LHC Cryogenics design and operation: optimization and reduction of the energy consumption

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Workshop Energy for Sustainable Science

Energy Management for Large-Scale Research Infrastructures

Outline

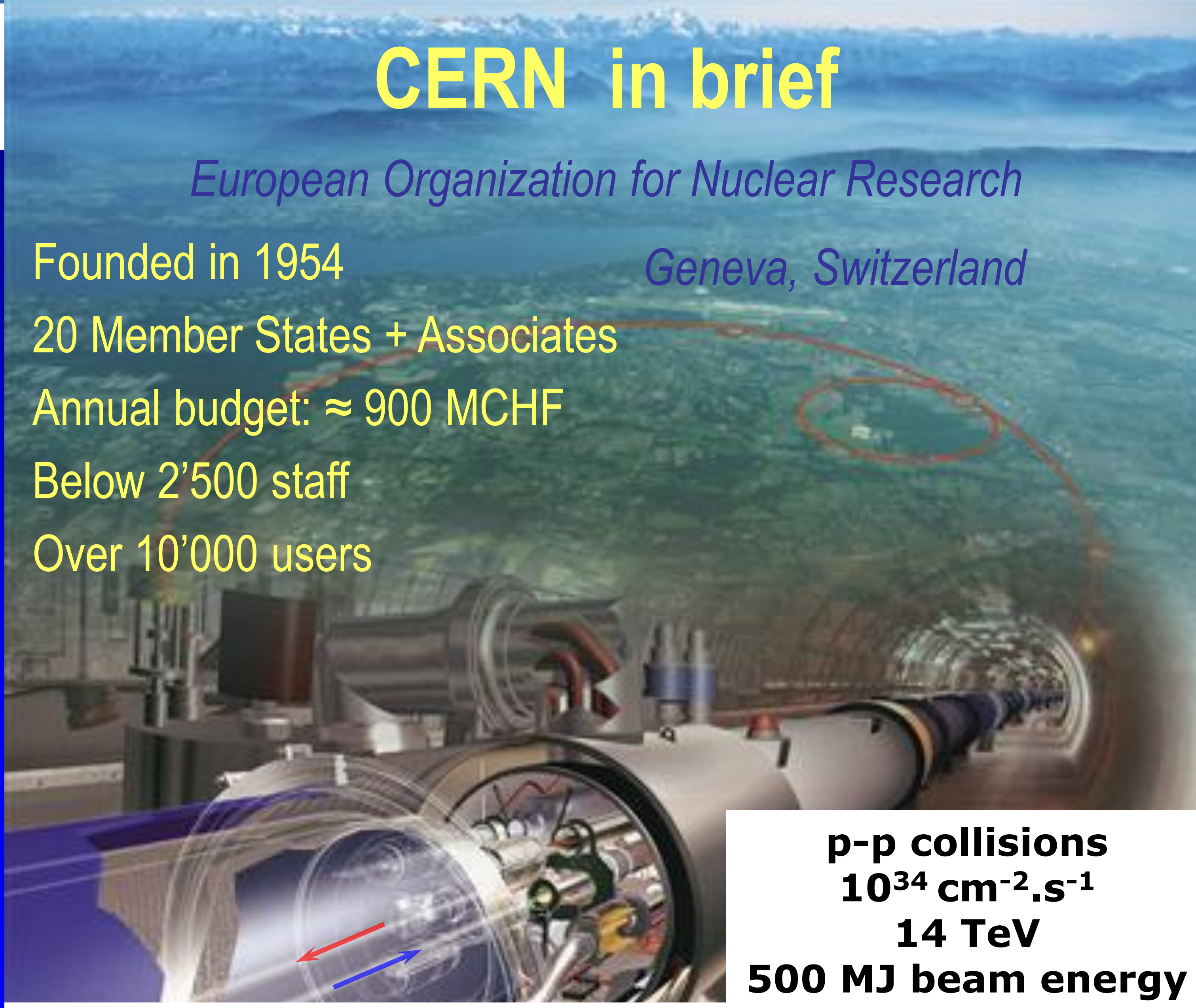
- Introduction to CERN and LHC Cryogenics
- Power input for refrigeration, design & implementation
  - The Carnot factor
  - The heat loads (final user + distribution)
  - The refrigerators
- Operation results, availability and power consumption
- Indentified alternatives for further optimisation
- Summary

CERN in brief

European Organization for Nuclear Research

Geneva, Switzerland

- Founded in 1954
- 20 Member States + Associates
- Annual budget: ≈ 900 MCHF
- Below 2’500 staff
- Over 10’000 users



p-p collisions
10^{34} cm^{-2}.s^{-1}
14 TeV
500 MJ beam energy

24 km of superconducting magnets @1.8 K, 8.33 T

Main reasons to superconducting

For accelerators in high energy physics

Capital Cost

- Compactness through higher fields

$E_{beam} \approx 0.3 \,.\, \mathbf{B} \,.\, r$ — [Gev] [T] [m]

$E_{beam} \approx \mathbf{E} \,.\, L$ — [Gev] [MV/m] [m]

Operating Cost

- Saving operating energy

Electromagnets:

Resistive: $P_{input} \approx E_{beam}$

Superconducting: $P_{input} \approx Pref$

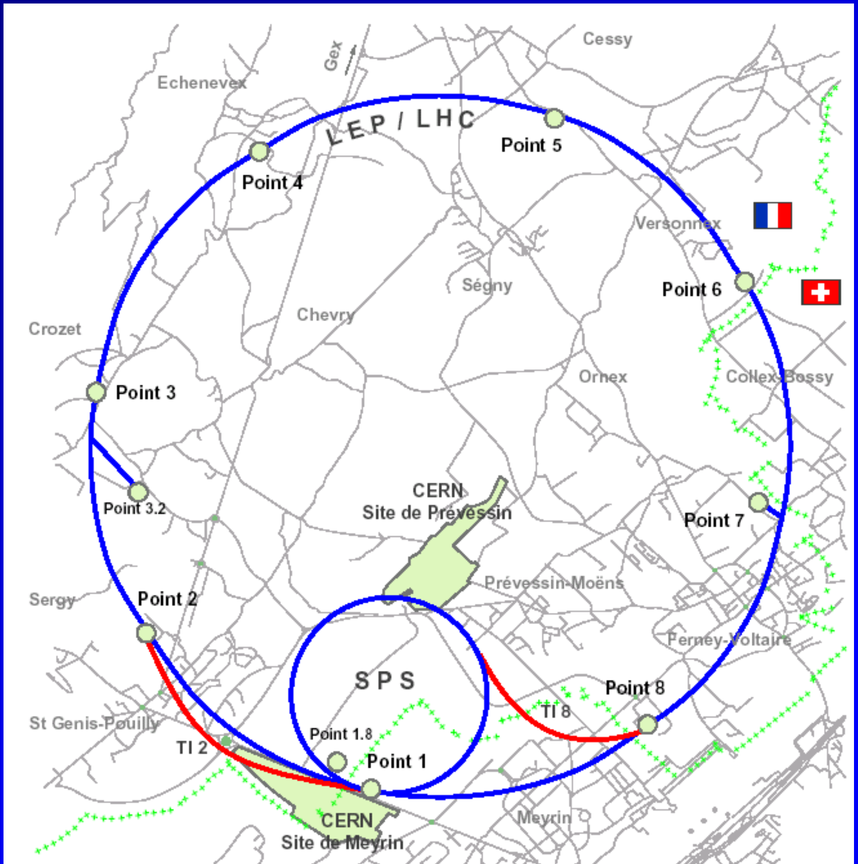
Acceleration cavities

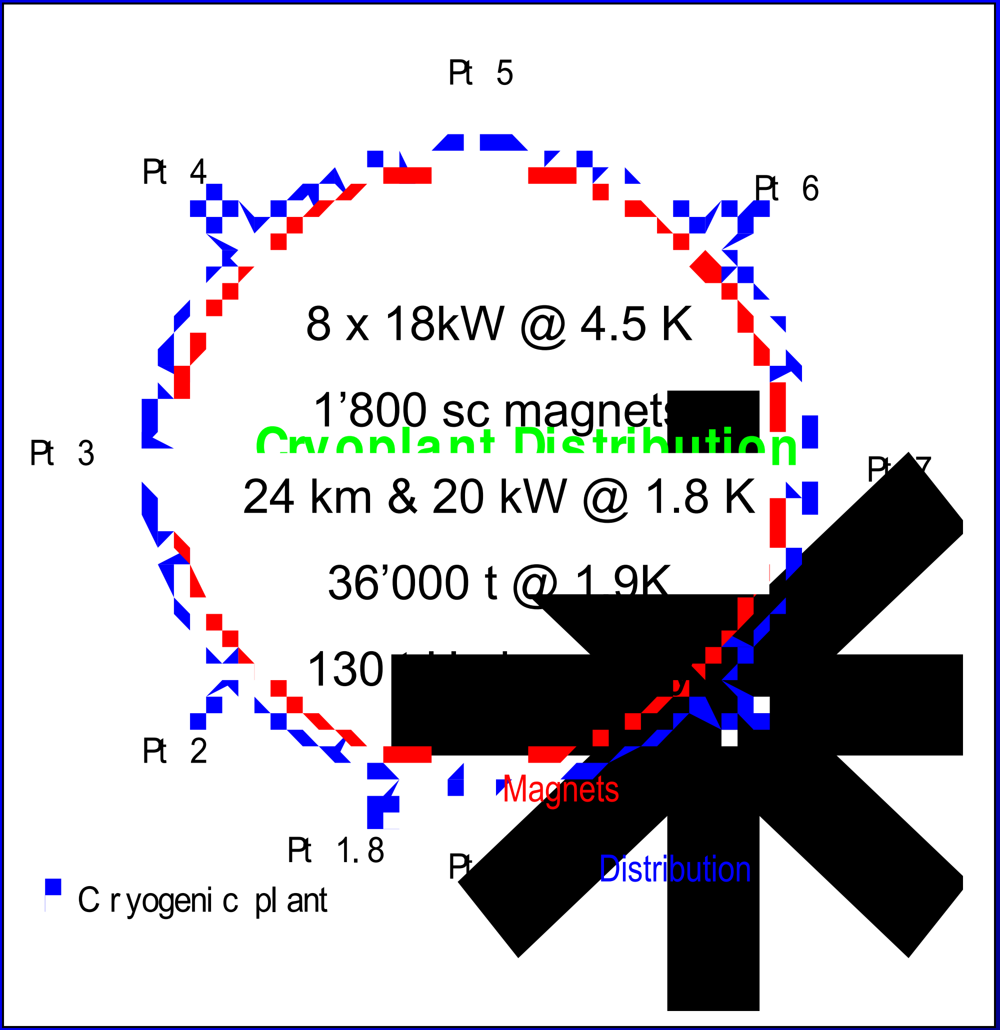
$P_{input} \approx Rs.L.\mathbf{E}^2/w$

$R_s \approx R_{BCS} + R_o$

$R_{BCS} \approx (1/T) \exp(-BT_c/T)$

Layout of LHC cryogenics

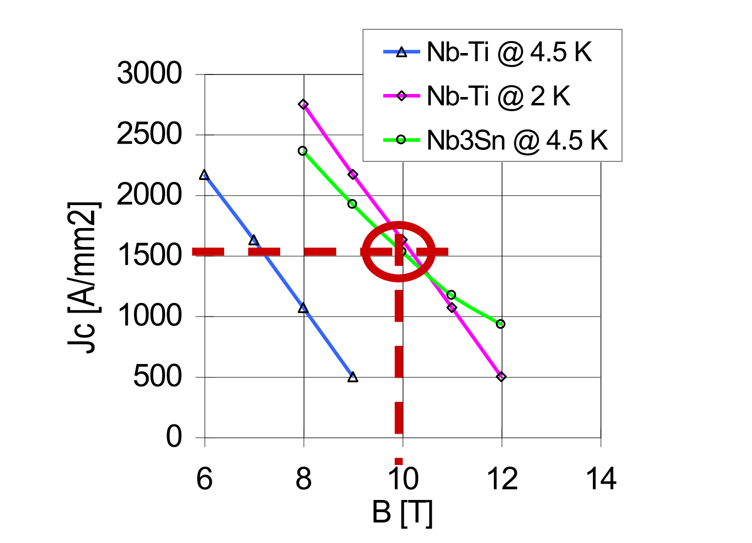


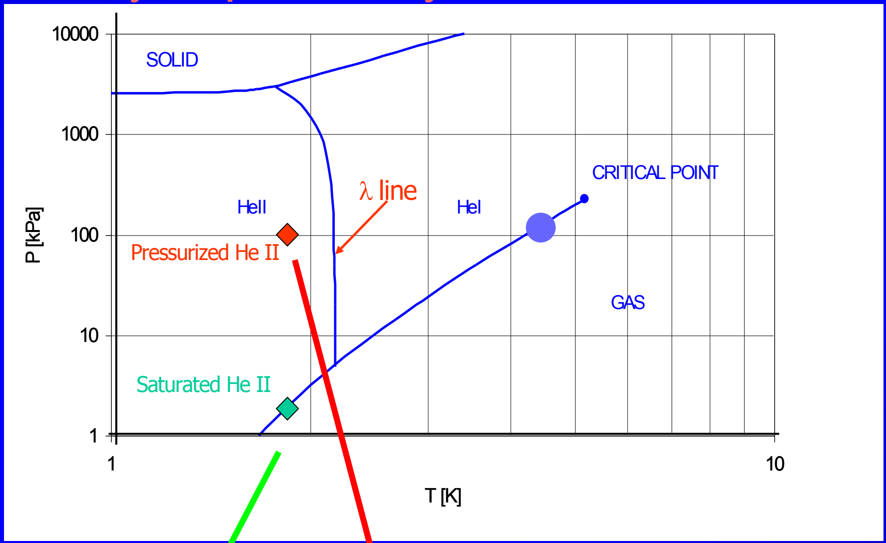


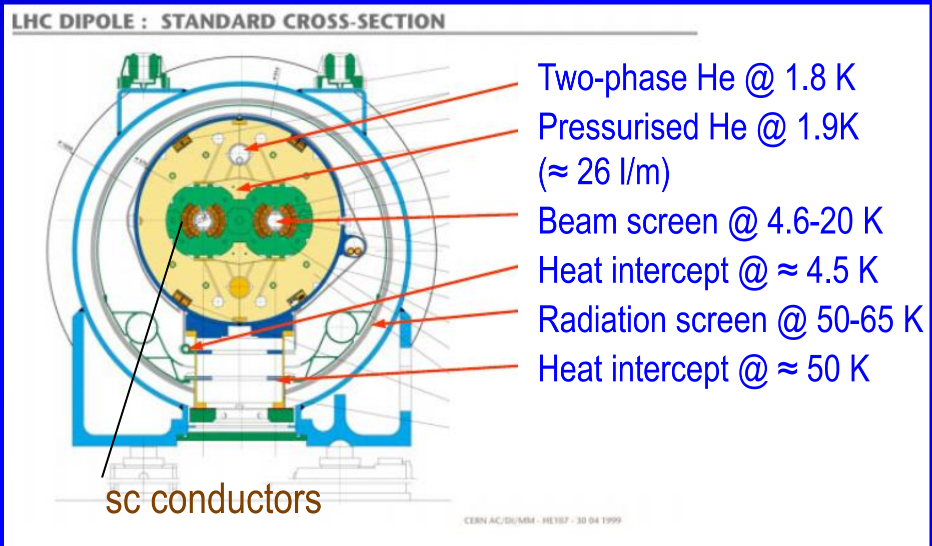
LHC cryogenics is the largest, the longest and the most complex cryogenic system worldwide

