



# Cryogenics for the Large Hadron Collider (LHC): design, construction, operation & upgrade

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EASITrain School 2, CEA Saclay  
1<sup>st</sup> October 2019

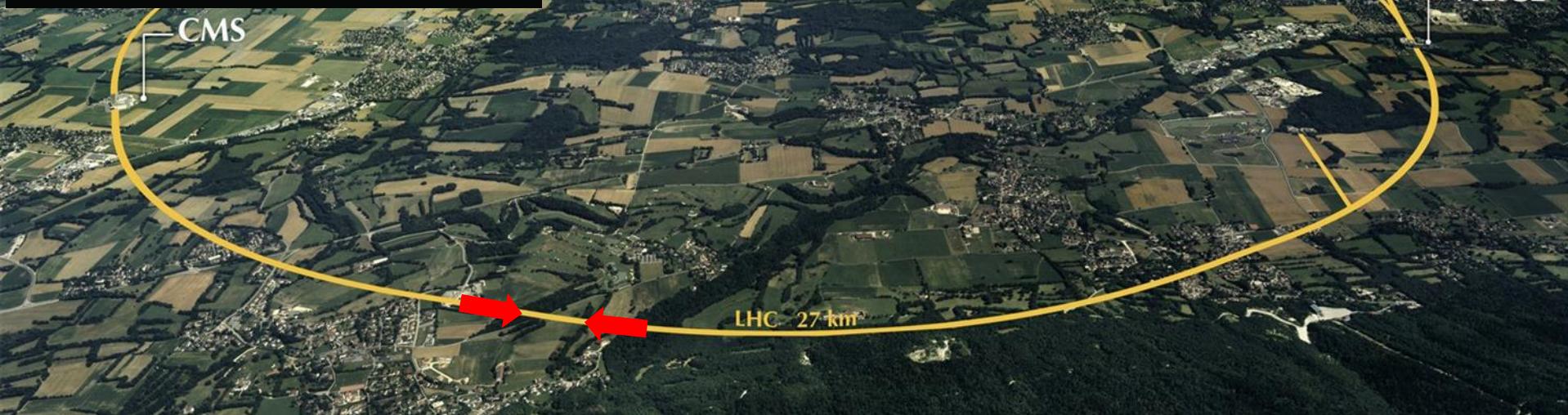
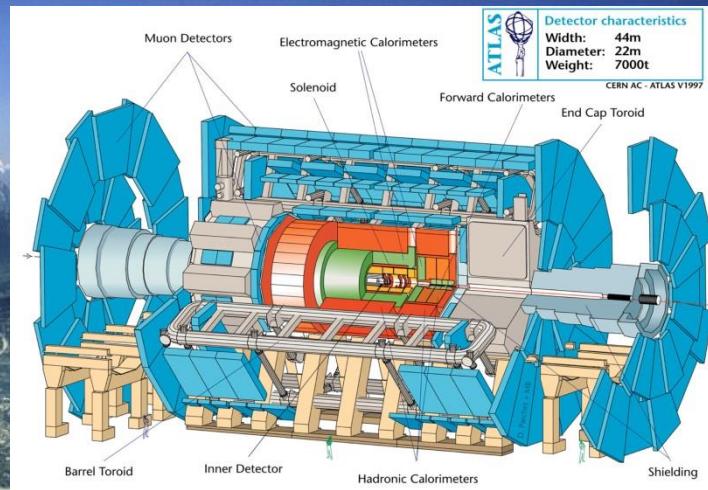
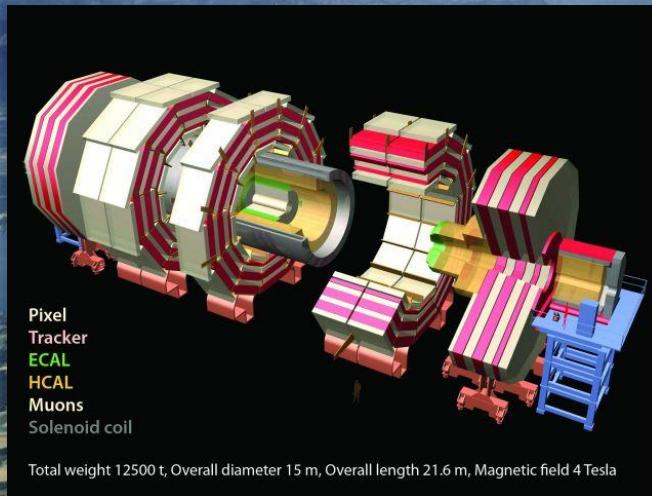


## Contents

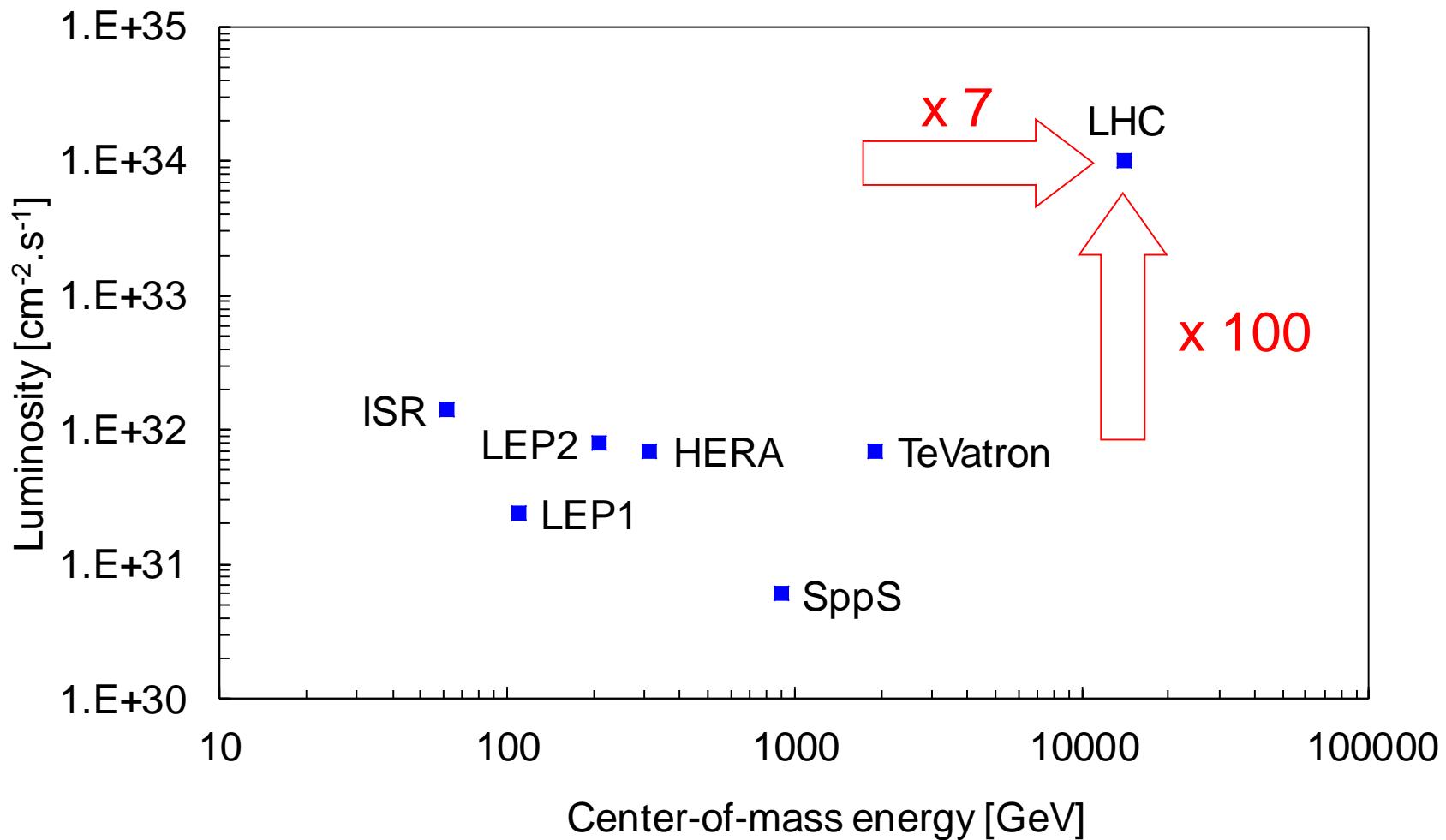
- Technical challenges of the LHC
- He II magnet cooling scheme
- Cryostat design and heat loads
- Refrigeration at 4.5 K and 1.8 K
- Specific He II technologies
- Instrumentation and controls
- Operation
- Upgrade



