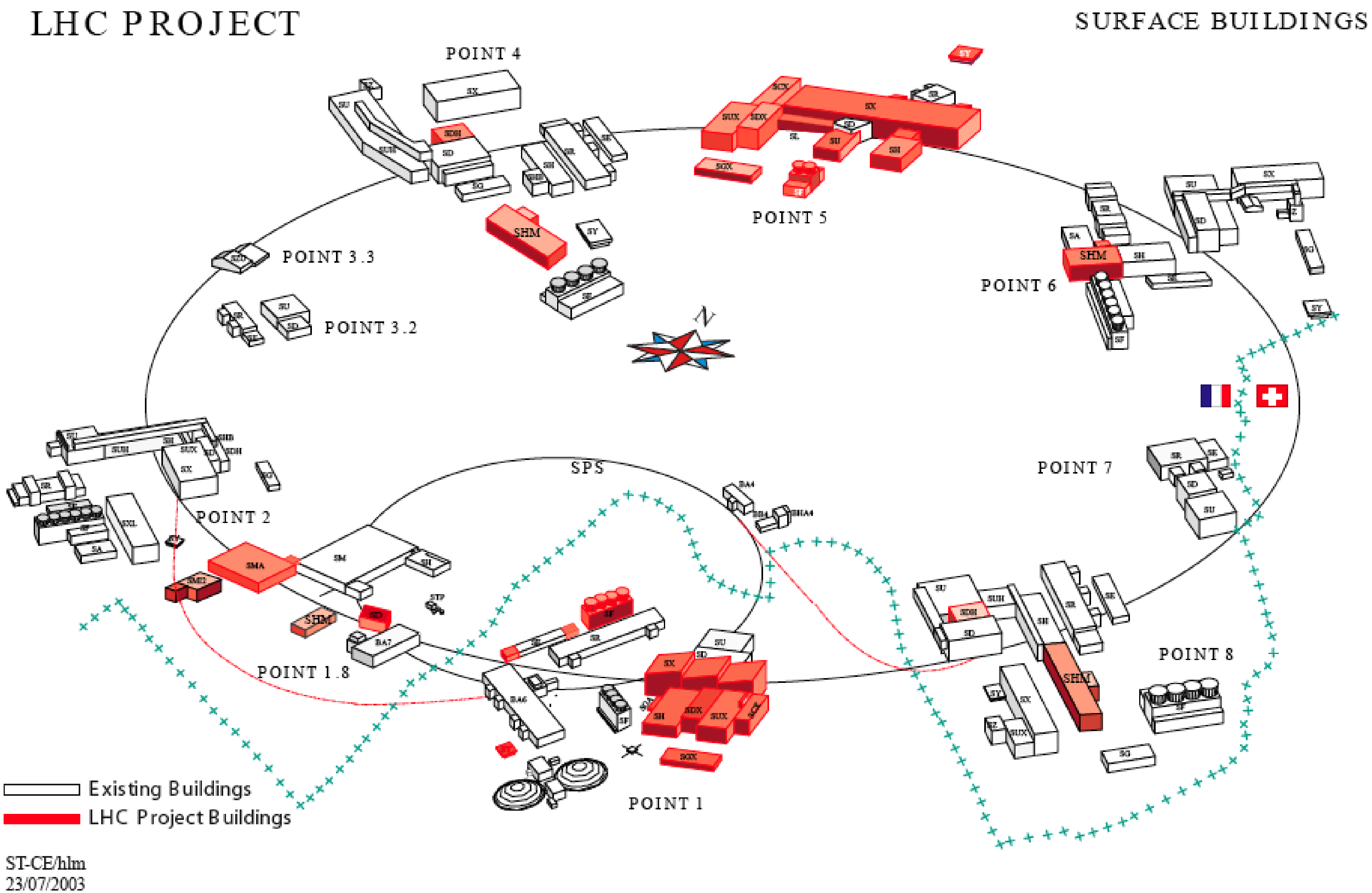


# Infrastructure at LHC technical area




Typical LHC surface Point

# LHC Surface Buildings (Technical)



# LHC Surface Buildings (Technical)

## LHC Point 6

Extracted from the "Etude d'impact du LHC" part of the "Déclaration d'Utilité Publique"



ue pour les contrôles des vibrations en surface. Ce
alement dans la sélection des constructions pour les-
éalables apparaîtraient utiles.

**nement**

le LHC pendant sa période de mise en service, puis
similaire au niveau sonore actuel du LEP, lui-même
ar le législateur.

, tels que compresseurs ou groupes électrogènes,
nents munis d'une isolation phonique suffisante pour
térieur reste conforme à la norme. Ce type de bâti-
déjà utilisé pour certaines installations du LEP. Il a été
IC compte tenu de l'expérience acquise.

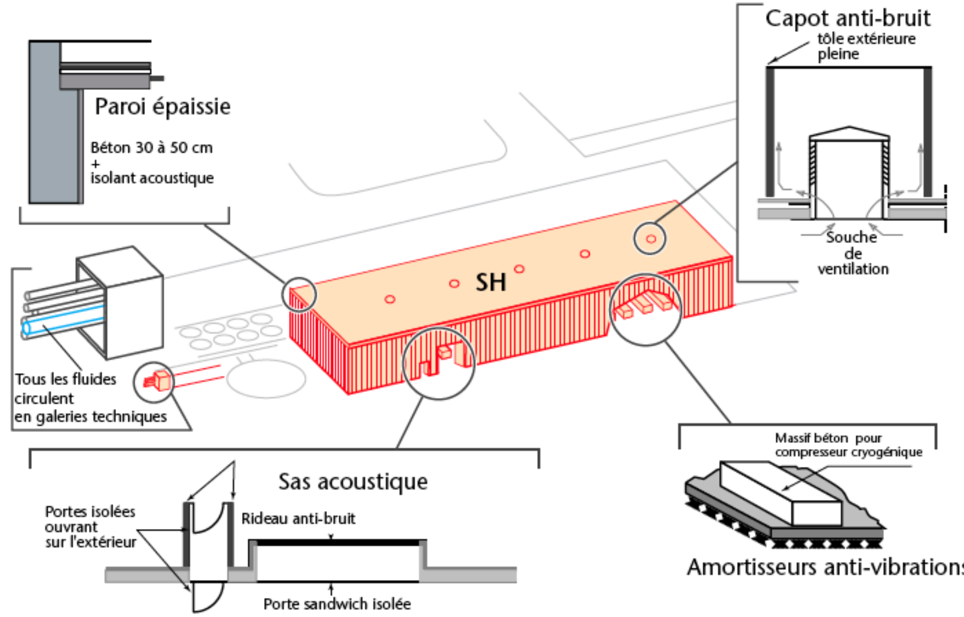



Figure 8.7 Isolation phonique des bâtiments de type SH

# Power cooling HVAC basic input

## Cryoplant-Unit basic parameters:

*250 W/W - 8C - 4%*

- Power:

  20kW@4.5K x 250 W/W => 5 MW power input

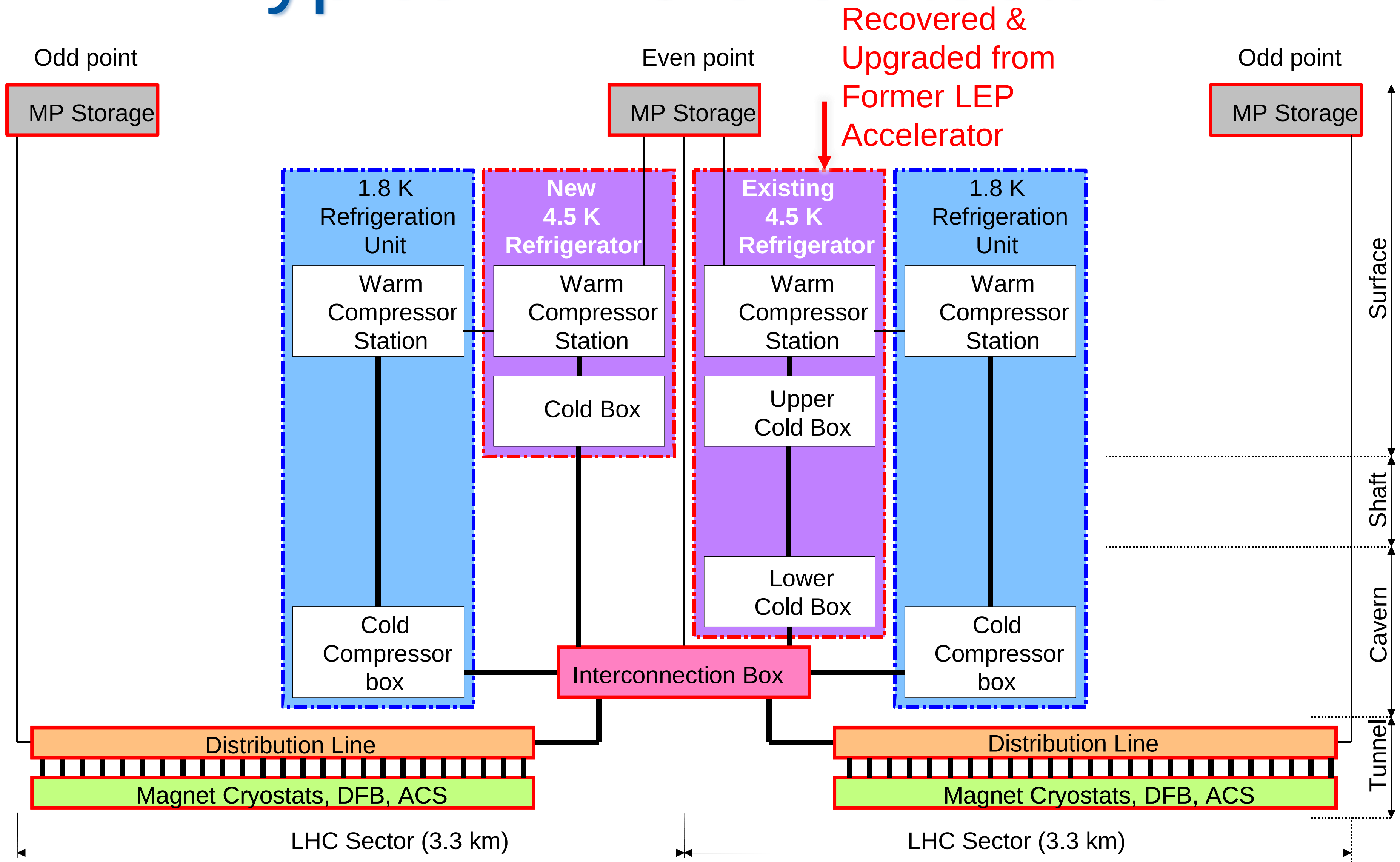
- Cooling:

  5MW / [ 8C (x Cp)] => 540 m3/h

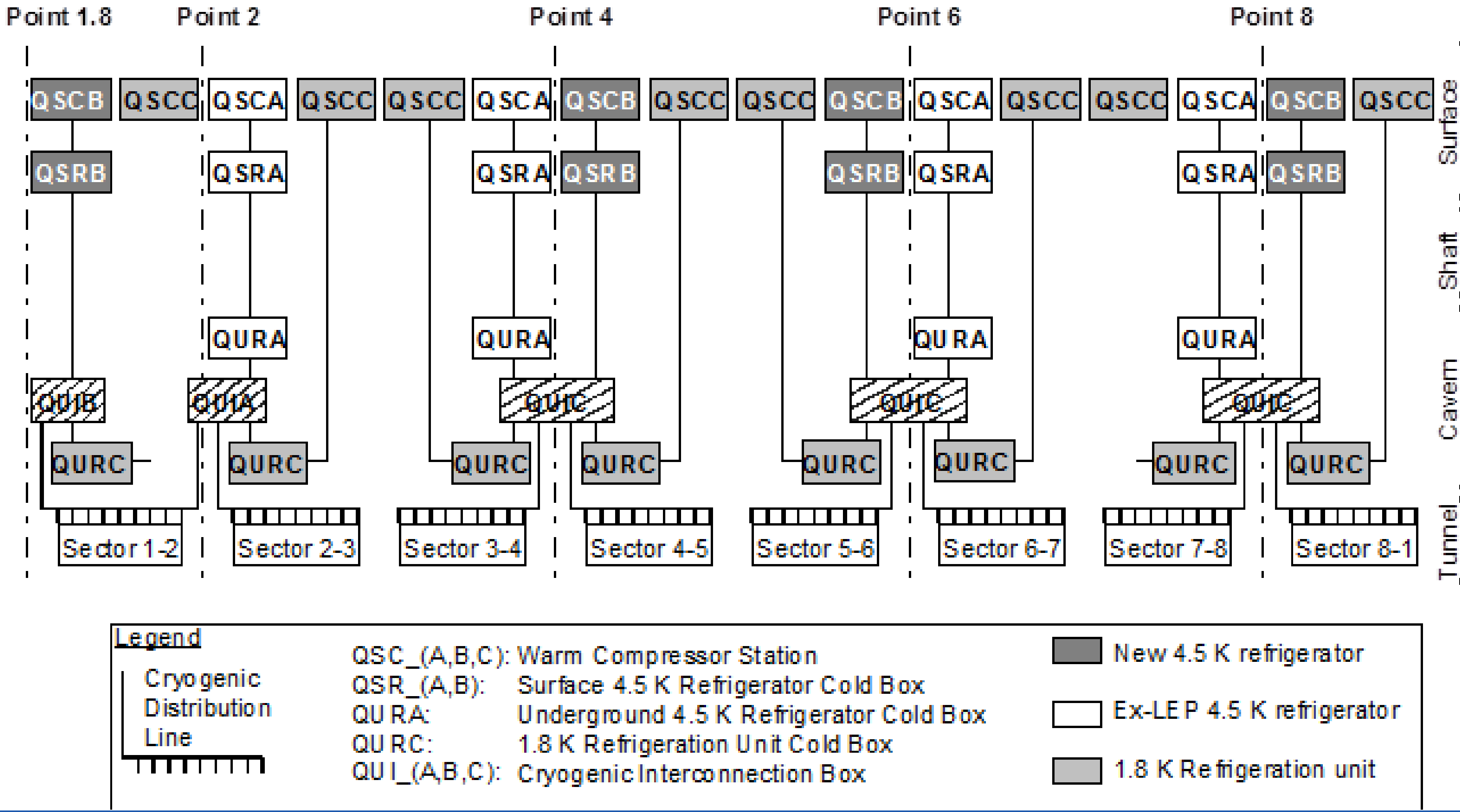
- HVAC:

  5MW x 4% => 200 kW

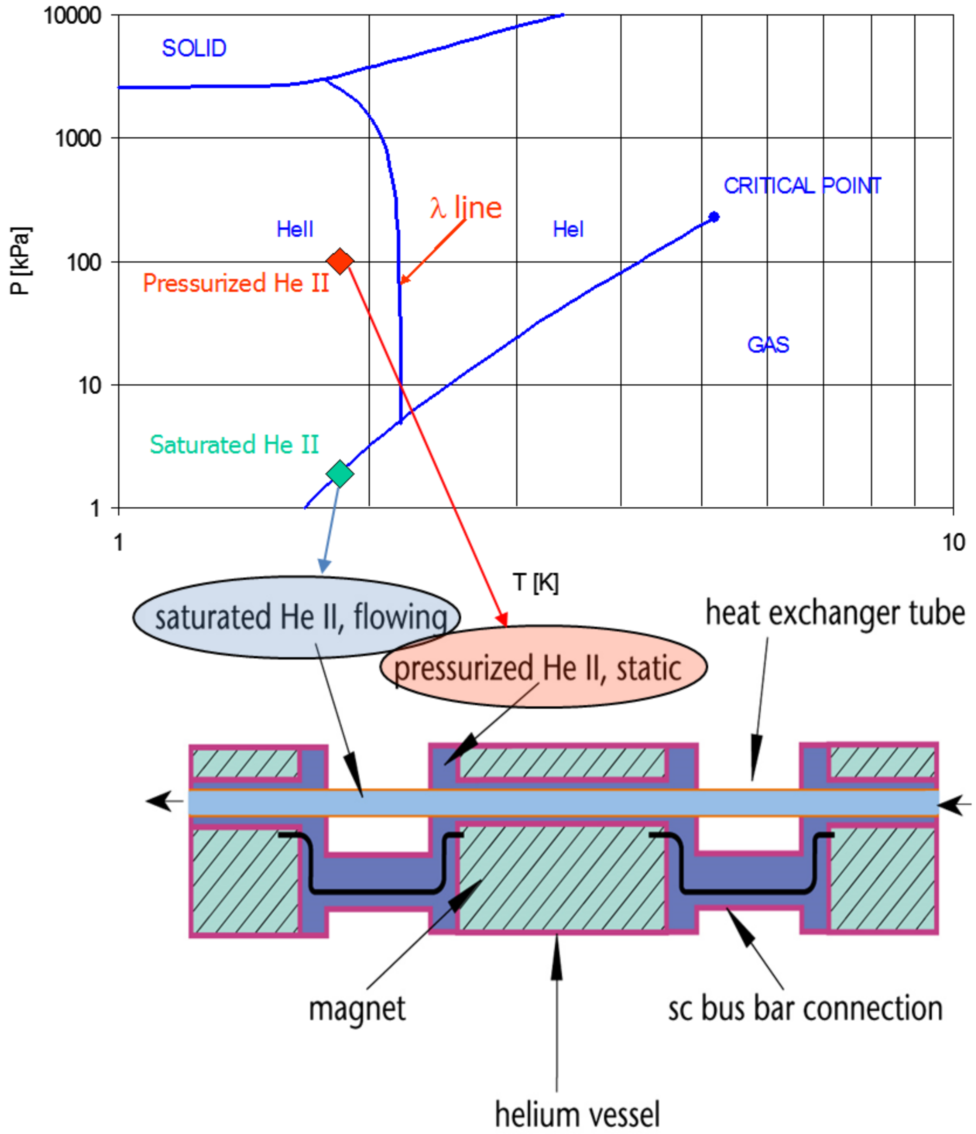
# Typical LHC architecture



# General architecture of the LHC cryogenic system
# Large scale Cryogenic Plants &
# Large scale of Transfer Lines for Cryogen Distribution



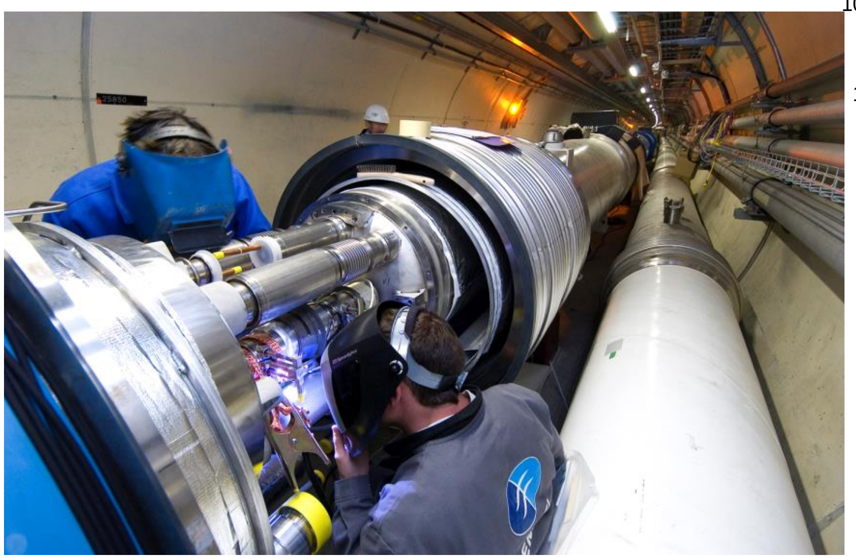
# Superfluid helium cooling principle

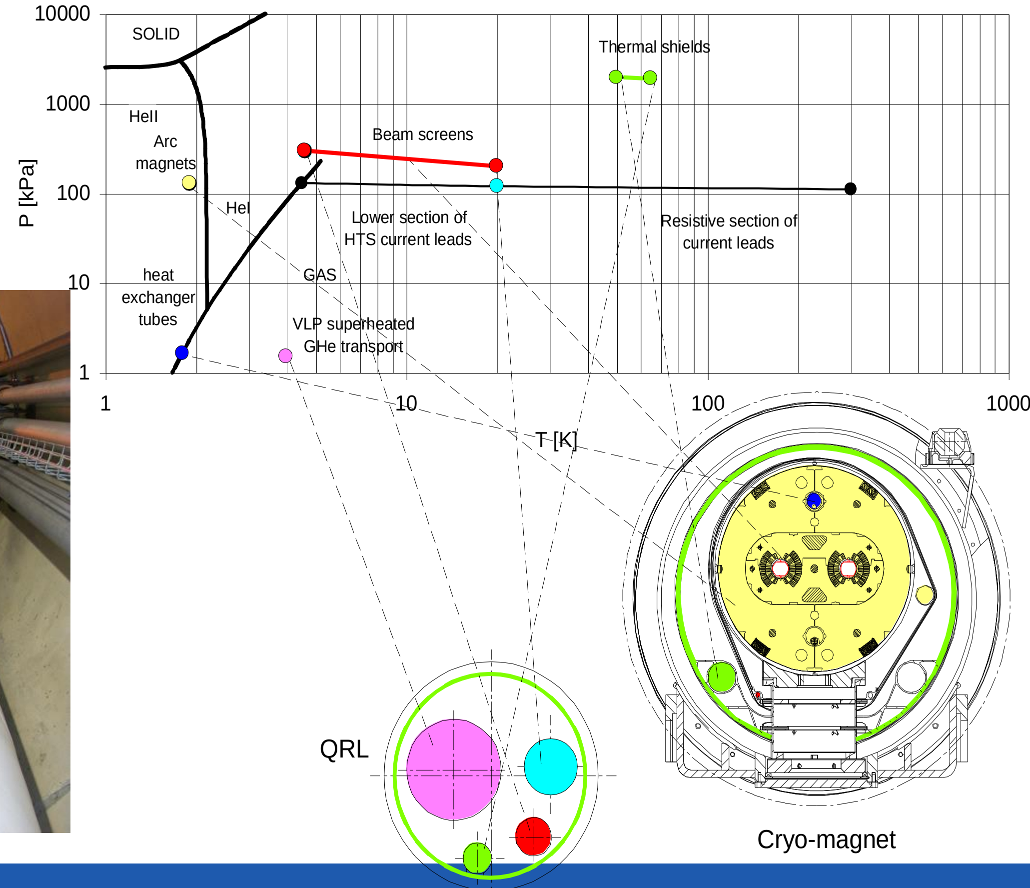


# Normal operating conditions

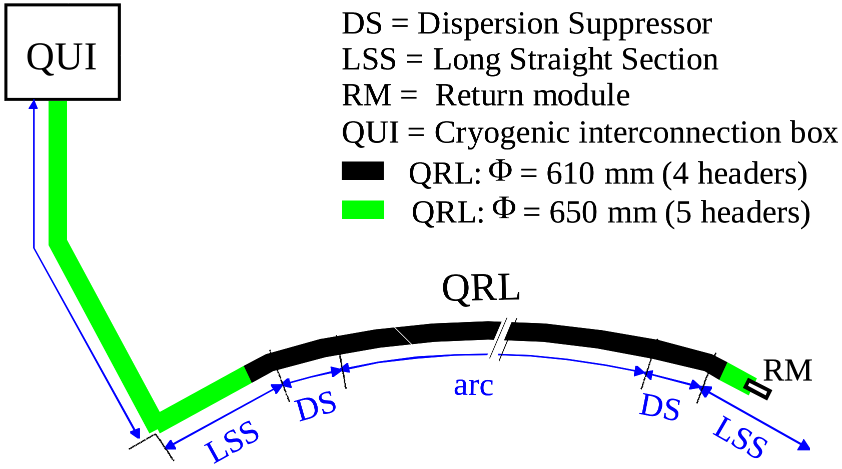
High thermodynamic cost of the refrigeration at 1.8 K: intercept the largest fraction of heat loads at higher and staged levels of temperature:

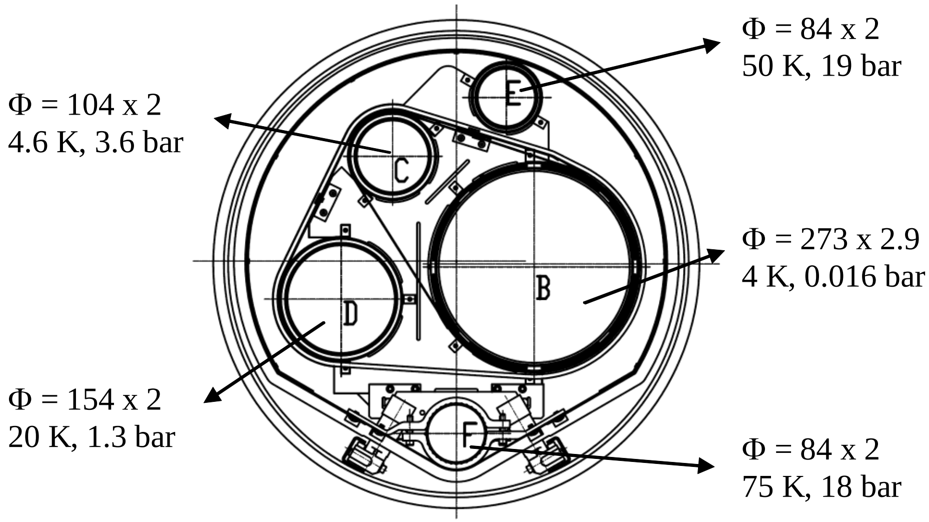
- 50 K to 75 K for thermal shield: first major heat intercept, protecting the cold mass from the bulk of heat in-leaks from ambient
- 4.6 K to 20 K: lower temperature heat interception and cooling of the beam screens protecting the magnet cold bore from beam-induced loads
- 1.9 K quasi-isothermal superfluid helium for cooling the magnet cold mass
- 4 K at very low pressure (VLP) for transporting the superheated helium flow coming from the distributed 1.8 K heat exchanger tubes across the sector length to the 1.8 K refrigeration units
- 4.5 K normal saturated helium for cooling special superconducting magnets in insertion regions and HTS current leads
- 20 K to 300 K cooling for the resistive upper sections of HTS current leads





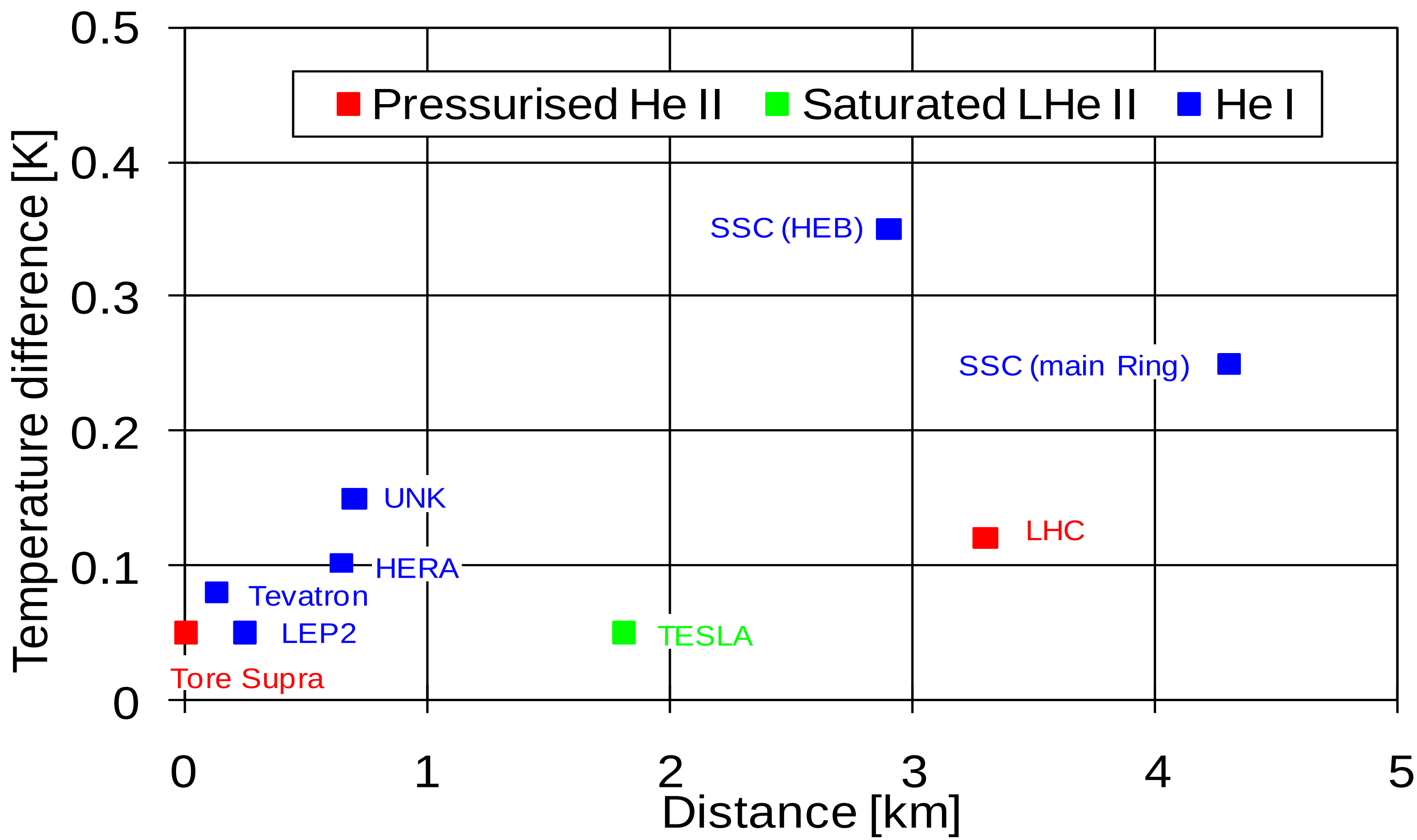
# Cryogen distribution line: QRL Layout and Cross-Section



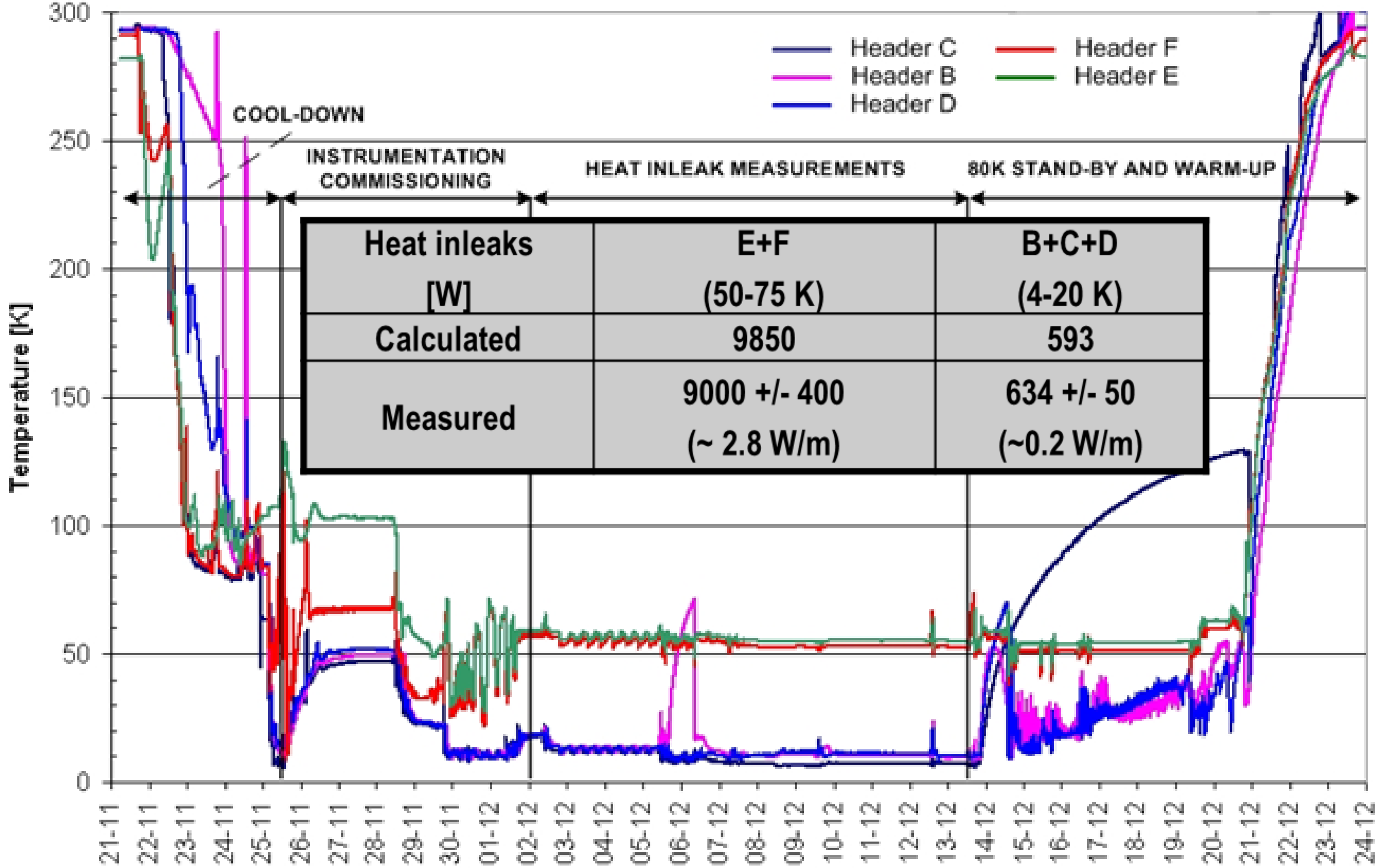




- 8 QRL sectors (8 x 3.3 km)
- Each QRL sector
  - continuous cryostat of ~3.2 km length: from the cryogenic interconnection box to the return module
  - connection to the superconducting magnets every 107 m

