First operational experience with the LHC Cryogenic System

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on behalf of the "Cryogenics Group"

Technology Department

IPAC 10 The 1st International Particle Accelerator Conference

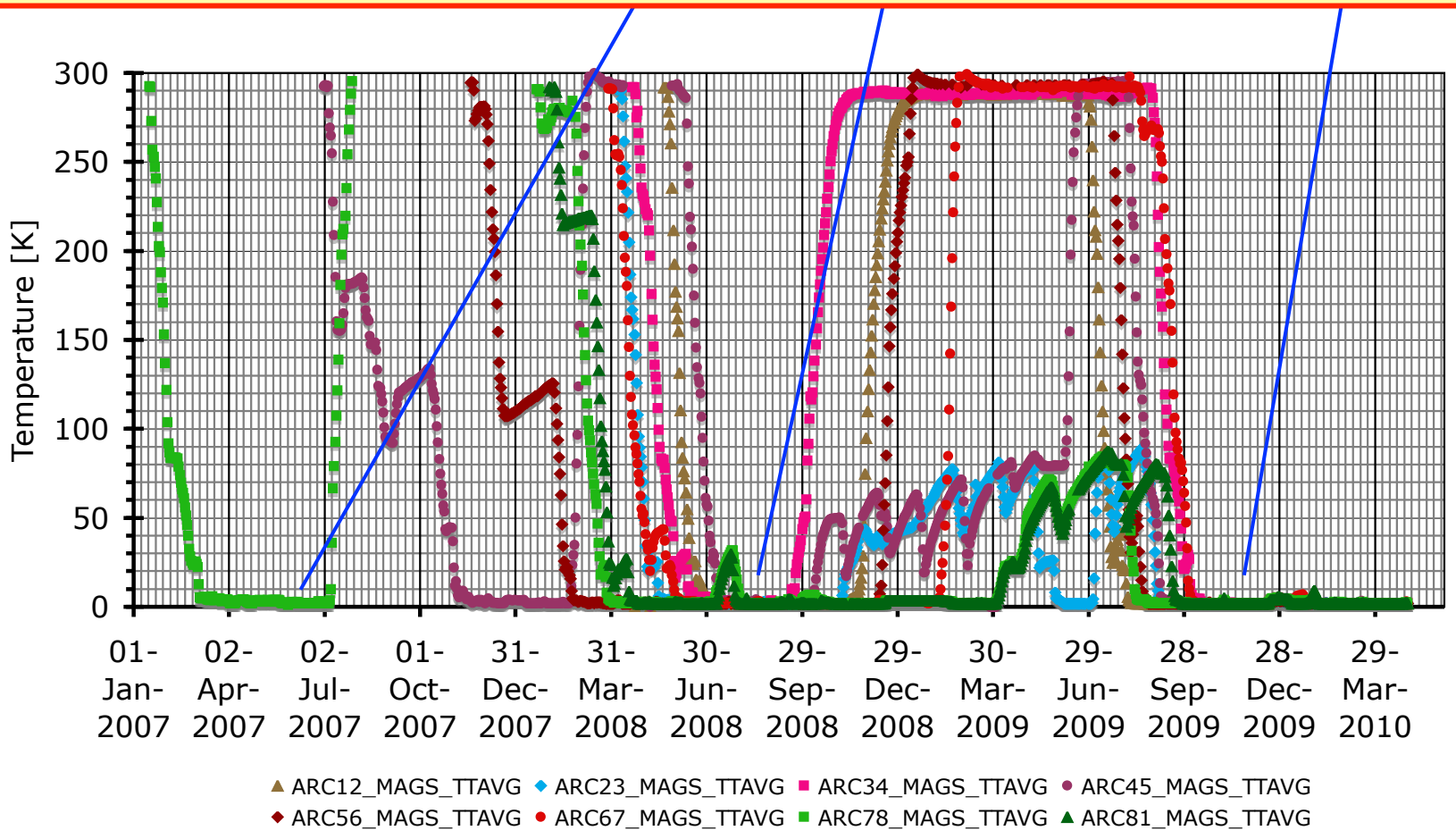
The 1st International Particle Accelerator Conference

Kyoto, Japan / May 23-28, 2010

Temperature of LHC sectors

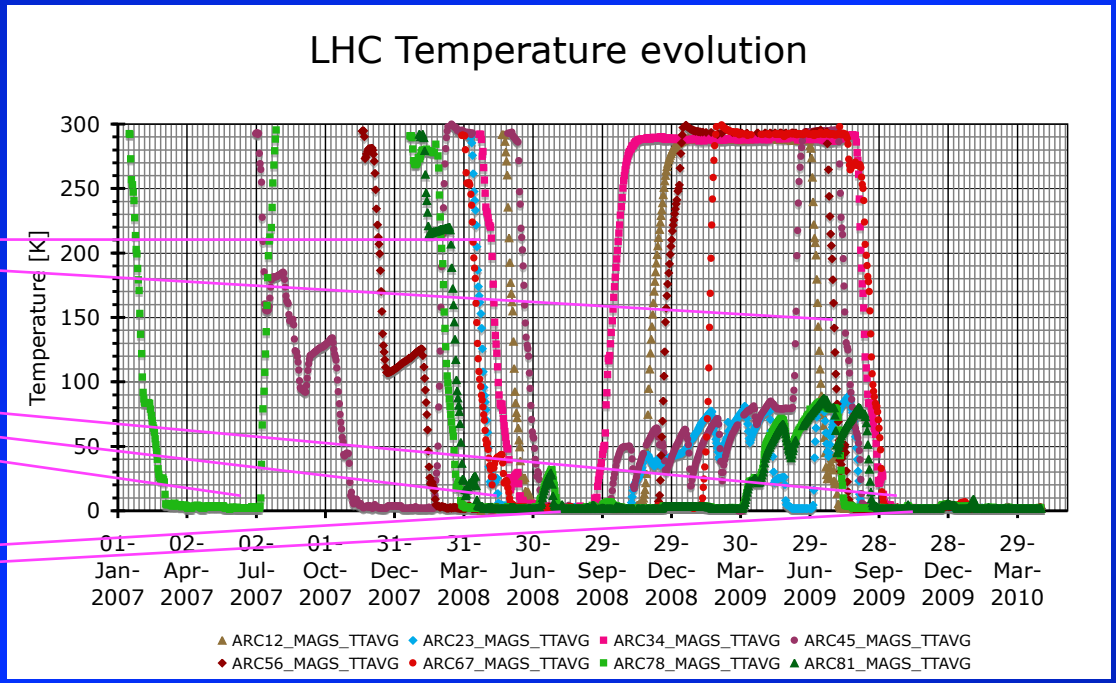
LHC Cryo-OP

Progressive learning, from pain to relative success, it works!