# Superconductivity and cryogenics are key technologies to the LHC and its large, multipurpose detectors

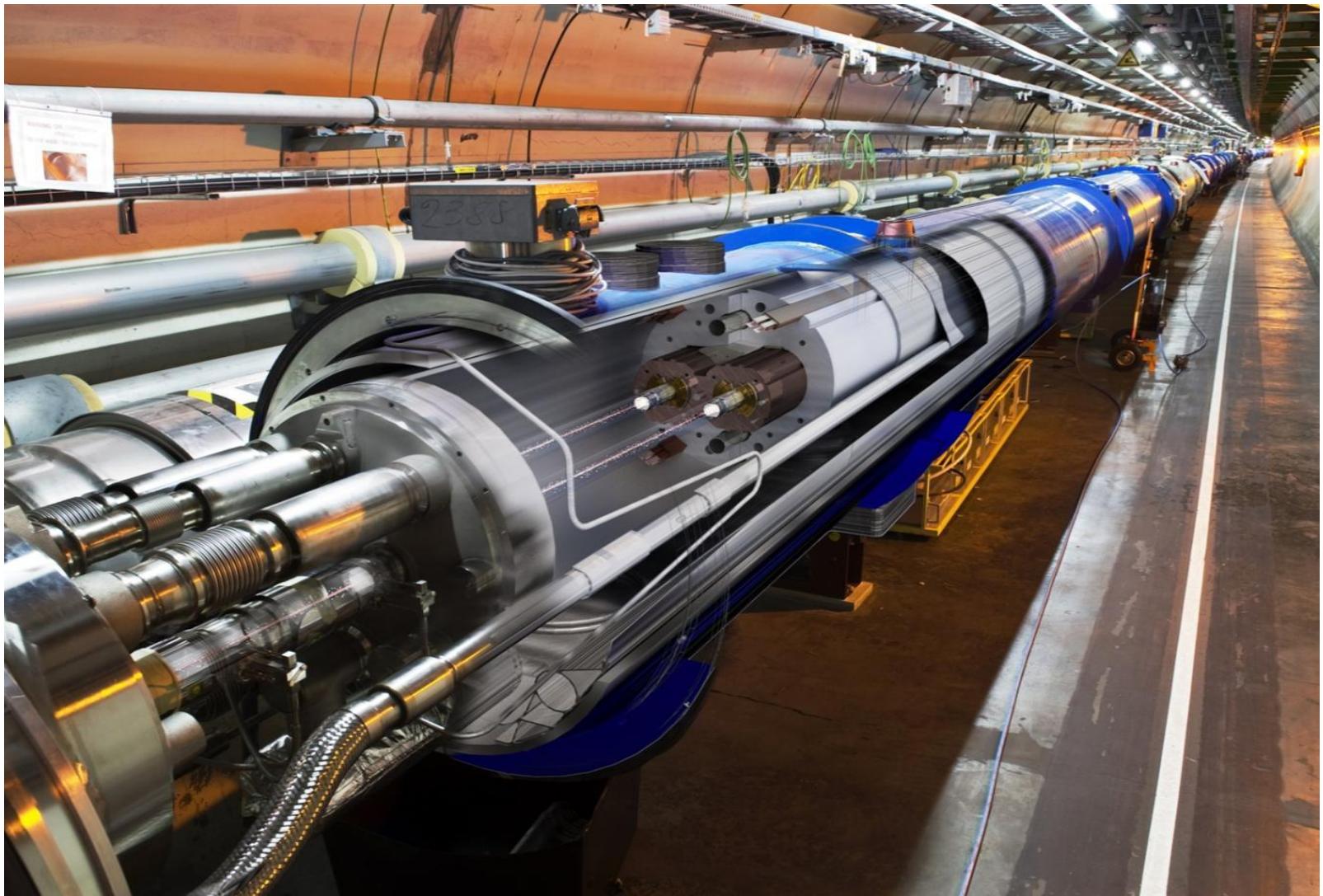


## A new territory in energy and luminosity

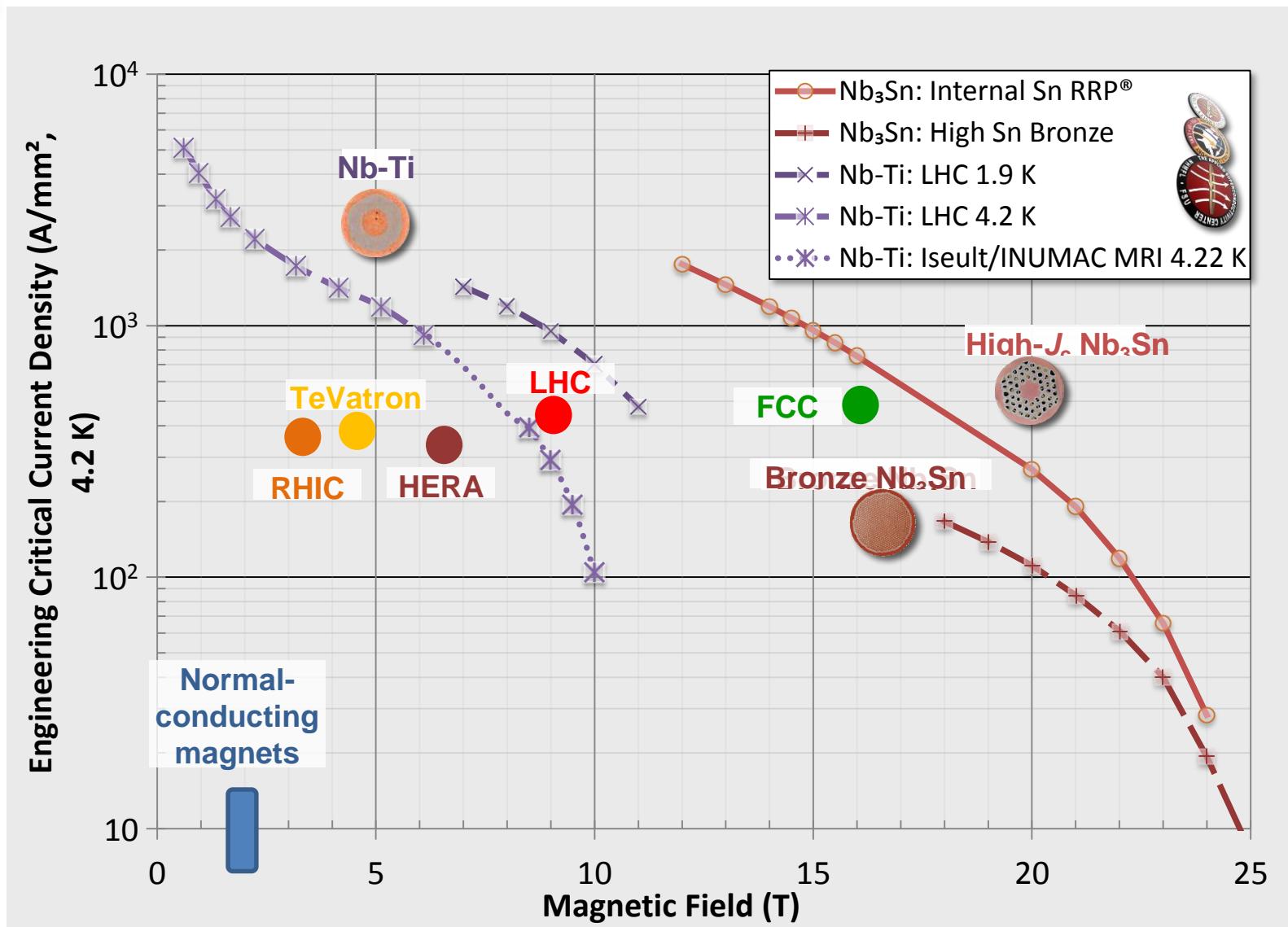


1232 twin-aperture superconducting dipoles

$B_{\text{nom}} = 8.33 \text{ T}$ ,  $I_{\text{nom}} = 11850 \text{ A}$

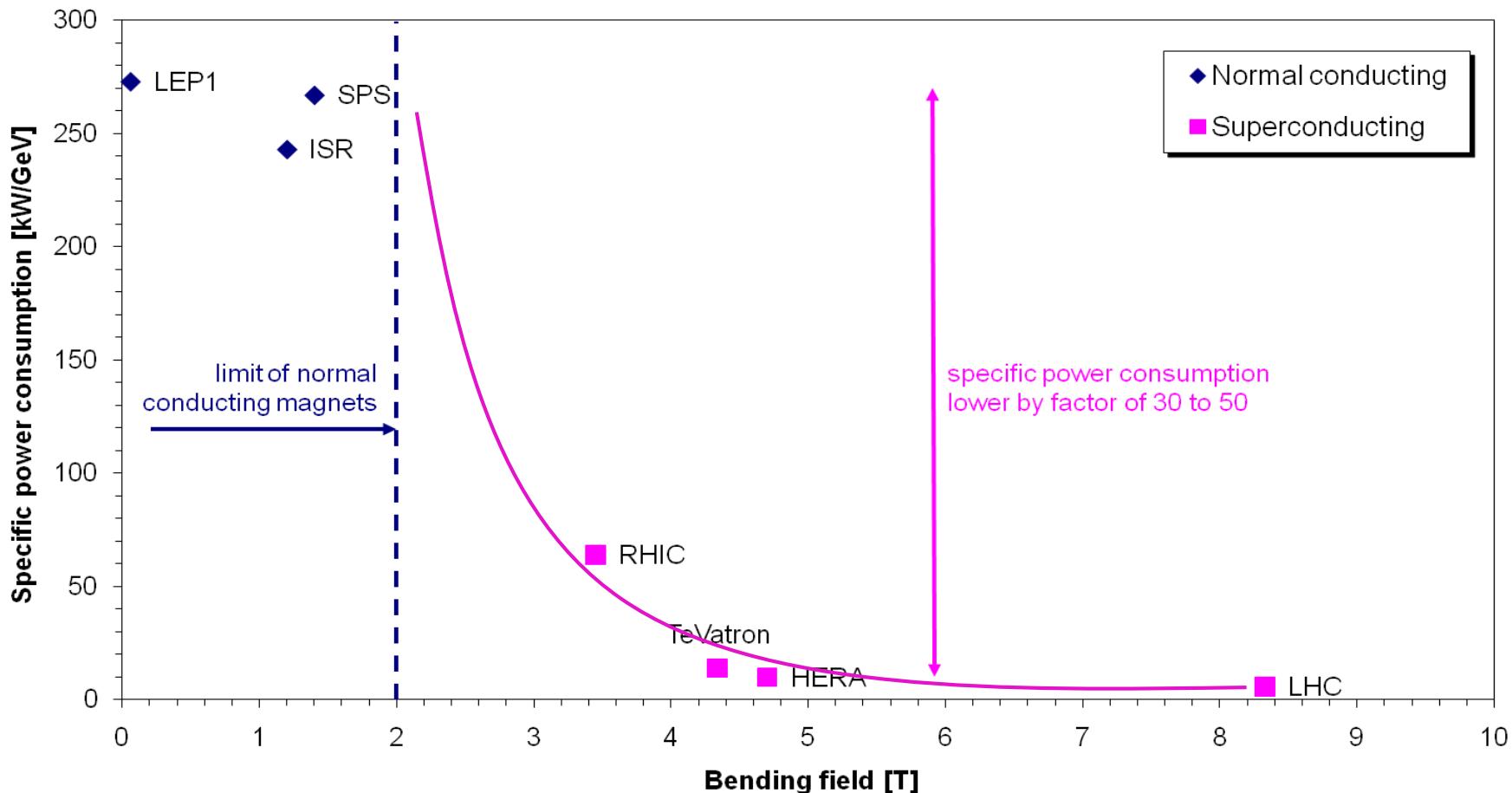


# Superfluid helium cooling enhances performance of Nb-Ti superconductor at high field



# Specific power consumption of particle colliders

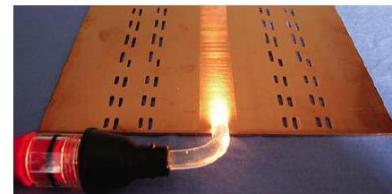
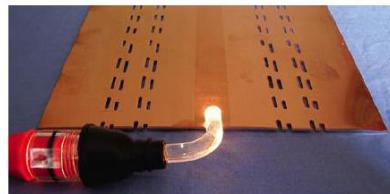
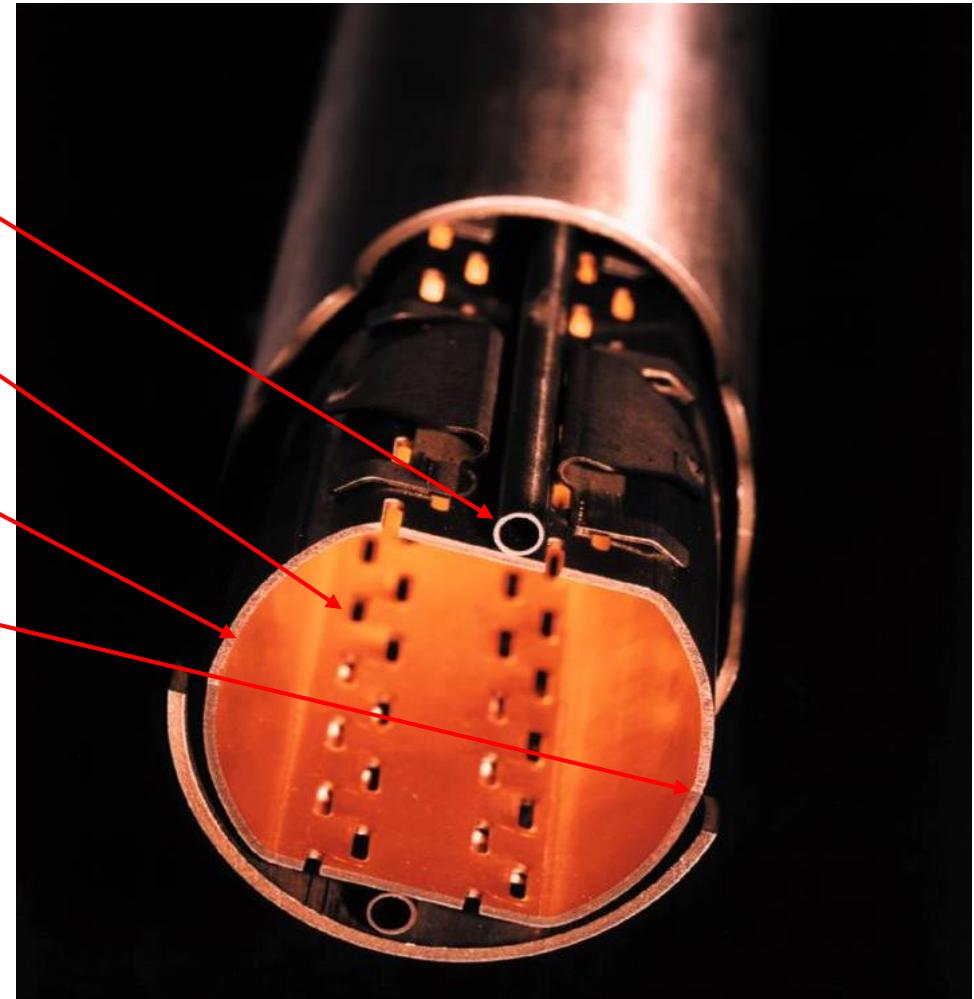
## Superconductivity and high fields allow strong reduction of the power bill!



## The beam screen

A multi-function component required by thermodynamics and beam physics

- Interception of beam-induced heat loads at 5-20 K (supercritical helium)
- Shielding of the 1.9 K cryopumping surface from synchrotron radiation (pumping holes)
- High-conductivity copper lining for low beam impedance
- Low-reflectivity sawtooth surface at equator to reduce photoemission and electron cloud





# Functions and constraints of LHC cryogenics

## Functions

- Maintain all magnets at operating temperature below 1.9 K
- Handle dynamic heat loads due to magnet powering and circulation of beams
- Cooldown/warmup magnets (37'500 tons) from/to room temperature in less than 3 weeks
- Handle magnet resistive transitions without loss of helium and recover from them in few hours

## Constraints

- Produce refrigeration in imited number of points (5) around machine circumference
- Re-use four 18 kW @ 4.5 K refrigerators from LEP2 project
- Distribute refrigeration in 3.3 km long sectors
- Tunnel slope 1.4 % leading to elevation differences of 150 m across the ring
- Minimize power consumption

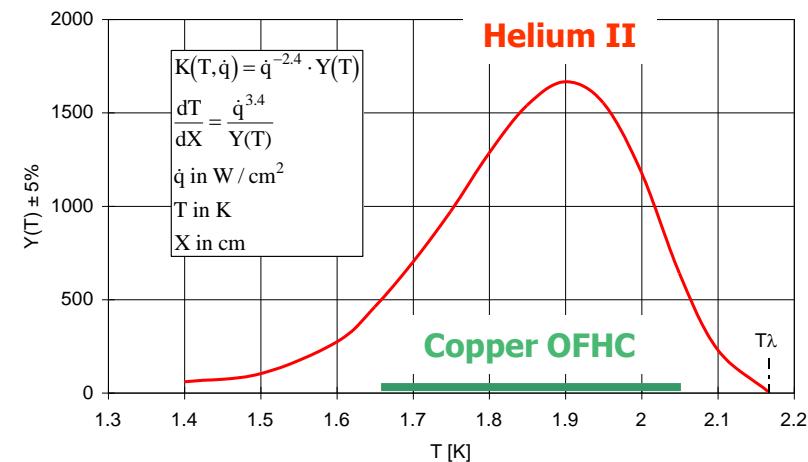
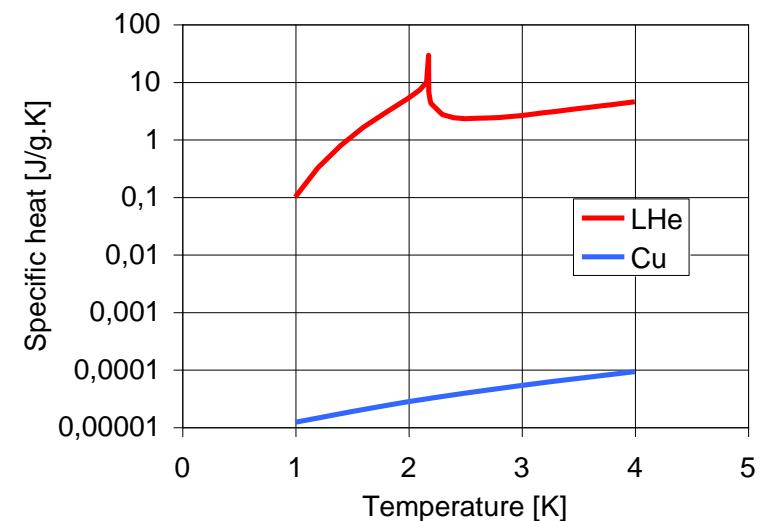


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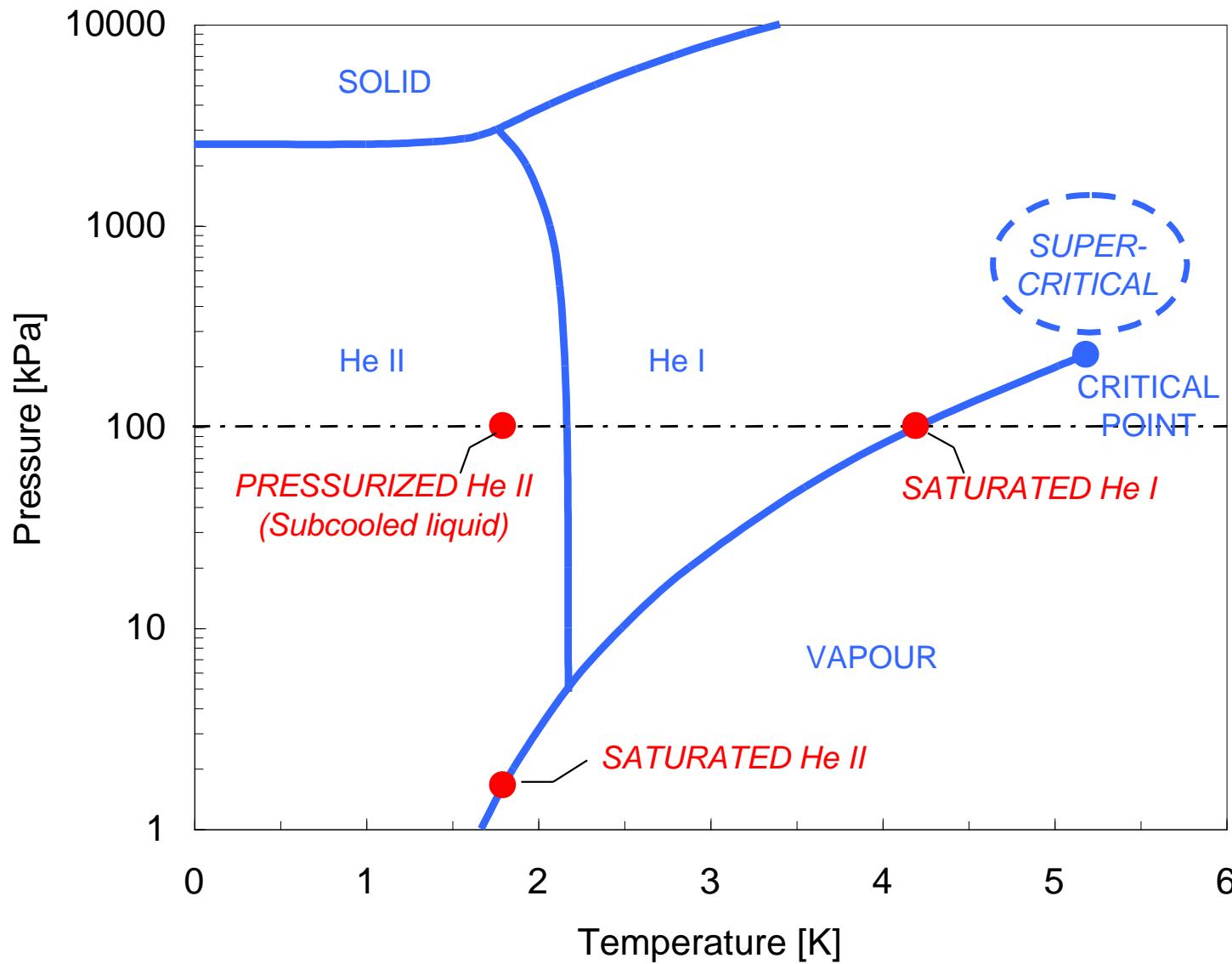
# Thermophysical properties of superfluid helium and engineering applications

- **Temperature** < 2.17 K  
 $\Rightarrow$  *superconductor performance*
- Low effective **viscosity**  $\Rightarrow$  *permeation*
  - 100 times lower than water at normal boiling point
- Very high **specific heat**  $\Rightarrow$  *stabilization*
  - $10^5$  times that of the conductor by unit mass
  - $2 \times 10^3$  times that of conductor by unit volume
- Very high **thermal conductivity**  
 $\Rightarrow$  *heat transport*
  - $10^3$  times that of OFHC copper
  - Peaking at 1.9 K
  - Still, insufficient for transporting heat over large distances across small temperature gradients





## Pressurized vs saturated He II



# Advantages & drawbacks of He II p

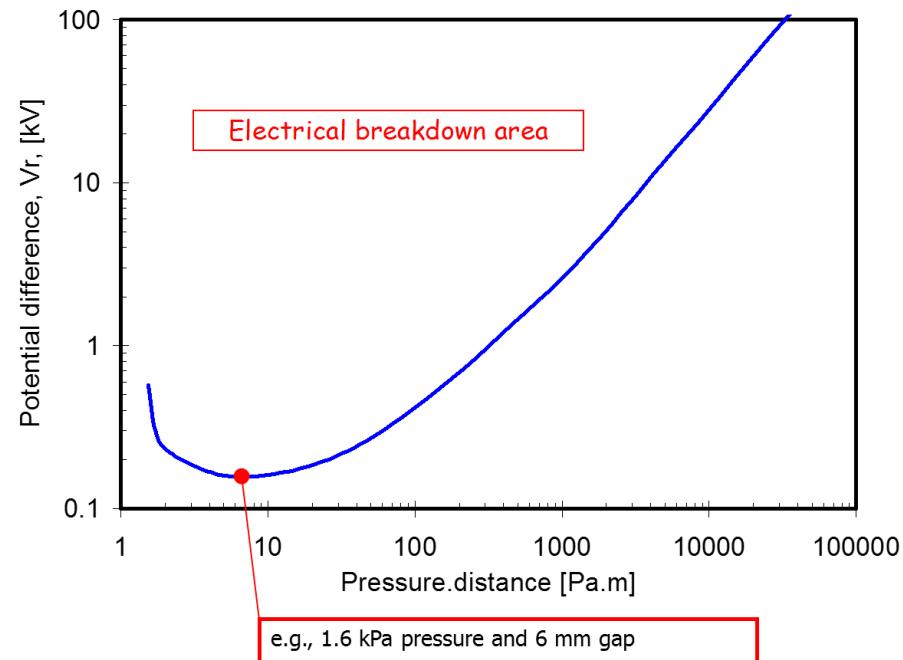
- **Advantages**

- limits the risk of air inleaks and contamination in large and complex cryogenic systems
- for electrical devices, limits the risk of electrical breakdown at fairly low voltage due to the bad dielectric characteristics of helium vapour (Paschen curve)

- **Drawbacks**

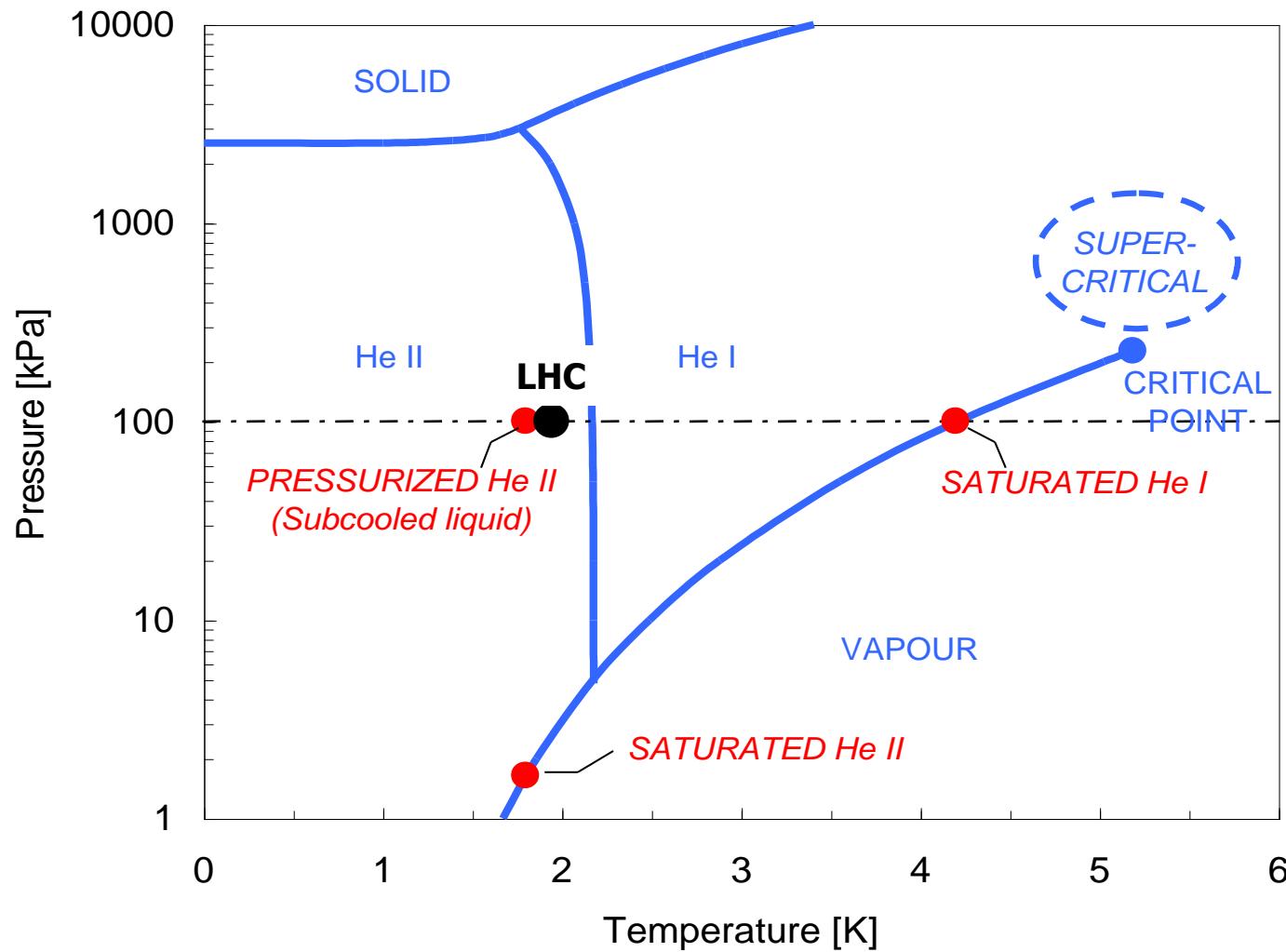
- one more level of heat transfer
- additional process equipment (pressurized-to-saturated helium II heat exchanger)

**Paschen curve for helium**



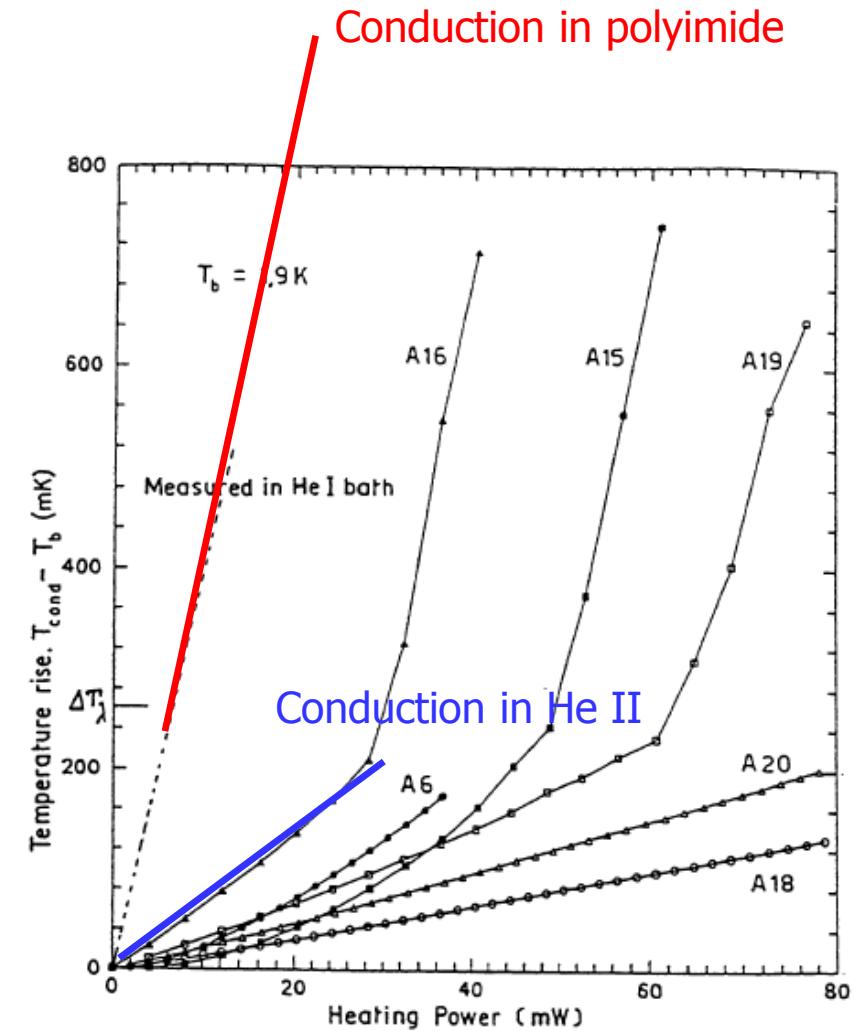
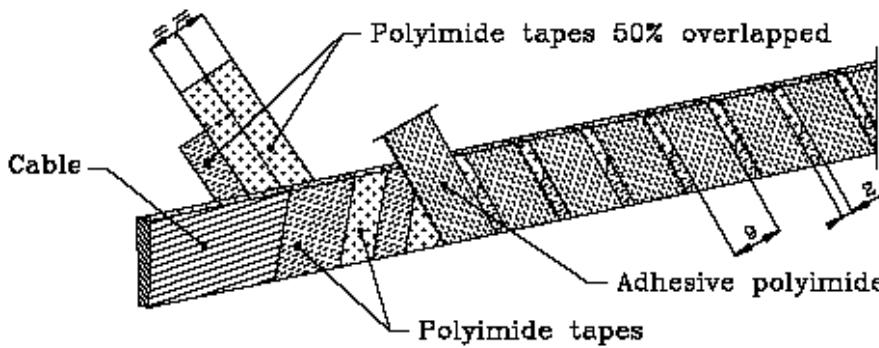