# Transport of refrigeration in large distributed cryogenic systems

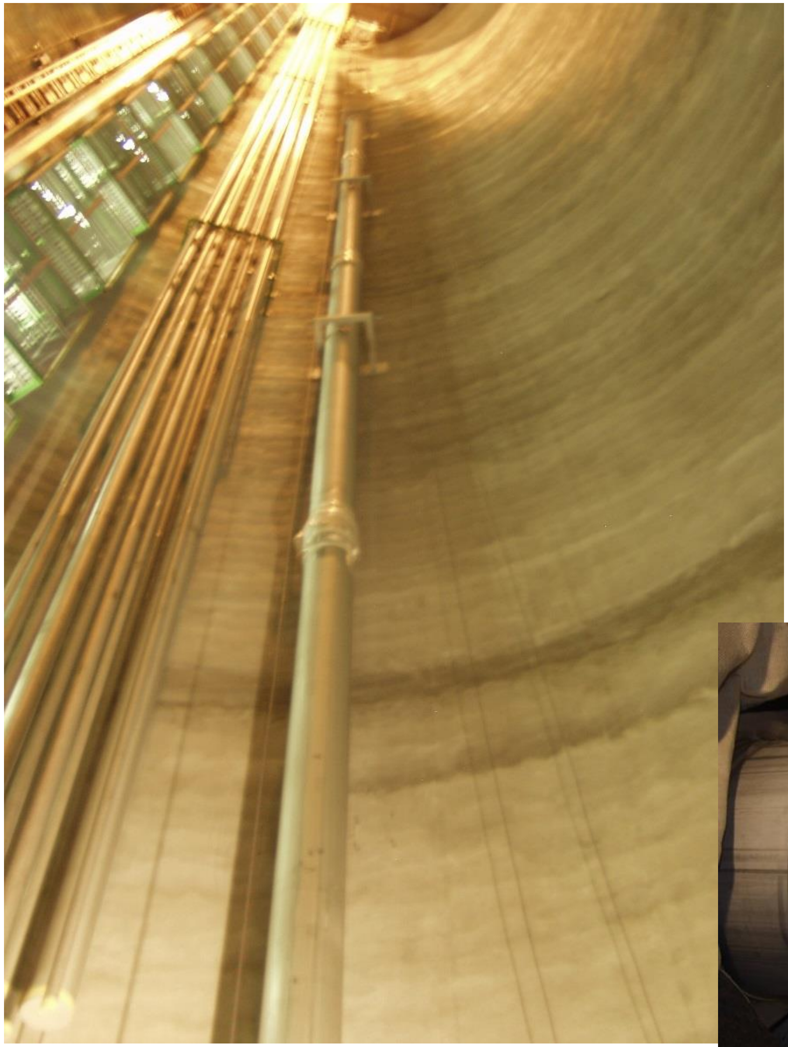


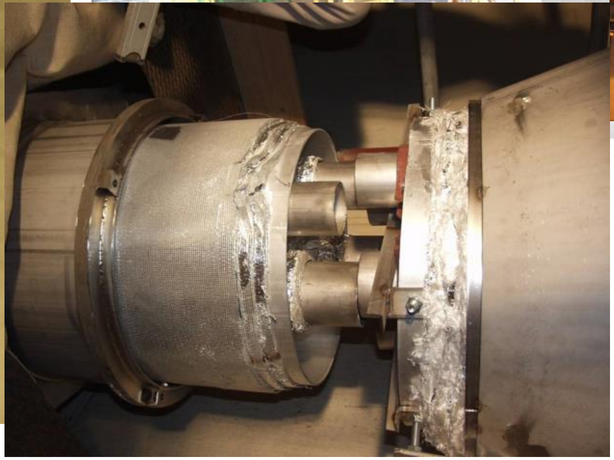
# QRL Line Heat Load Measurements




| Heat inleaks [W] | E+F (50-75 K) | B+C+D (4-20 K) |
|---|---|---|
| Calculated | 9850 | 593 |
| Measured | 9000 +/- 400 (~ 2.8 W/m) | 634 +/- 50 (~0.2 W/m) |

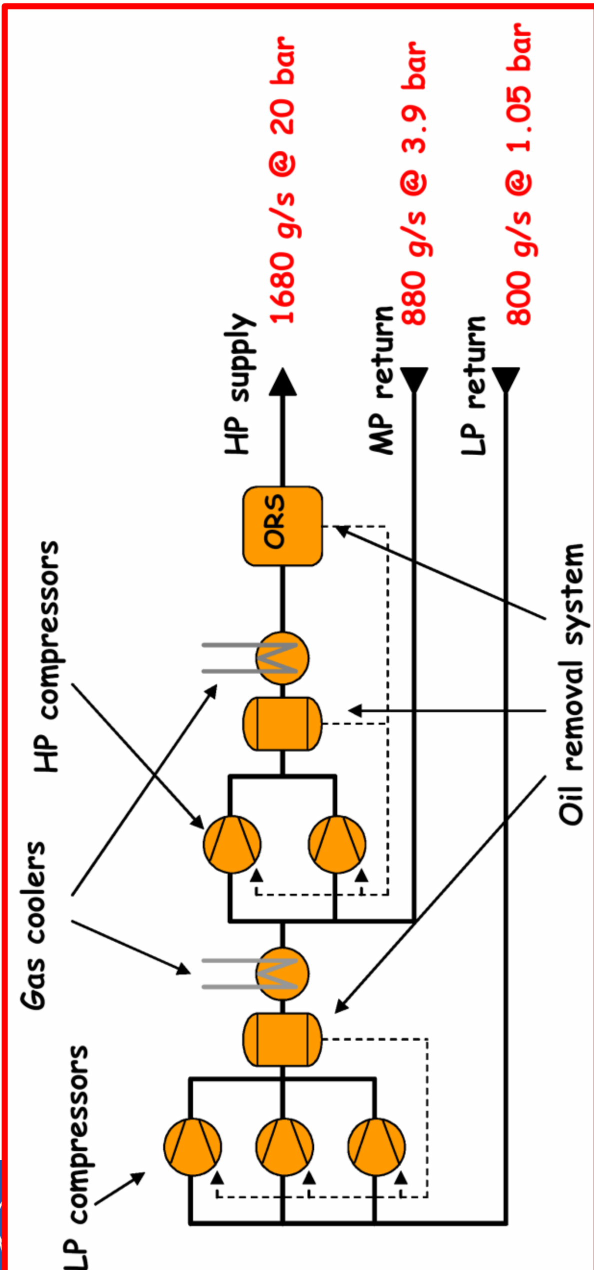
# LHC Vertical Transfer Lines (4.5 K)

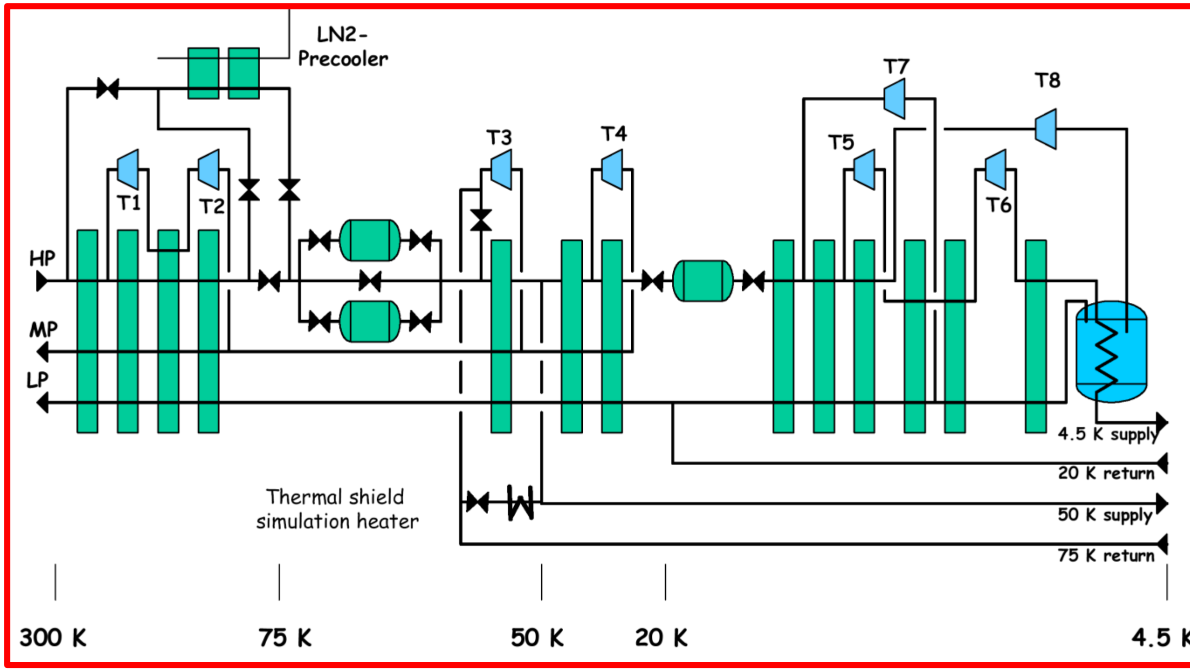


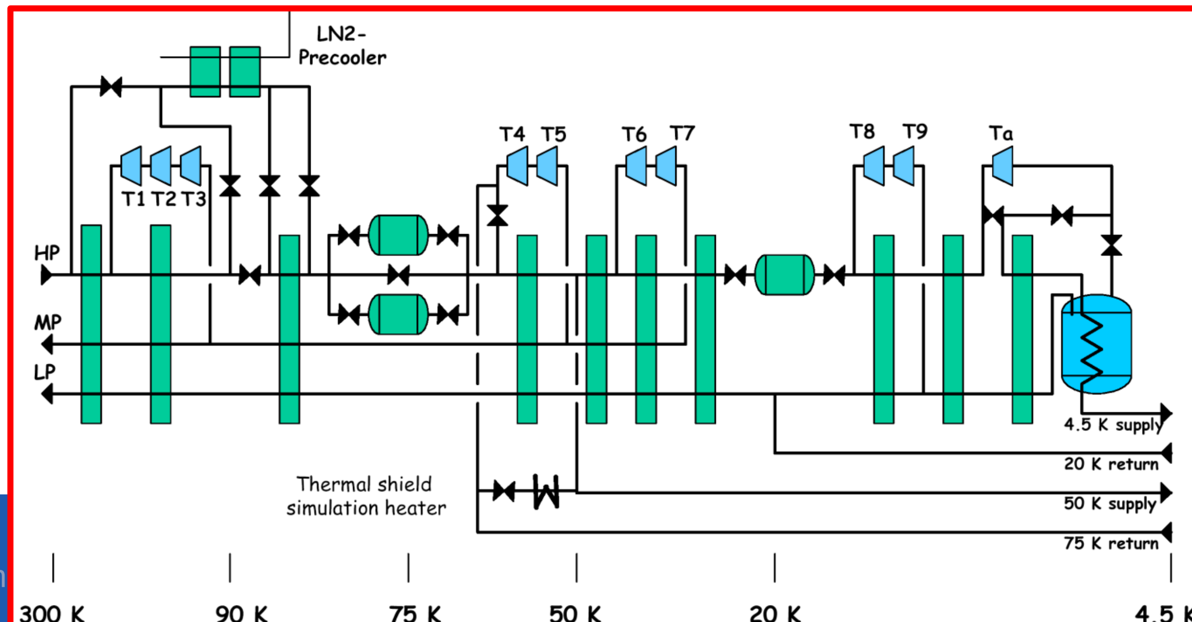


Totalizing approximately 800 m (all Points)

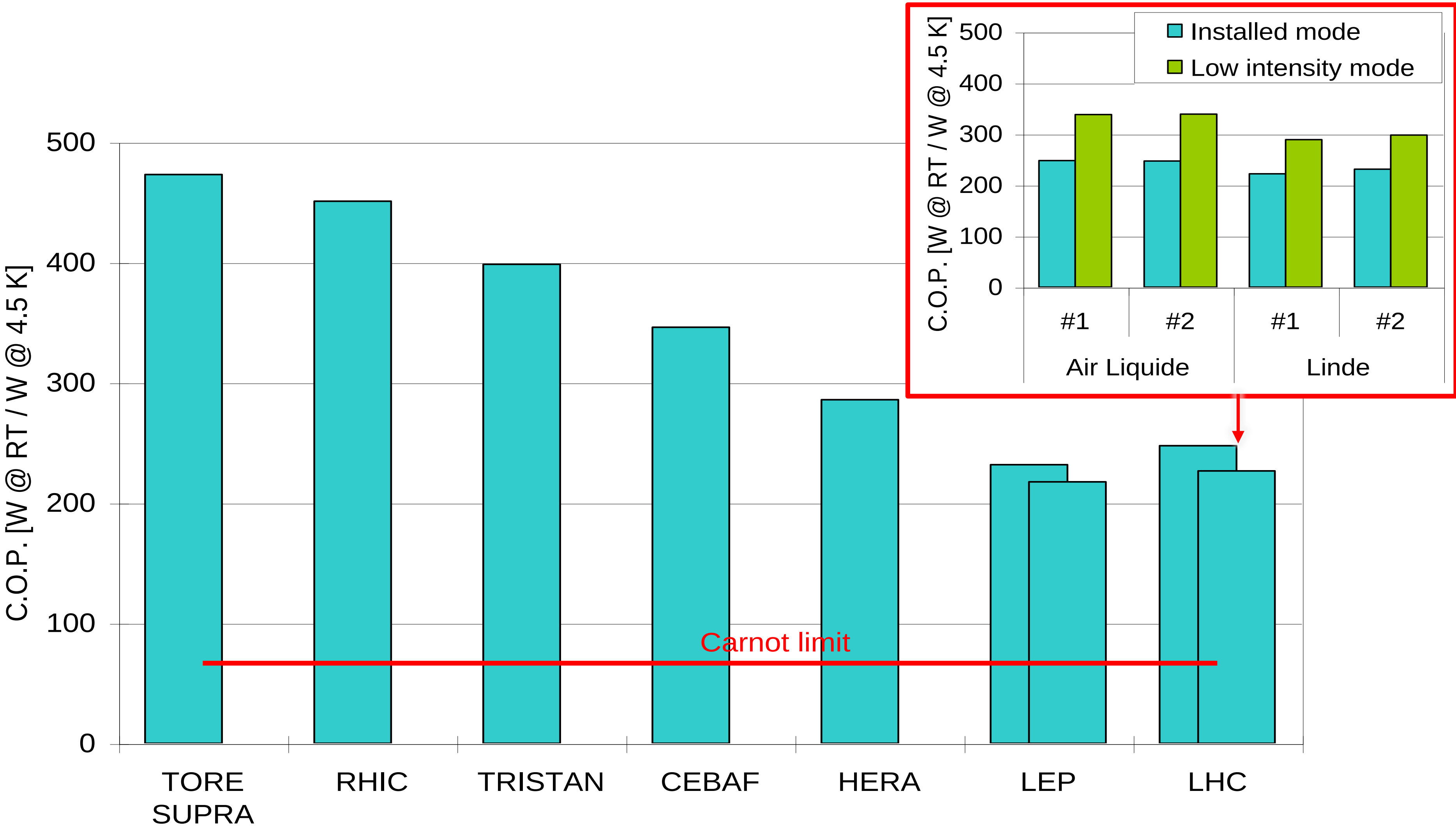
# Process cycle of 18 kW @ 4.5 K cryoplants