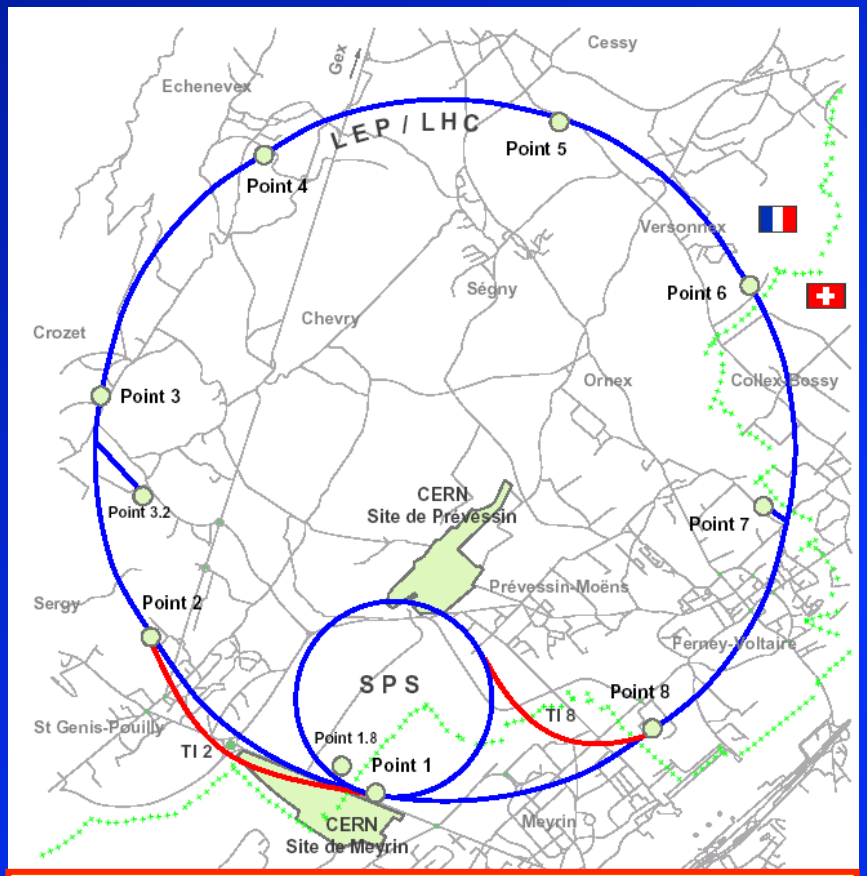


Outline

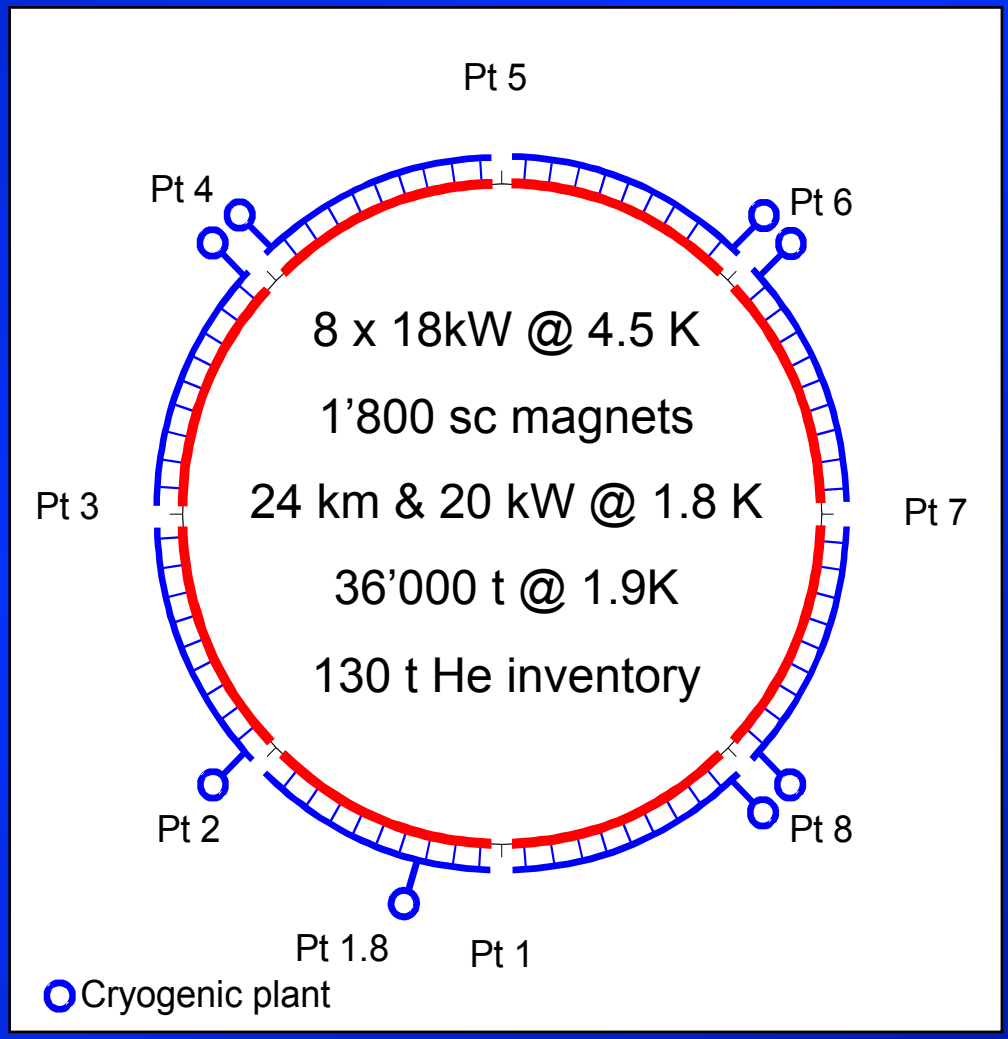
- Introduction
- Cool-down
- Tuning
- Operation
- Nice features !
- Consolidations
- Summary



Layout of cryogenics

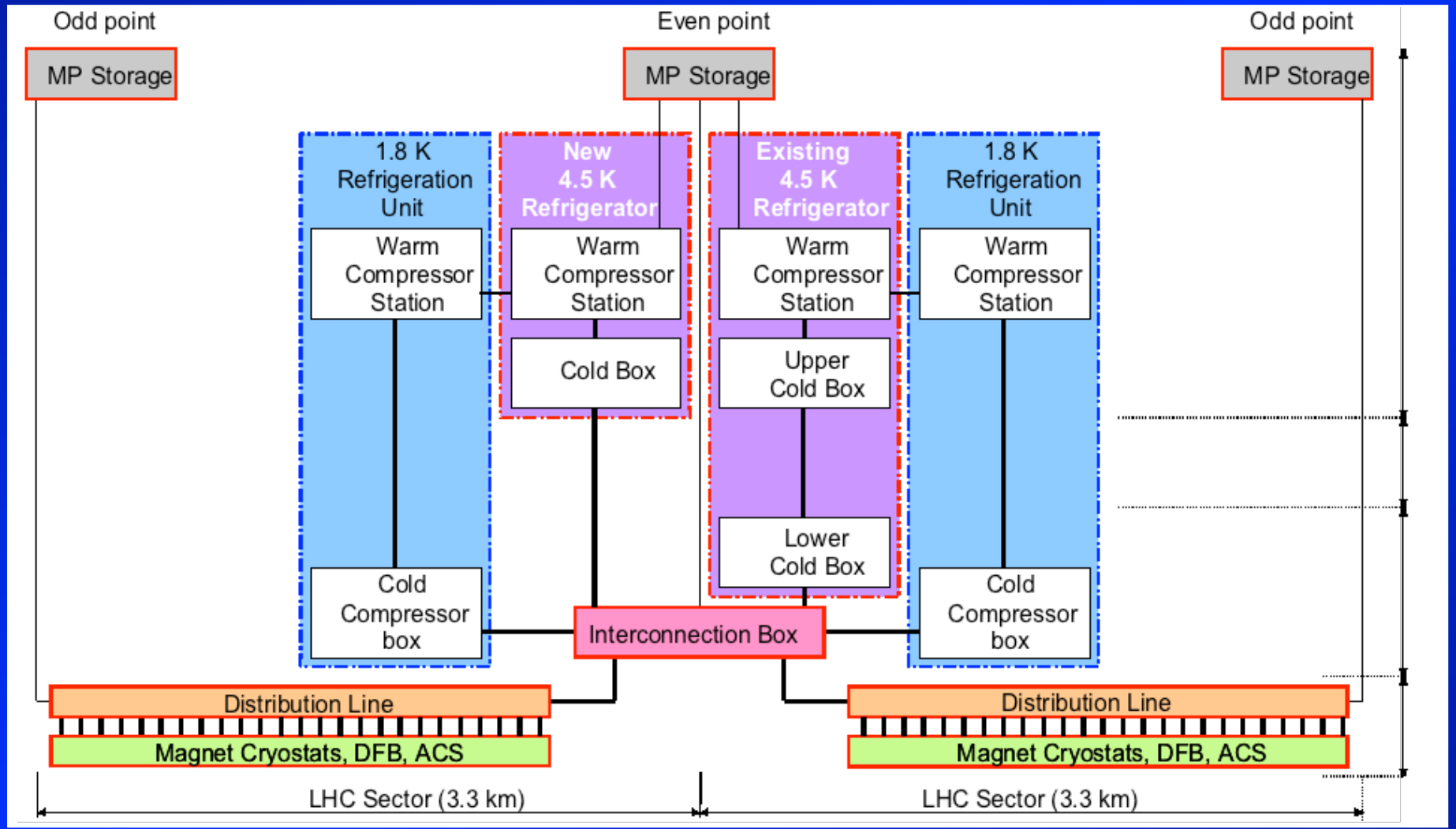


LHC cryogenics is the largest, the longest and the most complex cryogenic system worldwide



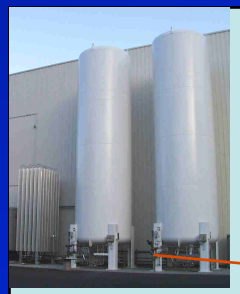
Cryogenic architecture

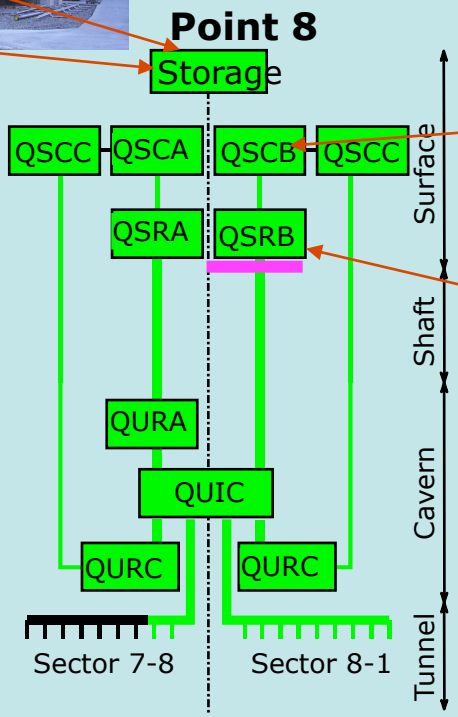
Typical LHC even point



Cryogenic sub-systems

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





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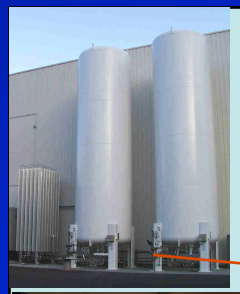