## Cooling LHC magnets with He II p



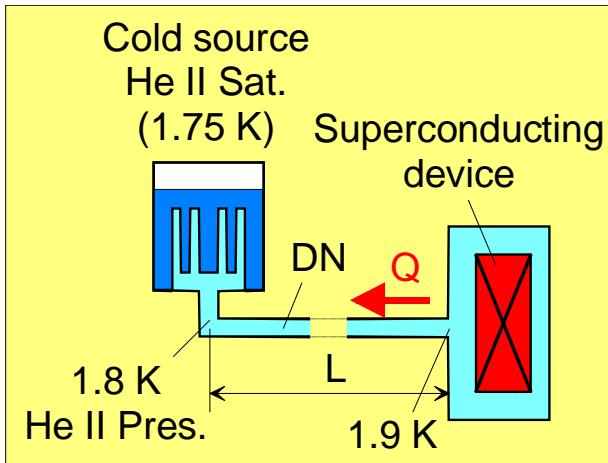
# Heat transfer across electrical insulation of LHC superconducting cable

Double wrap with partial overlap maintains porosity and percolation paths in electrical insulation of superconducting cable

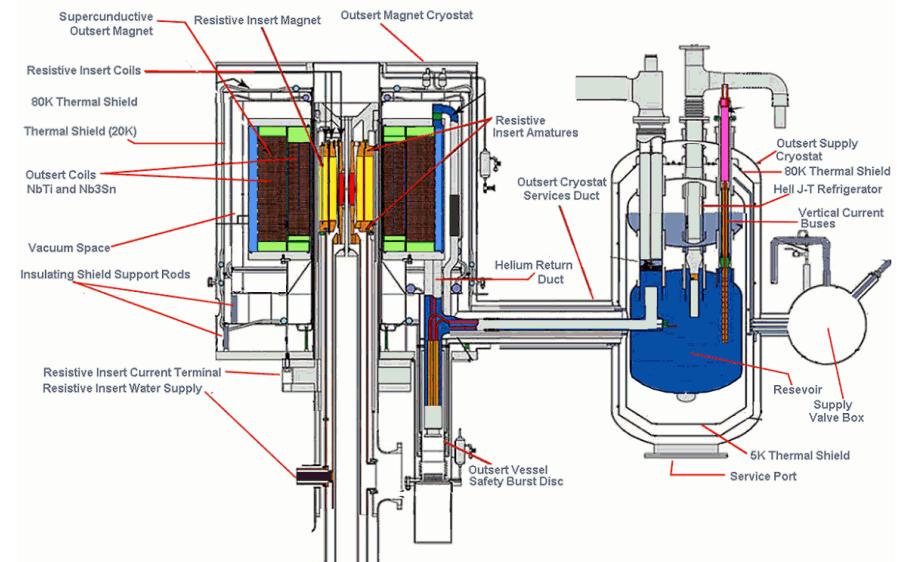


# Steady-state conduction in He II p from 1.9 to 1.8 K

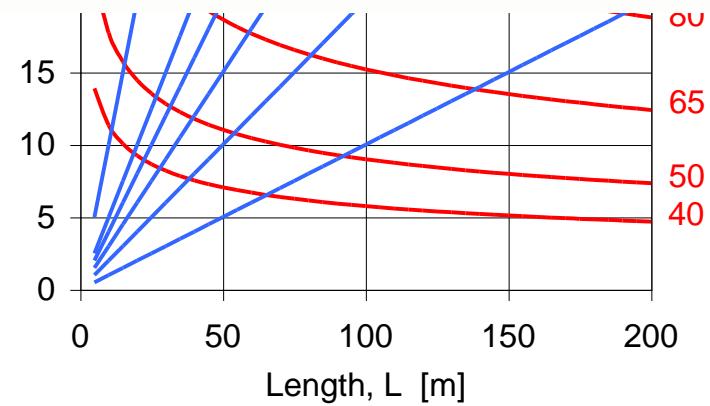
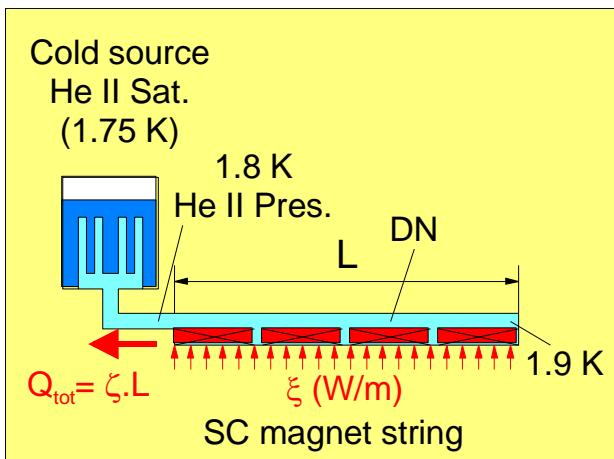
Lumped heat load



45 T hybrid magnet at NFMFL

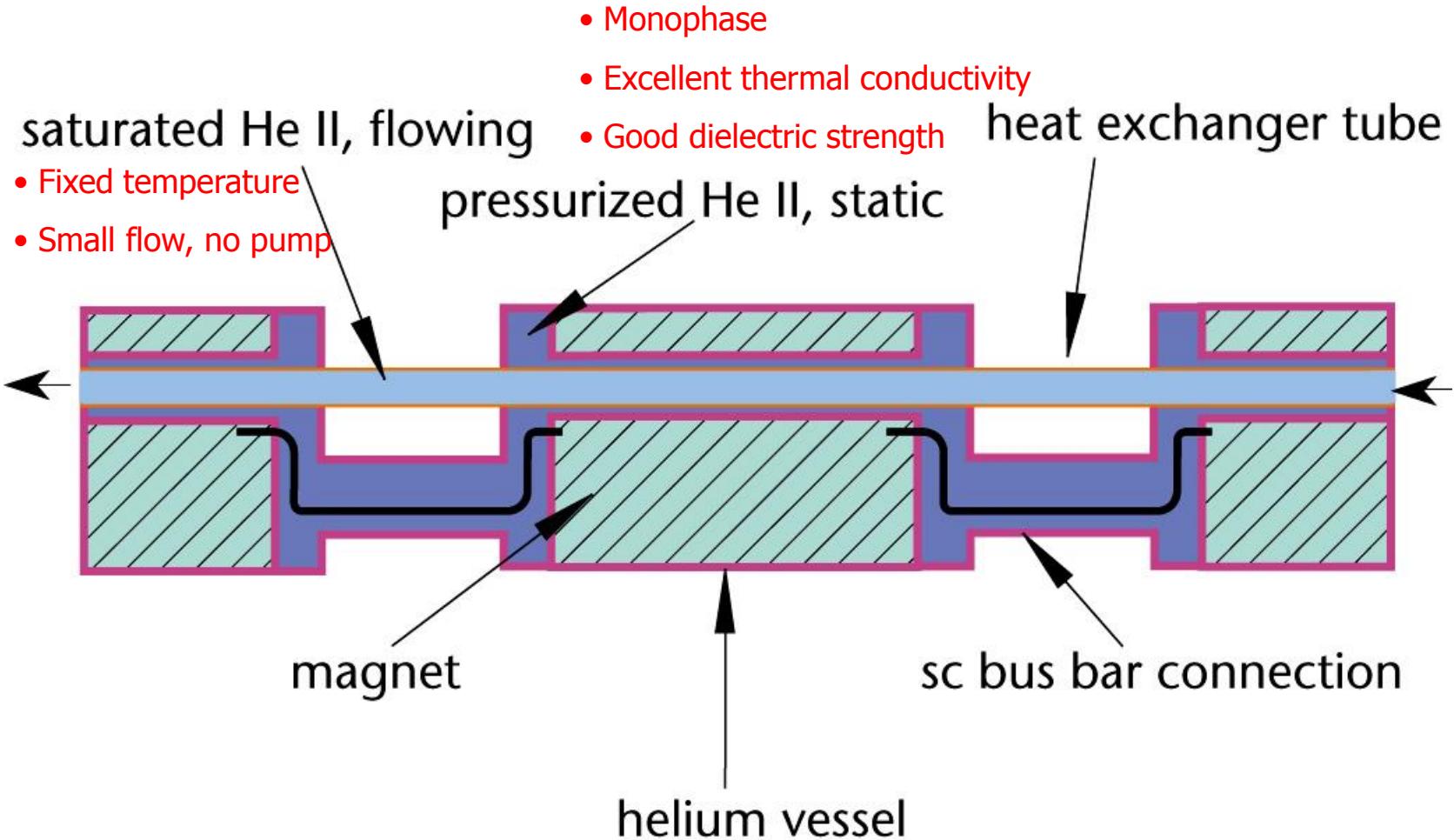


Linear distributed heat load



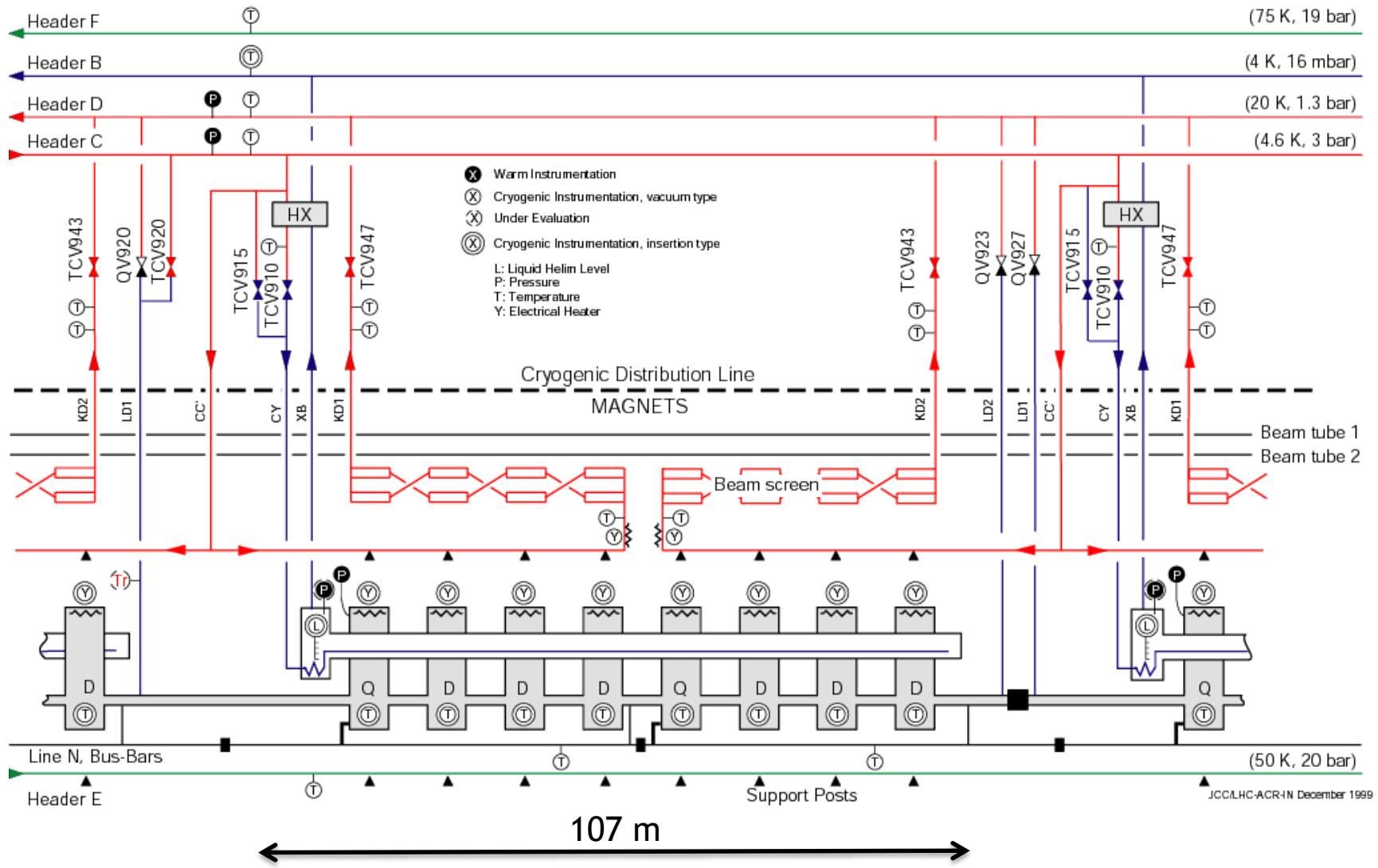
# Cooling magnet strings with superfluid helium

## Getting the best of helium transport properties

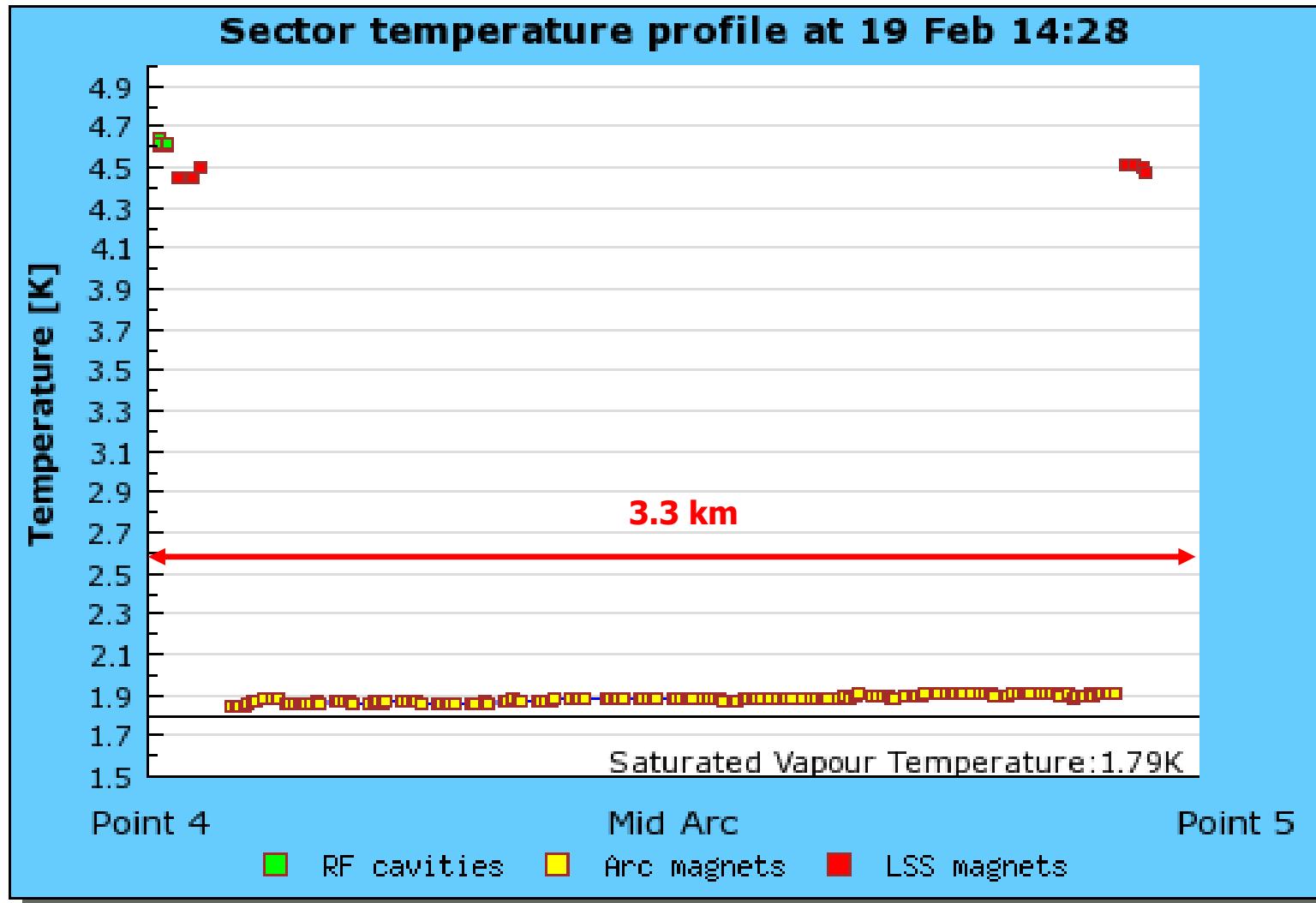




## LHC magnet string cooling scheme



## Cryogenic operation of LHC sector





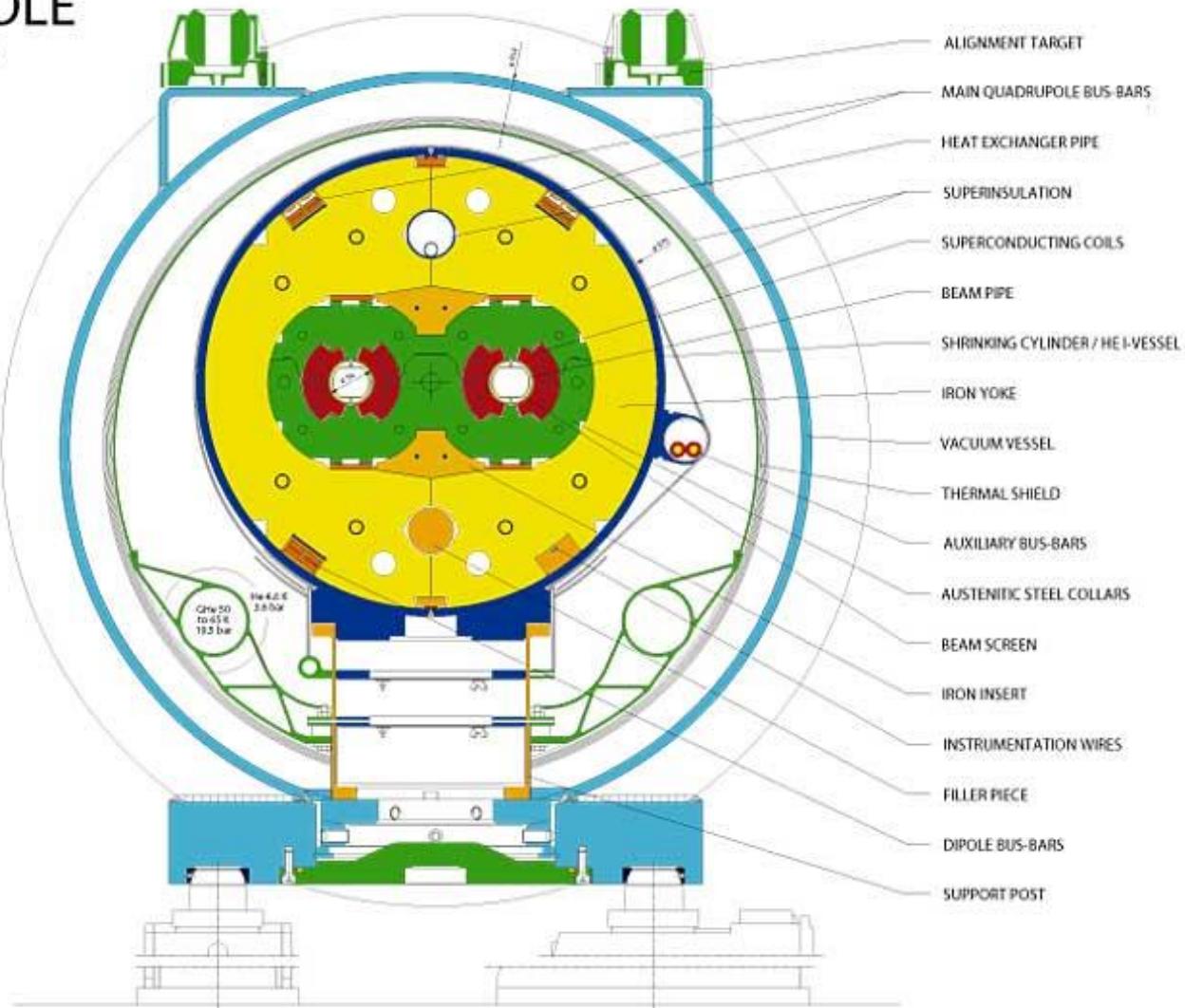
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# LHC cryostat cross-section

## LHC DIPOLE CROSS SECTION



# Thermal insulation techniques

## Multi-layer reflective insulation



10 layers around cold mass at 1.9 K

30 layers around thermal shield at 50-75 K



Cold surface area in LHC  $\sim$  9 hectares!