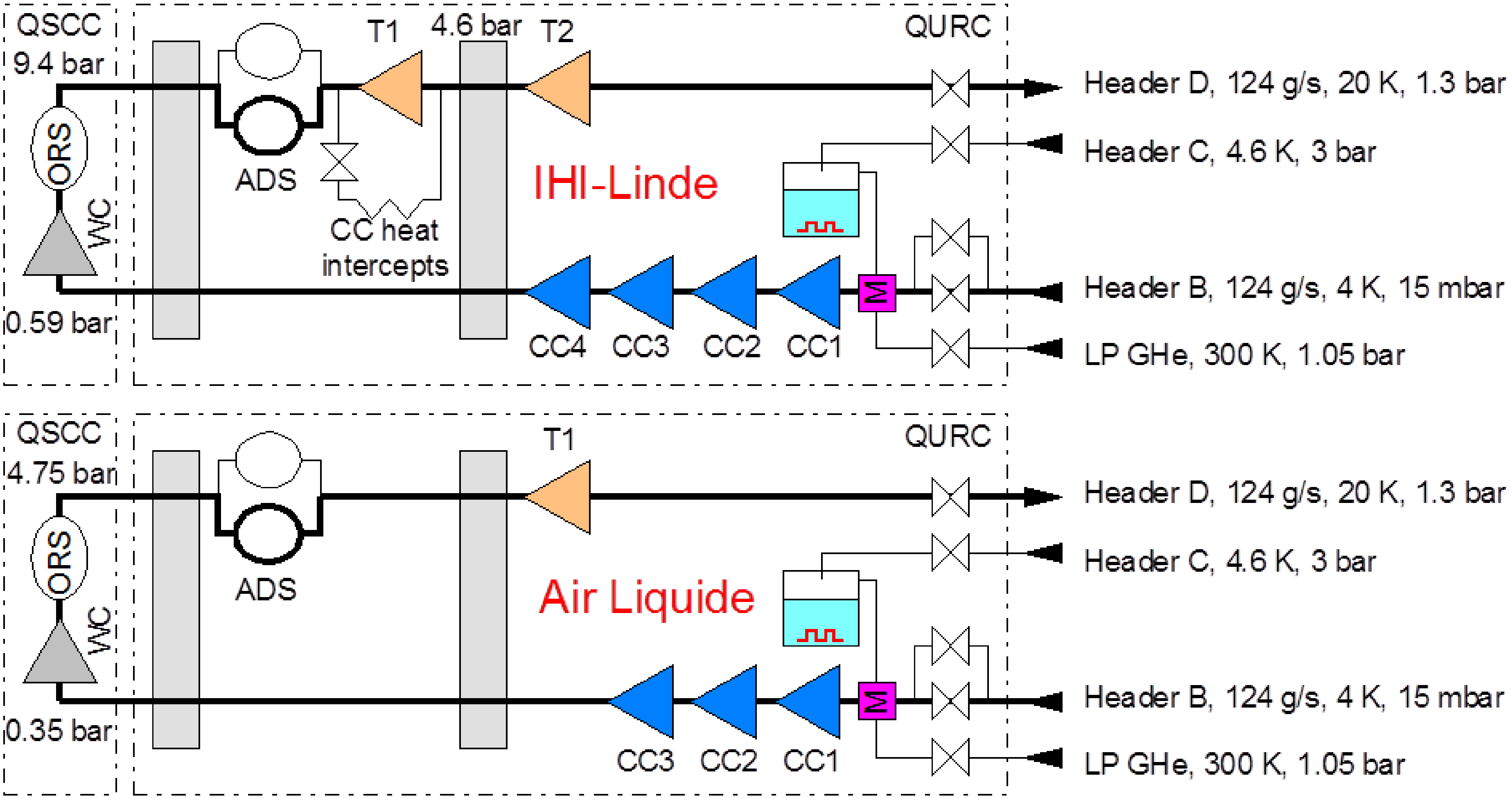
# C.O.P. of helium refrigerators



# LHC Accelerator Cryogenics 18 kW @ 4.5 K Units

Typical
Helium Compressors station
&
Cold Boxes

# 2.4 kW @ 1.8 K refrigeration cycles for the LHC



# LHC Accelerator Cryogenics 2.4 kW @ 1.9 K Units

IHI- Linde

Air Liquide

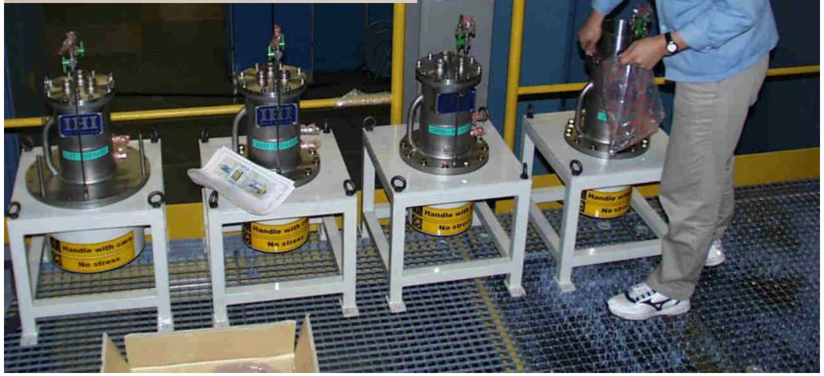
Warm Compressors & Cold Boxes

# Cold compressors for 1.8 K refrigeration

Air Liquide

IHI-Linde


Axial-centrifugal impeller



IHI-Linde; 4 cold compressor stages

## LHC Cold Compressors (speed range 100 – 800 Hz)

4 cold compressor stages

# Management of Cryogen

- Total **HELIUM** inventory at CERN: 170’000 kg
- LHC (accelerator & detectors) helium full inventory: 136’000 kg
- Additional strategic permanent storage during operation: 15’000 kg

- LHC (accelerator & detectors) liquid **NITROGEN** needs for a full cool down: 11’500 ton

(LHC accelerator full cool down: 10’000 ton in 33 continuous days; equivalent to 500 standard transportable containers delivered by industrial suppliers)

- In situ helium liquefaction for central services (up to 350’000 liter per year) and distribution by means of mobile containers ranging from 100 to 2’000 liter (users without dedicated cryogenic plant)

# Helium & Nitrogen Storage
## (Exclusively implemented at surface premises)

## Storage infrastructure (in brackets: capacity dedicated to LHC)

### Gas & liquid helium storage capacity at CERN

| Gas tank capacity [$m^3$] | 250 (at 2.1 MPa) | 80 (at 1.5 & 2.1 MPa) |
|---|---|---|
| Number of units at CERN | 58 (58) | 65 (40) |



| Liquid tank capacity [liter] | 120'000 (fixed) | 25'000 (fixed) | 11'000 (mobile) | 6'000 (fixed) |
|---|---|---|---|---|
| Number of units | 6 | 1 | 2 | 1 |


### Liquid nitrogen storage capacity at CERN

| Container capacity [liter] | 50'000 | 40'000 | 27'000 | 20'000 | 15'000 | 10'000 | 6'000 |
|---|---|---|---|---|---|---|---|
| Number of units | 14 (13) | 2 | 1 | 2 | 2 | 1 | 7 |

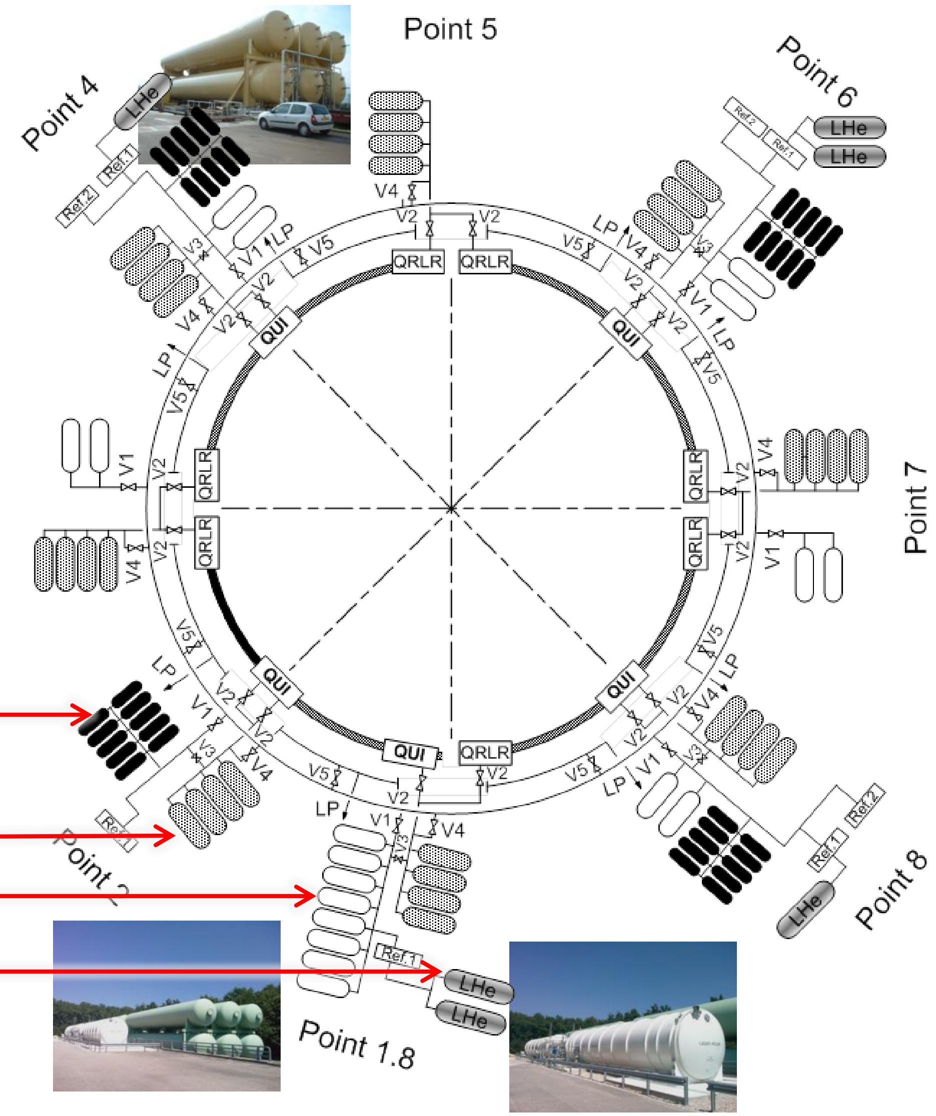
# LHC Helium Storage & Distribution

LHC Helium storage & Distribution (high grade gaseous helium ring line, 2 MPa, 27 km long, for LHC operation)

- ✓ *All helium storage means are located at ground facilities*
- ✓ *Helium ring line is located underground and interconnected to storage facilities*

**LHC helium**
Gas 80 m³ (at 1.5 and 2.1 MPa)
Gas 250 m³ (at 2.1 MPa)
Quench buffer*
Make-up
Liquid storage, 120'000 liter