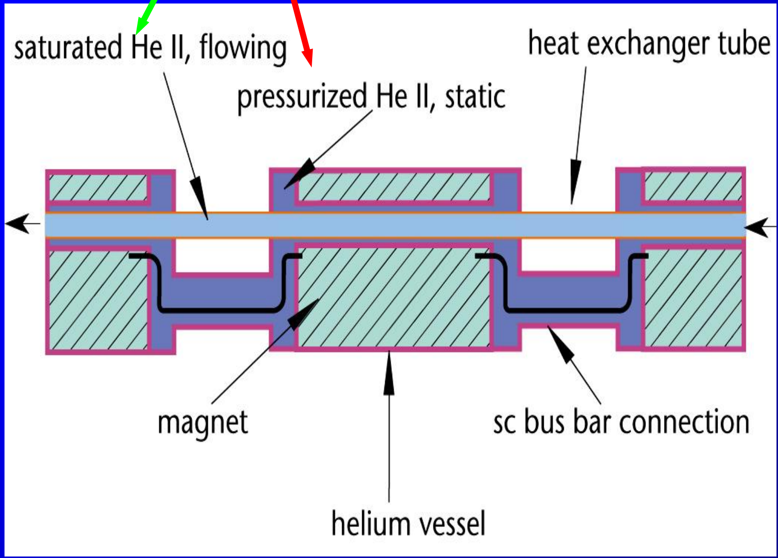
Magnet cooling scheme

Superconductivity served by superfluidity !

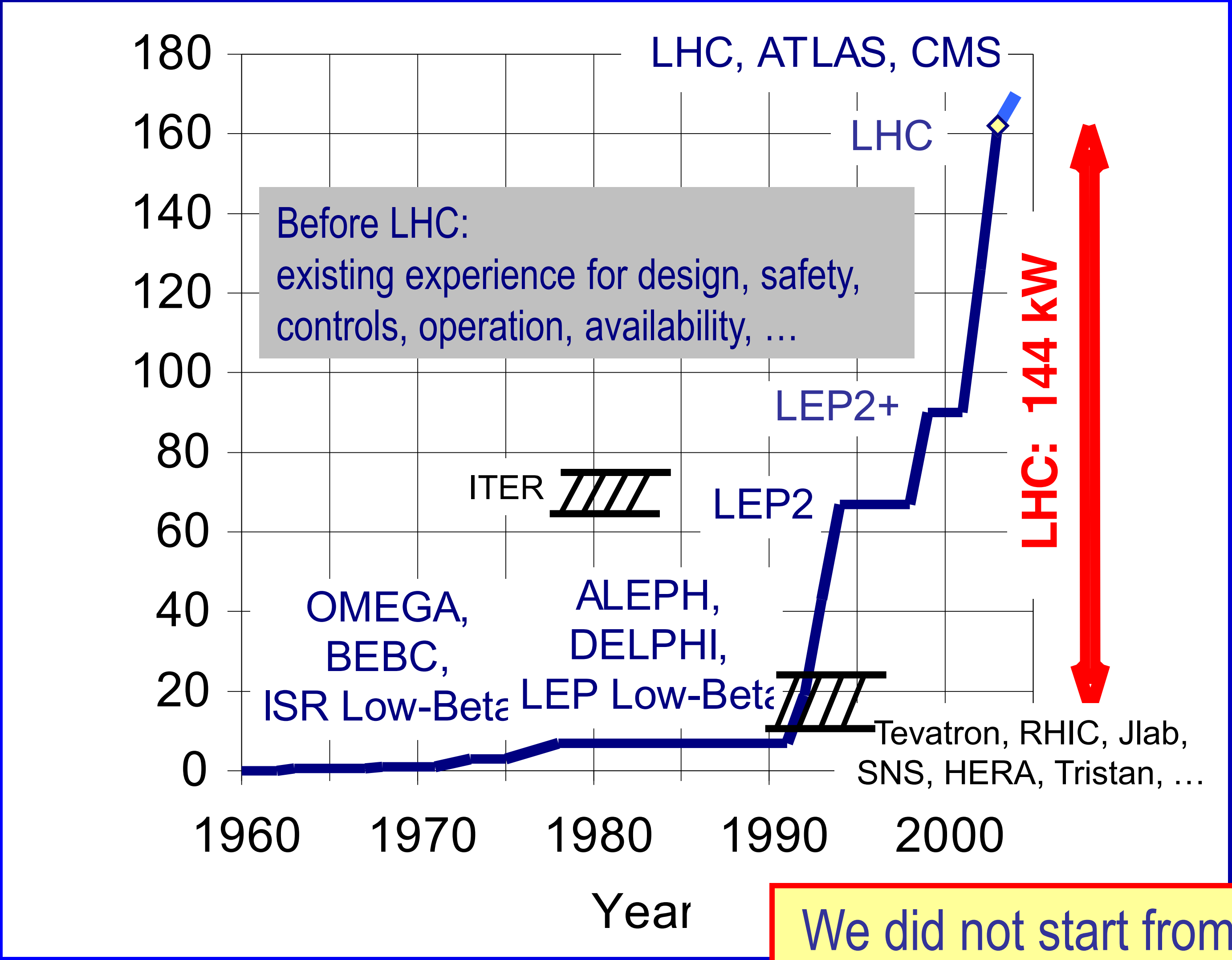








How does it compare ?



We did not start from scratch!

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Power input for refrigeration

Power Input ≈ Power@cold x Carnot / %w.r.tCarnot

4MW ≈ 18kW @ 4.5K x 66 / 30%

8 such plants installed for LHC + specific units for the 1.8K process

⇒ 40 MW installed electrical power

An idea of yearly operating costs (Power only)

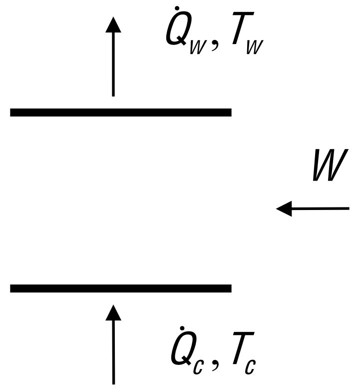
⇒ 11 months (320GWh) @ 60 CHF/MWh => 19.3 MCHF

⇒ Already 1% is about 0.2 MCHF !!!

An obvious incentive to optimise each of the above contributing factors !

The Carnot Factor (1/3)

The Carnot Factor is a direct consequence of the combination of first and second thermodynamic laws



First Law: $\dot{Q}_w + \dot{Q}_c + W = 0$

Second Law: $\frac{\dot{Q}_w}{T_w} + \frac{\dot{Q}_c}{T_c} \leq 0$

Power Input: $W \geq \dot{Q}_c \left(\frac{T_w}{T_c} - 1 \right)$

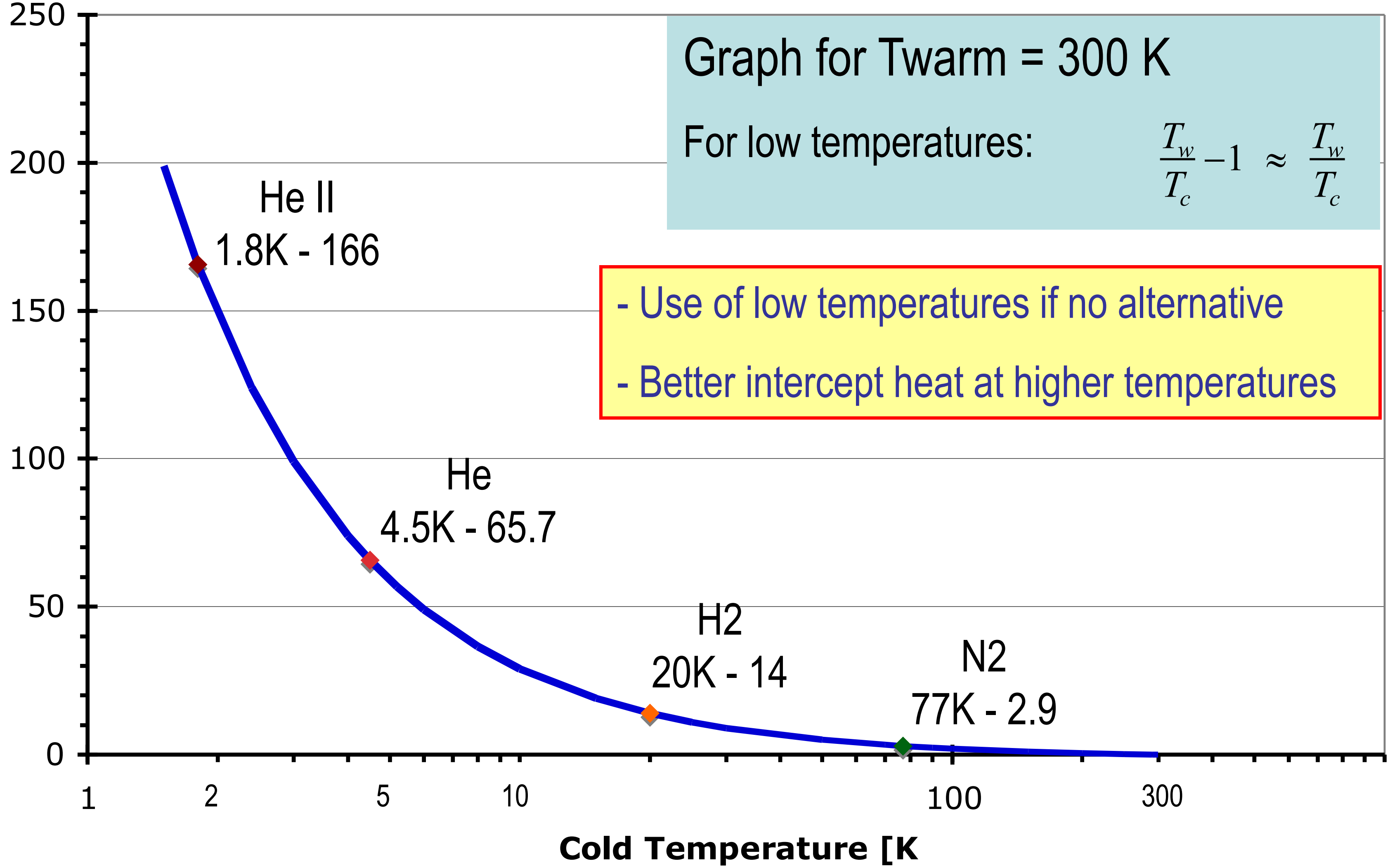
Carnot factor: $\frac{T_w}{T_c} - 1$

Heat / Work entering the system +

Heat / Work leaving the system -

This is THE governing effect for cryogenics

The Carnot Factor (2/3)