Thermal radiation from 290 K (black-body)  
 $\sim 400 \text{ W/m}^2 = 4 \text{ MW/ha}$

Heat flux from 290 K across 30 layers MLI  
 $\sim 1 \text{ W/m}^2 = 10 \text{ kW/ha}$

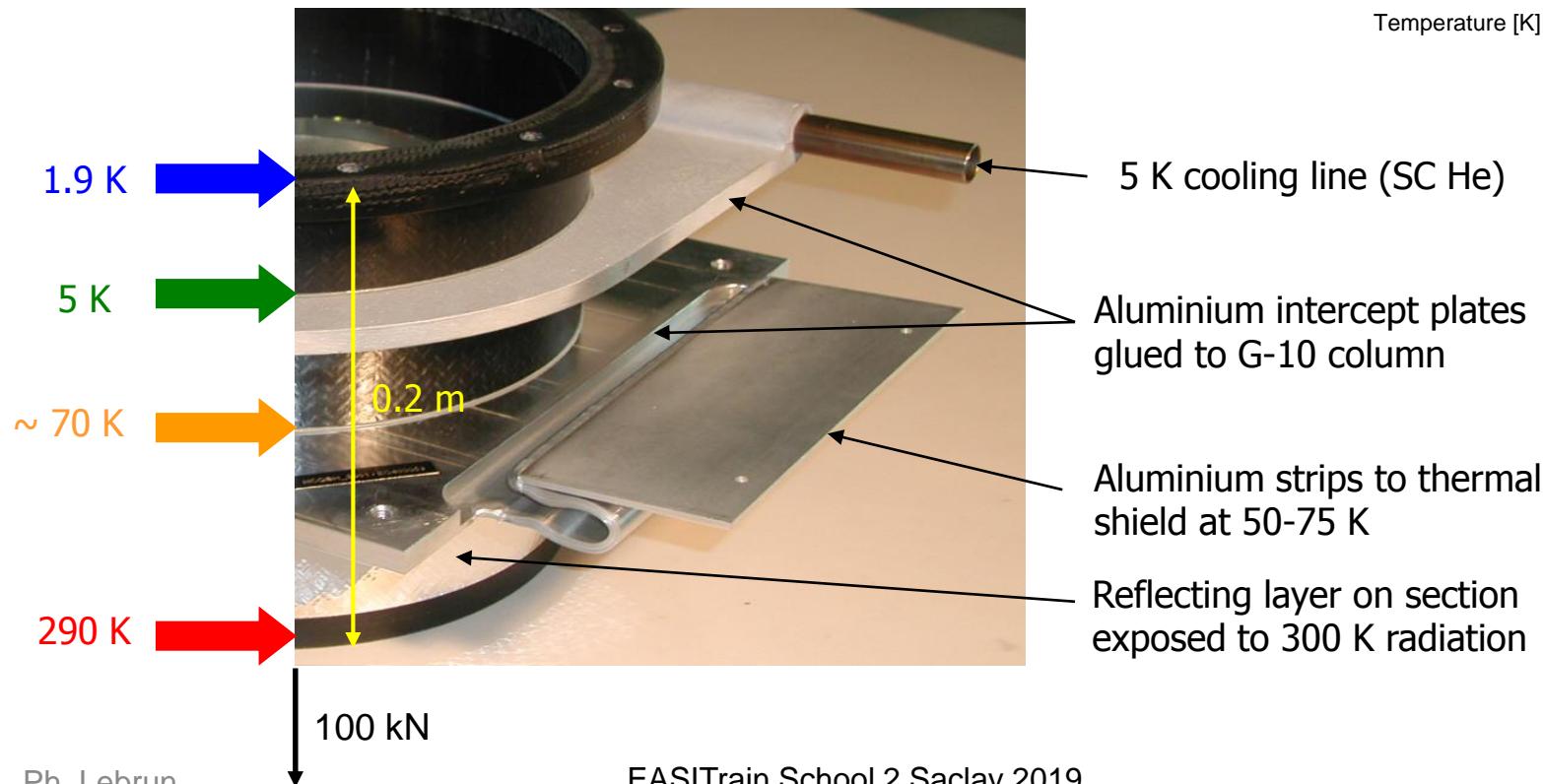
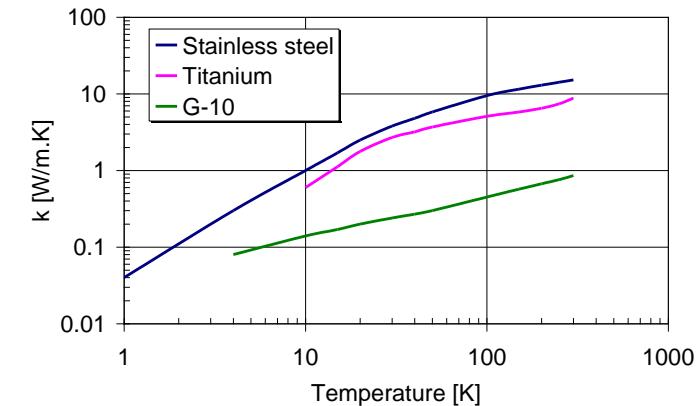
# Thermal insulation techniques

## Low-conduction non-metallic support posts

LHC cold mass to be supported = 37'500 tons

Conduction length = support height  $\sim 0.2$  m

At a compressive stress of 50 N/mm<sup>2</sup>, this requires a total support cross-section of 7.5 m<sup>2</sup>, representing a large thermal conduction path





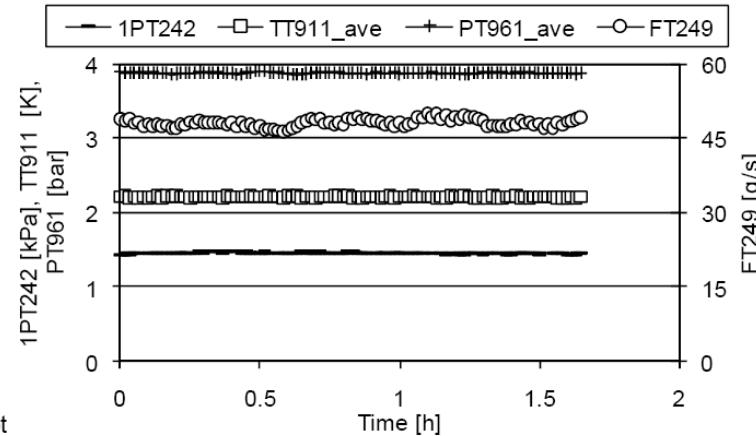
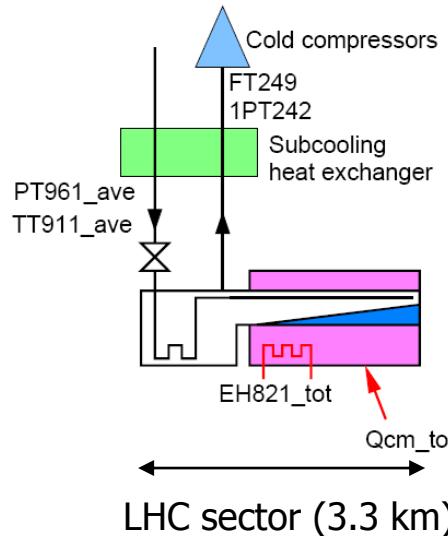
## Distributed steady-state heat loads [W/m] (Cryomagnets & distribution line in LHC arc)

Temperature	50-75 K	4.6-20 K	1.9 K LHe	4 K VLP
Heat inleaks*	7.7	0.23	0.21	0.11
Resistive heating	0.02	0.005	0.10	0
Beam-induced nominal**	0	1.58	0.09	0
Beam-induced ultimate**	0	4.36	0.11	0
Total nominal	7.7	1.82	0.40	0.11
Total ultimate	7.7	4.60	0.42	0.11

\* no contingency

** Breakdown	nominal	ultimate
Synchrotron radiation	0.33	0.50
Image current	0.36	0.82
Beam-gas Scattering	0.05	0.05
Photoelectron	0.89	3.07

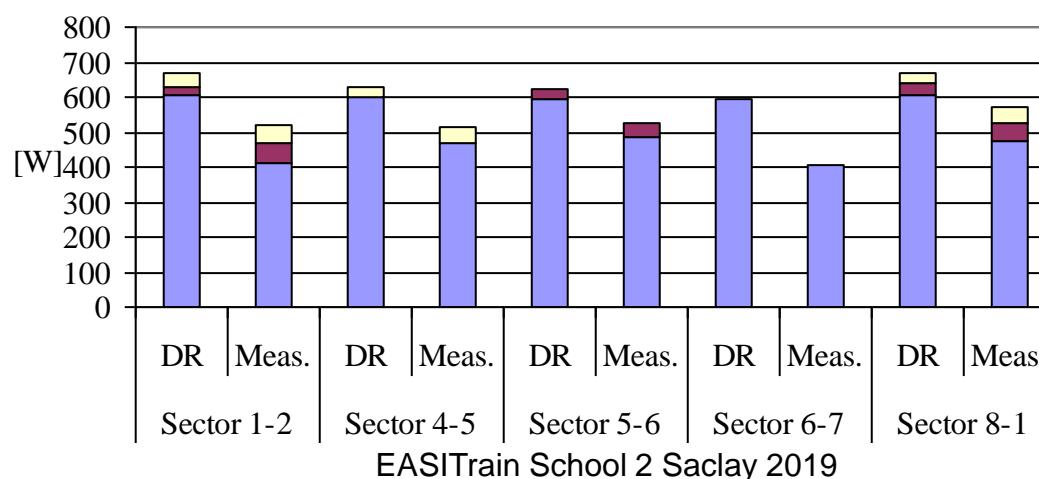
# Heat inleak measurements on full sectors confirm thermal budget



$$\dot{Q} = \dot{m} \Delta h(P, T)$$

Measured

He property tables



On average,  
measured values  
20 % lower than  
design estimates

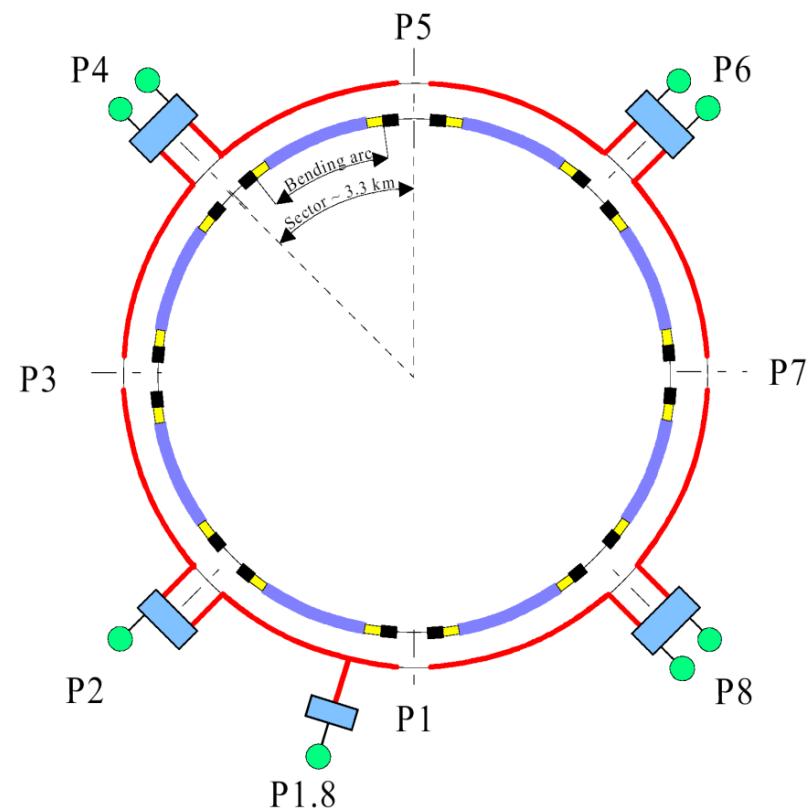
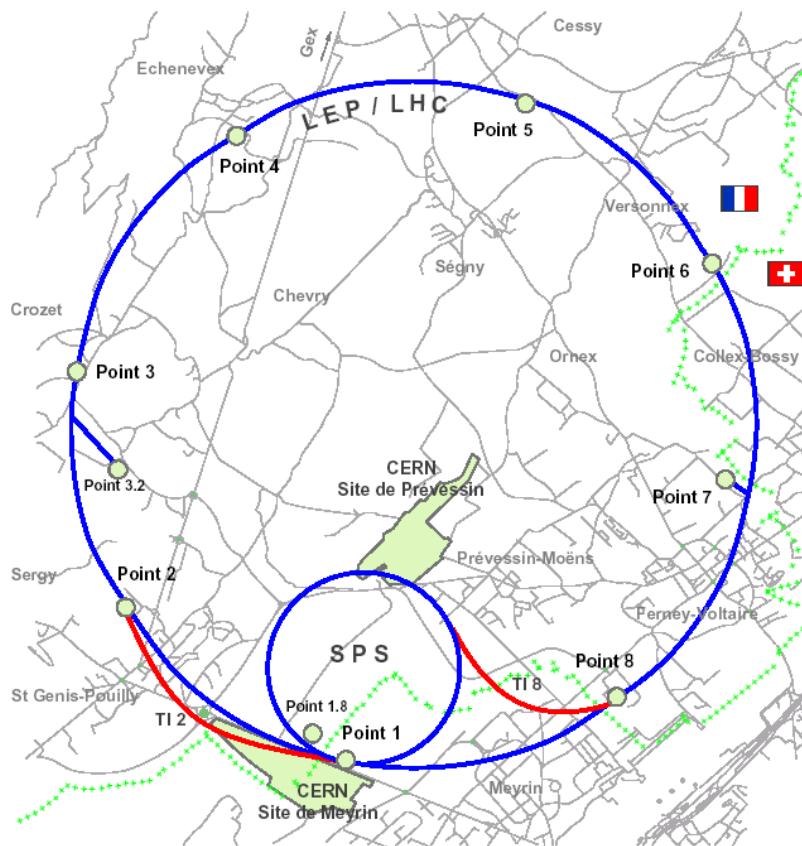


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## Layout of the LHC cryogenic system



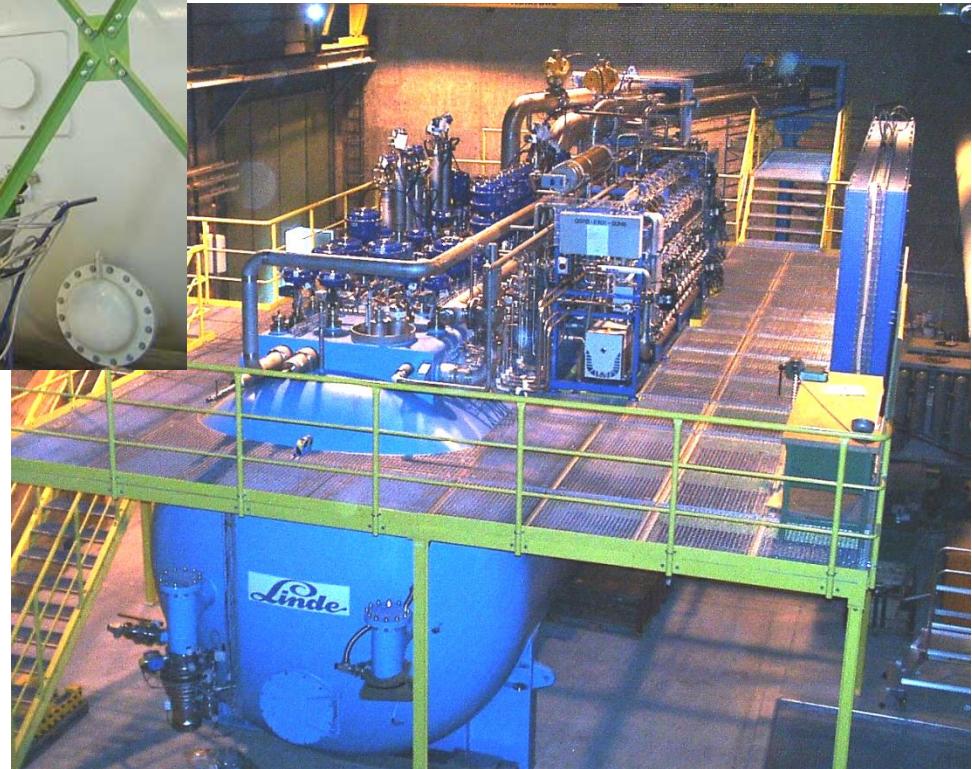
- 5 cryogenic islands
- 8 cryogenic plants, each serving adjacent sector, interconnected when possible
- Cryogenic distribution line feeding each sector