*No recovery compressors & high pressure purification systems



# LHC Accelerator Helium Inventory

## 130 tons

During steady state operation of the accelerator:

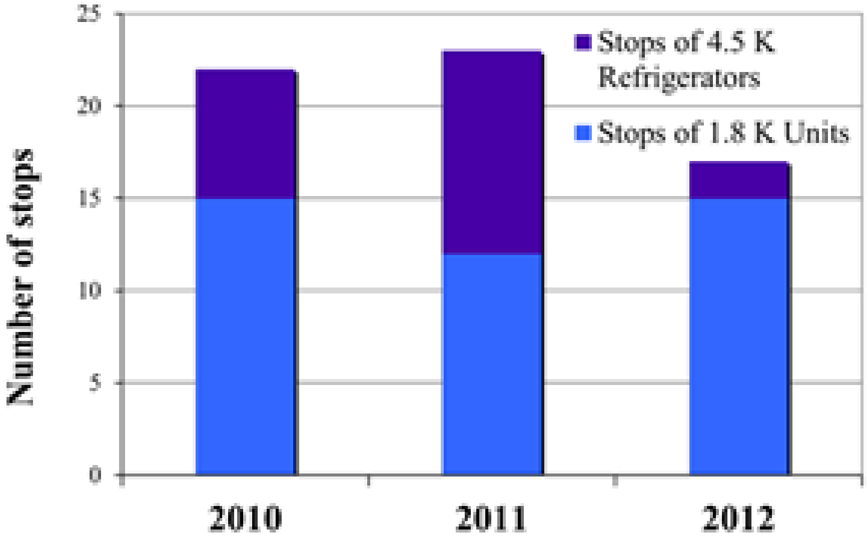
- ✓ 87 tons (helium II) contained in the helium vessels of the sc magnets
- ✓ 40 tons in the distribution and recovery lines
- ✓ 3 tons in the cryogenic plants
- ✓ Additional strategic liquid helium storage at CERN premises: 20 tons

Overall LHC helium Inventory:130 + 20 = 150 tons

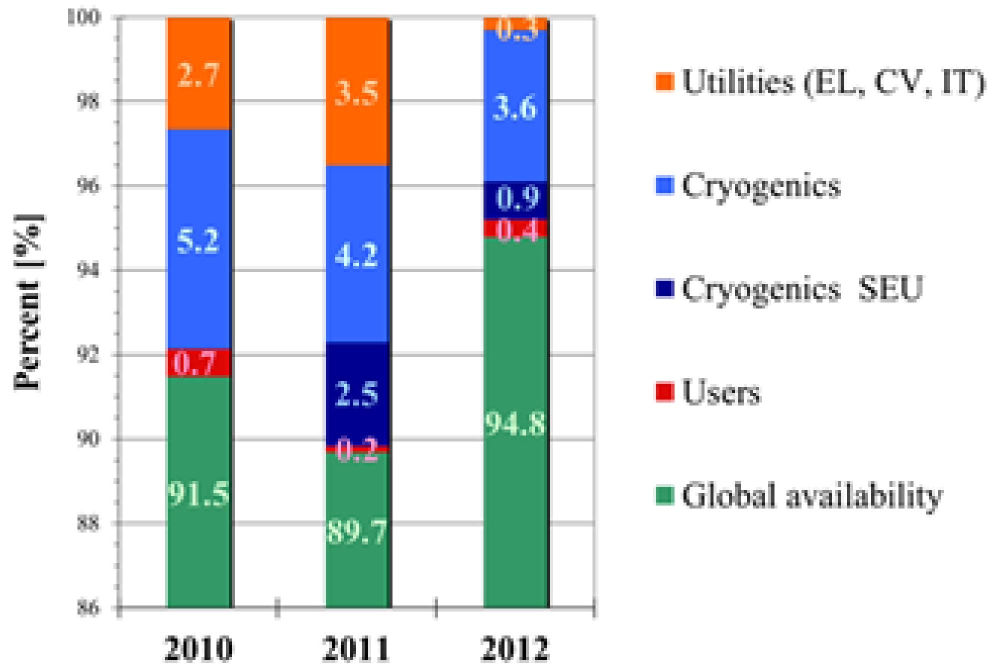
Storage capacity (surface premises) with respect to the Inventory (strategic storage not included, present only during operation):

- ✓ 45 tons (gas) in 80 $m^3$ (at 1.5 and 2.1 MPa) & 250 $m^3$ (at 2.1 MPa)
- ✓ 90 tons (liquid) in six 120'000 l horizontal tanks (not equipped with permanent re-liquefiers; project on-going); CERN introduced the concept of "virtual storage" at industrial suppliers premises for bridging the gap between the 130 tons of inventory and the long term storage capacity in the liquid tanks.

# Brief report from the first three-years LHC Physics Run (Cryogenic Operation)

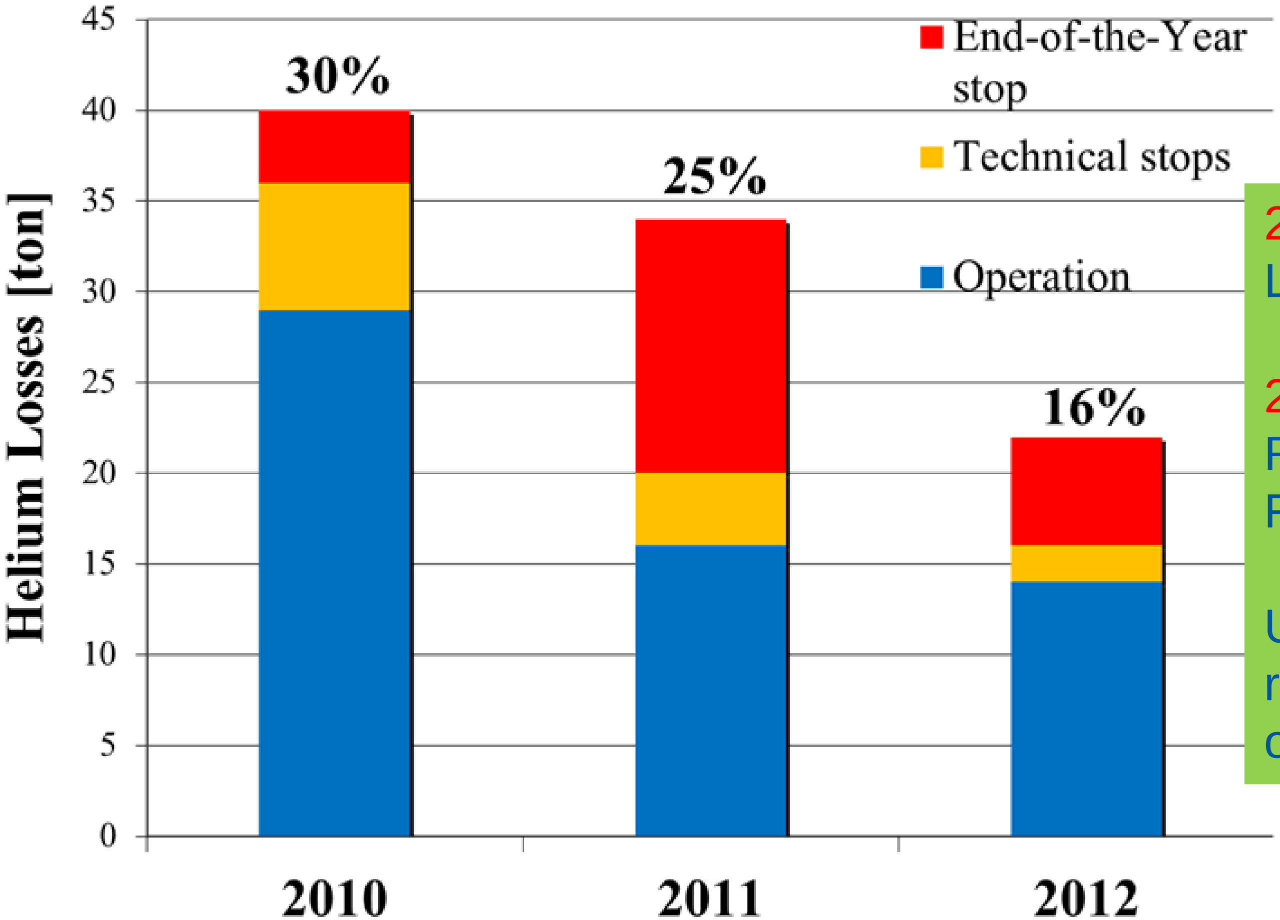



Statistics of the refrigeration plants long stops




Global availability results of the LHC cryogenic system and origin of main losses