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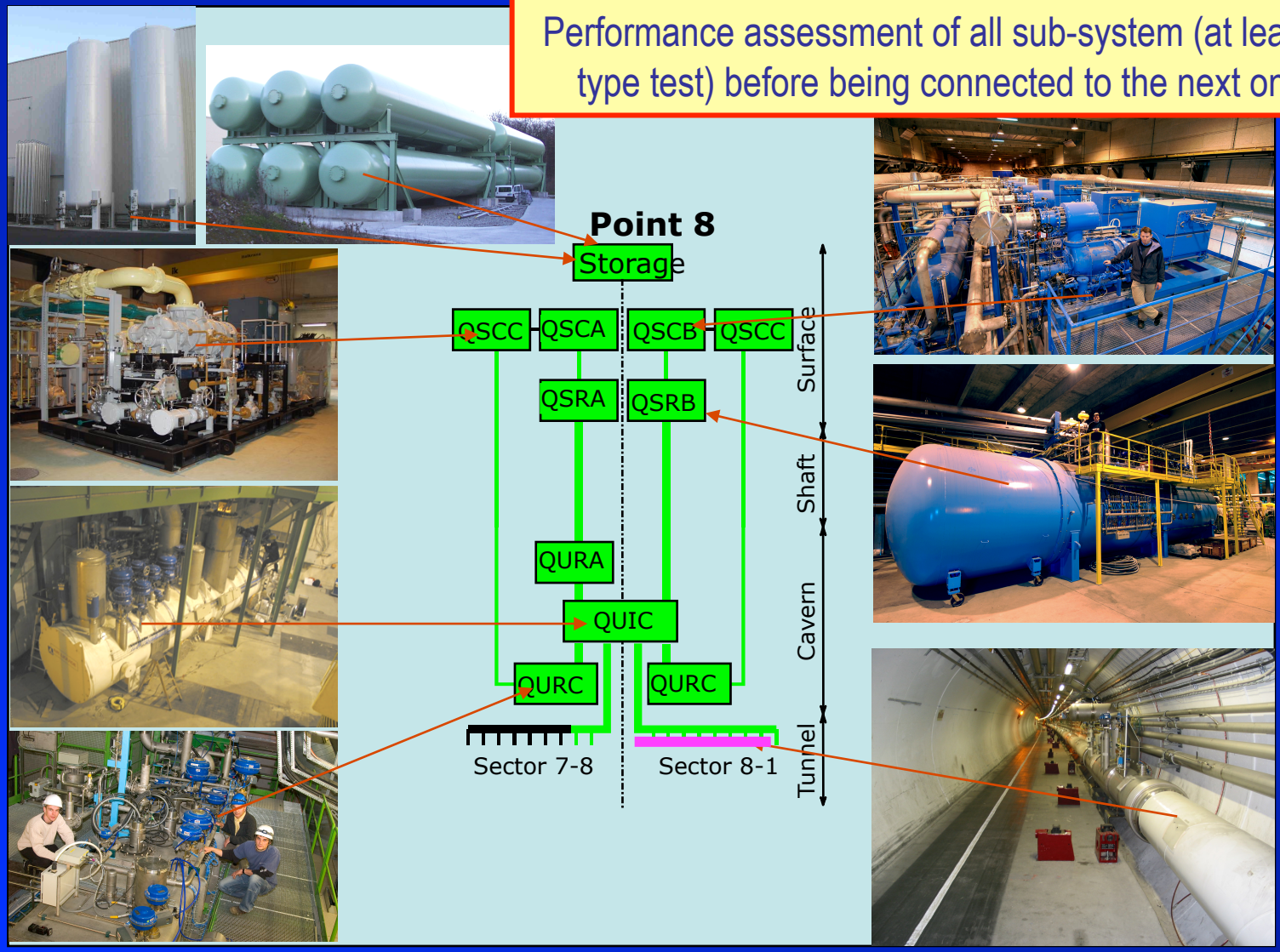
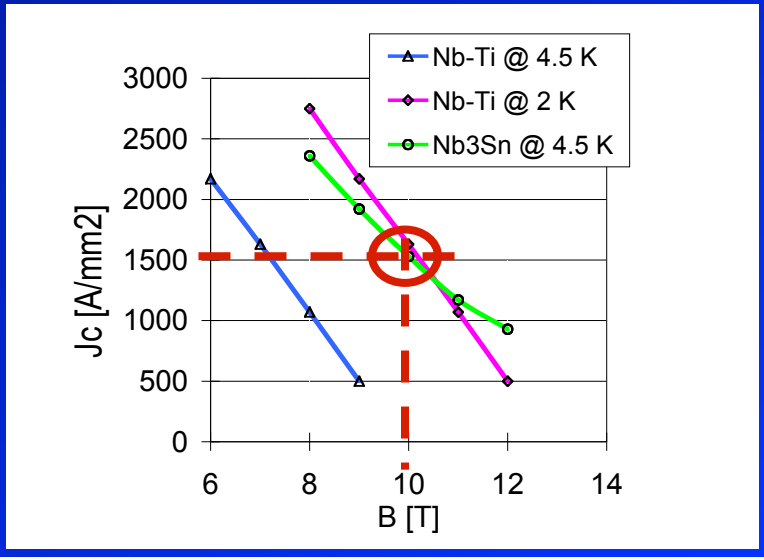
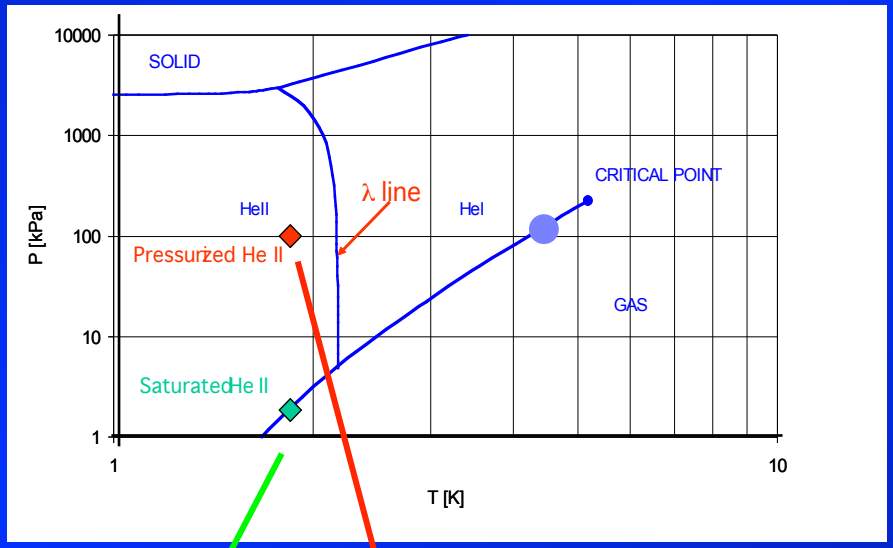
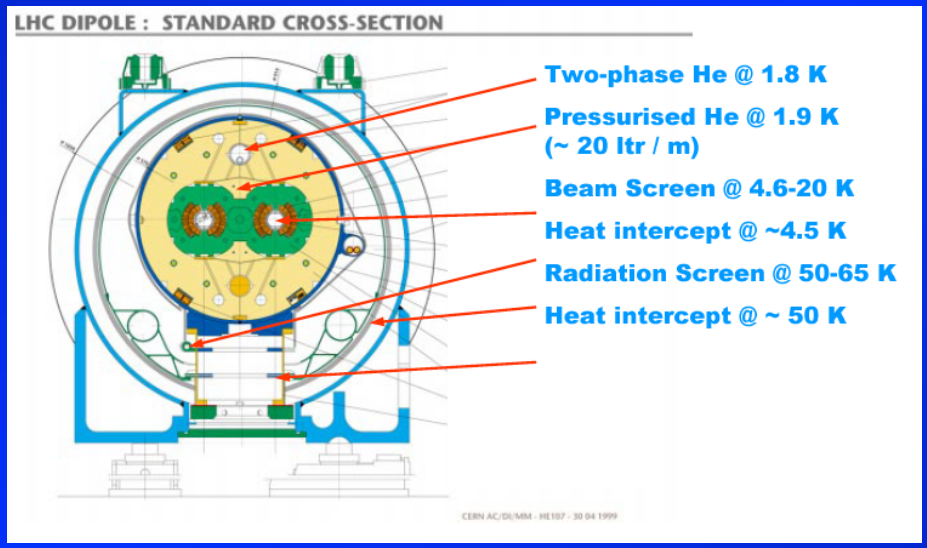
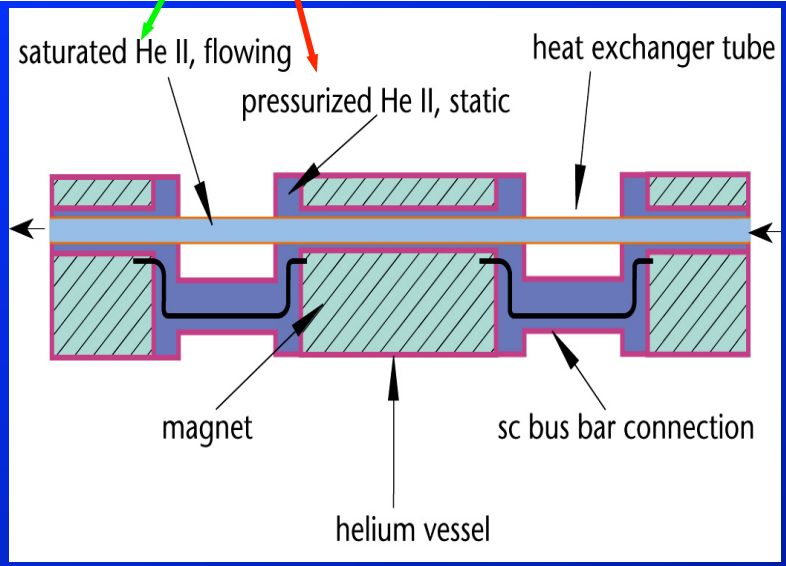


Magnet cooling scheme









Overall strategy

90ies
- The cryogenic team has always been responsible for the definition of the heat loads, RnD for innovative aspects, architecture for cooling and distribution, process selection

'01 - '06
- Commissioning of sub-systems were done one after each other, with performance assessment for all refrigerators and at least a type test of other sub-systems

'07 -
- The cryogenic system is operated transversally, from cooling capacity production to distribution and cooling of components (magnets, RF cavities, current leads)

Outline

- Introduction
- Cool-down
- Tuning
- Operation
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- Consolidations
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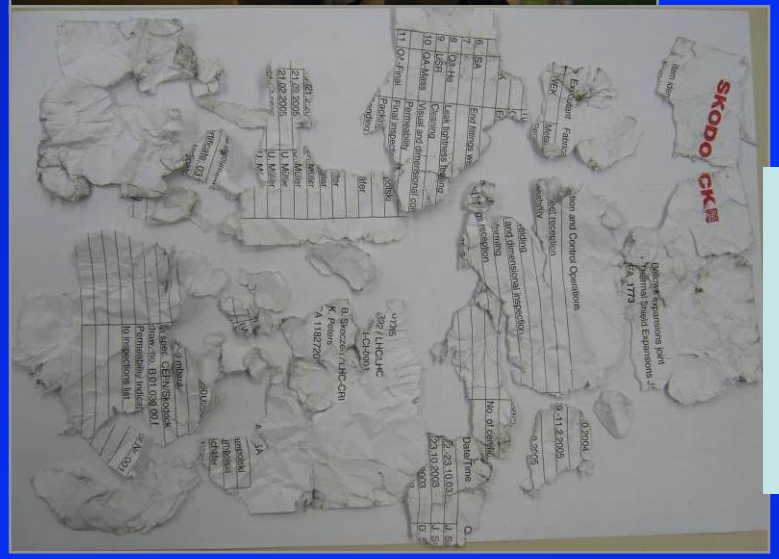
Flushing sectors before cool-down

Dust Debris
Kapton
Reports



And
possible
shorts in
diodes !

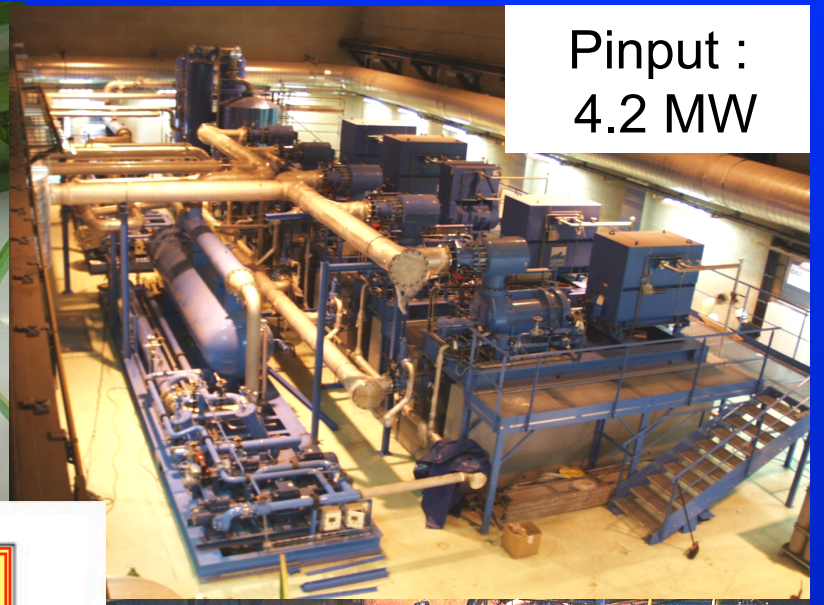
But the sooner the best !!!