## 18 kW @ 4.5 K helium refrigerators

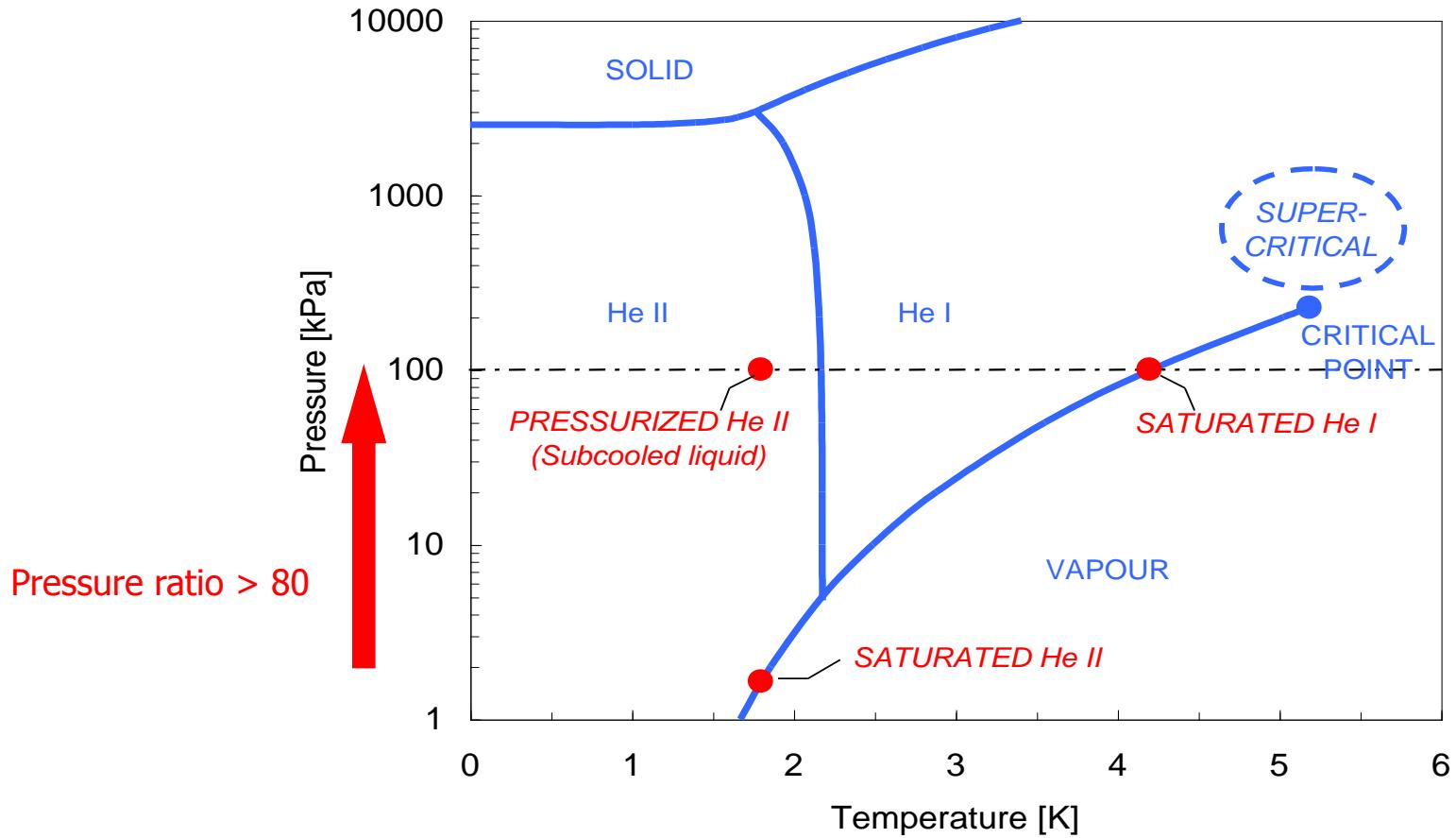


33 kW @ 50 K to 75 K  
23 kW @ 4.6 K to 20 K  
41 g/s liquefaction



High thermodynamic efficiency  
COP at 4.5 K: 220-230 W/W

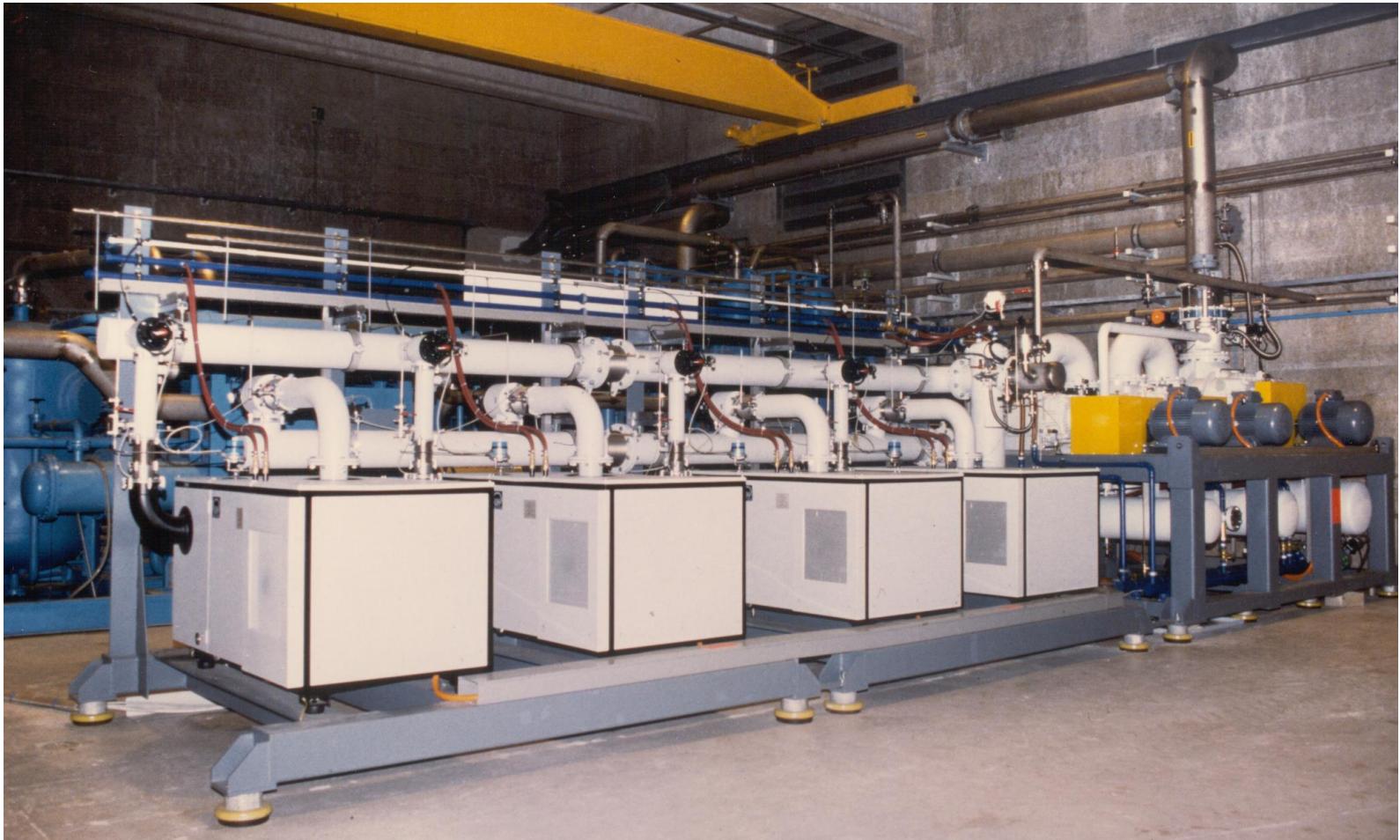
## Challenges of high-power 1.8 K refrigeration



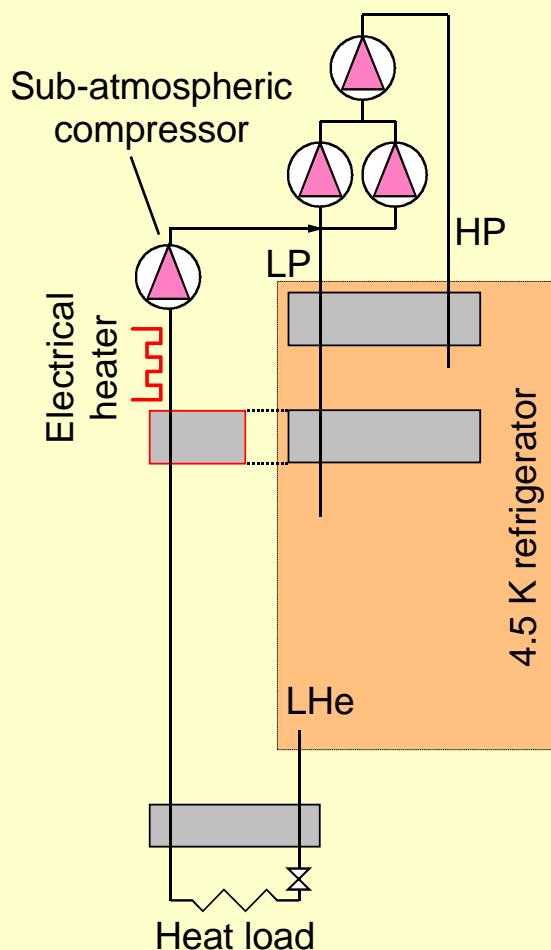
- Compression of large mass flow-rate of He vapor across high pressure ratio  
⇒ intake He at maximum density, i.e. cold
- Need contact-less, vane-less machine ⇒ hydrodynamic compressor
- Compression heat rejected at low temperature ⇒ thermodynamic efficiency



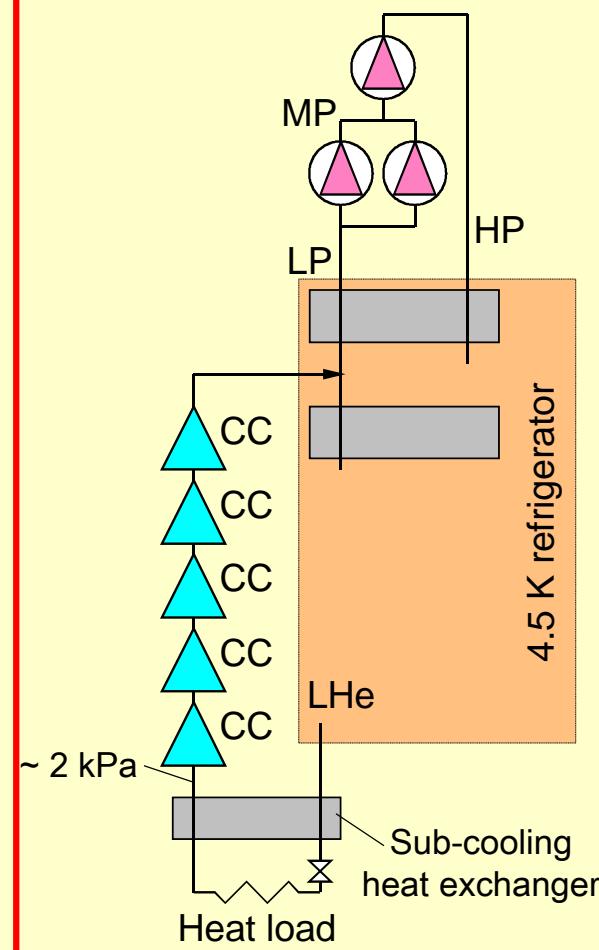
Warm pumping unit for LHC magnet tests  
3 stages of Roots + 1 stage rotary-vane pumps  
6 g/s @ 10 mbar (*1/160 of LHC!*)



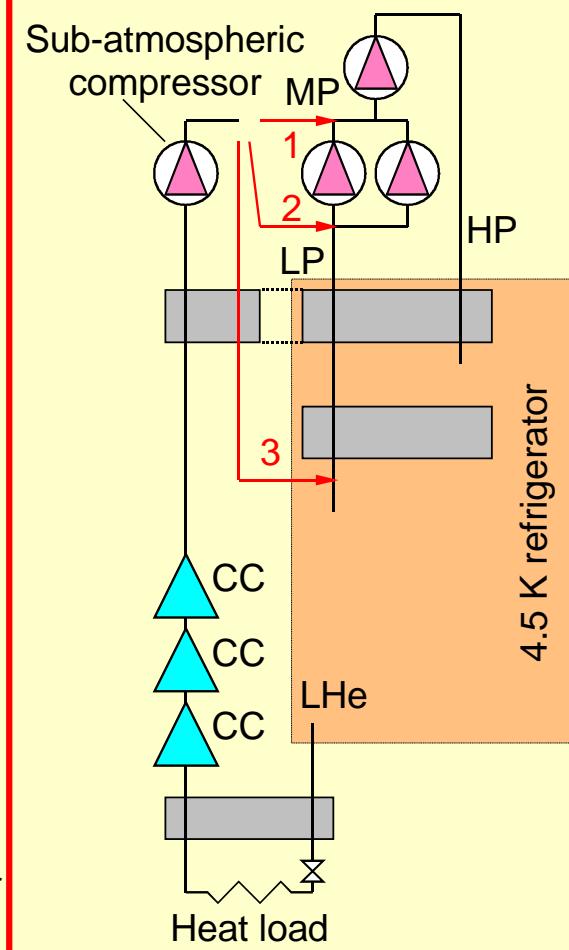
# Cycles for refrigeration below 2 K



**"Warm"**  
Compression



**"Integral Cold"**  
Compression



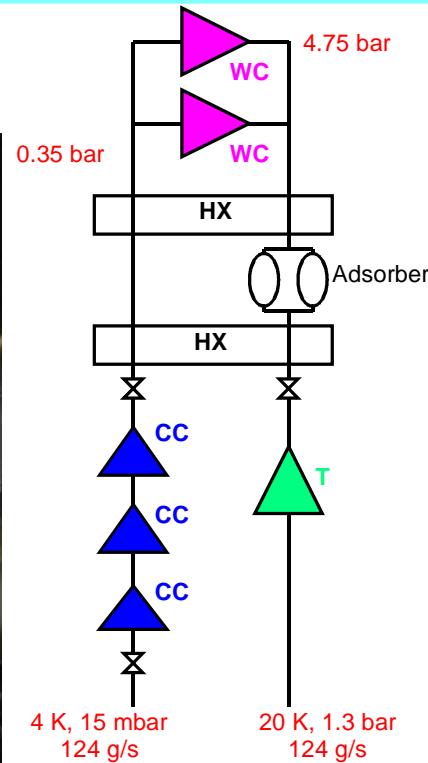
**"Mixed"**  
Compression

# 2.4 kW @ 1.8 K refrigeration units

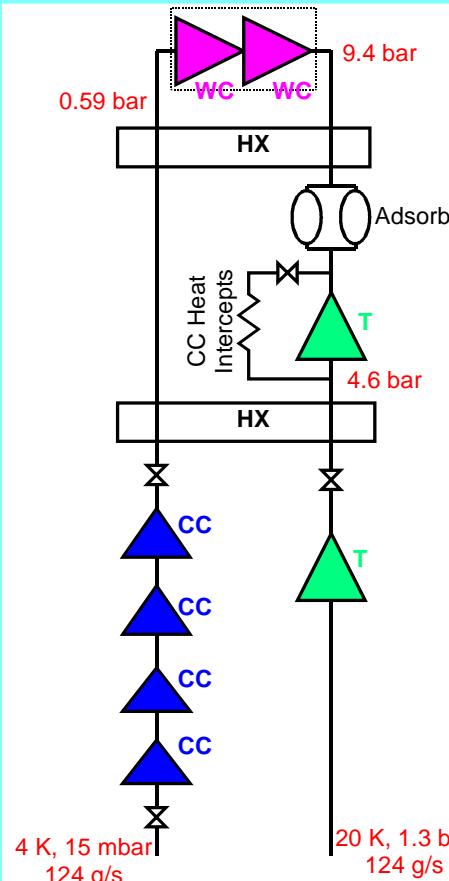
## Cold hydrodynamic compressors

### Electric drive 6'000 to 48'000 rpm, active magnetic bearings

#### 1.8 K Refrigeration Unit Cycles



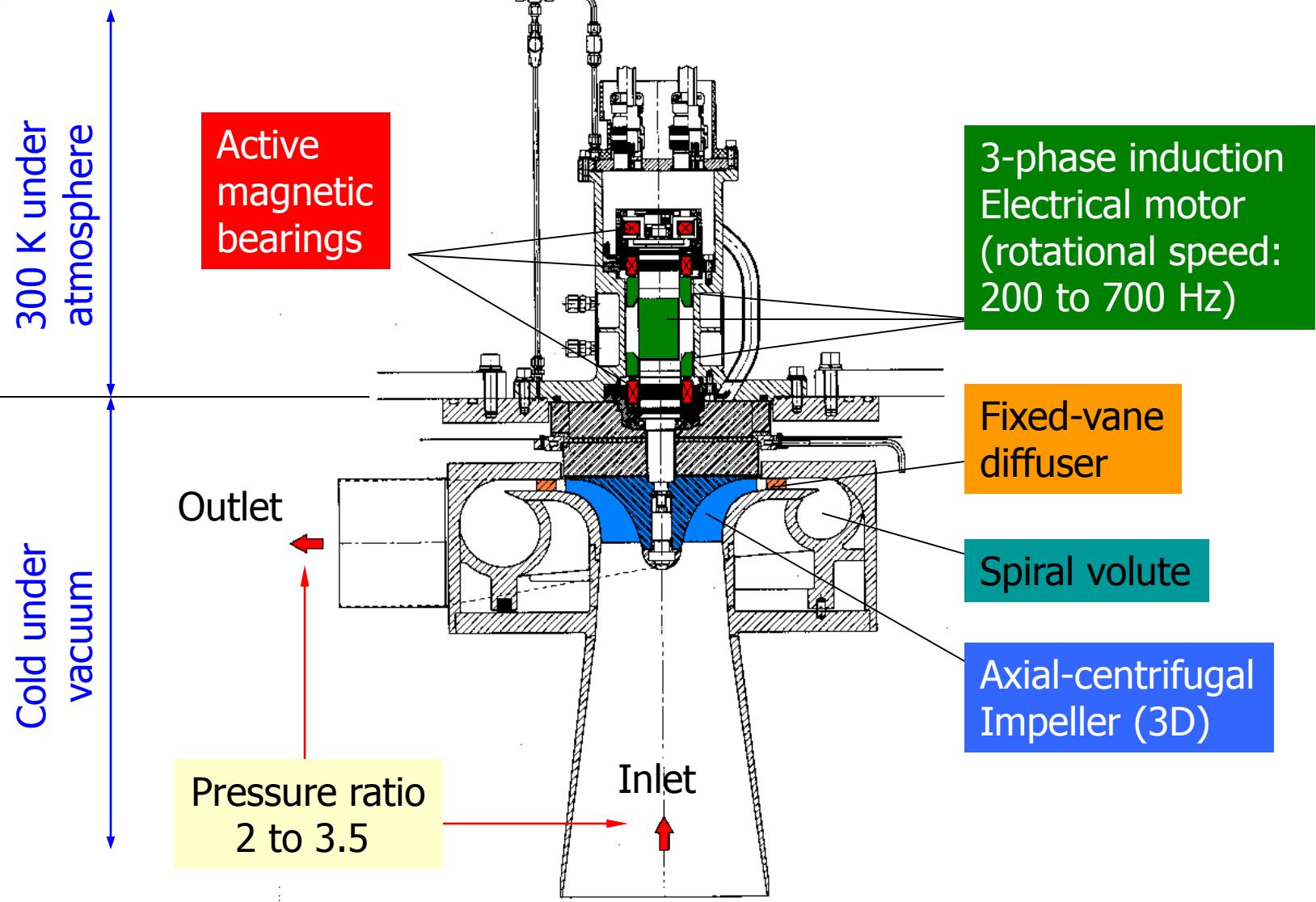
Air Liquide Cycle



IHI-Linde Cycle

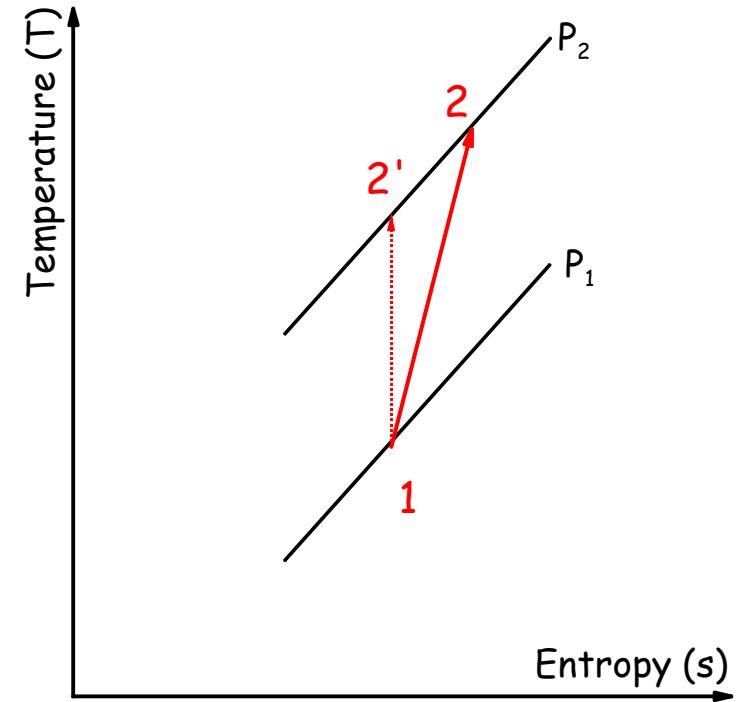
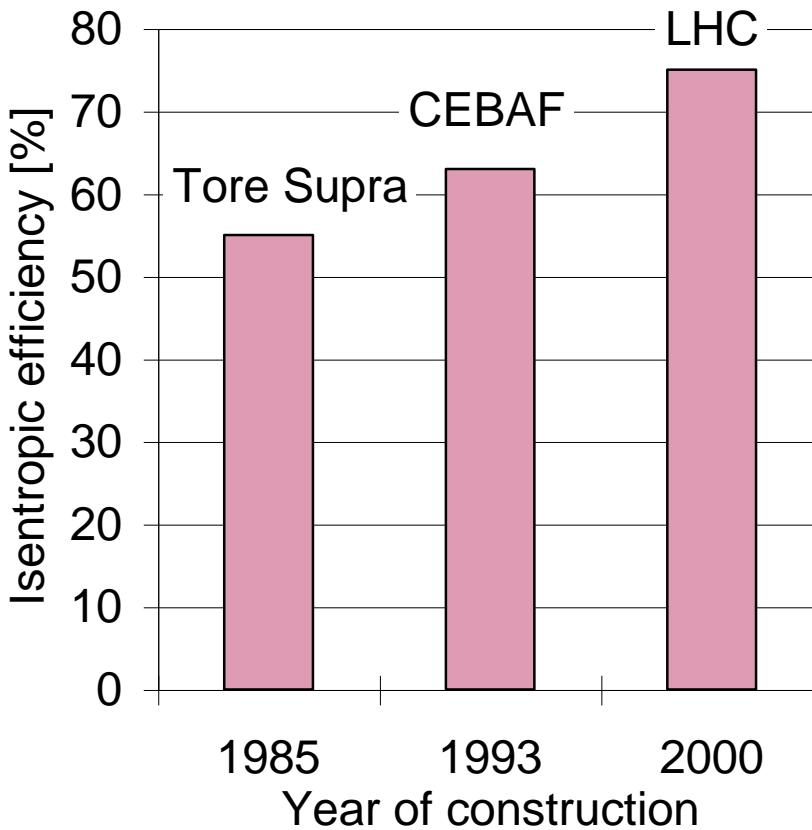