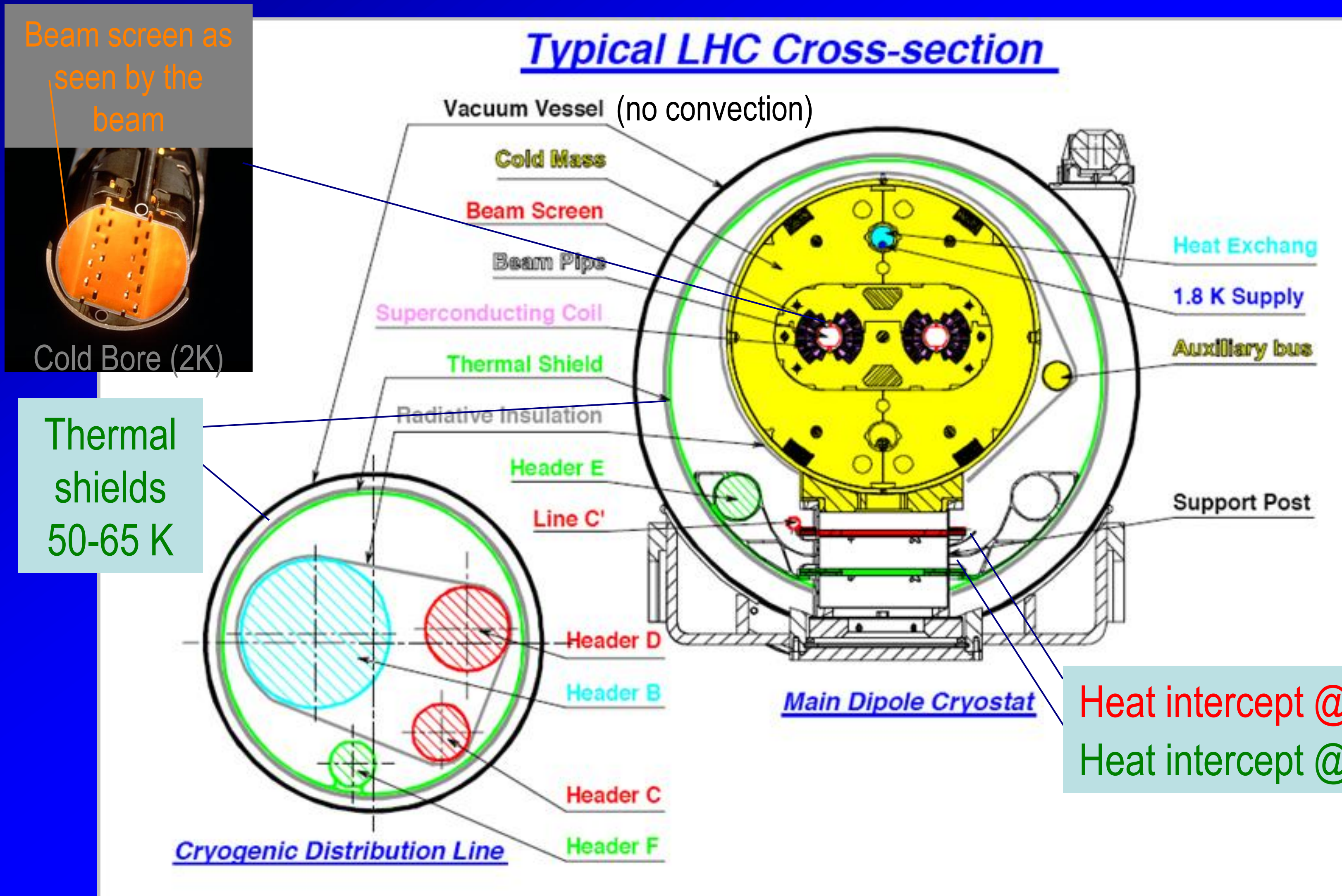


Graph for Twarm = 300 K

For low temperatures: $\frac{T_w}{T_c} - 1 \approx \frac{T_w}{T_c}$

- Use of low temperatures if no alternative
- Better intercept heat at higher temperatures

The Carnot Factor (3/3)



Thermal shields 50-65 K

Heat intercept @ ≈ 4.5 K
Heat intercept @ ≈ 50 K

Minimising heat loads (1/4) 90'ies

Power Input ≈ Power@cold x Carnot / %w.r.tCarnot

Heat loads management: Very detailed and methodic accounting of the various contributions, centralised contingency factors, periodic follow-up

RnD: Large design & optimisation efforts for the cryostat and its sub-components

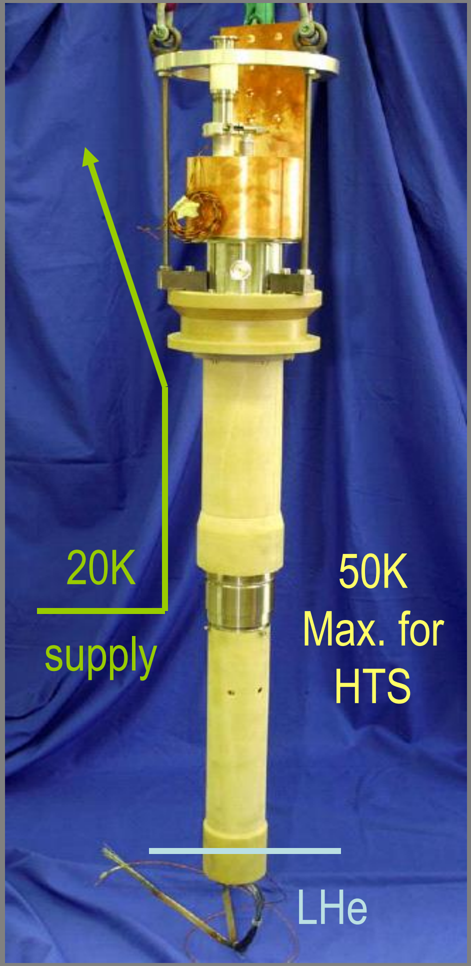
Non-metallic composite support post for magnets, with heat intercepts

Multi-layer insulation

Other RnD examples

90'ies

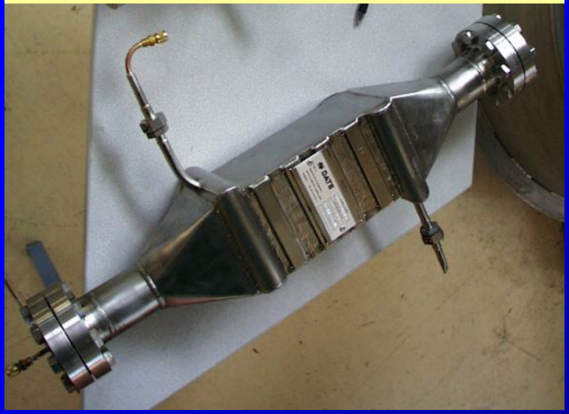
High Temperature Superconducting leads



Below 2K specific components

Cold Compressors

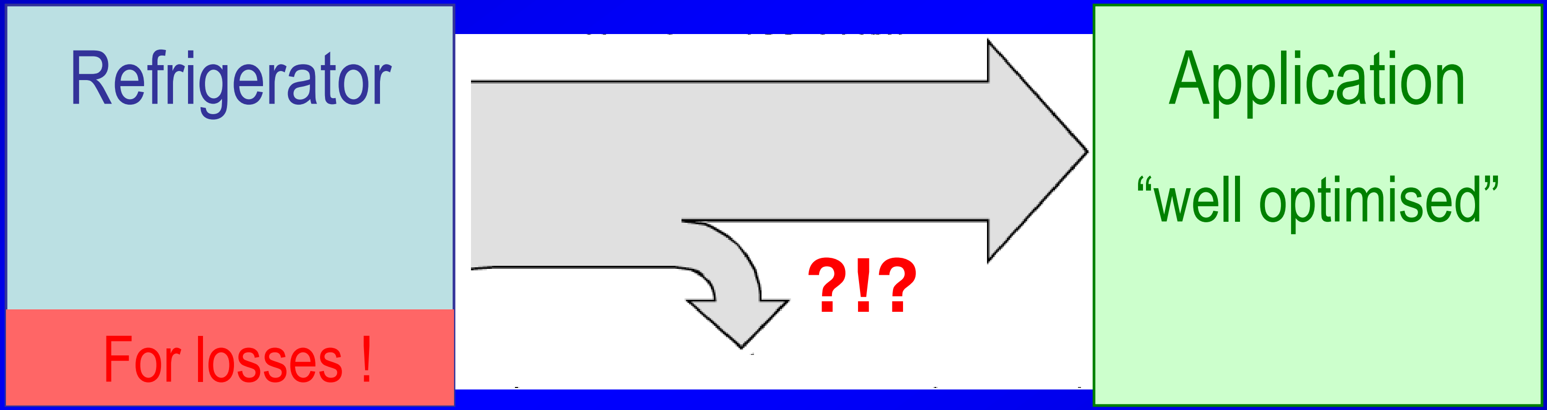
Stainless Steel Plate heat exchangers



Significant reduction of heat loads (≈ 25%)

Exergy, Introduction

Large scale (capacity) superconducting applications require distributing cooling power over long distances (high flow rates) with minimised temperature gradients for high thermodynamic efficiency

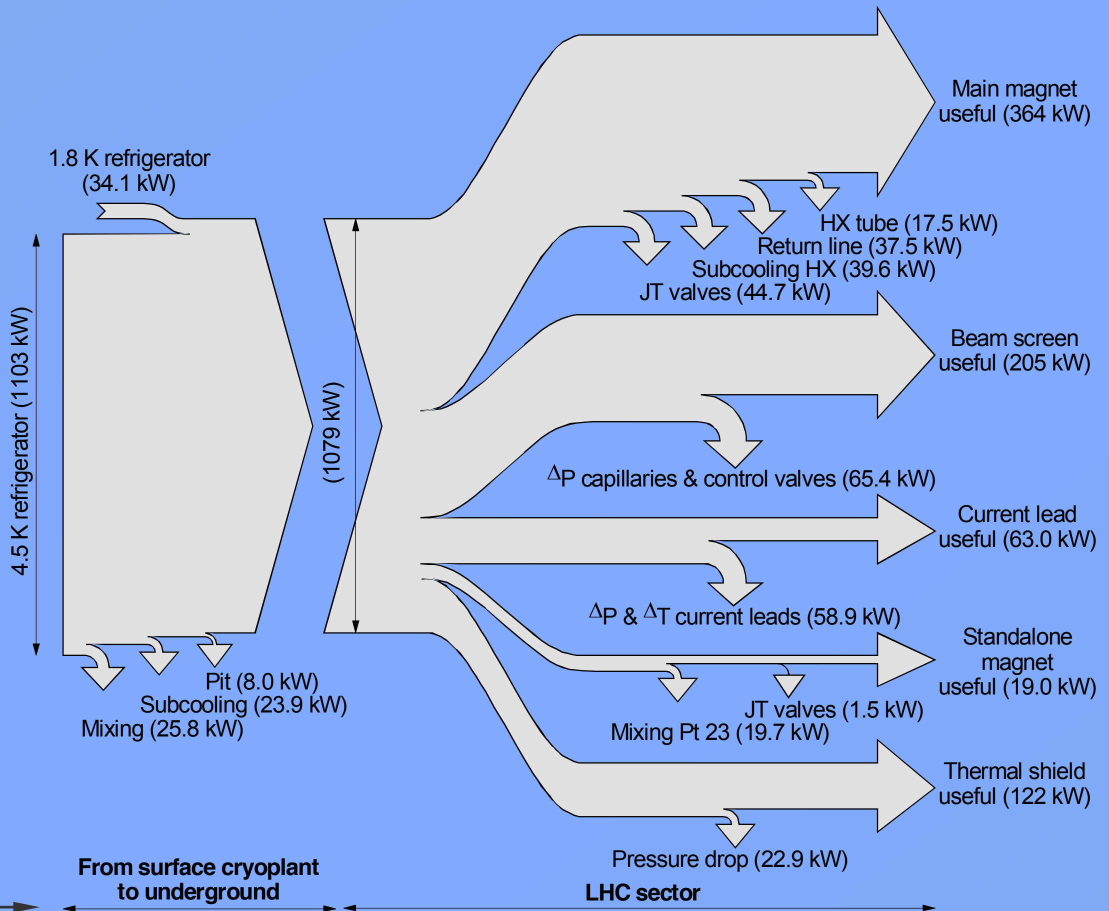


Exergy analysis (applied in the past for refrigeration plants) has been proposed as a way to quantify distribution losses, with the potential to help technical arbitration amongst competing solutions