Single sector cool-down sequence

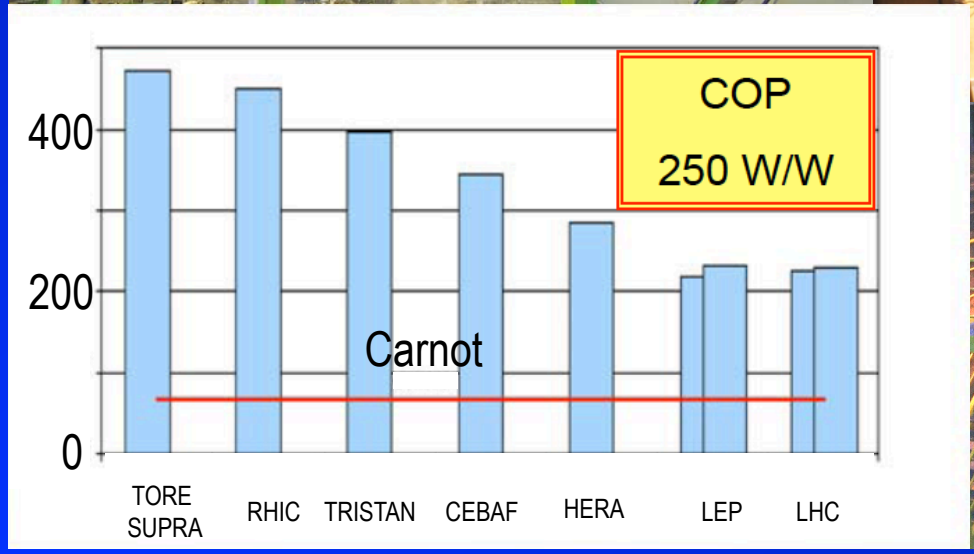
- From room temperature to 80K: Precooling with liquid nitrogen(LN2)
  4700 tons of material to be cooled, 1200 tons of LN2 (64 trucks of 20 tons)
  Three weeks for the first sectors, a bit more than two weeks now
- From 80K to 20K: Cooldown with Helium turbines
  Almost three weeks for the first sectors, one week now
- From 20K to 4.5K: Continued with He turbines
  Filling some 10 tons of helium in the machine at this stage
  One to three weeks for the first sector, three days now
- From 4.2K to 1.9K: Cold compressors (15 mbar)
  Two weeks (+) for the first sector, two days now