## Specific features of LHC cold compressors





## Performance of LHC cold compressors



$$\eta_{is} = \frac{H_{2'} - H_1}{H_2 - H_1}$$



## Warm sub-atmospheric screw compressors



Compound two-stage screw compressor

Mycom



WCS at CERN:  
125 g/s @ 0.6 bar  
or  
4600 m<sup>3</sup>/h @ 15 °C



## Warm sub-atmospheric screw compressors

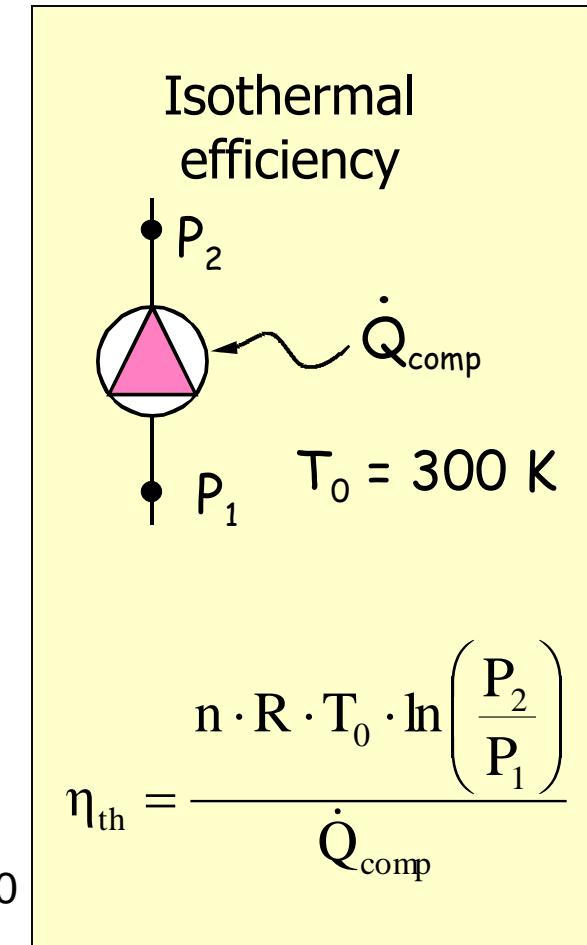
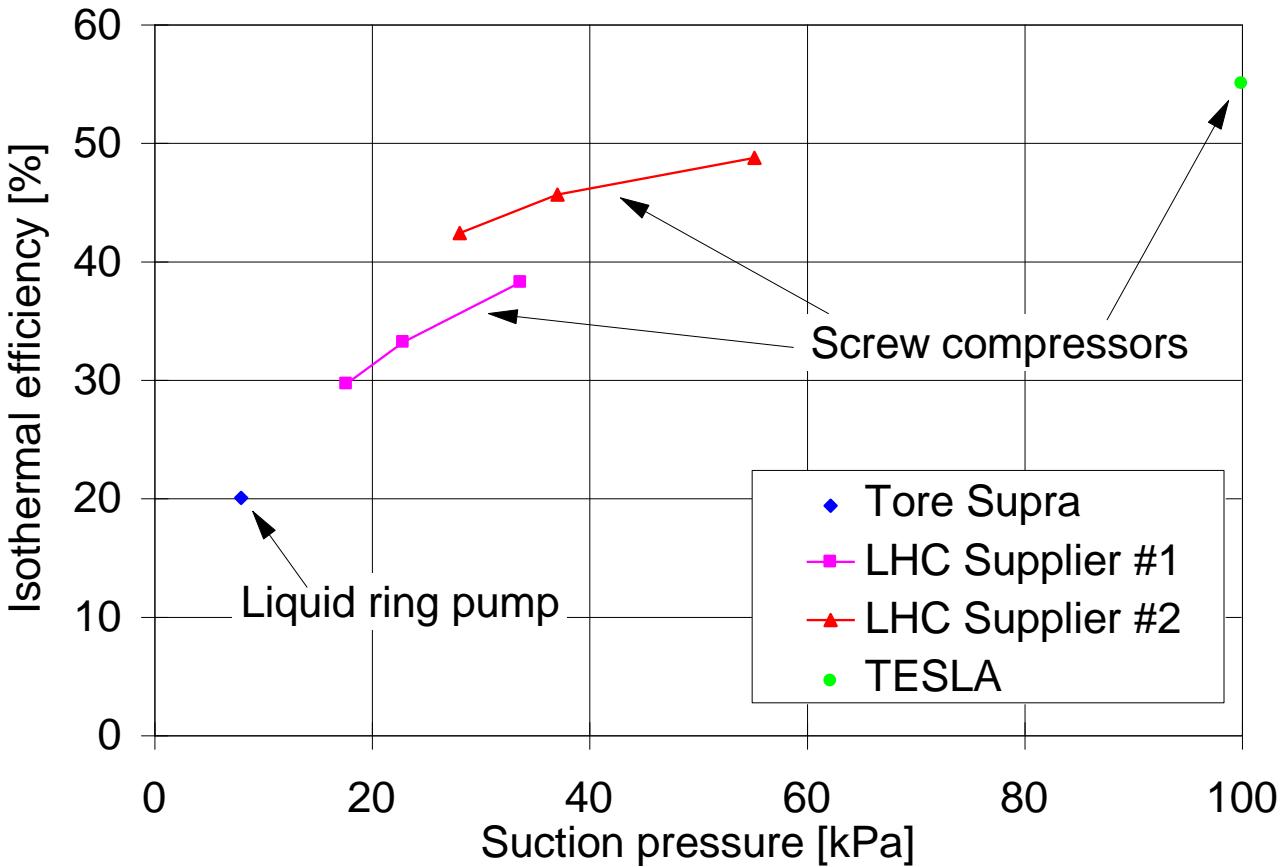


WCS at CERN:  
125 g/s @ 0.35 bar  
or  
2 x 3900 m<sup>3</sup>/h @ 15 °C

Kaeser

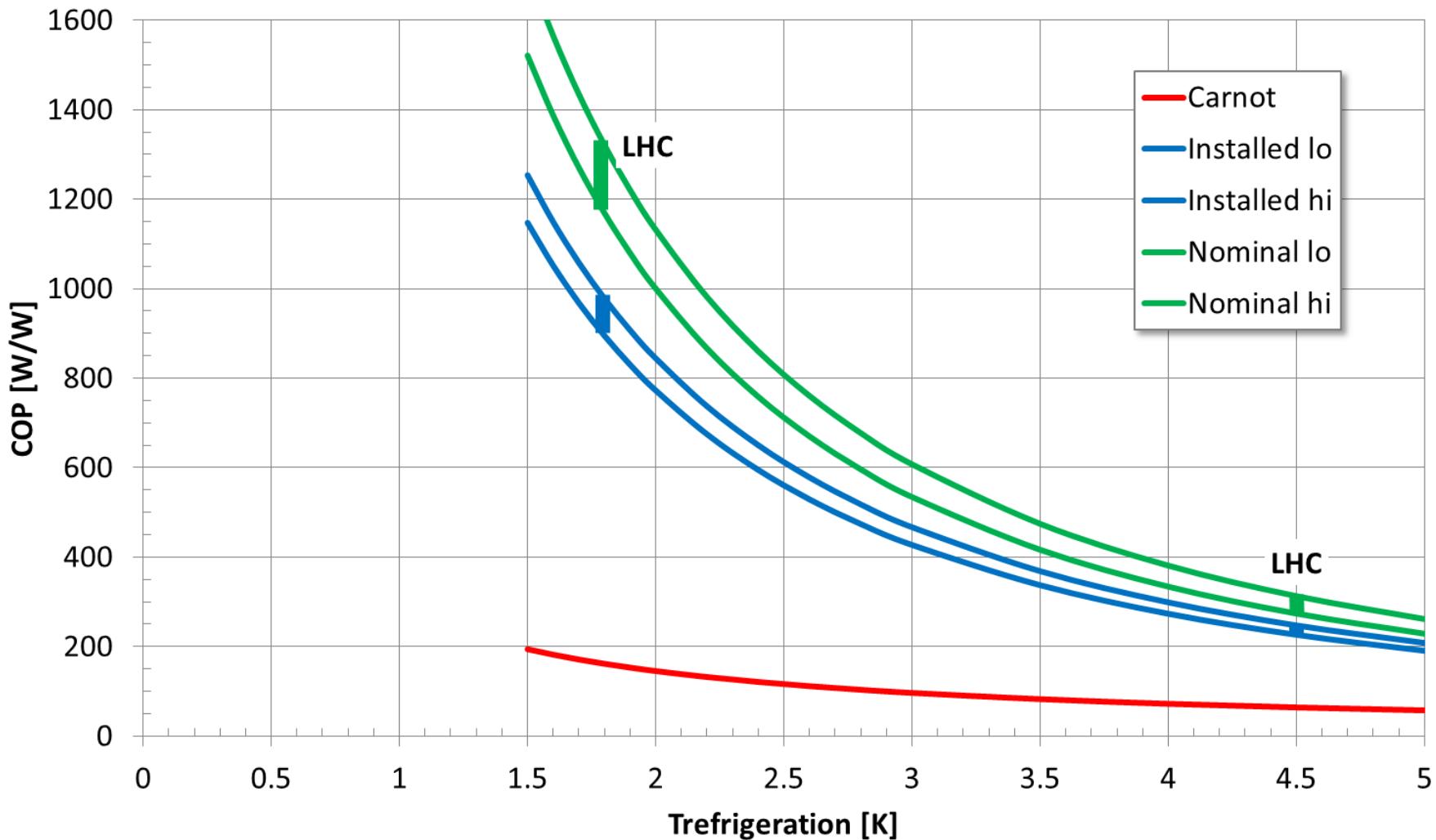


# Isothermal efficiency of warm subatmospheric compressors





## C.O.P. of LHC cryogenic plants

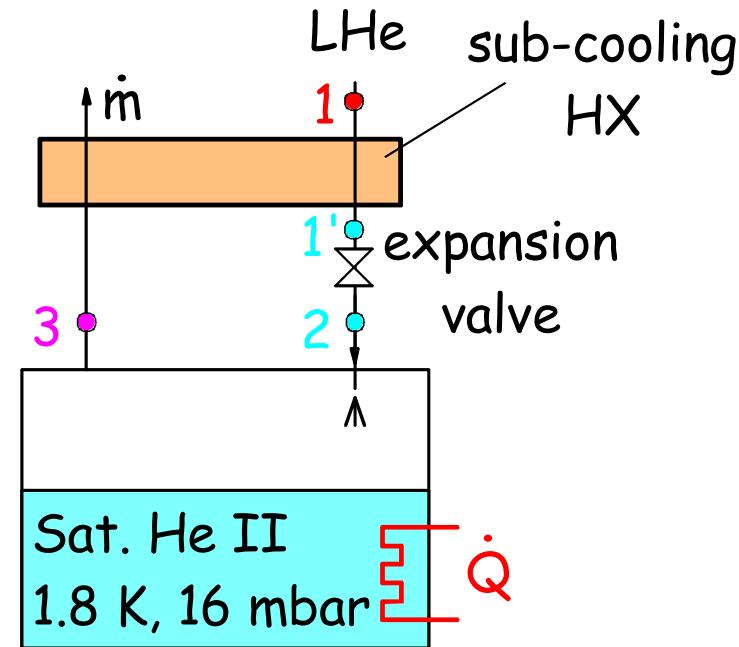
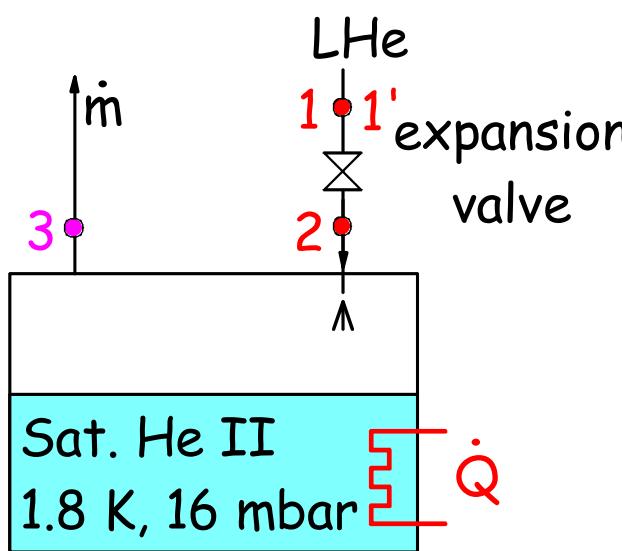




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## Efficiency of Joule-Thomson expansion



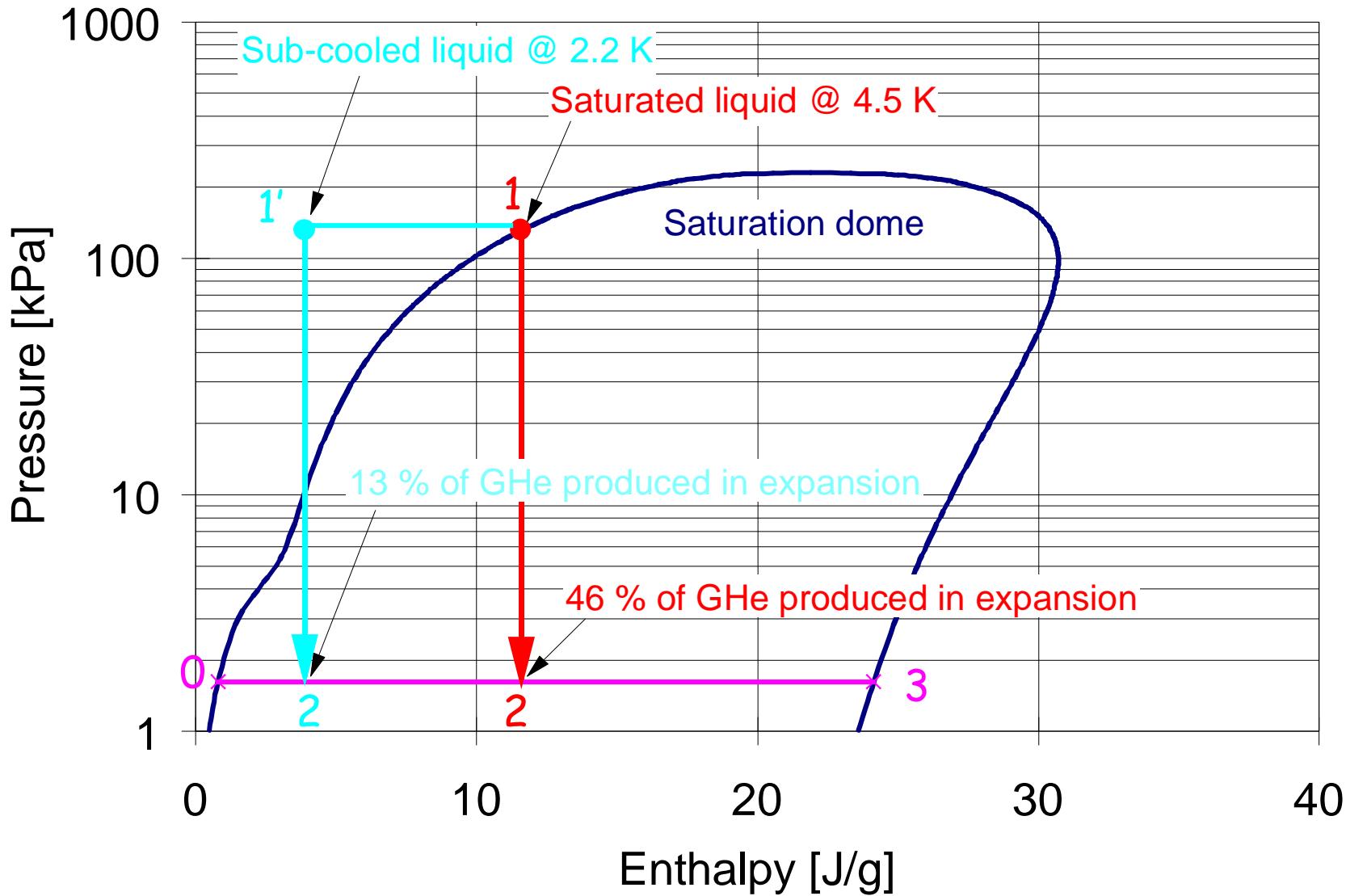
Sub-cooling efficiency :

$$\eta_{sc} = \frac{H_3 - H_2}{H_3 - H_0} \quad \text{Enthalpy of pure liquid}$$

Sub-cooling	$T_{1'} [K]$	$H_3 - H_2 [J/g]$	$H_3 - H_0 [J/g]$	$\eta_{sc} [\%]$
without	4.5	12.6	23.4	54
with	2.2	20.4	23.4	87