# LHC Accelerator Helium Management



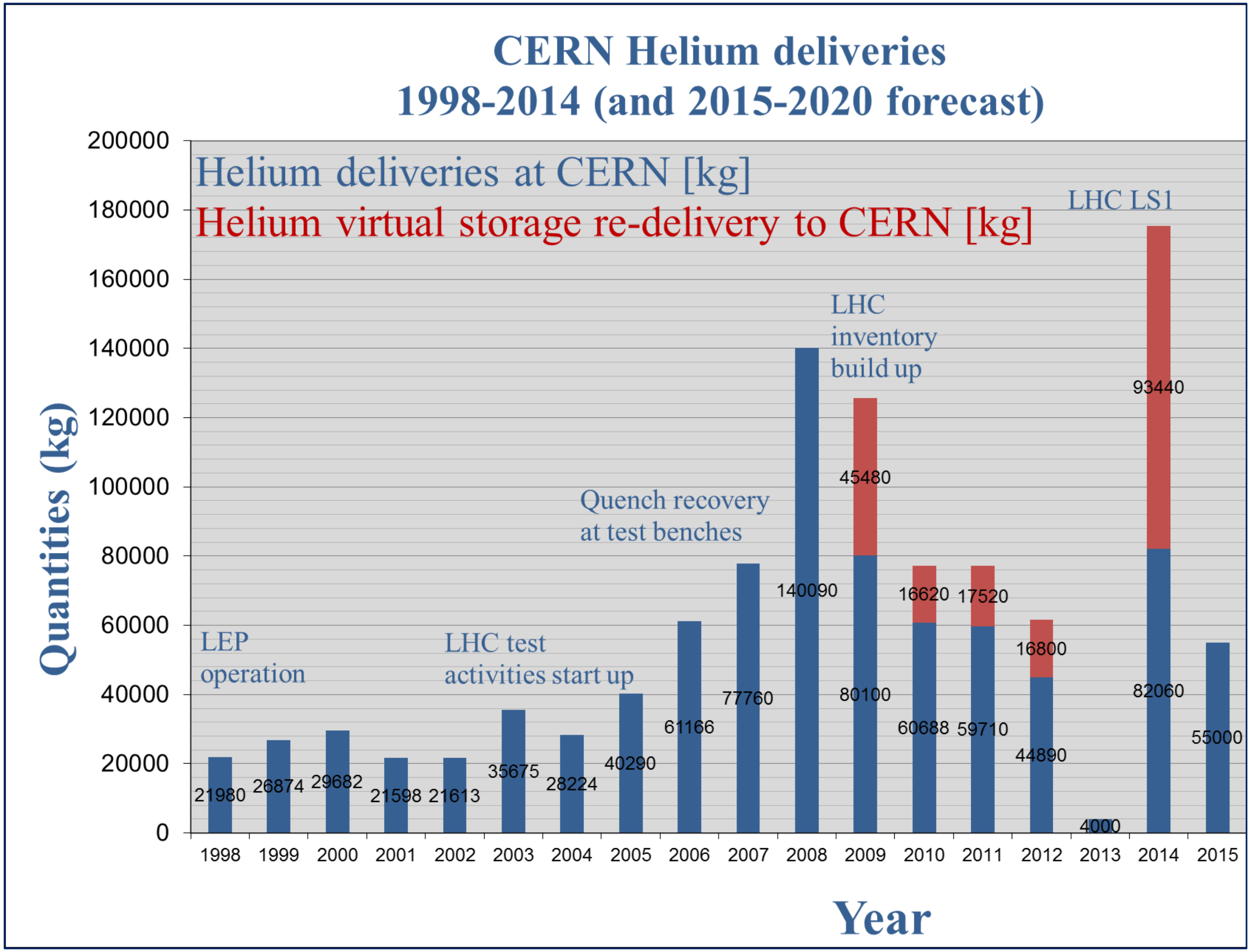

2013-2014
Long shutdown 1

2015:
Resuming Operation
For Physics Run 2

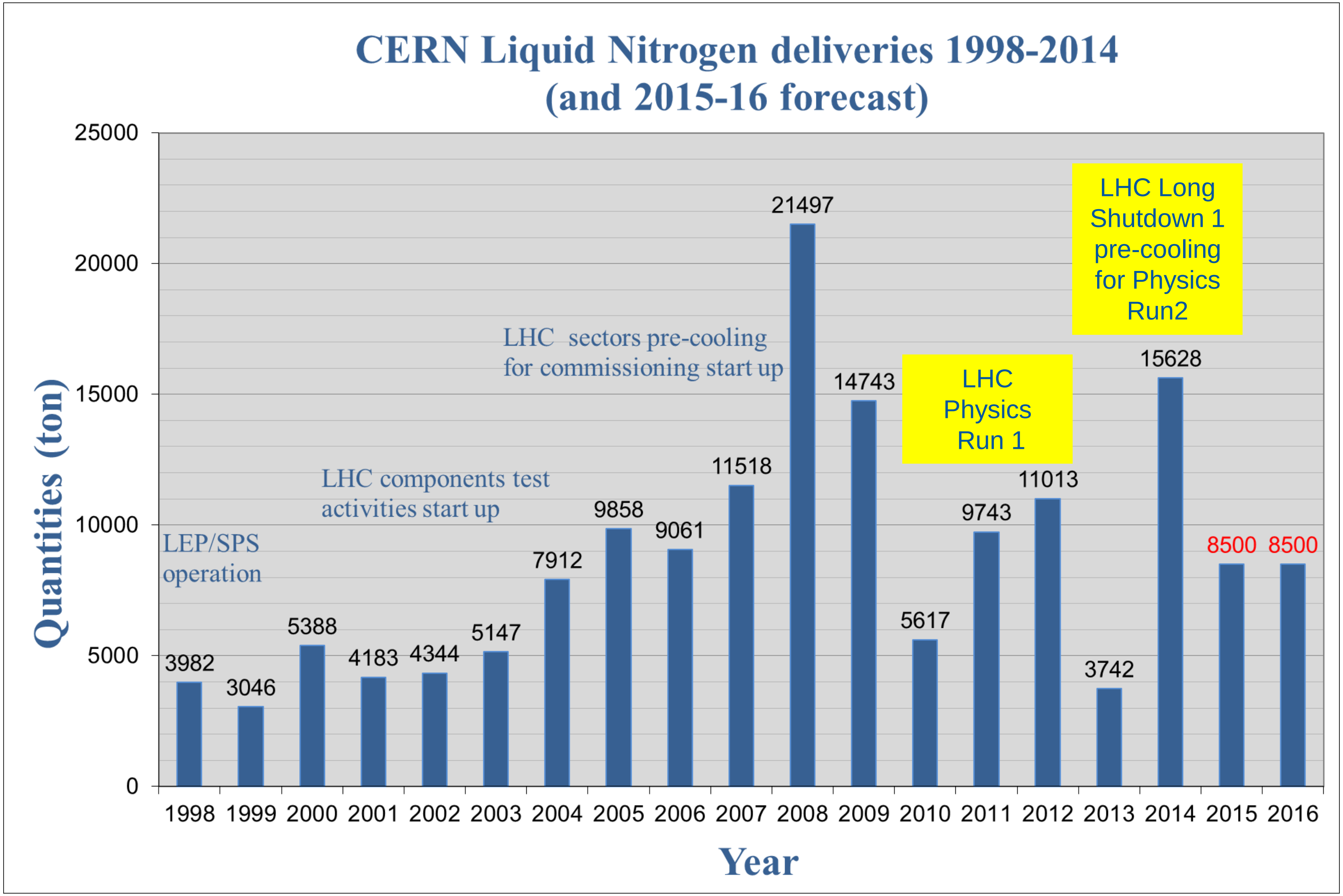
Up to now very encouraging results: losses near to 10% of the LHC helium inventory

## LHC Run 1: Helium losses during the first three-years run

# Helium Supply at CERN



# Nitrogen Supply at CERN



# Main information from LHC cryogenic system

LINEAR COLLIDER COLLABORATION

## *CERN-LHC Cryogenic System Components*

| Component | Dimensions | Quantity | Specification |
|---|---|---|---|
| 4K Helium Liquefiers/ Refrigerators | 20 x 8 m | 8 | 18 kW @ 4.5 K |
| Main Compressors stations | 15 x 12 m | 8 | 1500 g/s |
| 2K Superfluid Helium Refrigerators | 10 x 8 m | 8 | 2.4 kW @ 1.8 K |
| Recovery Compressors | 6 x 6 m (typical non-LHC system) | n/a | LHC: No recovery compressors |
| Liquid Helium Storage Tanks | $\phi$ 3.5 m x 21 m | 6 | 110000 L |
| Helium Gas Storage Tanks | 30 x 16 m | 58 | 250 $m^3$ |
| Liquid Nitrogen Storage Tanks | 10 x 5 m | 13 | 50000 L |
| Cooling Towers | 40 x 22.5 m | 8 | SF1 |

*20140425/FUSE Meeting with CERN/Cryogenic Cavern/NAKAI H.* 13

# Conclusions (Summary)

High objective:

attempt to be useful to the ILC strategic decisions on cryogenic system and cryogen storage implementation

# Conclusions (Summary) 1/2

The LHC helium cryogenic system:

- ✓ 8 x 18 kW @ 4.5 K and 8 x 2.4 kW @ 1.8 K cryogenic units
- ✓ Totalizing 25 km long transfer lines for cryogen distribution successfully manufactured, installed and operated
- ✓ Main constraints:
  - ➢ 8 x 3.3 km-long sectors
  - ➢ Deep underground with limited access shafts and technical service areas
  - ➢ 1.4 % slope and elevation differences (hydrostatic heads)
  - ➢ Suburban and rural region
  - ➢ Environmentally respectful approach (full Impact Study produced in collaboration and agreement with the Authorities)

# Conclusions (Summary) 2/2

- Helium compressors stations (for both 4.5 K & 1.8 K units): all located at surface premises
- 4.5 K cold boxes: located at surface premises (with the exception of the four former units recovered from the LEP project (located underground due to the dedicated application for sc cavities operated at 4.5 K)
- 1.8 K units: all located underground
- Gaseous and liquid helium storage: all located at surface premises; no cryogen storage underground (exception of the continuous LHC cryostat in operation)
  - Personnel access to the LHC tunnel in presence of liquid helium is strictly conditioned
  - Liquid nitrogen is forbidden in LHC accelerator underground facilities (exceptions for experimental caverns due to high volume)

# Thank you for your attention

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# 低温工学

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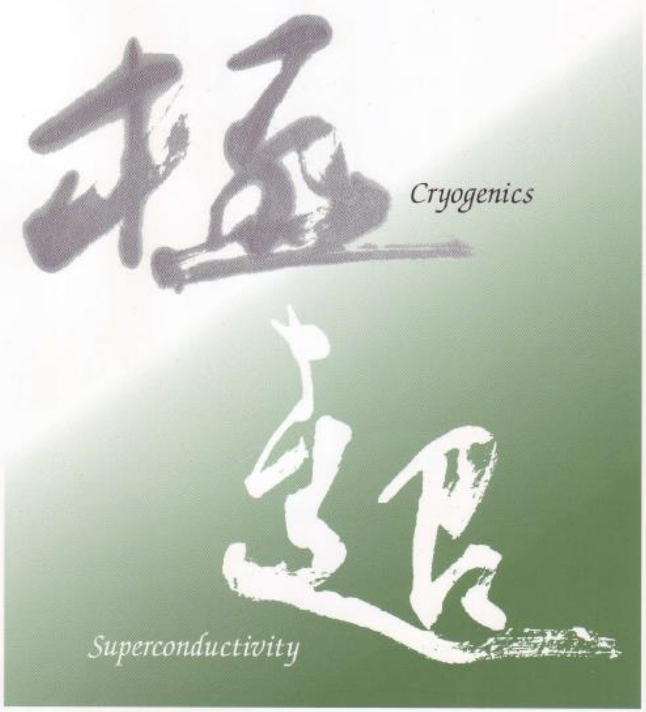


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**Focused Review**

# The LHC Cryogenic System and Operational Experience from the First Three Years Run

Dimitri DELIKARIS[*1] and Laurent TAVIAN[*2]

**Synopsis**: The LHC (Large Hadron Collider) accelerator helium cryogenic system consists of eight cryogenically independent sectors, each 3.3 km long, all cooled and operated at 1.9 K. The overall, entropy equivalent, installed cryogenic capacity totalizes 144 kW @ 4.5 K including 19.2 kW @ 1.8 K with an associated helium inventory of 130 ton. The LHC cryogenic system is considered among the most complex and powerful in the world allowing the cooling down to superfluid helium temperature of 1.9 K. of the accelerators' high field superconducting magnets distributed over the 26.7 km underground ring. The present article describes the LHC cryogenic system and its associated cryogen infrastructure. Operational experience, including cryogen management, acquired from the first three years of LHC operation is finally presented.

**Keywords**: high energy accelerators, large scale cryogenics, superconducting magnets

(Some figures in this article may appear in colour only in the electronic version)

## 1. Introduction

The LHC (Large Hadron Collider) consists in a deep underground, 26.7 km circumference, accelerator[1] equipped with high field superconducting magnets totalizing the unprecedented cold mass of 36,000 ton and operated in superfluid helium at the temperature of 1.9 K.

The LHC cryogenic system[2] consists in eight 18 kW at 4.5 K helium refrigerators each of them respectively combined with eight 2.4 kW at 1.8 K refrigeration units, the latter based on several stages of hydrodynamic cold compressors process.

From the operational point of view, this implementation subdivides the LHC accelerator into eight cryogenically independent sectors, each of 3.3 km long (**Fig. 1**). Each LHC sector is connected to a pair of refrigerators, the first one providing the cooling capacity at 4.5 K, the second one completing the cooling down to the operating temperature of 1.9 K[3]. Based on the LHC sector cryogenic scheme, considering the string of super-conducting magnets as a continuous cryostat, the cryogenic fluids are distributed by means of a dedicated compound cryogenic distribution line circling the LHC tunnel.

Regarding the cryogen inventory, with the installation and operation of the LHC cryogenic system, the associated infrastructure for storage and management of the helium and nitrogen has been drastically upgraded in order to fulfill and secure the entire spectrum of operational requirements. The overall helium inventory of the LHC accelerator amounts to 130 t. The accelerator pre-cooling from ambient temperature down to 80 K is performed by vaporizing 10,000 t of liquid nitrogen stored at surface premises.

Operational procedures and process control are duplicated for each LHC sector thus optimizing the steady-state operation by the cryogenic team. The availability results of the global LHC cryogenic system from the first 2010–2012 years physics run have been in constant progress, starting at 90% the first year and ending nearly to 95% in 2012, corresponding to an equivalent availability of more than 99% per individual LHC sector.

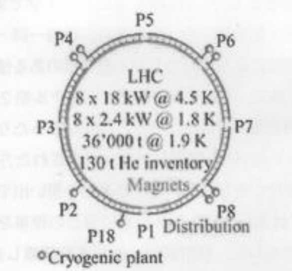


Fig. 1　Layout of the LHC cryogenic system.