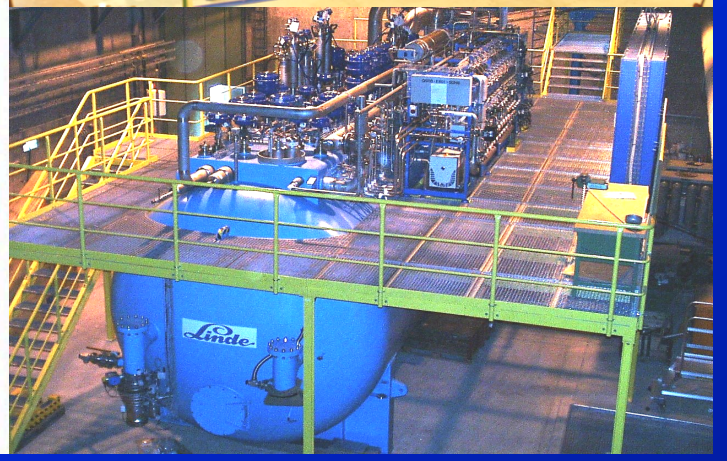
18 kW @ 4.5 K Refrigerators

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



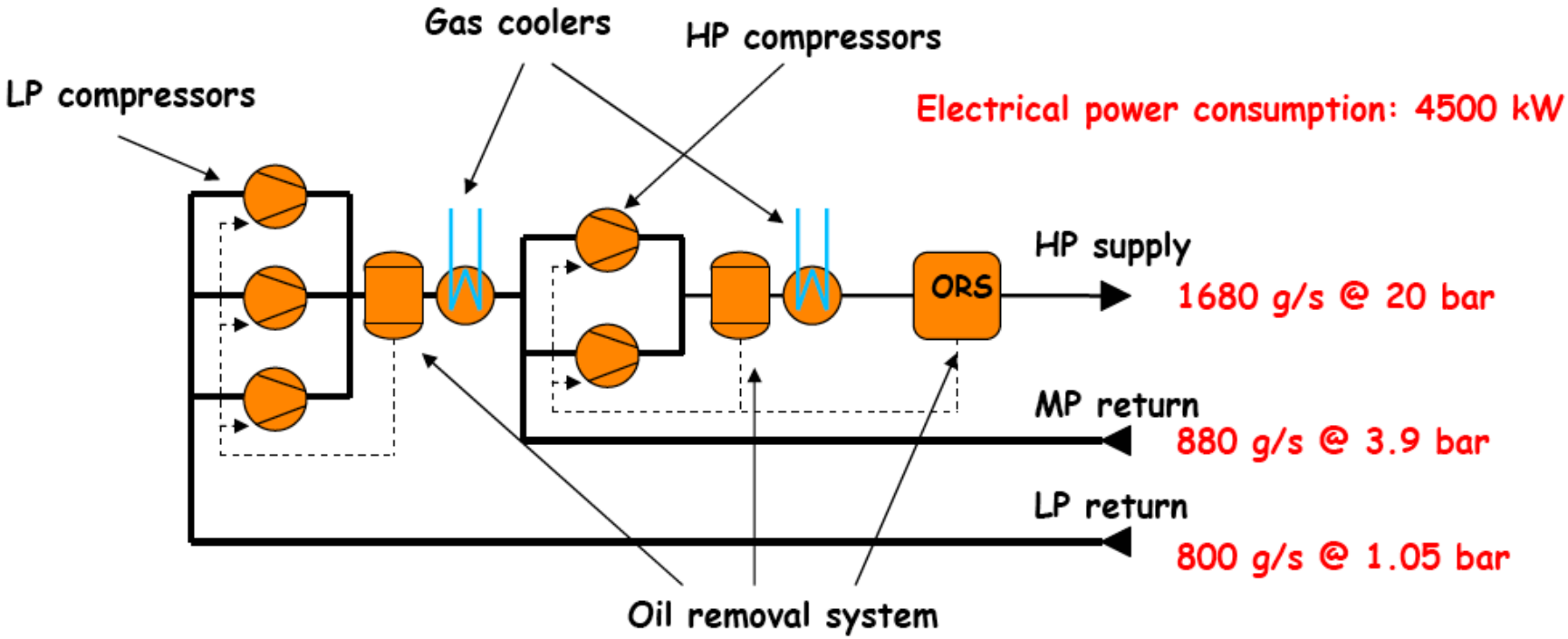
Pinput :
4.2 MW





LHC 18 kW @ 4.5 K Refrigerator

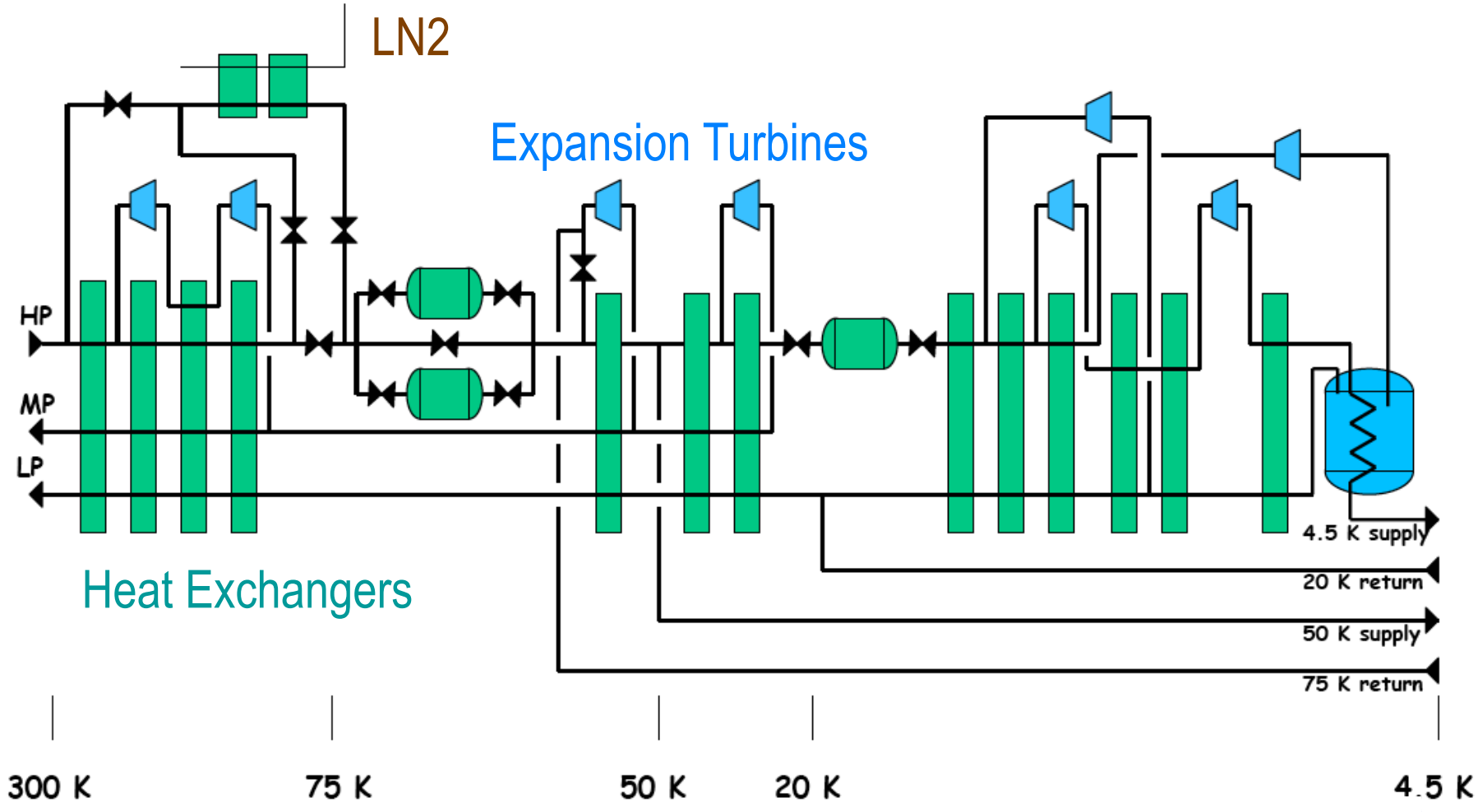
Compressor stations



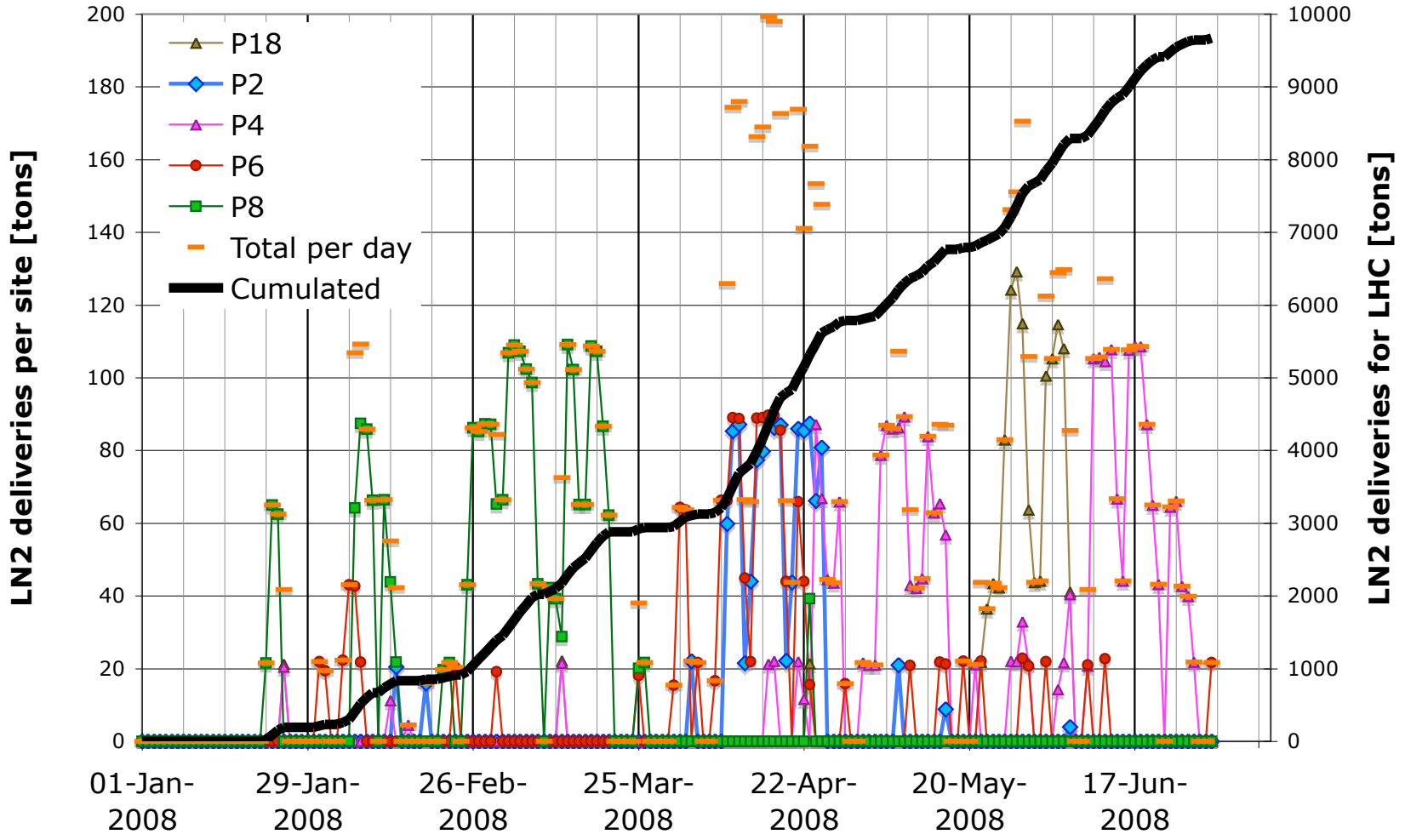
Identical installation for both suppliers, i.e. all new 4.5 K refrigerators

LHC 18 kW @ 4.5 K Refrigerator

Process cycle for Air Liquide



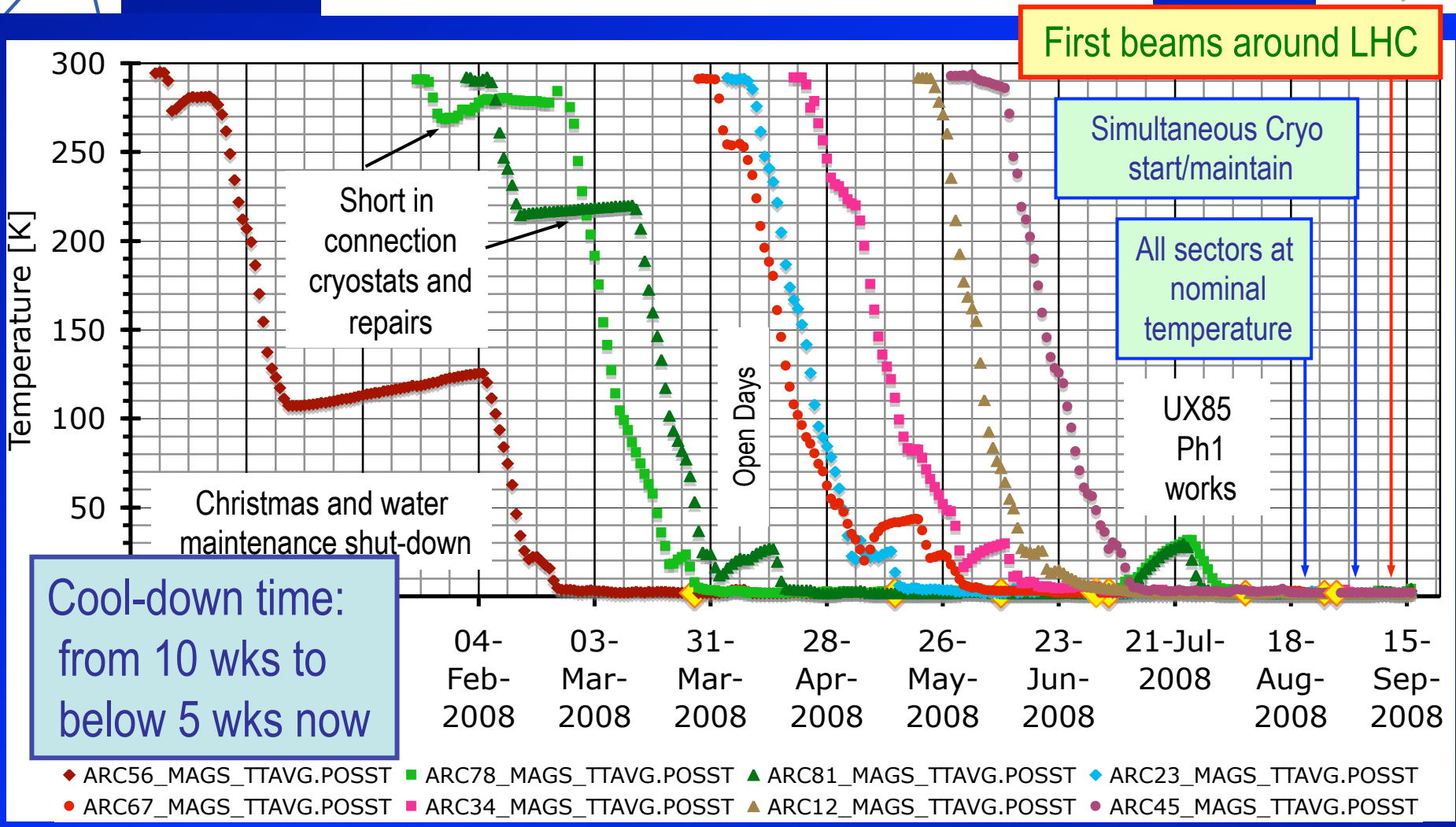
Pre-cooling to 80K with LN2



Heavy logistics: (so far from 6h to 22h, 6 days/week)

- 2008: 500 trucks (20 tons) for 7 sectors in 5 months
- 2008: 400 trucks (20 tons) for 5 sectors in 3 months