LHC Distribution, Exergy Flow Diagram

1.8 K Units (2400 W)

4.5 K Refrigerator (18 kW)



1.8 K Main Magnets (Arcs) 73 %

Beam Screen Shielding 76 %

Current Leads Cooling 52 %

4.5 K Magnets (Straight sections) 47 %

Thermal Shield 84 %

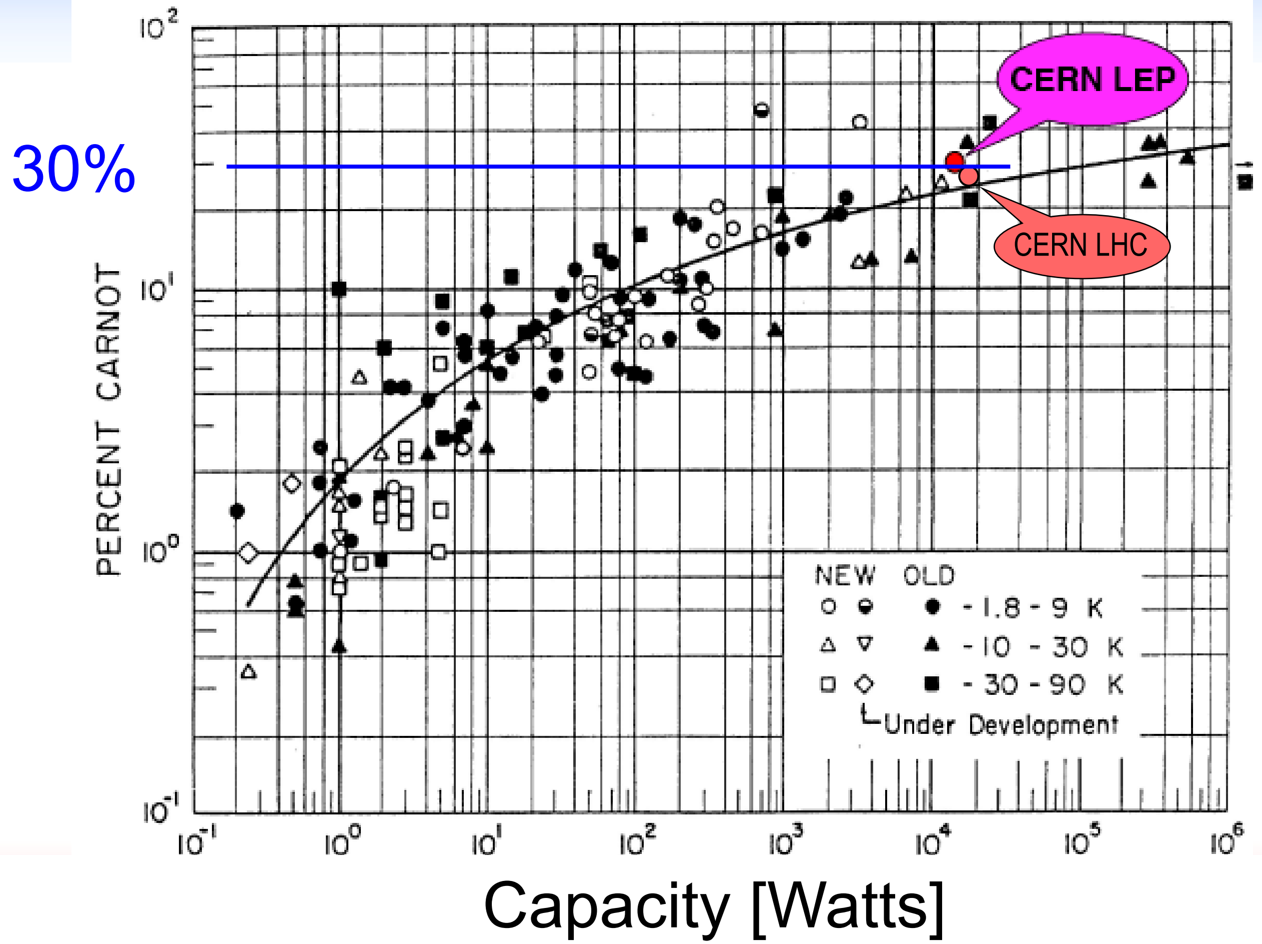
30 % of Carnot | 95 % | 72 %

68 %

Helium refrigerators

Power Input ≈ Power@cold x Carnot / %w.r.tCarnot

LE DIAGRAMME DE STROBRIDGE

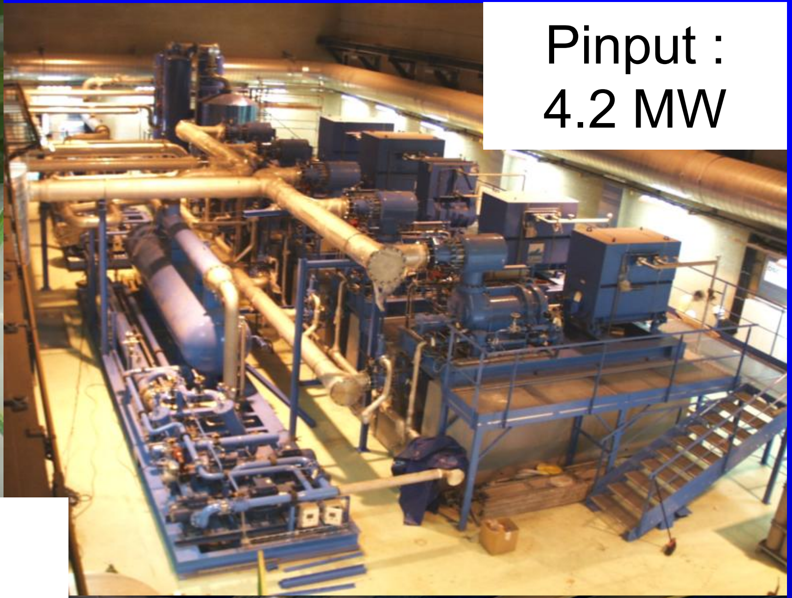


The efficiency w.r.t Carnot does not depend on the temperature, but rather on the size

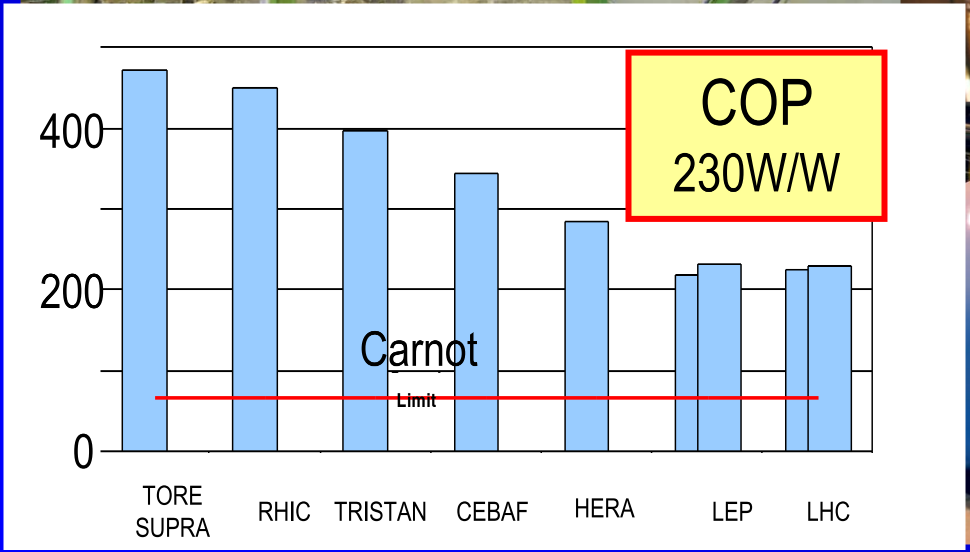
The largest possible the best !

18 kW @ 4.5 K Refrigerators

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



Pinput :
4.2 MW



COP
230W/W

Contracting refrigerators

Similar amounts !

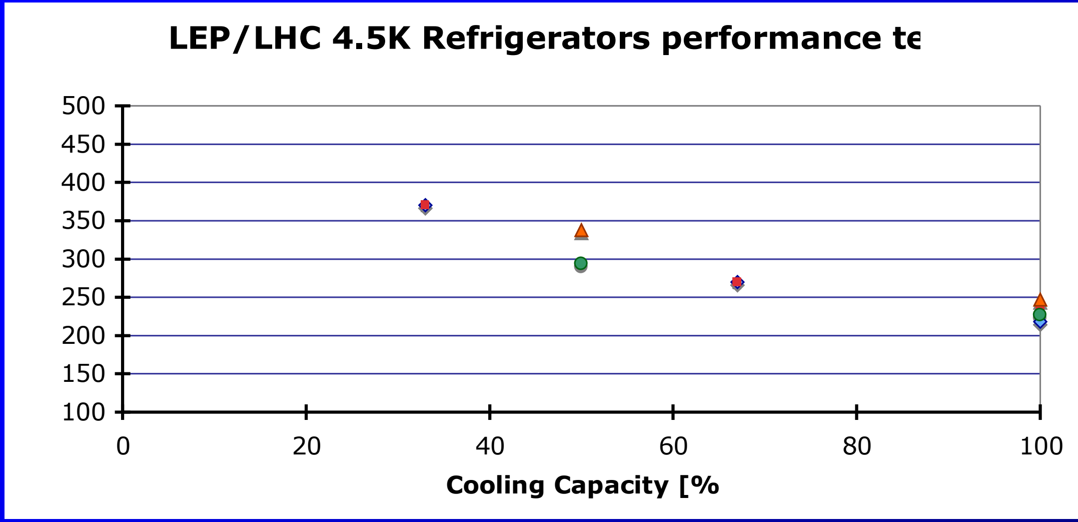
Adjudication : LOWEST   CAPITAL Cost   +   OPERATING cost over 10 years

Values provided in quotations by bidders

1/3 Low load   2/3 Max load   *(6600 hr/yr)*

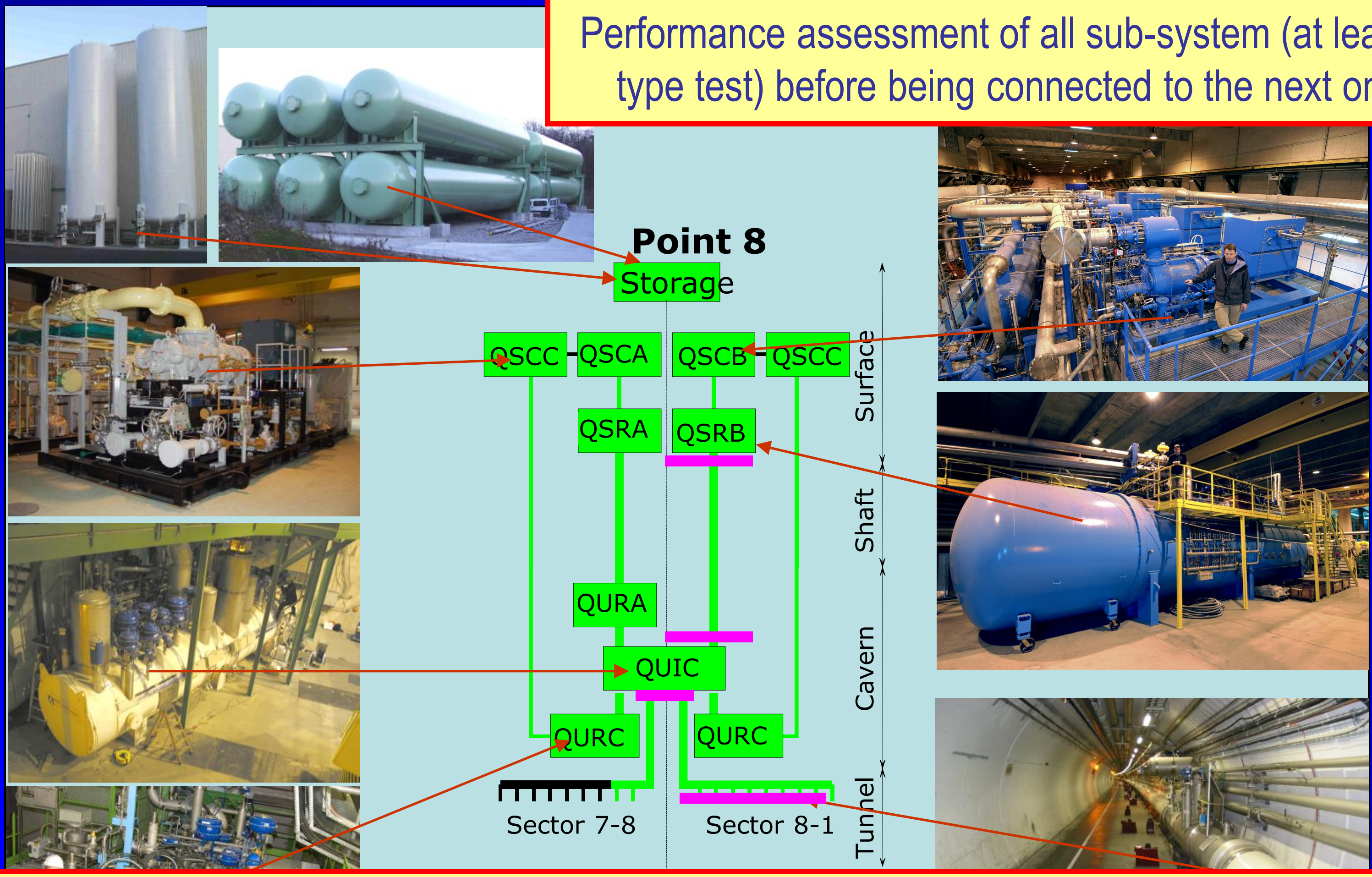
Operating cost: Garanteed power consumption x hours x 60 CHF/MWh

Real performance measured for acceptance, with bonus/malus correction



Testing the cryogenic sub-systems

Performance assessment of all sub-system (at least a type test) before being connected to the next one



A coherent approach with the contracting approach; a way to get familiar with process optimisation and tuning for availability