## Subcooling before J-T expansion



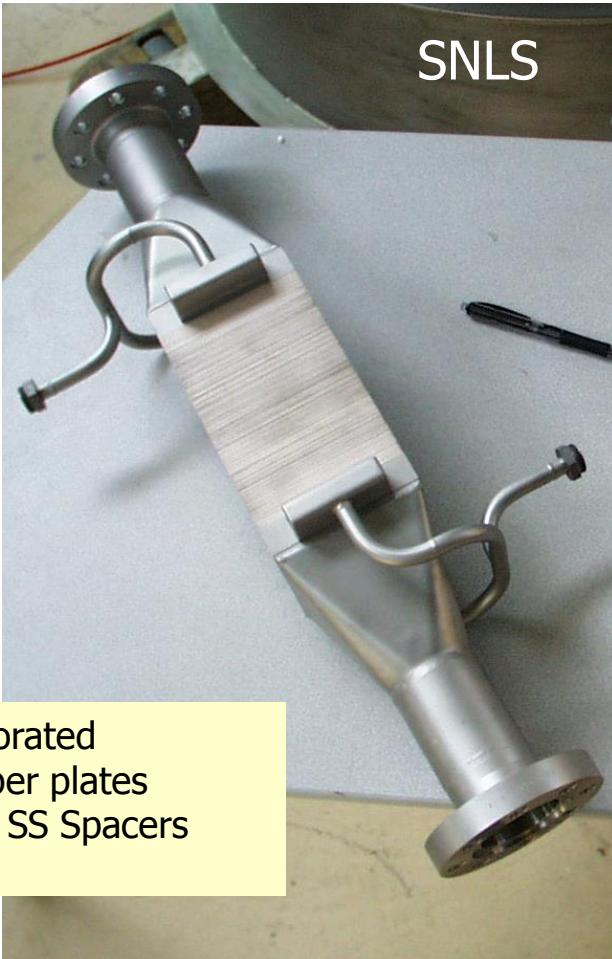


## Subcooling HX technologies for LHC

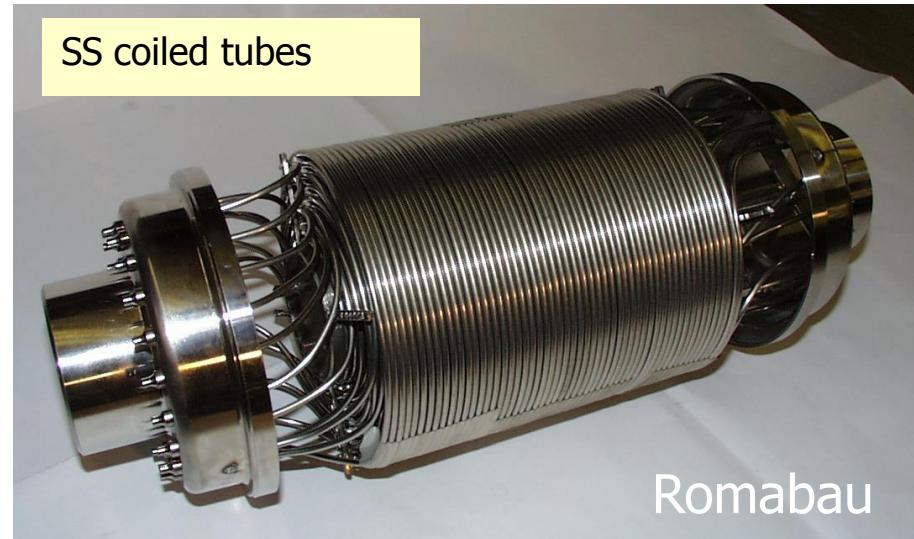
Mass-flow: 4.5 g/s

$\Delta P$  VLP stream: < 1 mbar

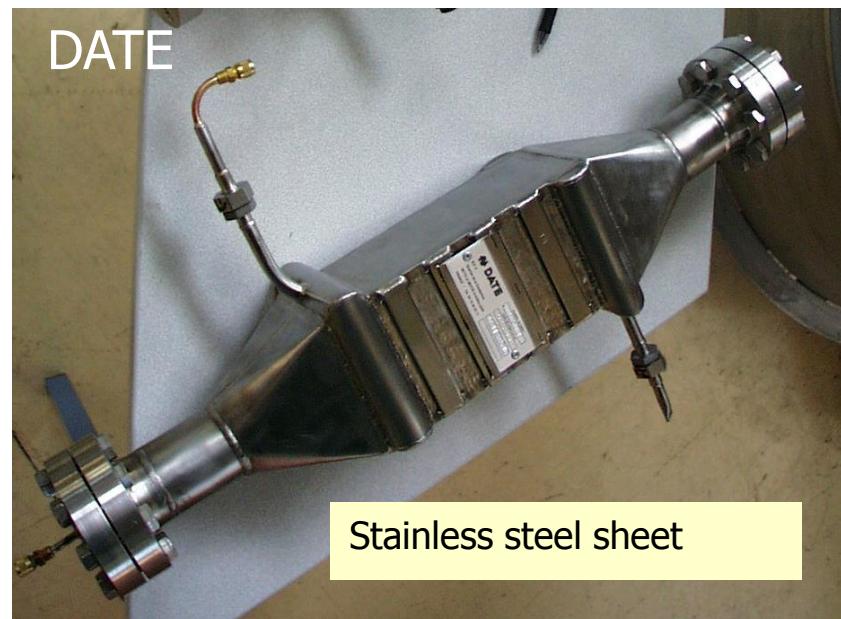
Sub-cooling T: < 2.2 K



Perforated  
copper plates  
with SS Spacers



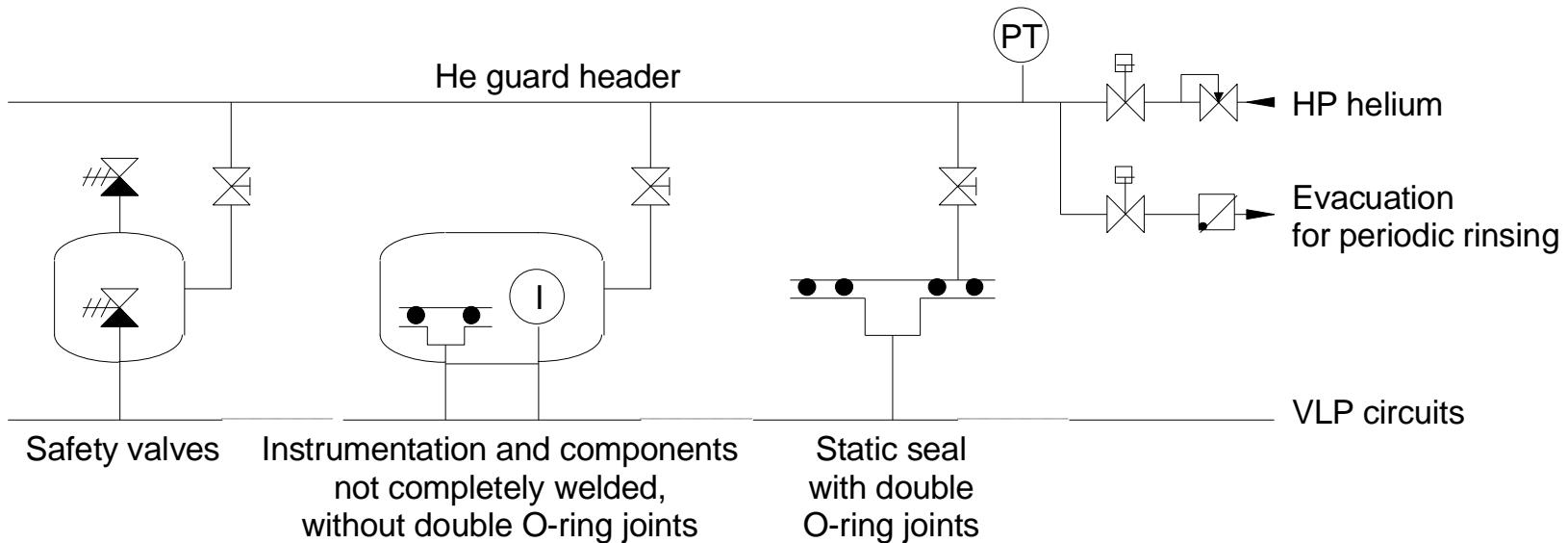
Romabau



Stainless steel sheet

## Protection against air inleaks

- Motor shaft of warm sub-atmospheric compressors placed at the discharge side to work above atmospheric pressure.
- For sub-atmospheric circuits which are not under guard vacuum or not completely welded, apply helium guard protection on dynamic seal of valves, on instrumentation ports, on safety relief valves and on critical static seals





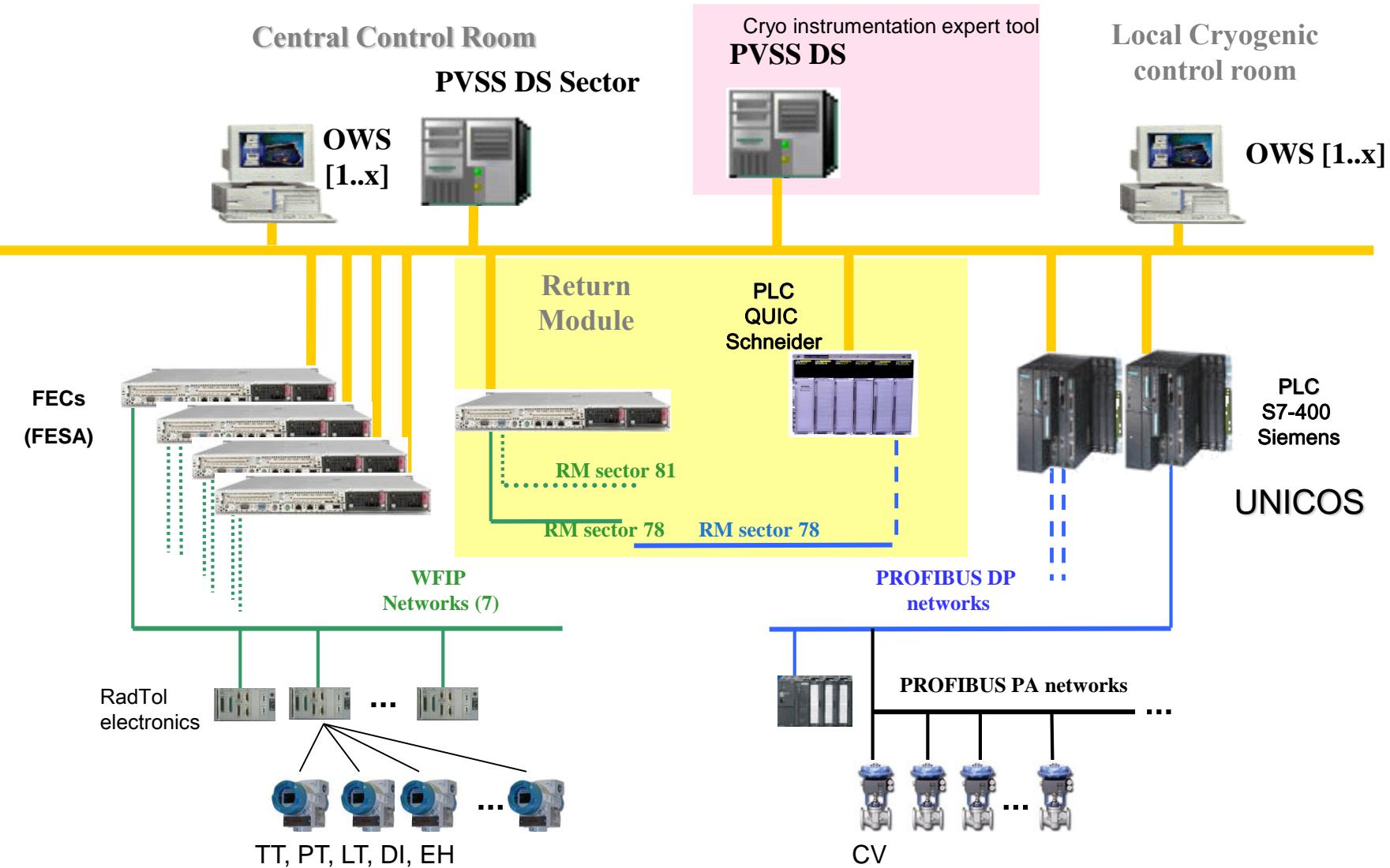
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# Controls for LHC cryogenics

21300 AI, 7000 AO, 18400 DI, 4200 DO  
4700 analog control loops





# Cryogenics in CERN Accelerator Control Centre

Fixed displays

Trend curves

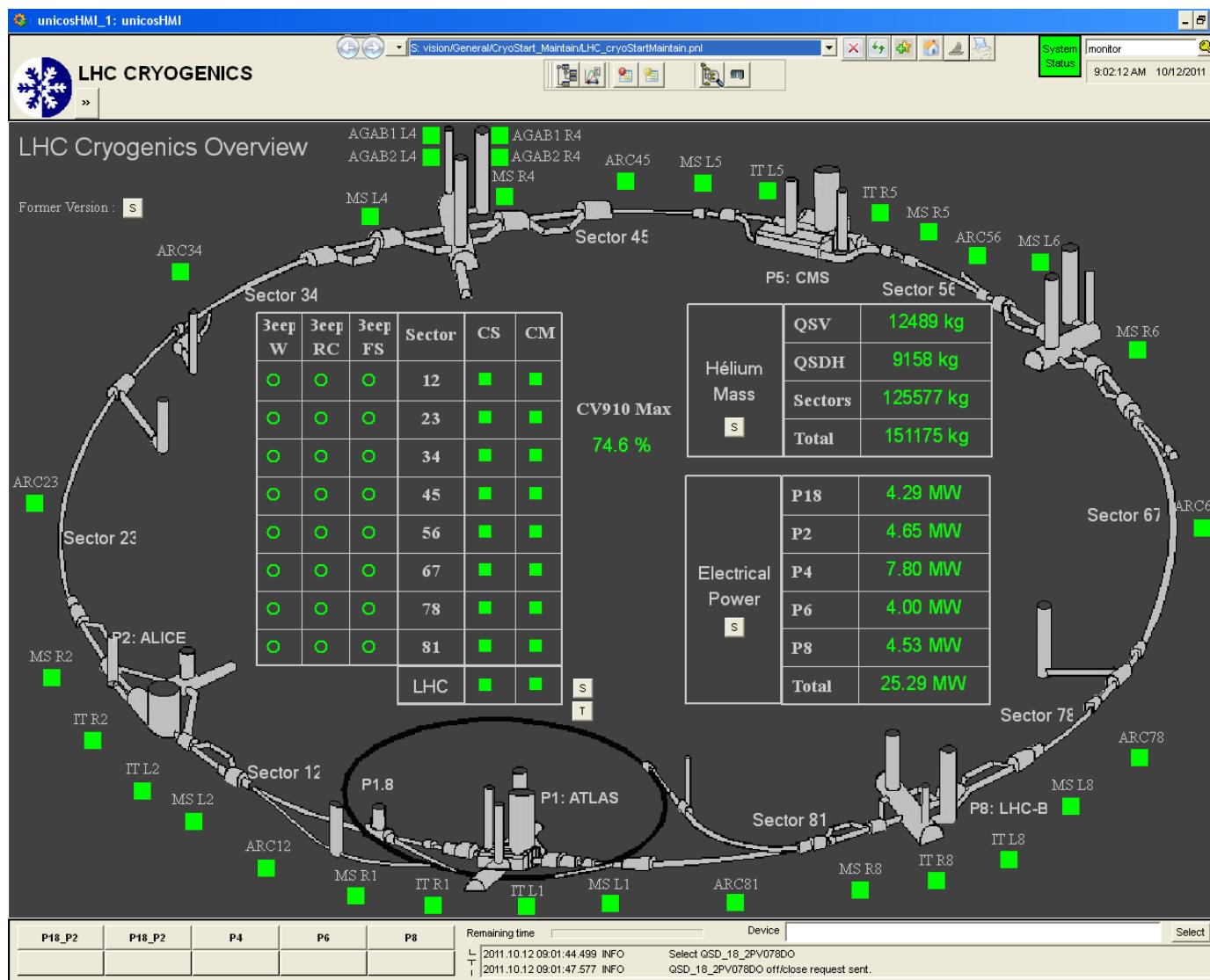
Process synoptics and control

On shift 24/7





# Display of cryogenic operation indicators



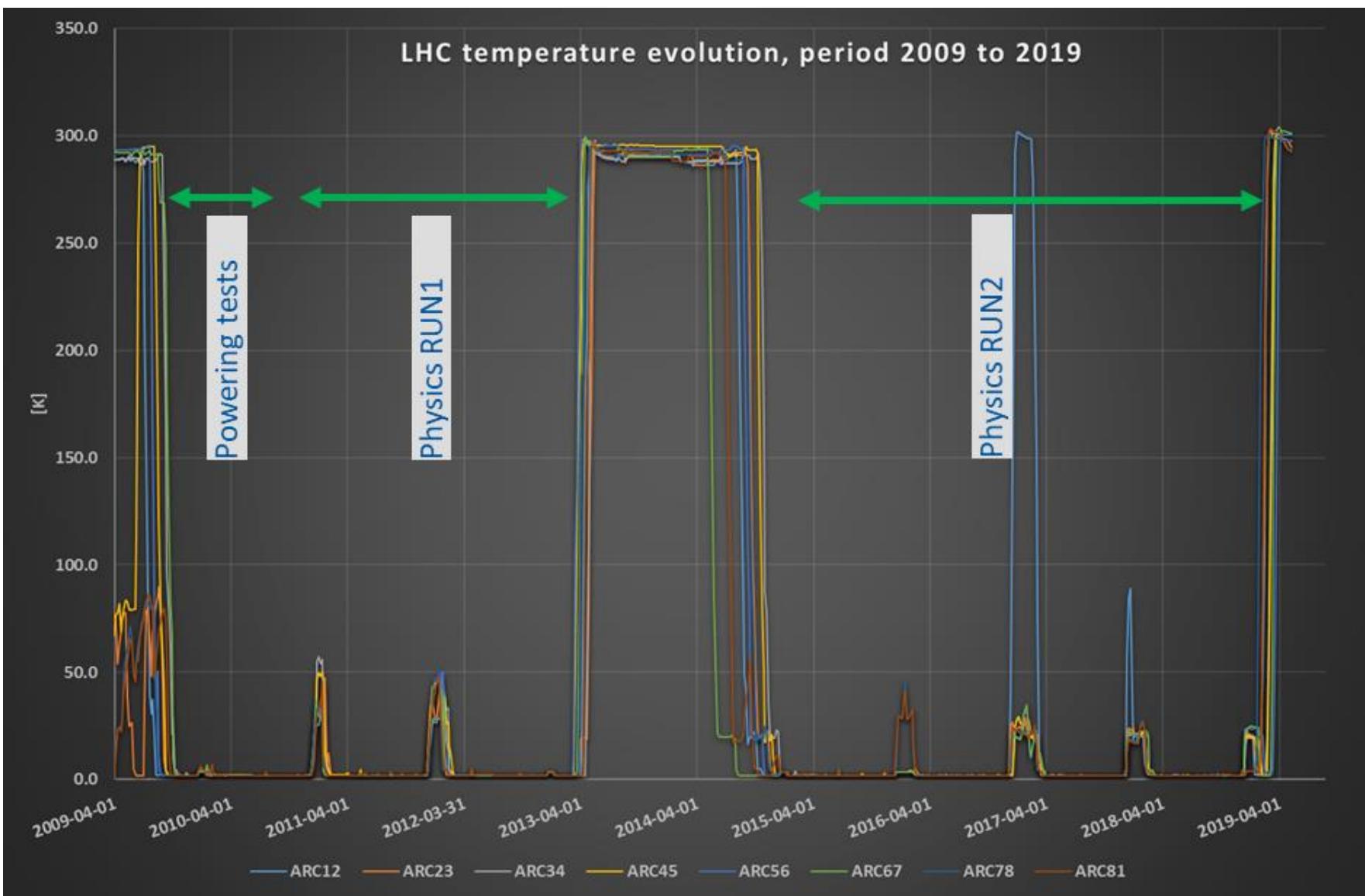


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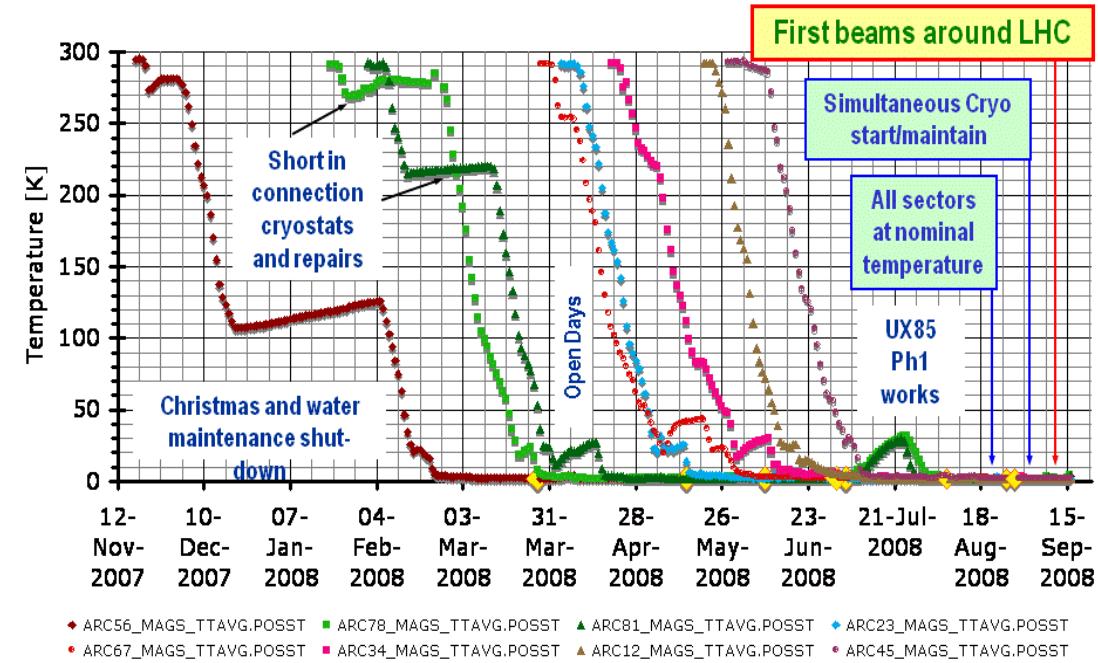
# LHC temperature history 2009-2019 (D. Delikaris)