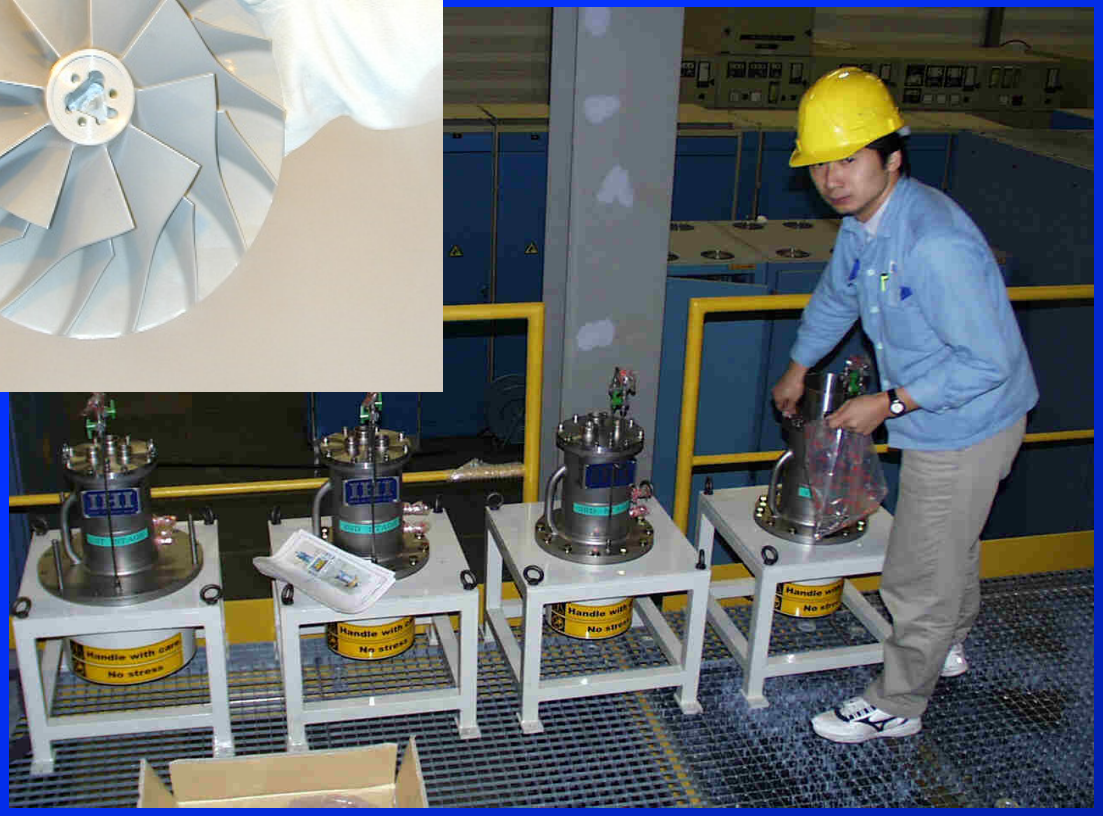
First cool-down of LHC sectors



Cool-down time: from 10 wks to below 5 wks now

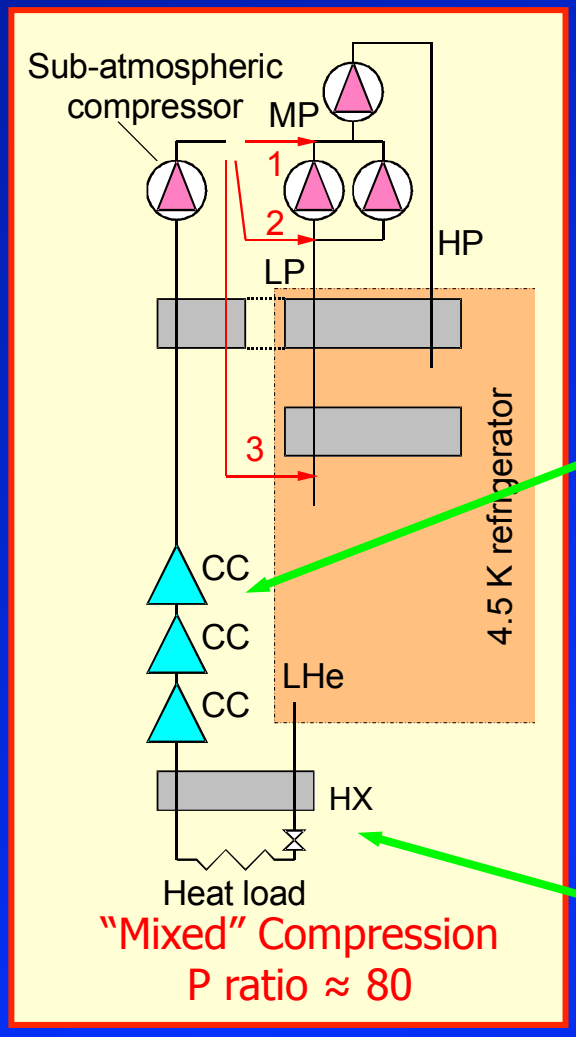
Cooling sectors + Cryo tuning + Powering activities

Hydrodynamic cold compressors for 1.8 K ref.

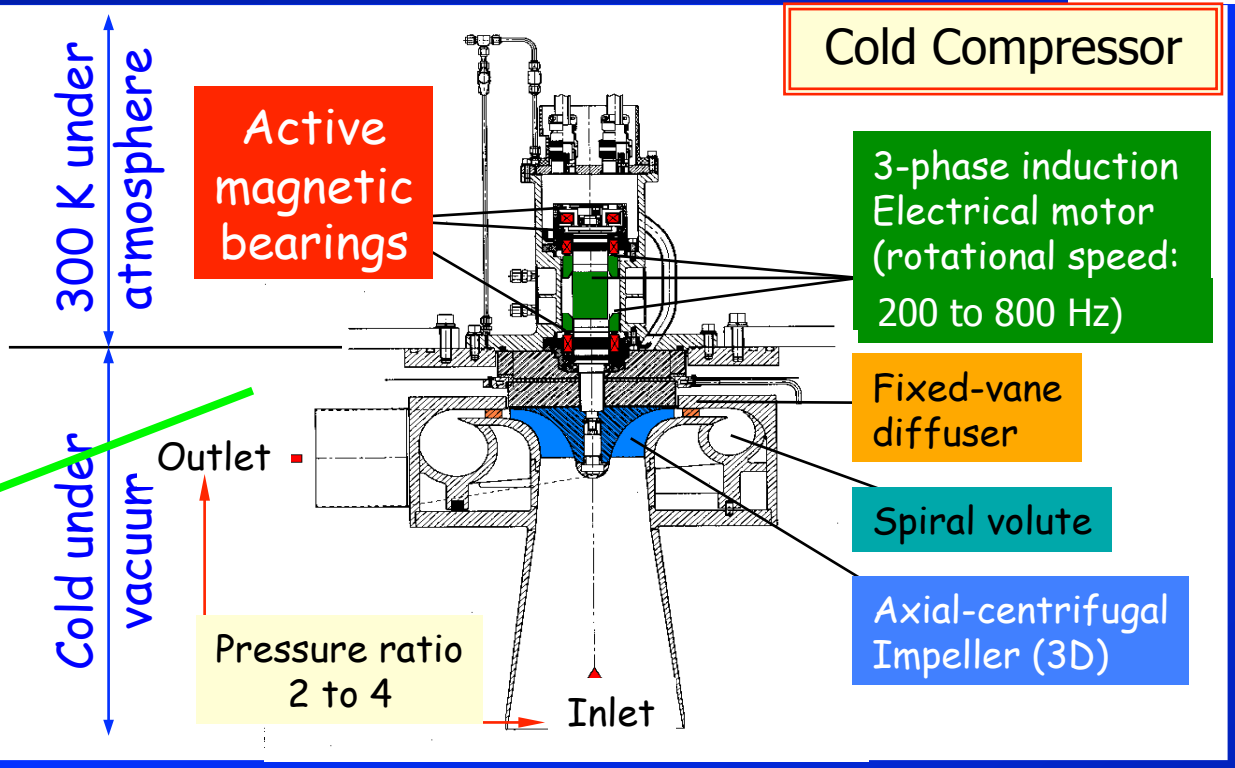


125 g/s GHe from 15 mbar with 4 stages

1.8 K cycle and specificities



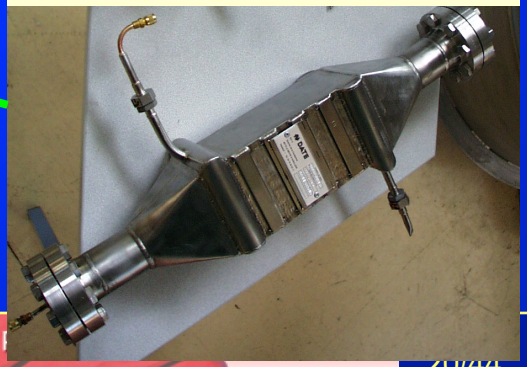
"Mixed" Compression
P ratio ≈ 80



Cold Compressor

- 3-phase induction Electrical motor (rotational speed: 200 to 800 Hz)
- Fixed-vane diffuser
- Spiral volute
- Axial-centrifugal Impeller (3D)

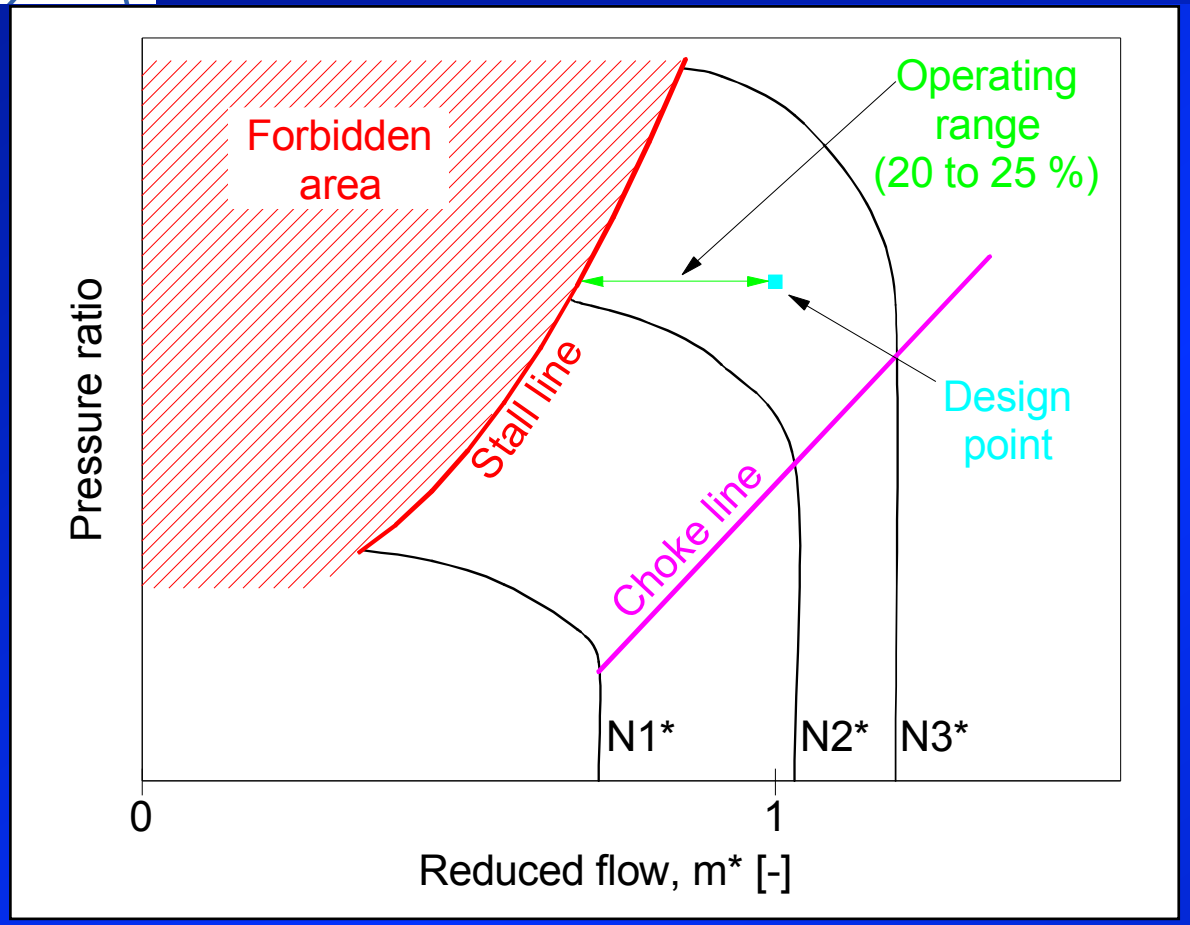
Stainless Steel Plate



CC:
- 3D wheels
- Bearings (300K)