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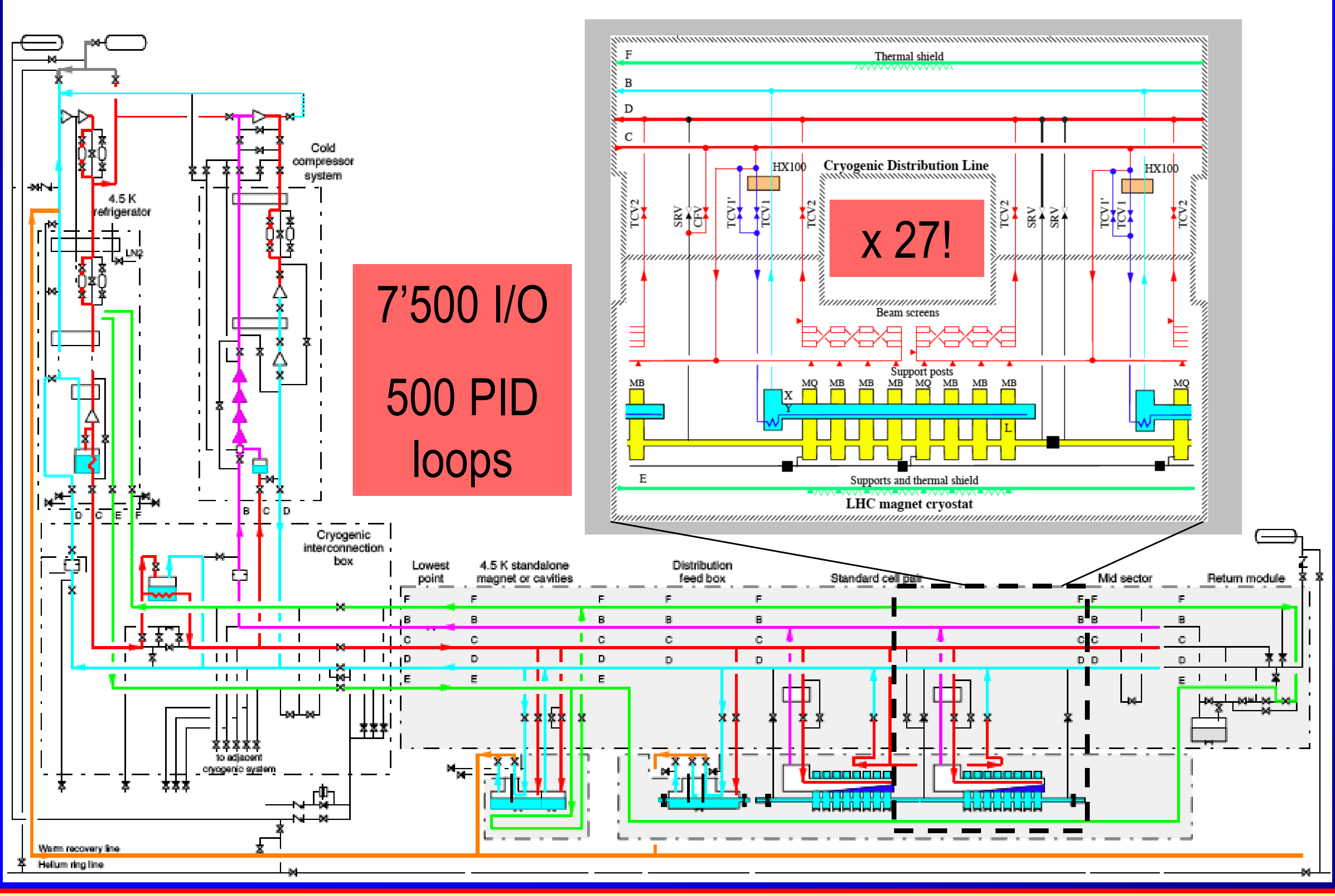
Tuning one of 8 LHC sectors