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[*1] CERN, European Organization for Nuclear Research
1211 Geneva 23, Switzerland
E-mail: Dimitri.Delikaris@cern.ch
[*2] CERN, European Organization for Nuclear Research
1211 Geneva 23, Switzerland
E-mail: Laurent.Jean.Tavian@cern.ch
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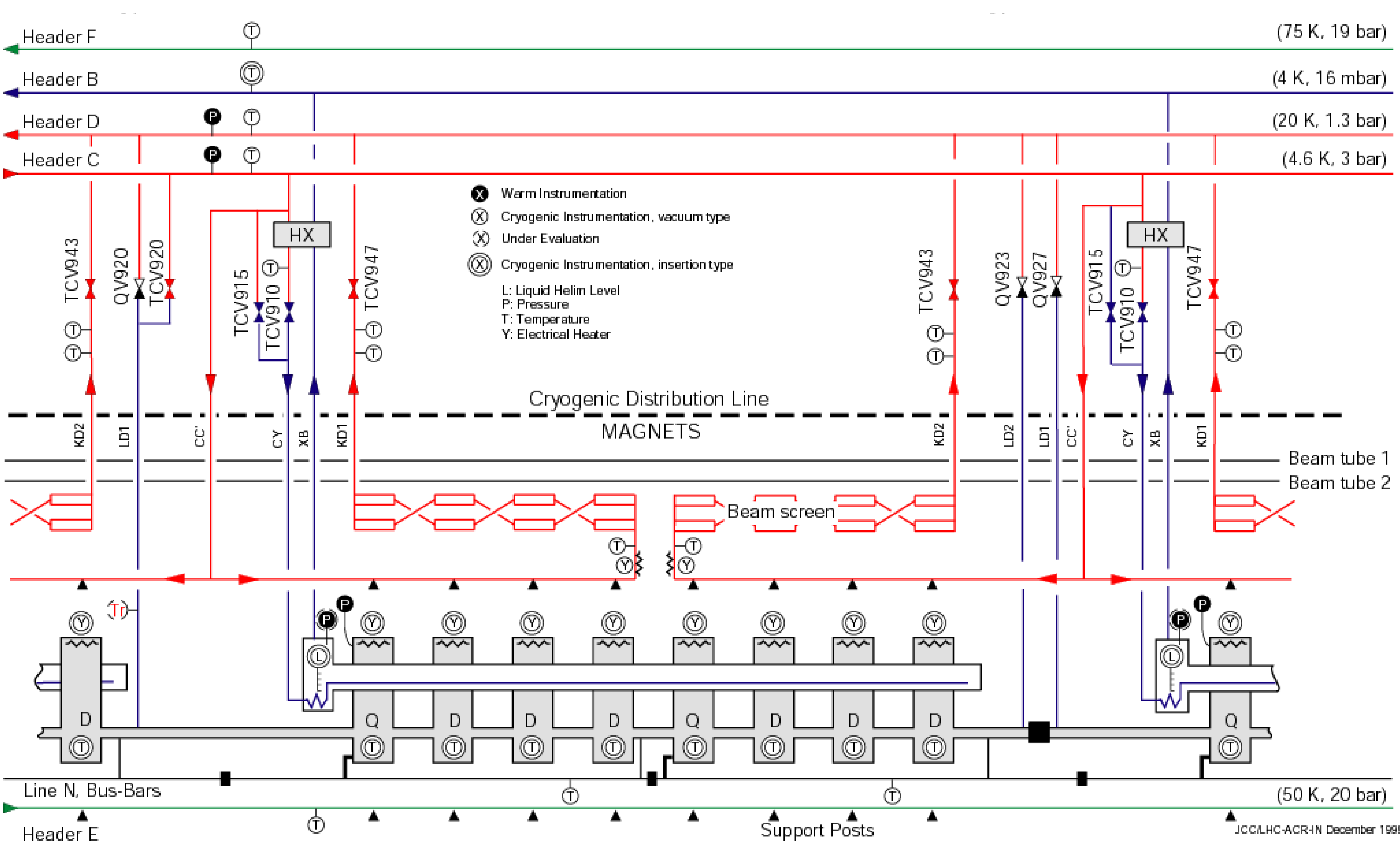
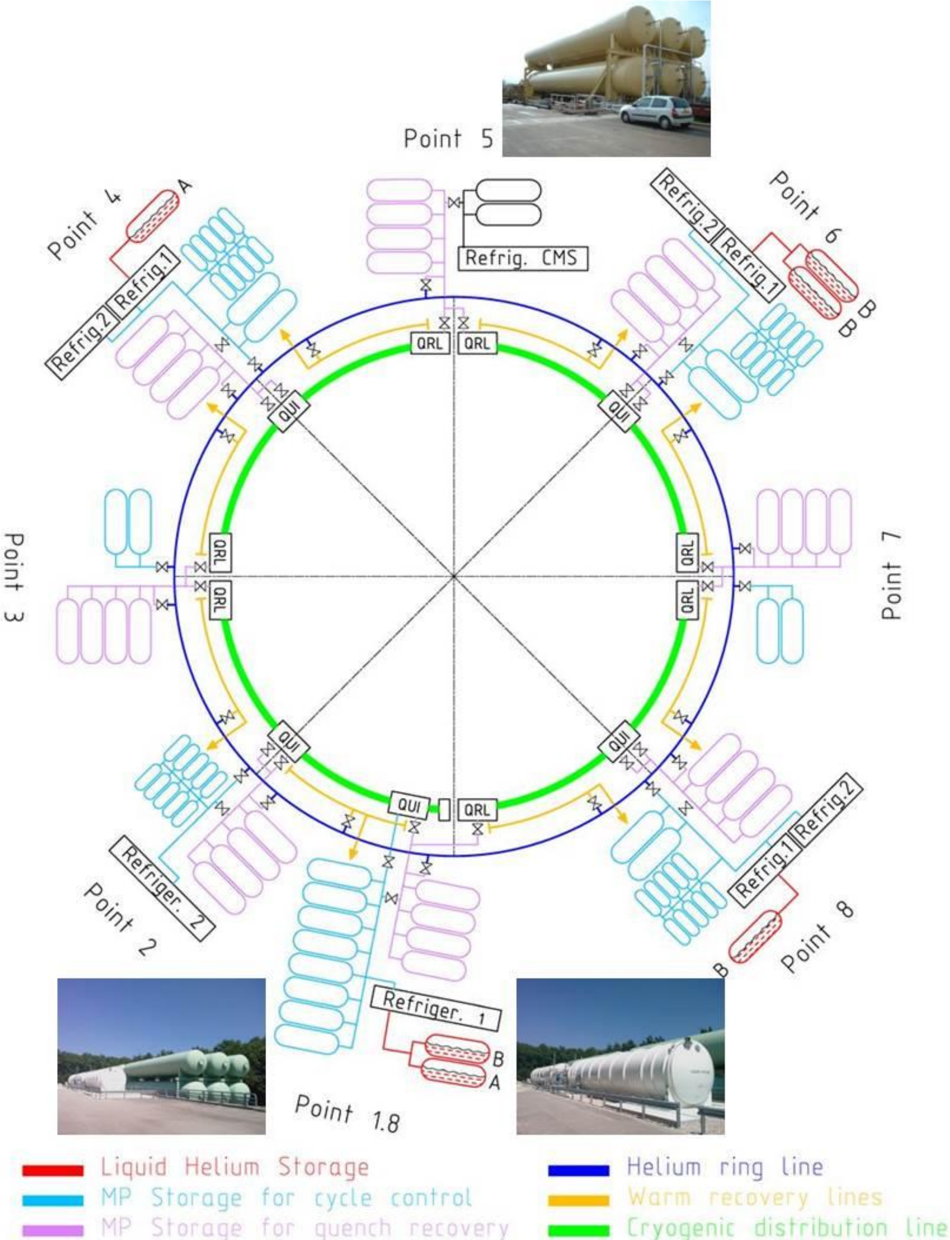
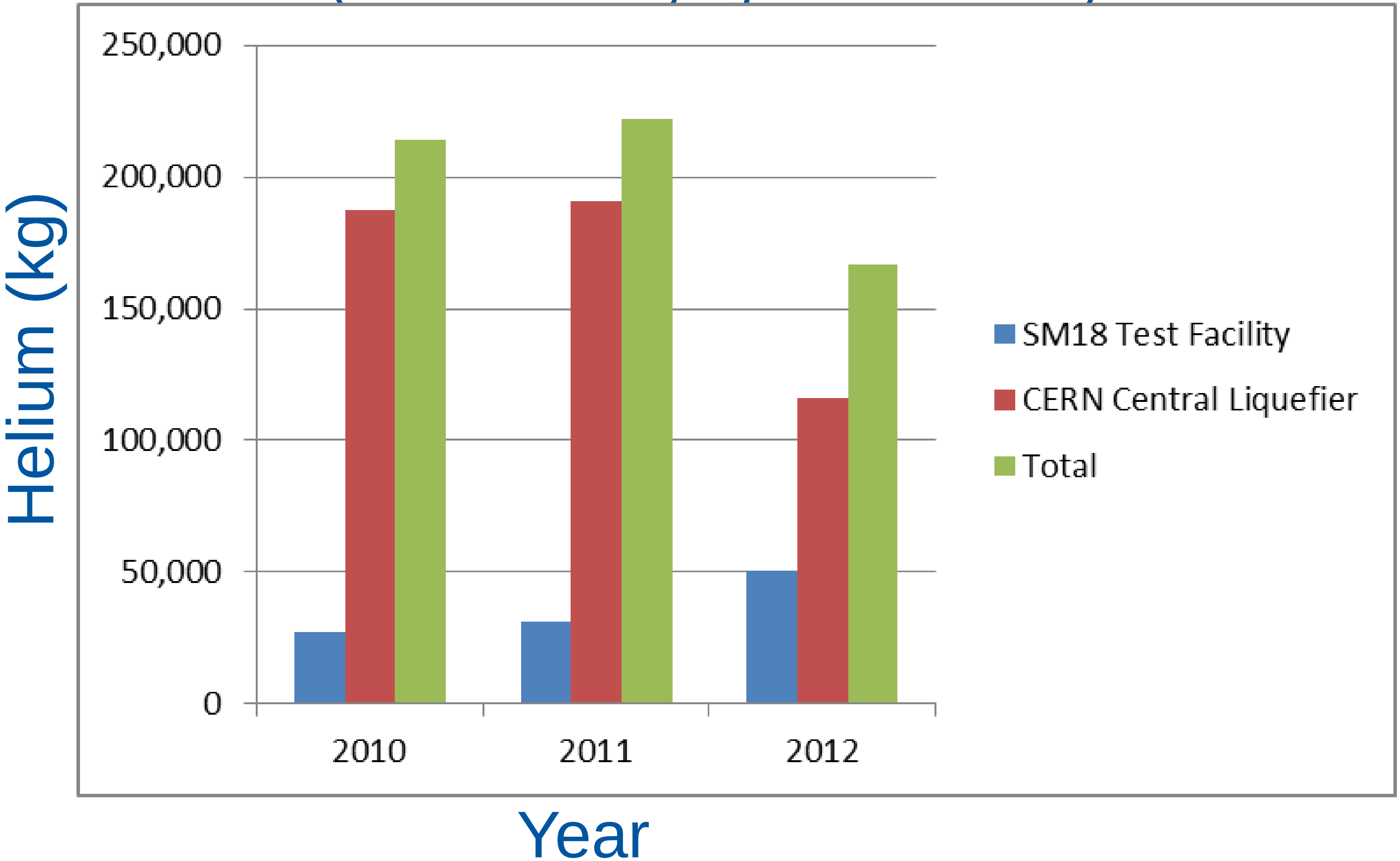
# Backup slides

# Magnet-cell cooling scheme




Point 5
Refrig. CMS
Point 4
Refrig.1
Refrig.2
A
Point 6
Refrig.2
Refrig.1
B
B
Point 3
Point 7
QRL
QUI
Point 2
Refriger. 2
Point 8
Refrig.1
Refrig.2
B
Refriger. 1
B
A
Point 1.8
Liquid Helium Storage
MP Storage for cycle control
MP Storage for quench recovery
Helium ring line
Warm recovery lines
Cryogenic distribution line

# Helium recovery & purification (non- LHC cryogenic facilities)



# Cryogen Strategy at CERN

With respect to the procurement and management of very large cryogen inventory (helium and nitrogen):

- ✓ Helium procurement strategy: combination of multi-industrial suppliers & multi-sourcing approach implemented
- ✓ Nitrogen procurement strategy: secure logistics by multi-industrial suppliers approach implemented
- ✓ Helium is classified as strategic product by the CERN
- ✓ All adequate means are implemented in order to secure the general inventory
- ✓ For the test benches and internal distribution facilities, highest priority is set for systematic recovery & purification