HX:
- Very Low Pressure

Cold compressors



Definition of reduced parameters:

$$m^* = \frac{m}{m_0} \cdot \sqrt{\frac{Tin}{Tin_0}} \cdot \frac{Pin_0}{Pin}$$

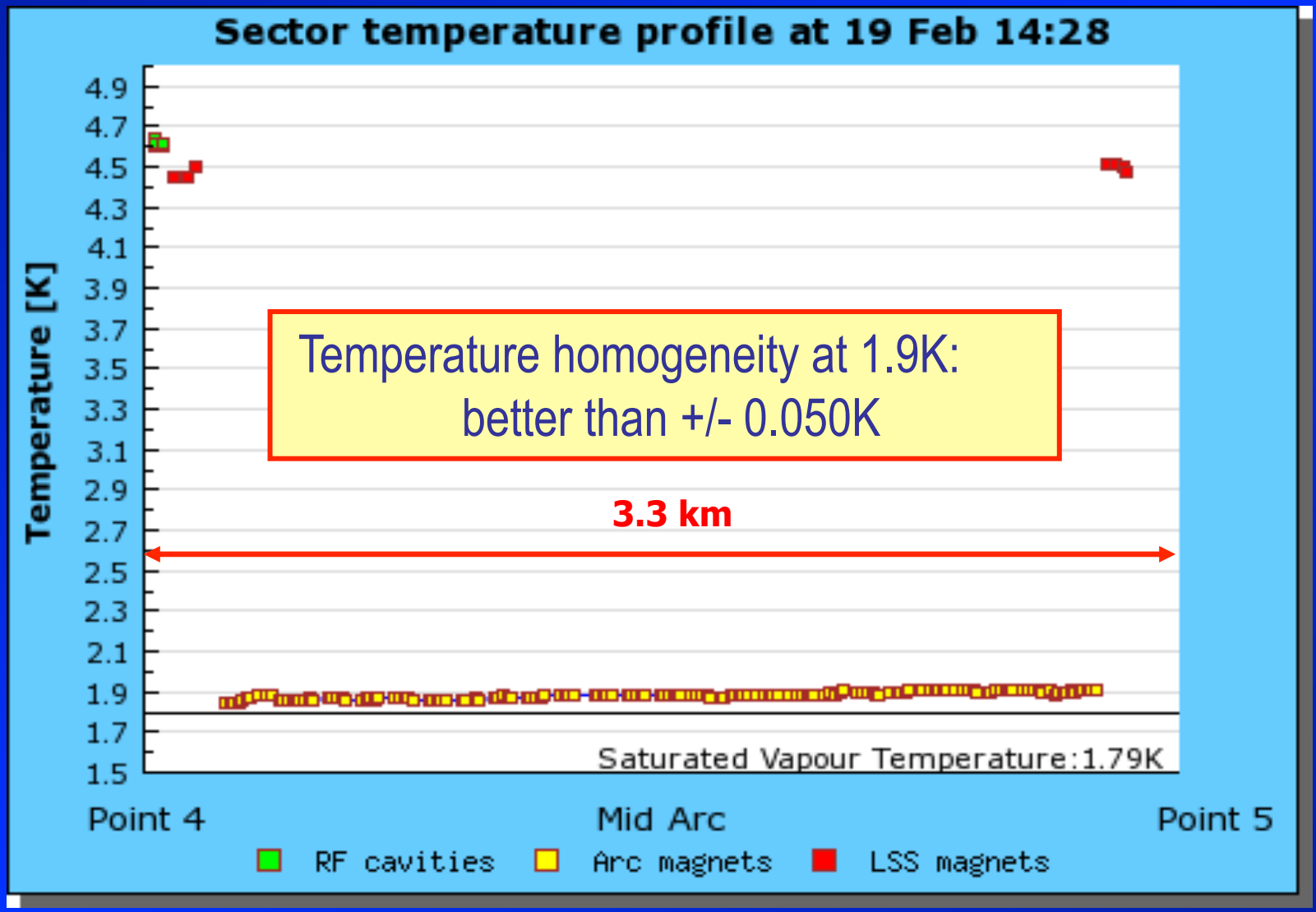
and

$$N^* = \frac{N}{N_0} \cdot \sqrt{\frac{Tin_0}{Tin}}$$

m: mass-flow
Tin: Inlet temperature
Pin: Inlet pressure
N: Rotational speed
Subscript 0: Design condition

Complex operation of hydro-dynamic compressor:
- high rotational speed: up to 800 Hz,
- reduced operation range at constant pressure ratio.

Typical LHC sector temperature profile



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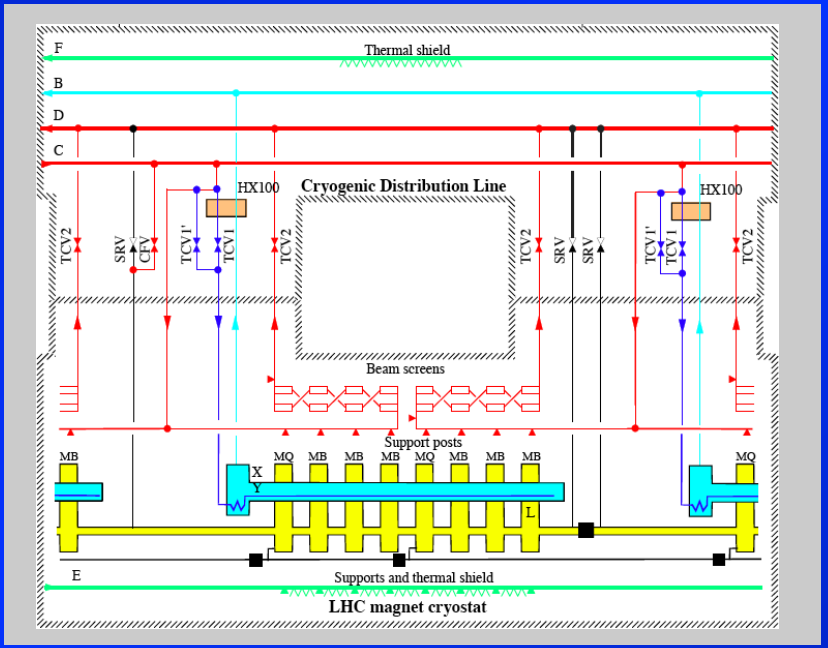
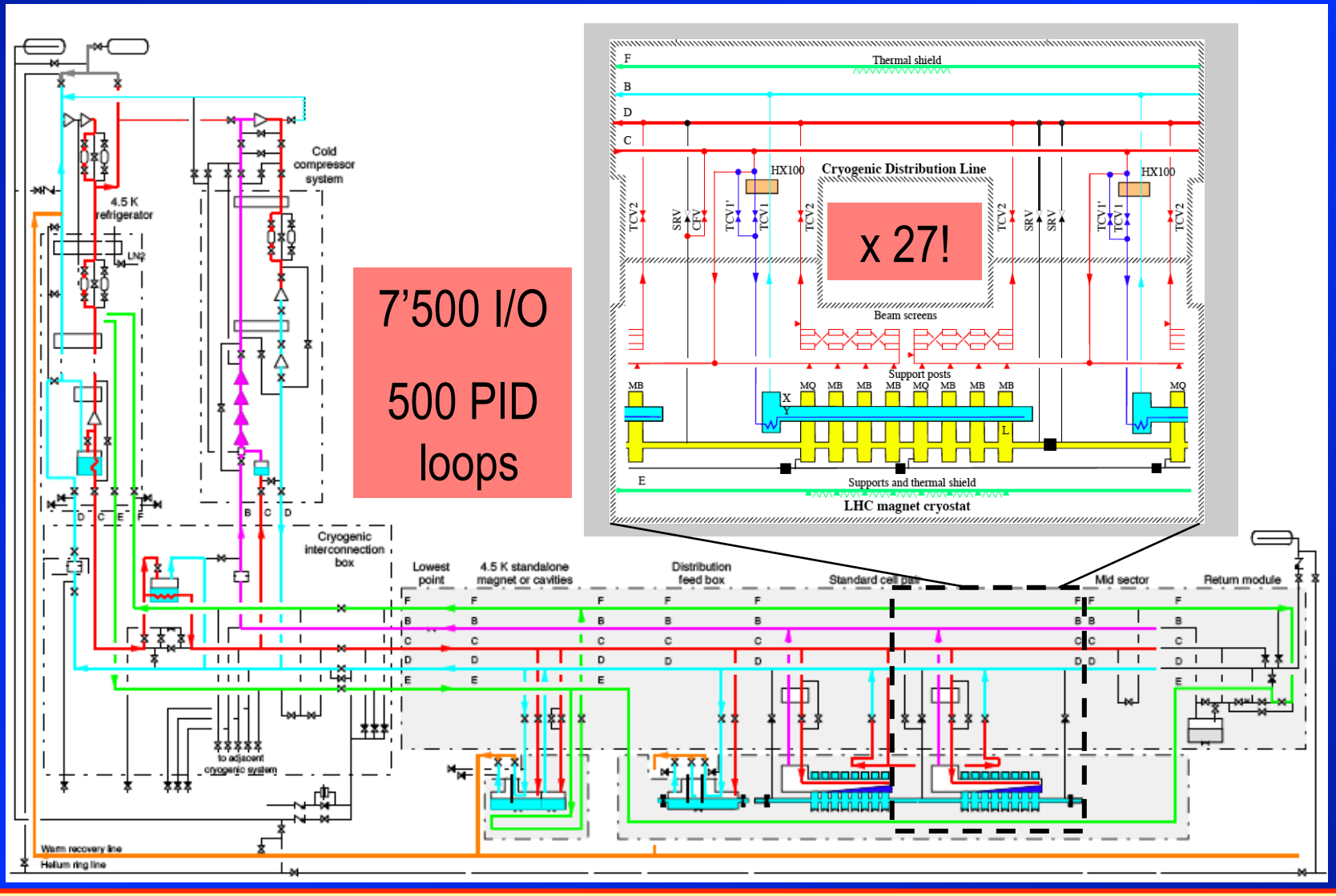
Tuning one of 8 LHC sectors