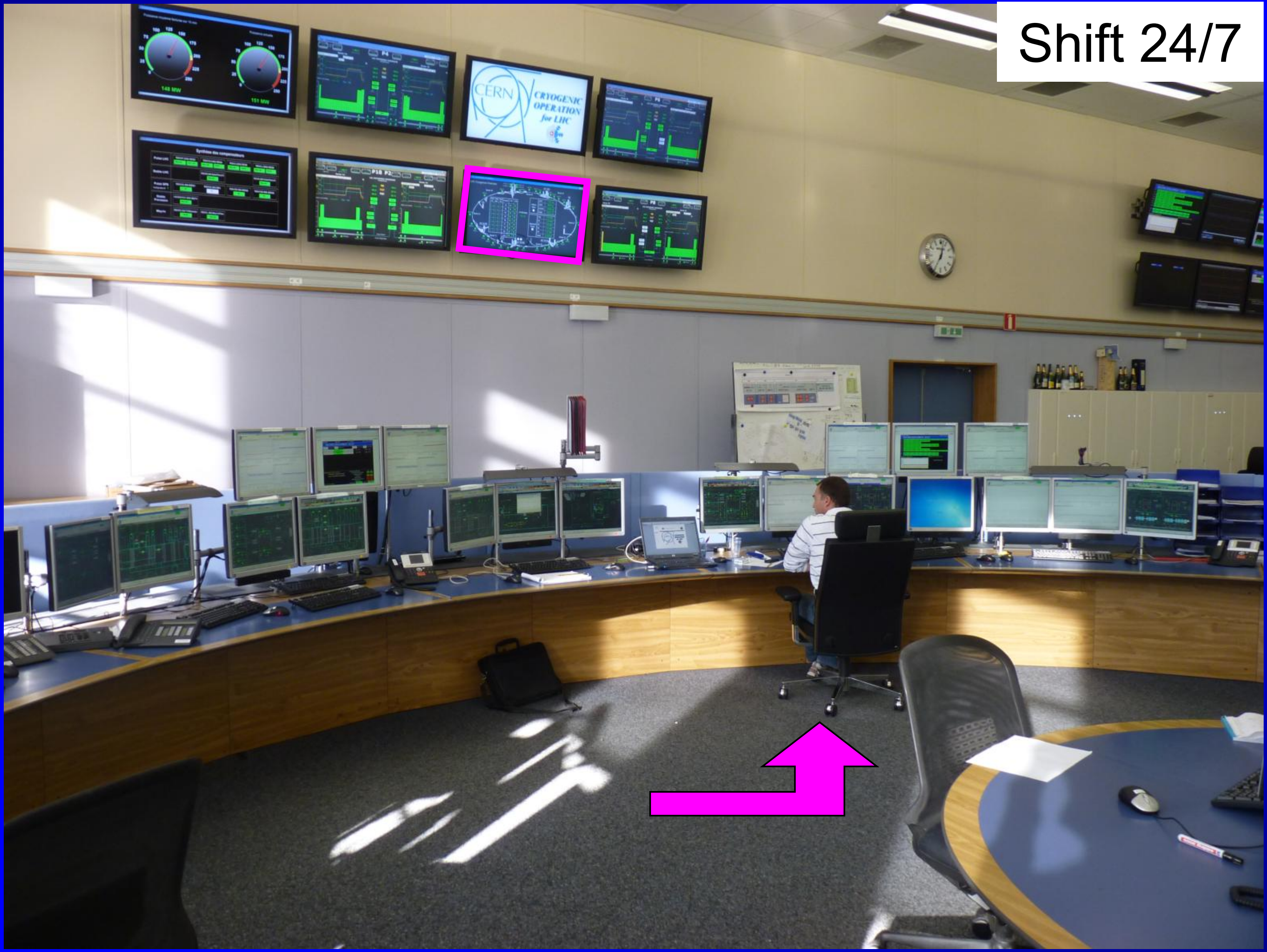


7'500 I/O

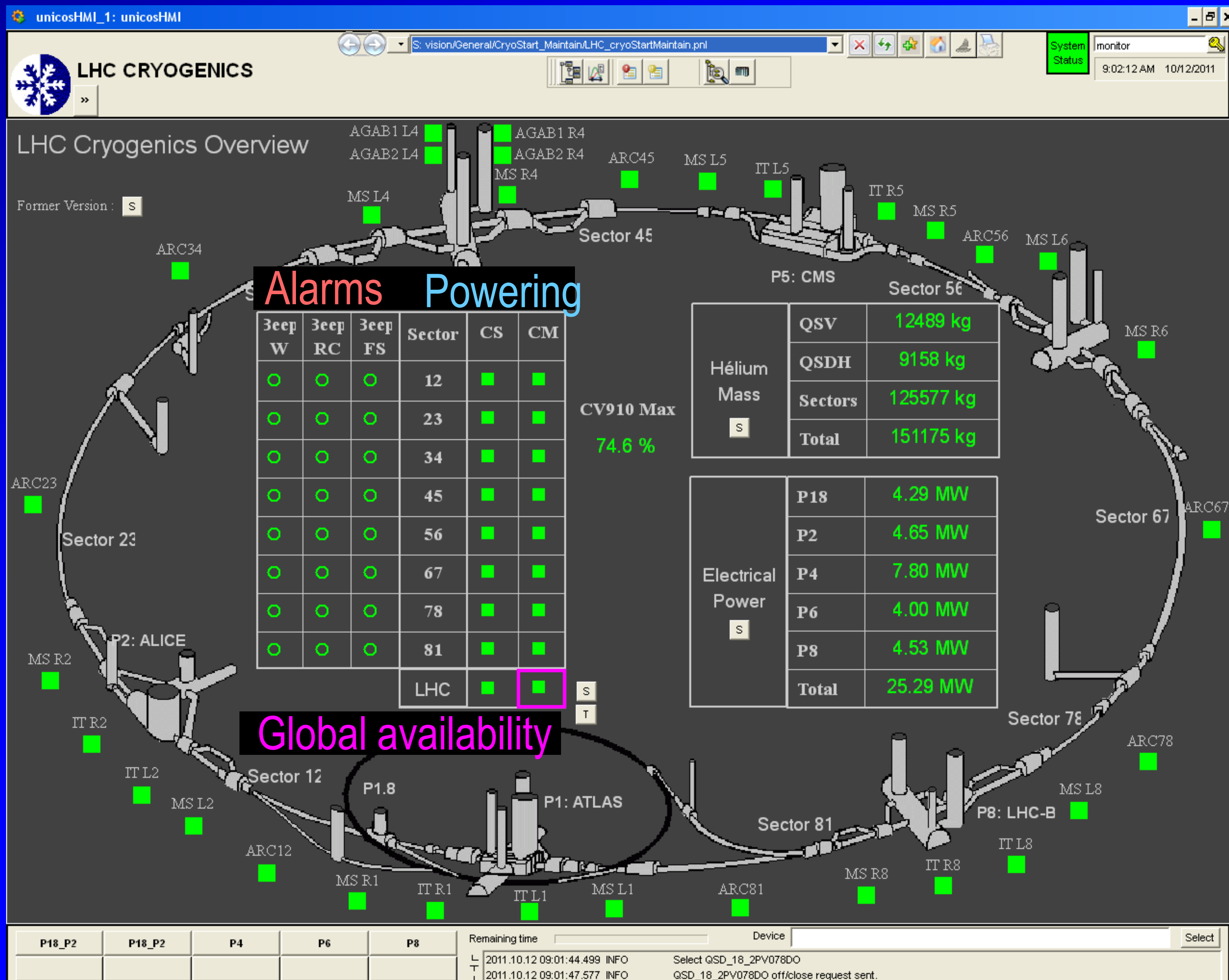
500 PID loops

Functional analysis, Methodic and systematic approach, a bit of time …

Cryo operator in Cern Central Control room

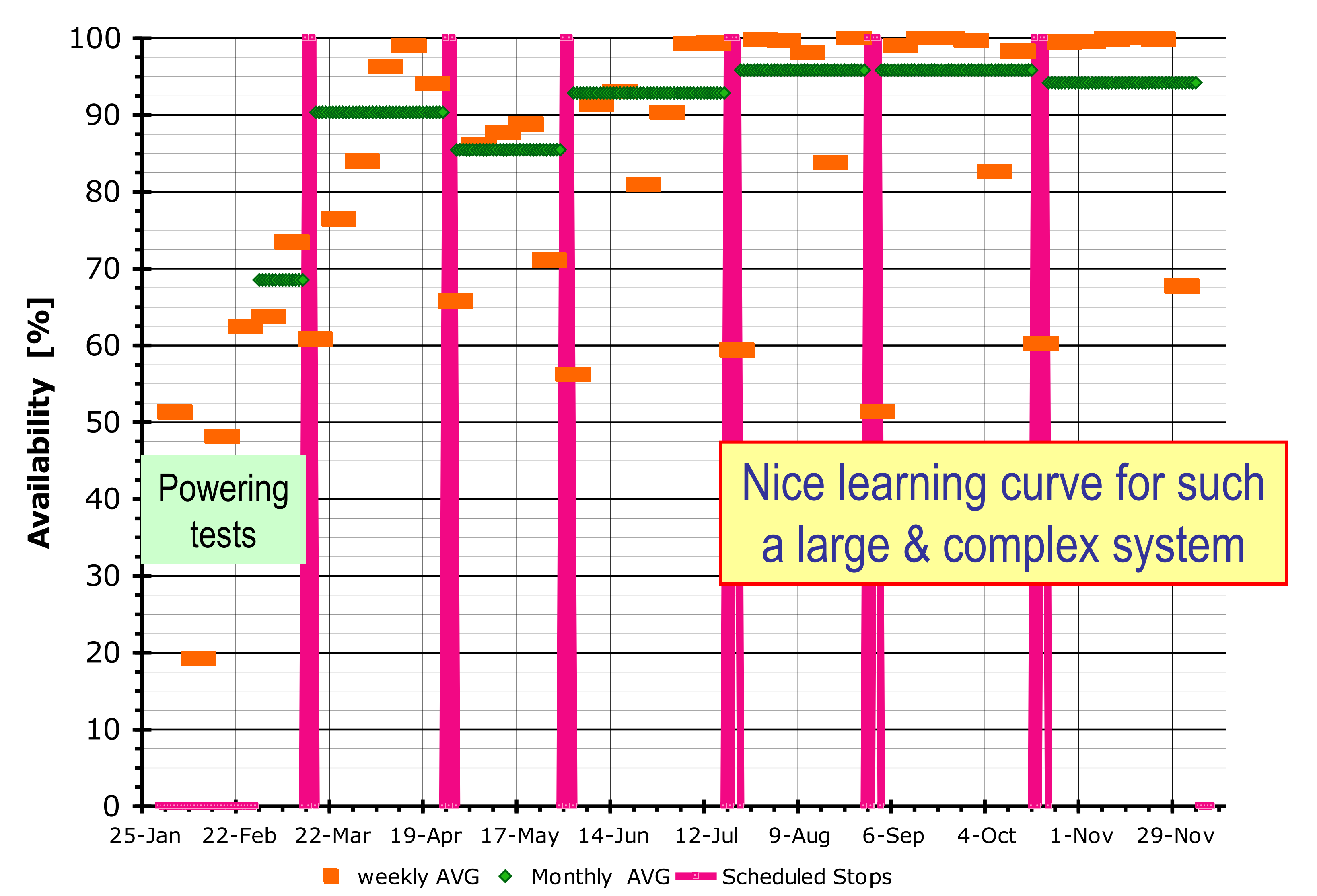


Operation, indicators

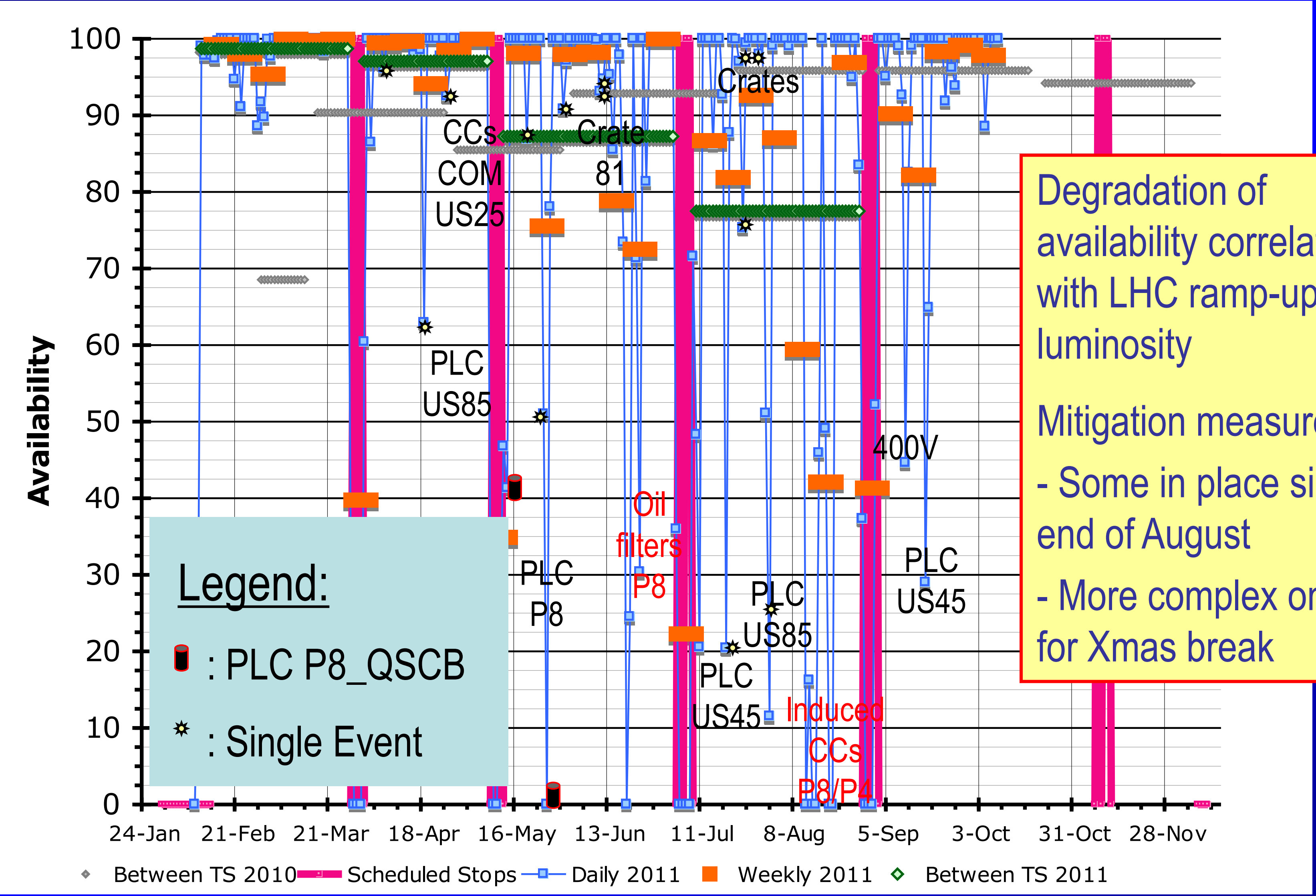


LHC Cryo global availability 2010

Based on LHC_Global_CryoMaintain signal per unit of time



LHC Cryo global availability 2011



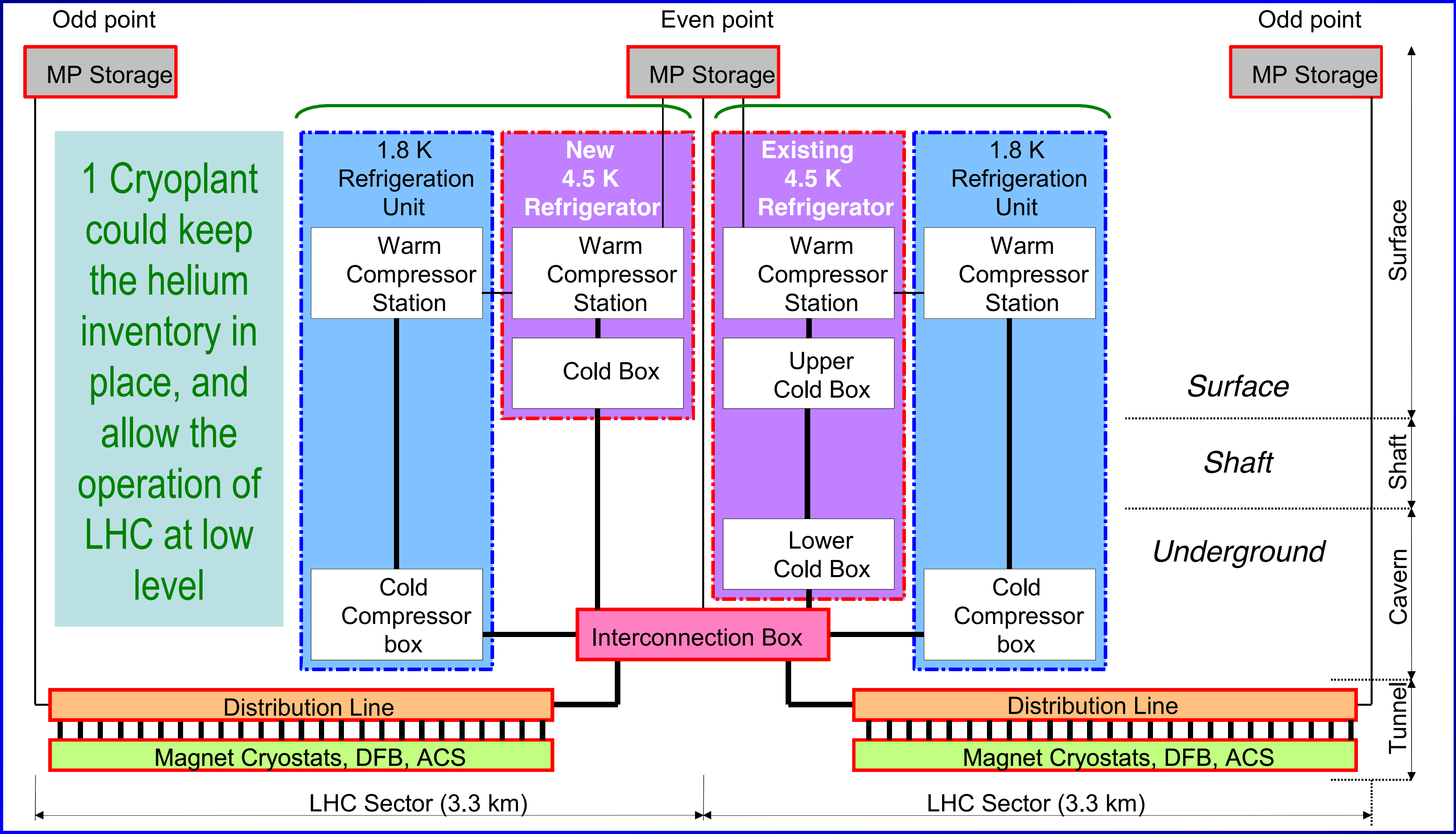
Degradation of availability correlated with LHC ramp-up in luminosity

Mitigation measures:

- Some in place since end of August
- More complex ones for Xmas break

Cryogenic architecture

Typical LHC even point



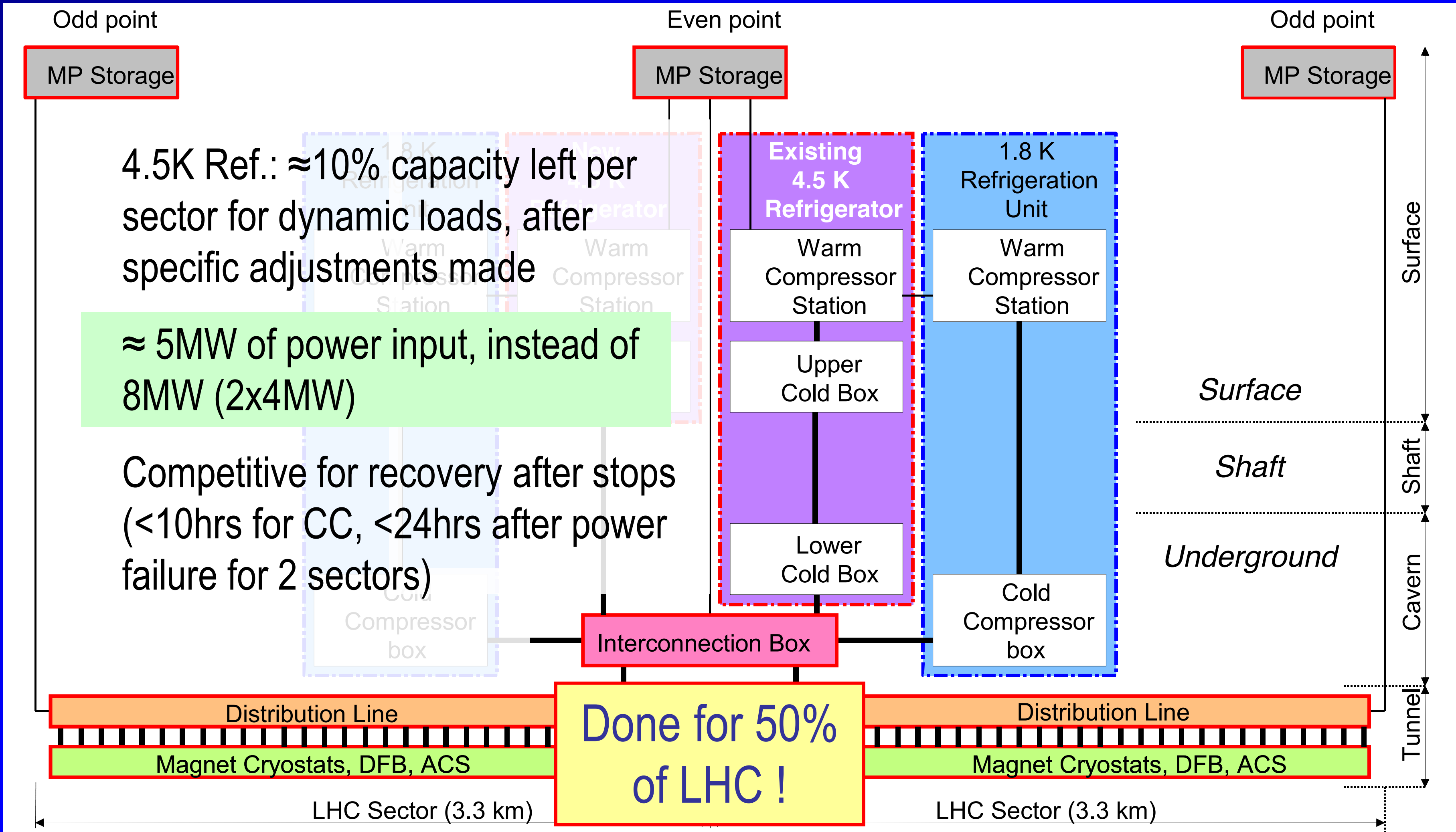
Efficient operation at low load

Typical LHC even point

- 4.5K Ref.: ≈10% capacity left per sector for dynamic loads, after specific adjustments made

≈ 5MW of power input, instead of 8MW (2x4MW)

- Competitive for recovery after stops (<10hrs for CC, <24hrs after power failure for 2 sectors)