# Precooling 37'500 t magnets with 10'000 t liquid nitrogen



Cooldown to 80 K: 600 kW per sector  
with up to ~5 tons/h liquid nitrogen



## Helium inventory management



Total He inventory of LHC accelerator: 135 tons  
On-site storage: 125 tons  
« Virtual » storage contract: 60 tons

Storage capacity GHe @ 2 MPa, Tambient:

- 58 x 250 m<sup>3</sup> tanks
- 40 x 80 m<sup>3</sup> tanks



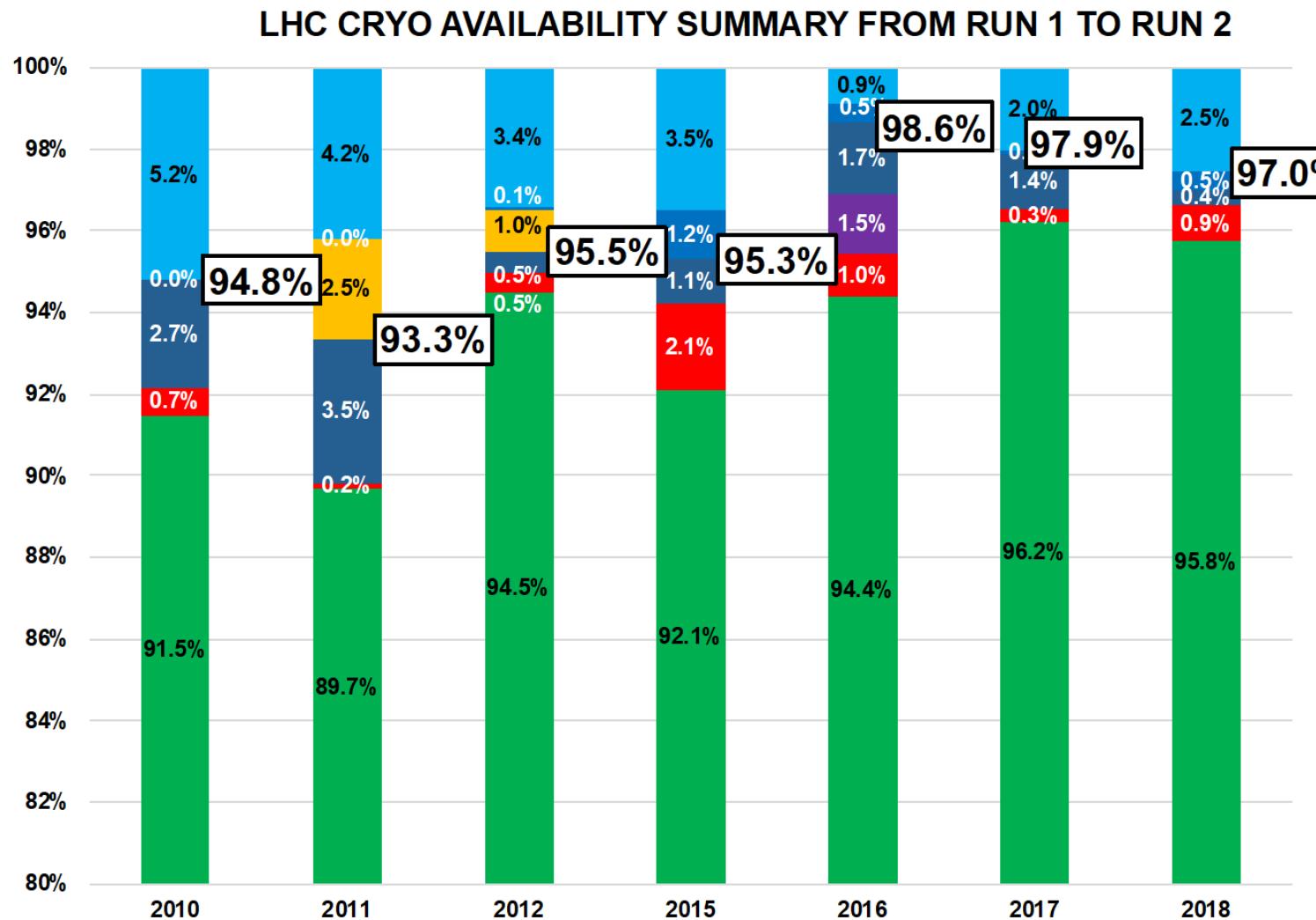
Storage capacity LHe @ 0.1 MPa, 4.5 K:

- 6 x 120'000 liter vacuum-insulated vessels



# Availability of LHC cryogenics 2010-2018

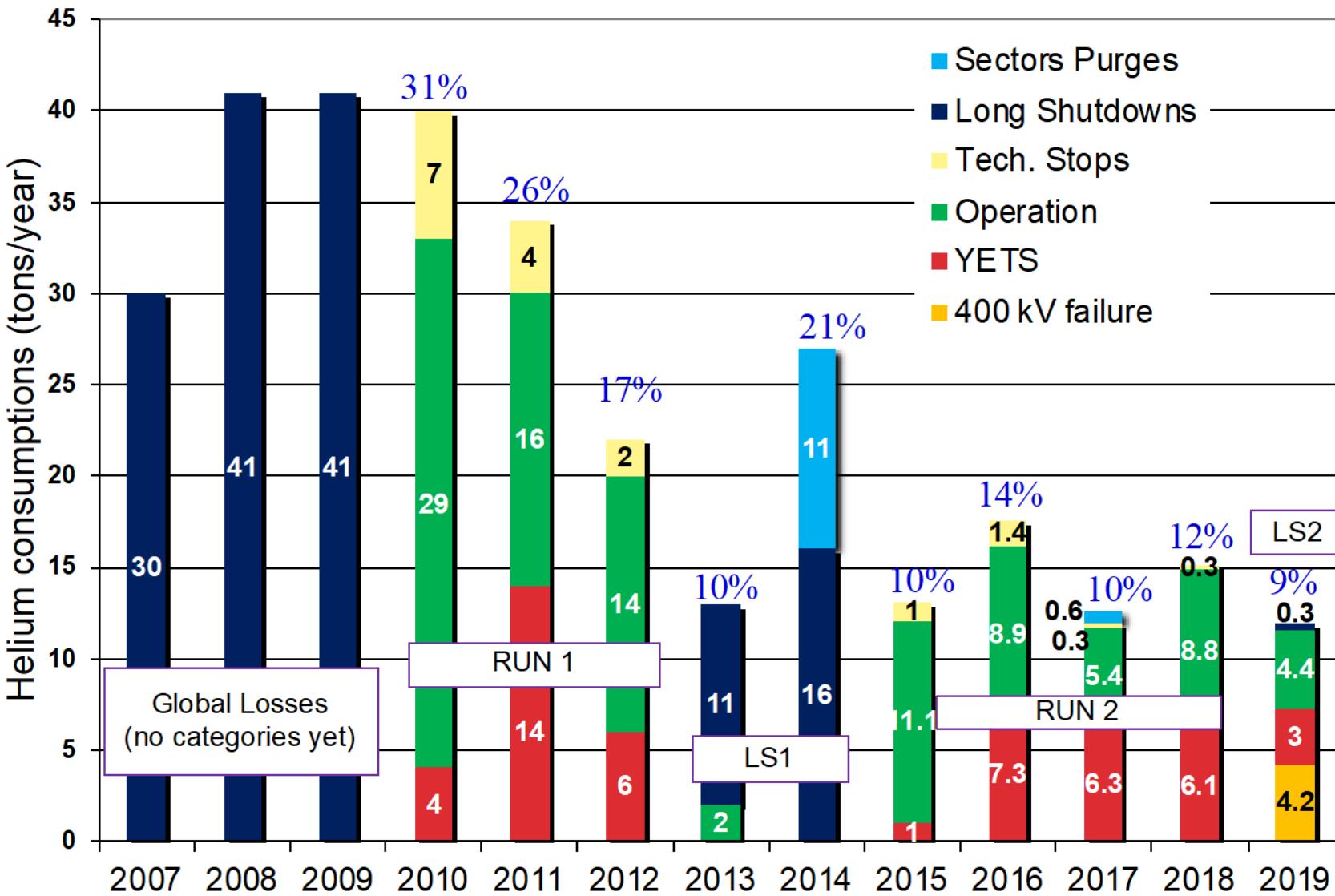
## (D. Delikaris)





# LHC helium losses 2007-2019

(D. Delikaris)



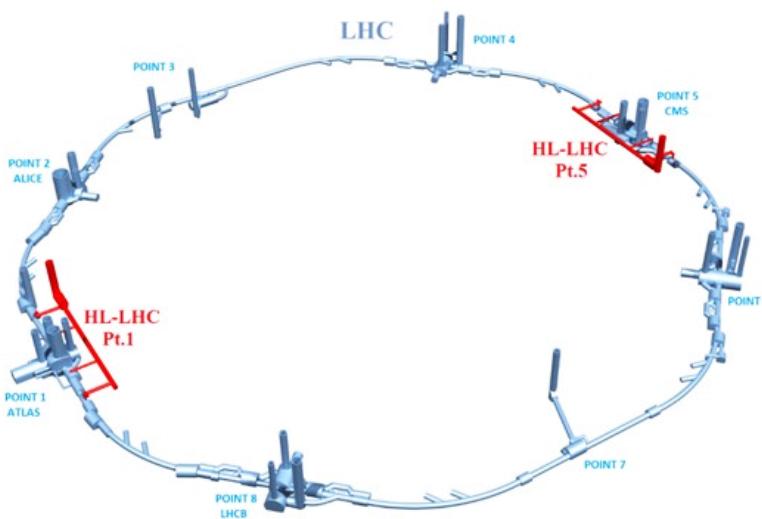


## Contents

- Technical challenges of the LHC
- He II magnet cooling scheme
- Cryostat design and heat loads
- Refrigeration at 4.5 K and 1.8 K
- Specific He II technologies
- Instrumentation and controls
- Operation
- **Upgrade**

## The HL-LHC project Objectives and contents

- Determine a **hardware configuration** and a set of **beam parameters** that will allow the LHC to reach the following targets:
  - enable a total integrated luminosity of  $3000 \text{ fb}^{-1}$
  - enable an integrated luminosity of  $250\text{-}300 \text{ fb}^{-1}$  per year
  - design for  $\mu \sim 140$  ( $\sim 200$ ) (peak luminosity of  $5$  ( $7$ )  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ )
  - design equipment for ‘ultimate’ performance of  $7.5 \text{ } 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  and  $4000 \text{ fb}^{-1}$



### Major intervention on 1.2 km of LHC ring

- New IR-quads using  $\text{Nb}_3\text{Sn}$  superconductor
- New 11 T  $\text{Nb}_3\text{Sn}$  (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection

## Paths to high luminosity

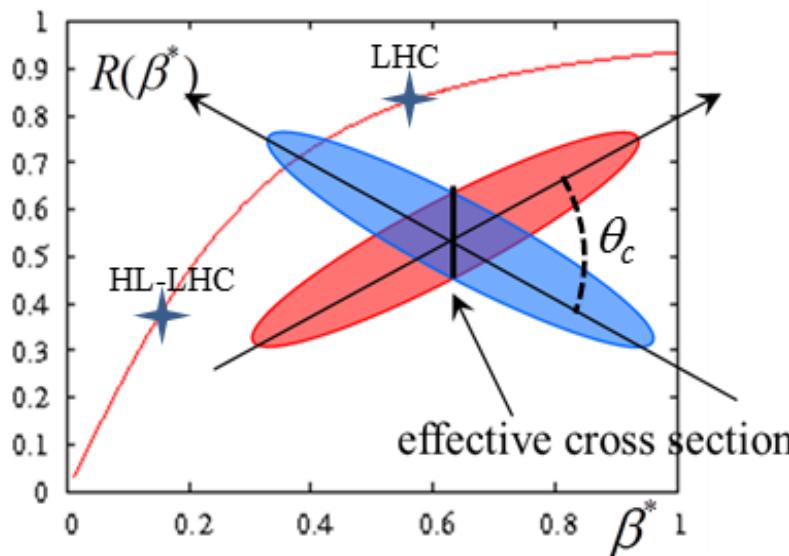
Increase bunch population

Increase R = reduce crossing angle?

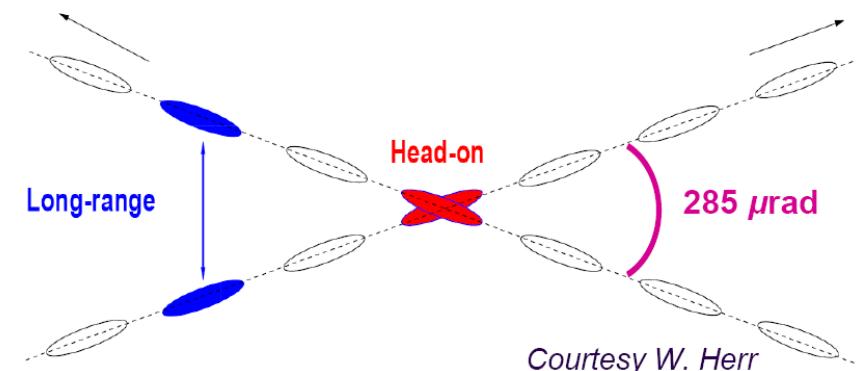
$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi \beta^* \epsilon_n} R; \quad R = 1 / \sqrt{1 + \frac{\theta_c \sigma_z}{2\sigma}}$$

Reduce beta at collision

Reduce emittance

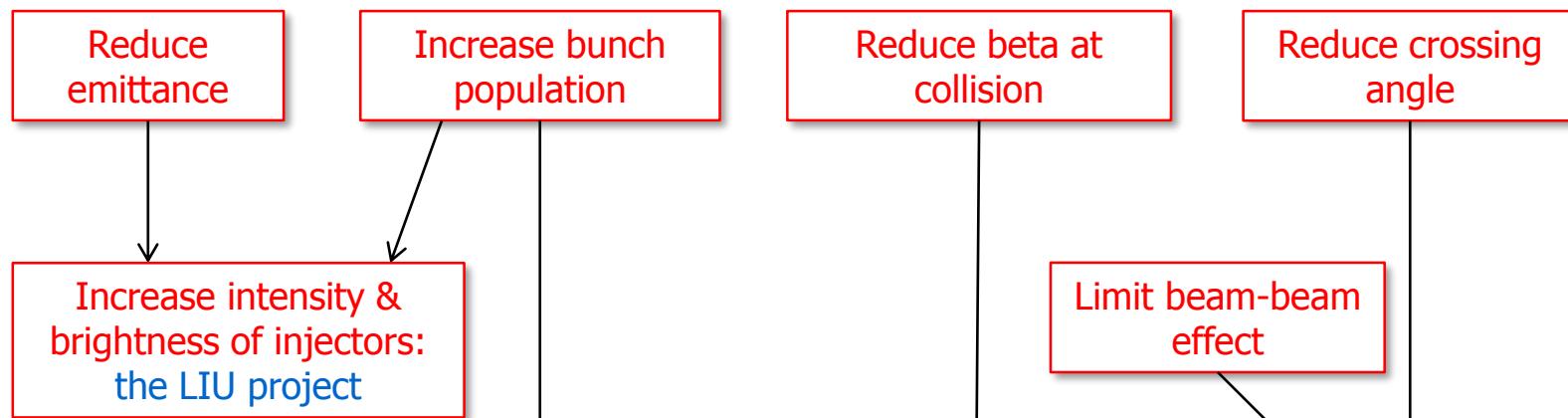


Beam-beam effect precludes too low crossing angle

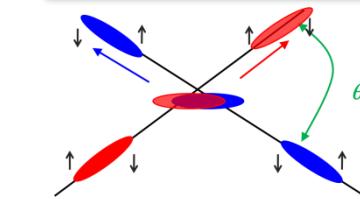
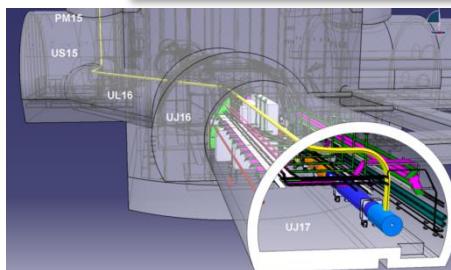


# The HL-LHC project

## From accelerator physics to technology

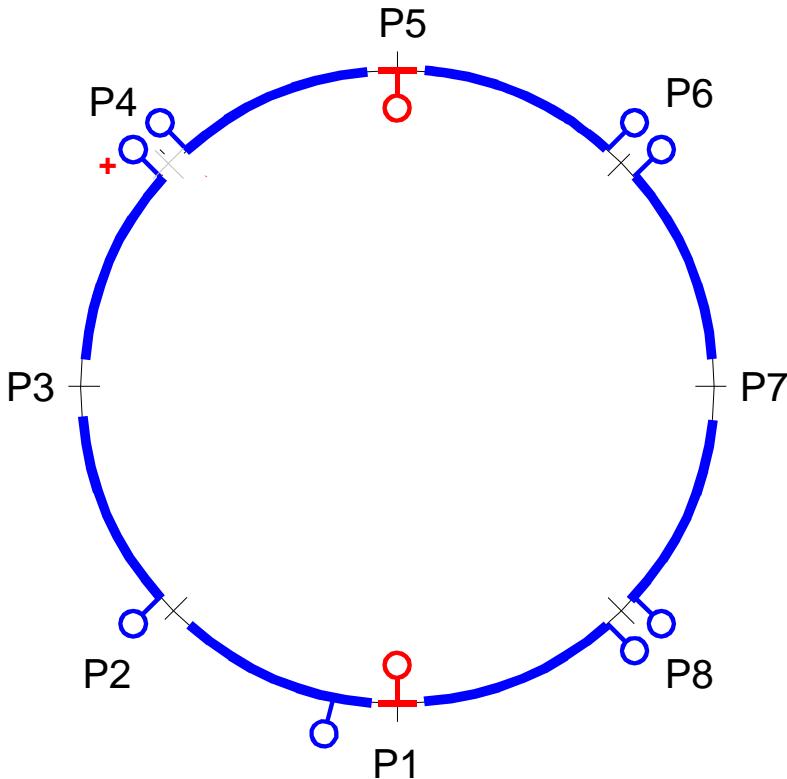


More powerful cryogenics  
Improved collimation  
Improved machine protection  
Stronger R to E → relocation





## Additional cryogenics for HL-LHC (S. Claudet)



- Existing cryoplant
- New HL-LHC cryoplant

- P1 and P5
  - 2 new cryoplants ( $\sim 15$  kW @ 4.5 K incl.  $\sim 3$  kW @ 1.8 K)
  - 2 x 750m cryo-distribution for high-luminosity insertions
- P4
  - upgrade (+2 kW @ 4.5 K) of existing LHC cryoplant (18 kW @ 4.5 K)



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