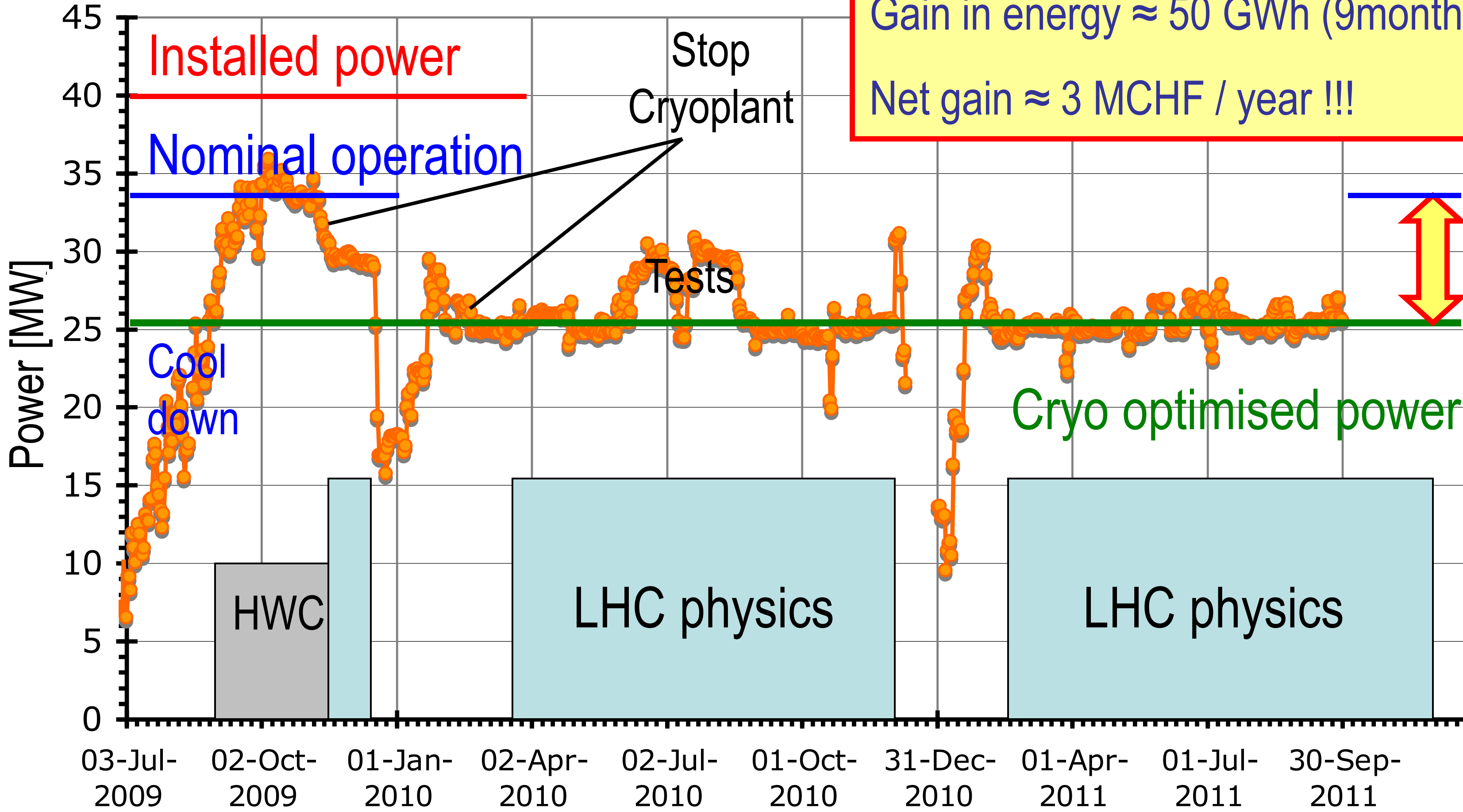
Done for 50% of LHC !

Power Consumption

Power consumption reduced by ≈ 8 MW

Gain in energy ≈ 50 GWh (9months)

Net gain ≈ 3 MCHF / year !!!



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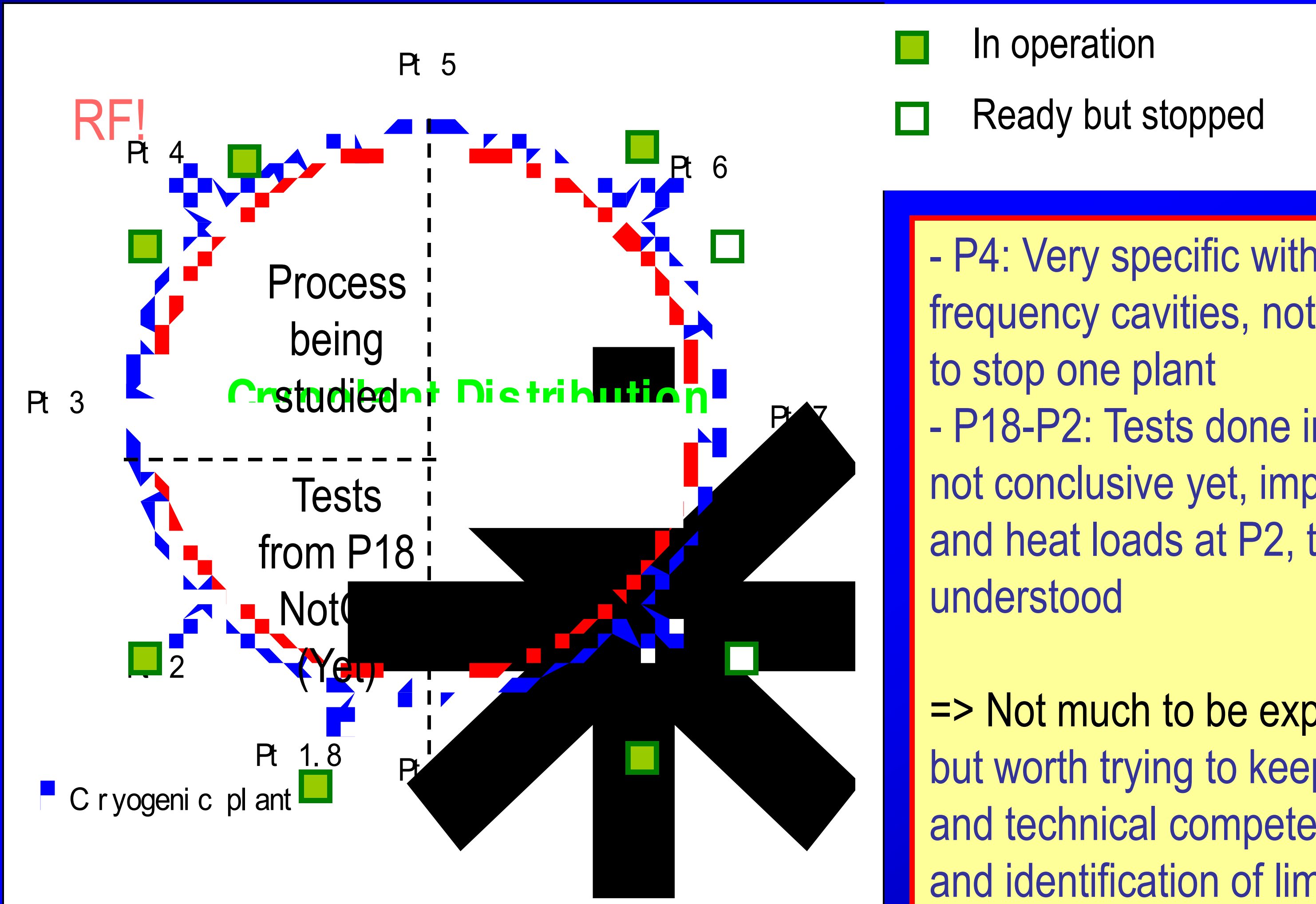
What else could be done ?

- Further optimise the operation of the cryogenic system with the 2 remaining sites to be operated with 1 Refrigerator for 2 sectors
  [Cryo + LHC OP]
- Evaluate the possibility,impact and effects of allowing reduced cooling water temperature to better match atmospheric conditions
  [Cryo + Cooling]
- Evaluate the possibility, impact and effects of recovering heat at the compressor station
  [Cryo + Cooling + CERN]
- If heat recovery would be interesting, evaluate the possibility, impact and effects of changing the LHC operation schedule (with steady operation in winter time to combine two above effects)
  [Cryo + Cooling + CERN]

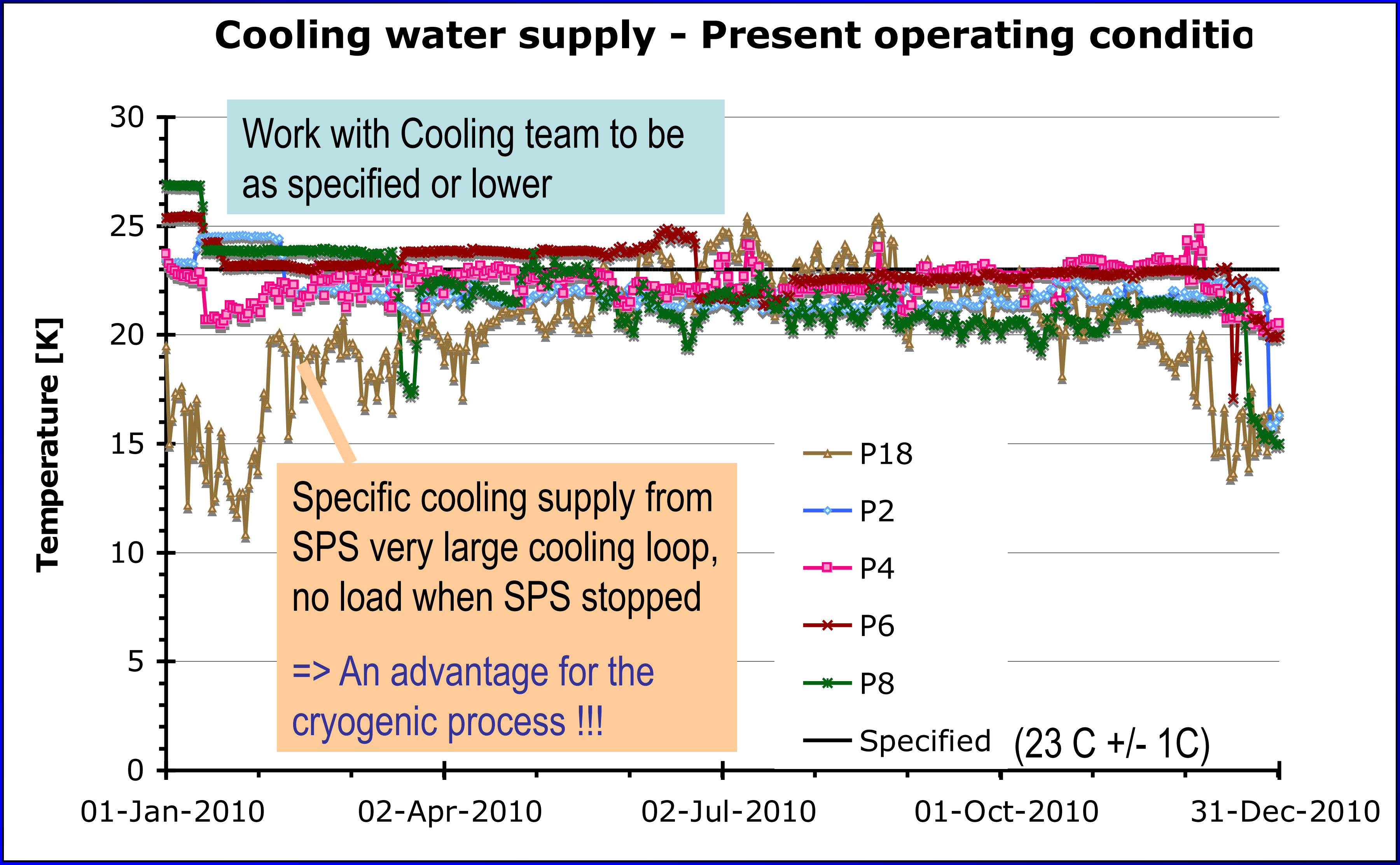
Reducing cryoplants in operation ?



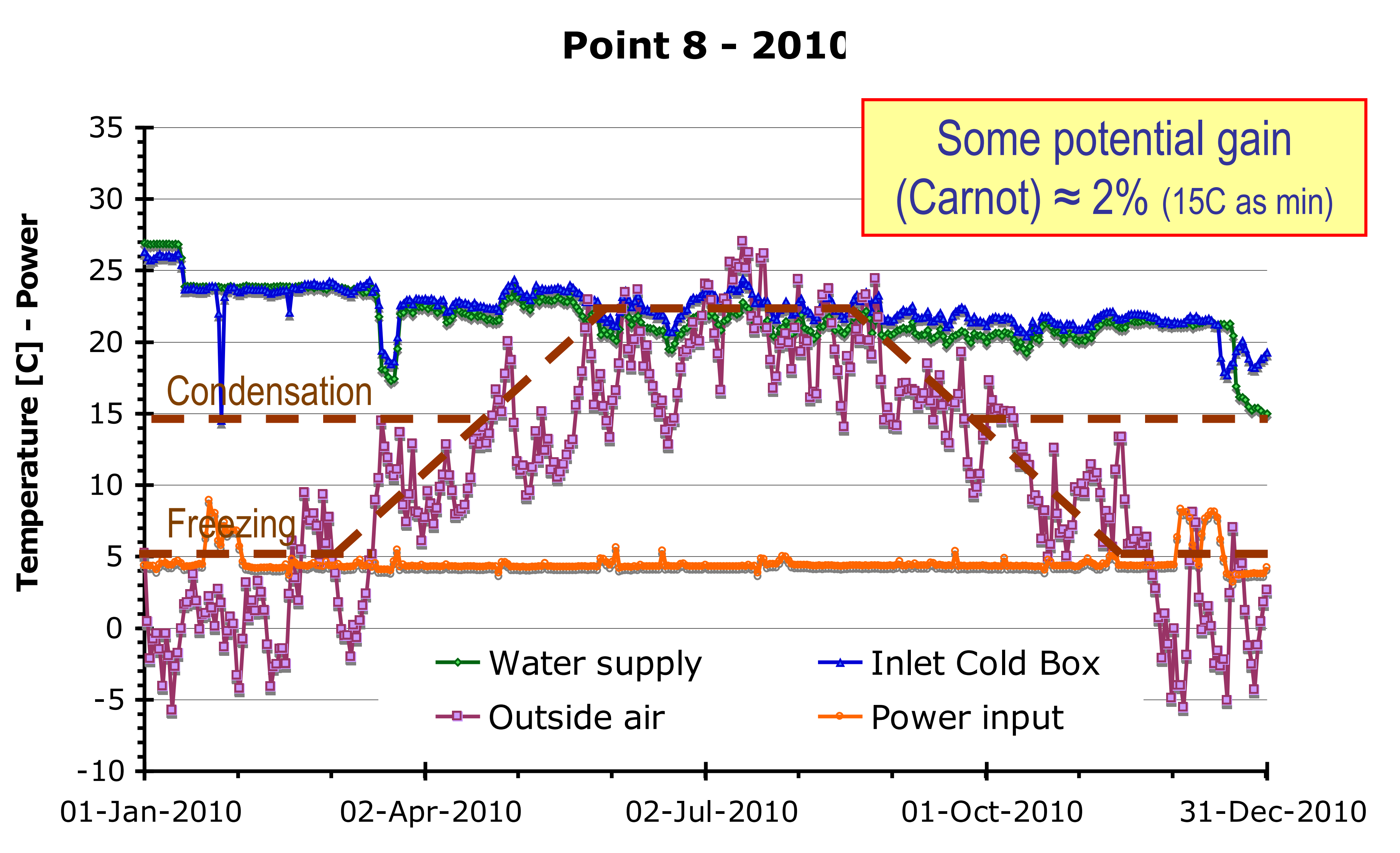
- P4: Very specific with Radio-frequency cavities, not foreseen to stop one plant
- P18-P2: Tests done in 2010 not conclusive yet, impedance and heat loads at P2, to be understood

=> Not much to be expected, but worth trying to keep process and technical competencies, and identification of limits

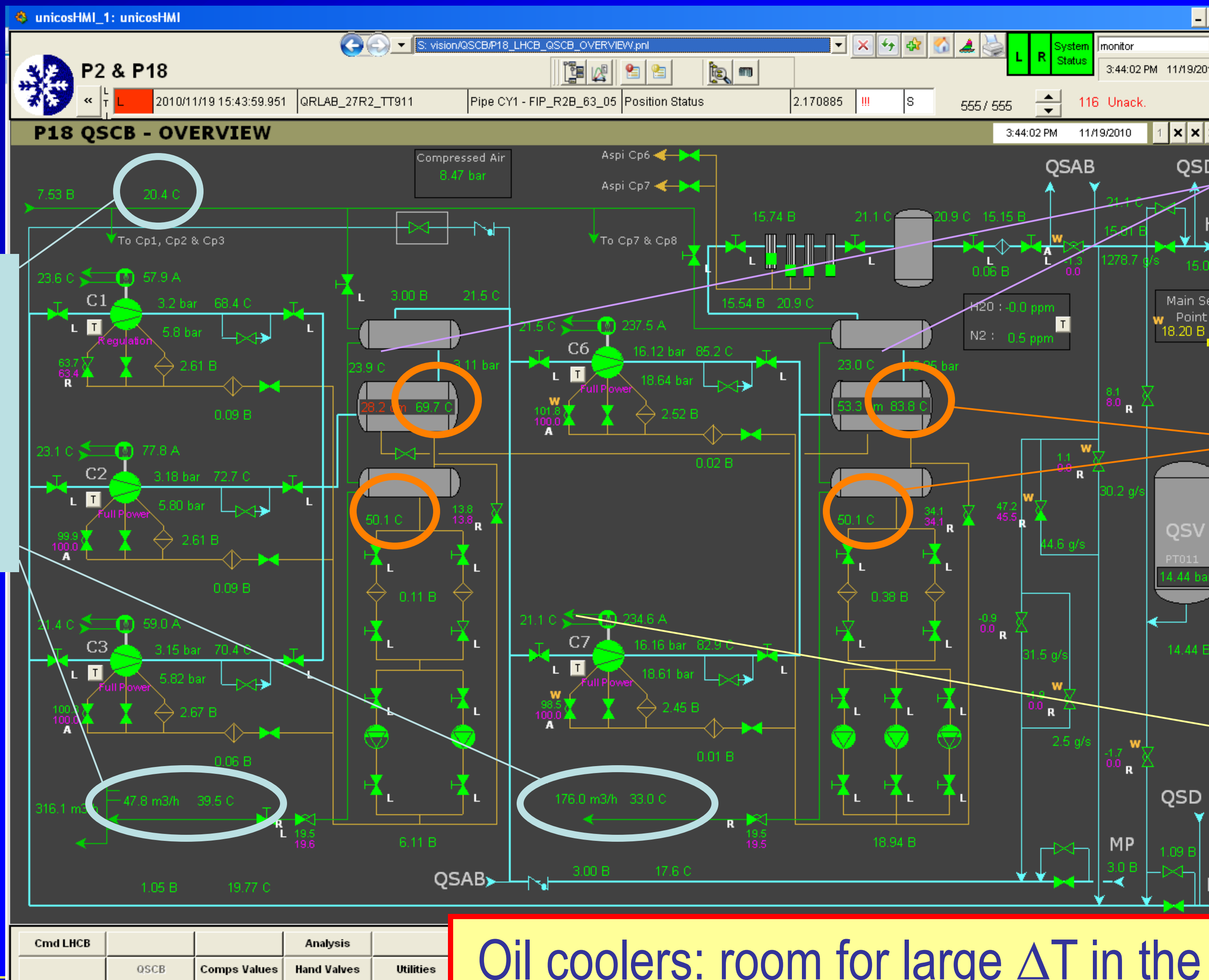
Cooling water temperature (1/2)



Cooling water temperature (2/2)



Compressor station flow scheme



Water:

Inlet & Outlet conditions

Up to 3.5MW/Ref.

Helium:

Poor ΔT (≈3C)

Some 100s kW

Oil:

Inlet & Outlet conditions

Up to 3MW/Ref.

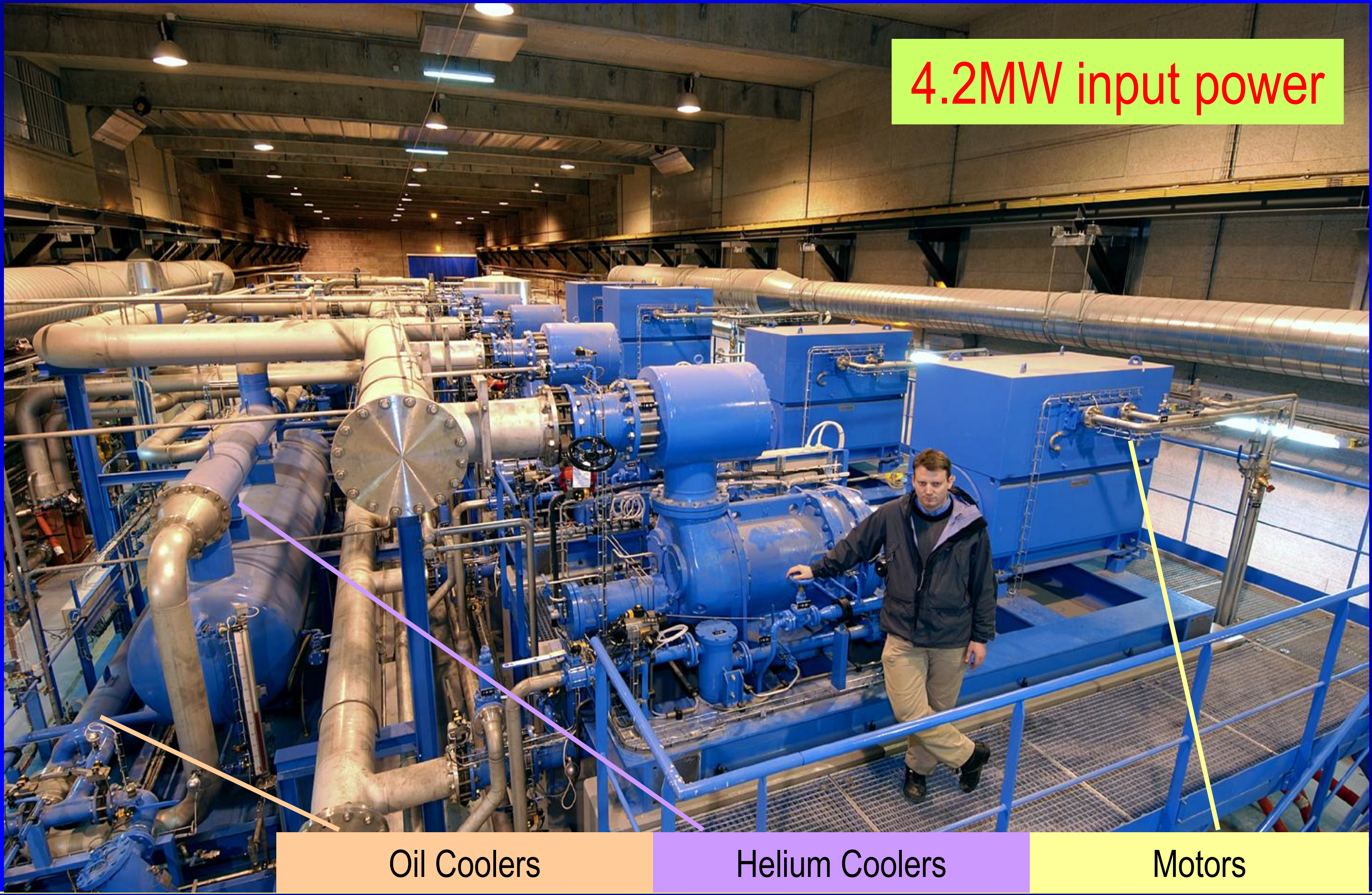
Motors:

Poor ΔT (≈3C)

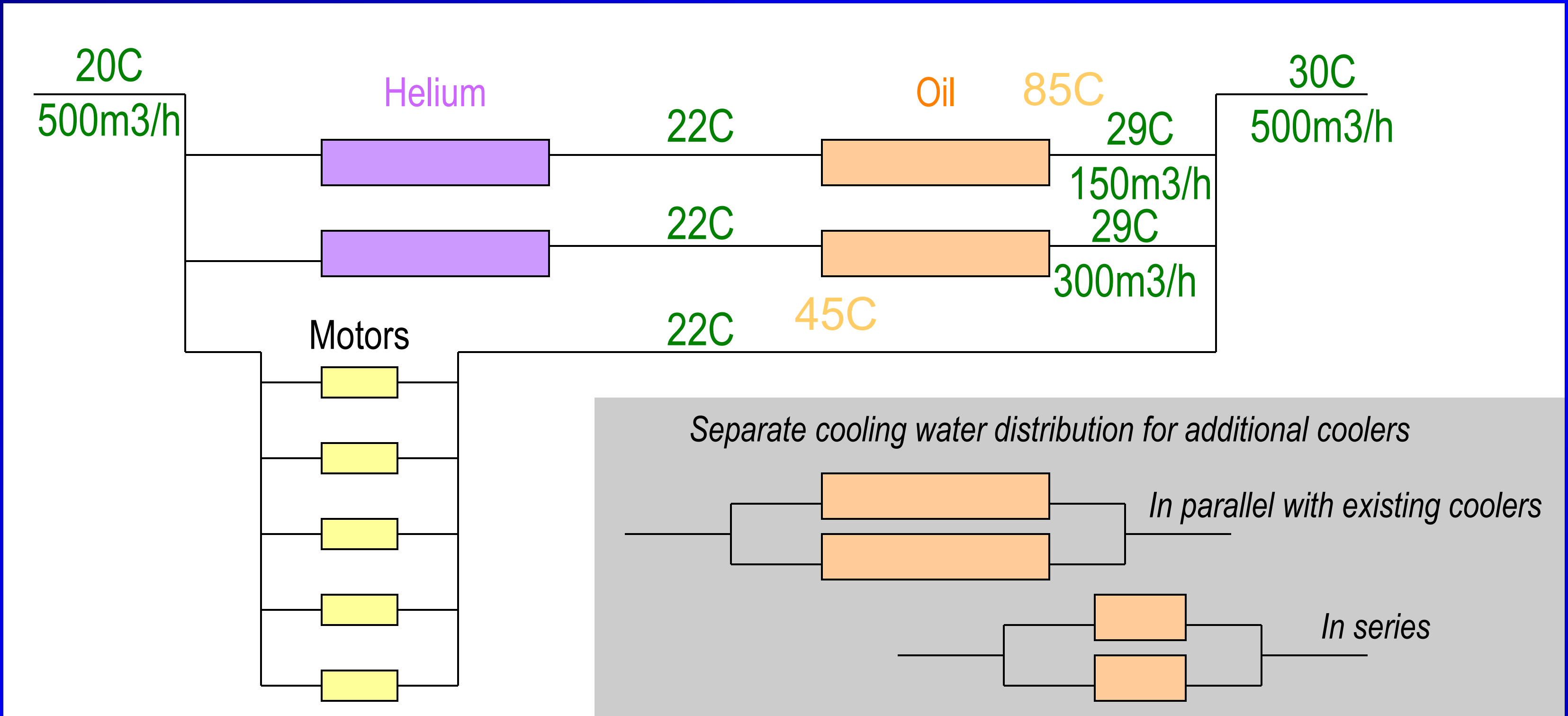
Few kw

Oil coolers: room for large ΔT in the MW range

View of a compressor station



Heat recovery potential



For Cryogenics:

- Only oil coolers concerned (fraction?)

- Only with existing technology and no serious operational risk !

From Cooling point of view:

- Warmer temperatures / bacteria
- Transients / other users

Not so straightforward, worth a study ?

Summary

- LHC cryogenics is the largest, the longest and the most complex cryogenic system worldwide. From design to operation, availability and energetic efficiency have played key roles.
- We could achieve a reasonable global availablity (around 95%) so far with beams while operating close to best reasonably possible efficiency of the cryogenic system (25MW for 40MW installed) and reducing helium losses during beams operation period
- Potential improvements, but with impacts on others: (global optimum!)
  - Lowering the cooling water temperature
  - Moderate heat recovery (still in the MW range)
- Future systems will have to evaluate such new features at design!