From LHC Magnet String test

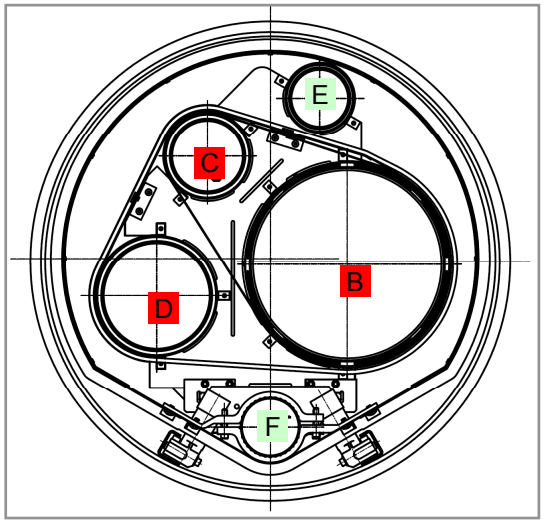
Tuning one of 8 LHC sectors

LHC Cryo-OP



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

An idea of time constants !



	Diam. [mm]	Volume [m3]
C	100	25.9
D	150	58.3
B	250	162.0

$$m' = Ro \cdot V \cdot S$$

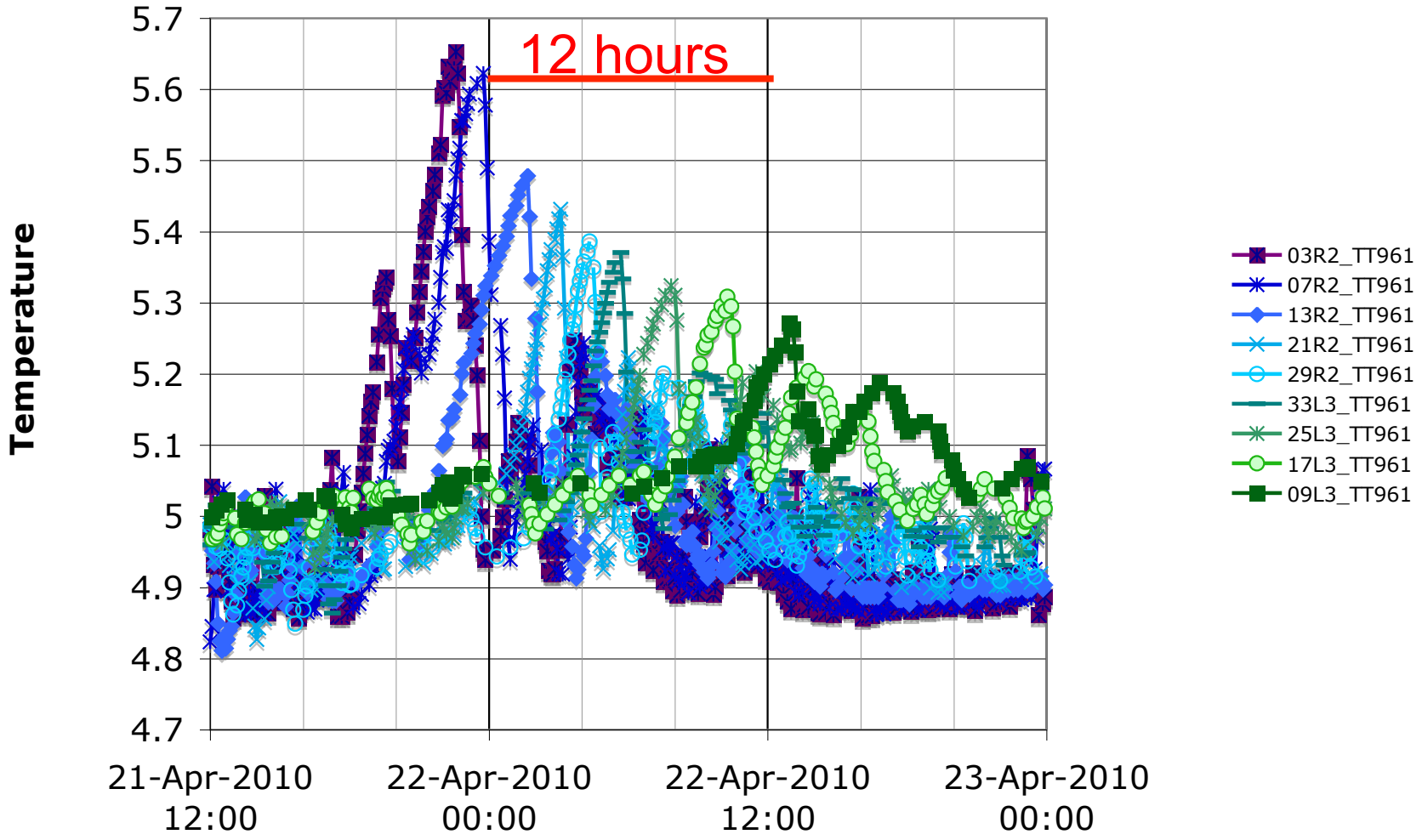
From QUI to QRL_RM

≈ 3300m

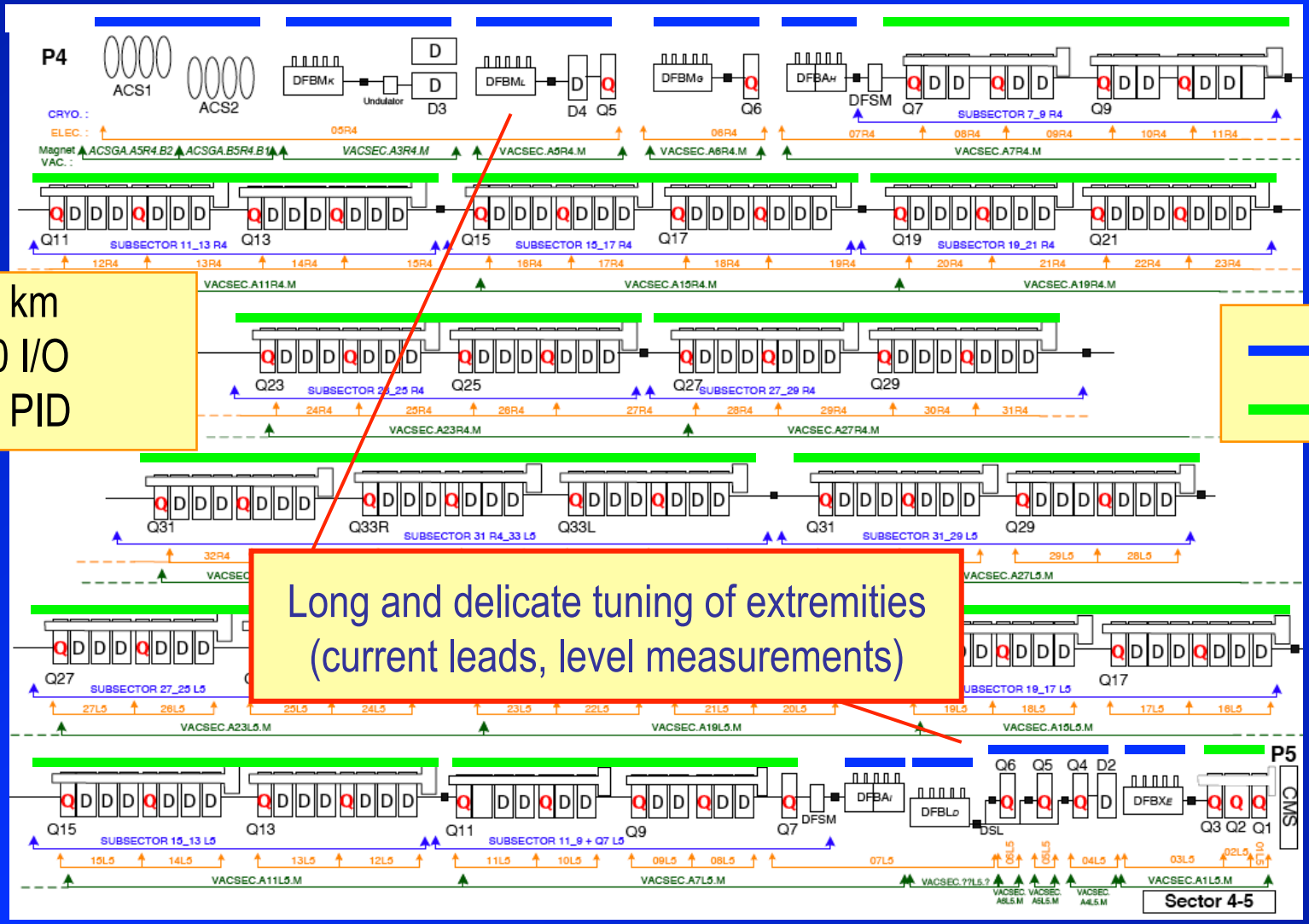
	Density [g/l]	Mass [kg]	Time flight
C [3B, 5K]	118	3058	5 - 12h
D [1.3, 8K]	8	467	1 - 4h
B [0.015, 4K]	0.18	29	4 - 12'

Changes on « supply conditions » may have an effect some hours later …

Warm bump propagation



LHC Sector 4-5 scheme



3.3 km
5000 I/O
400 PID

Long and delicate tuning of extremities
(current leads, level measurements)

4.5 K
1.9 K

LHC Cryogenic commissioning

- 2 K magnets in ARC
  - LT/EH at return modules
  - LT of SSS in ARC
  - EH at lowest point
  - EH of cold masses & beam screens
  - ⇒ Possible pump-down and cool-down of magnets, including tests with cold compressors

Principle set-up in 2007, foreseen during the (target =two) weeks after ARC magnets @ 4.5K,

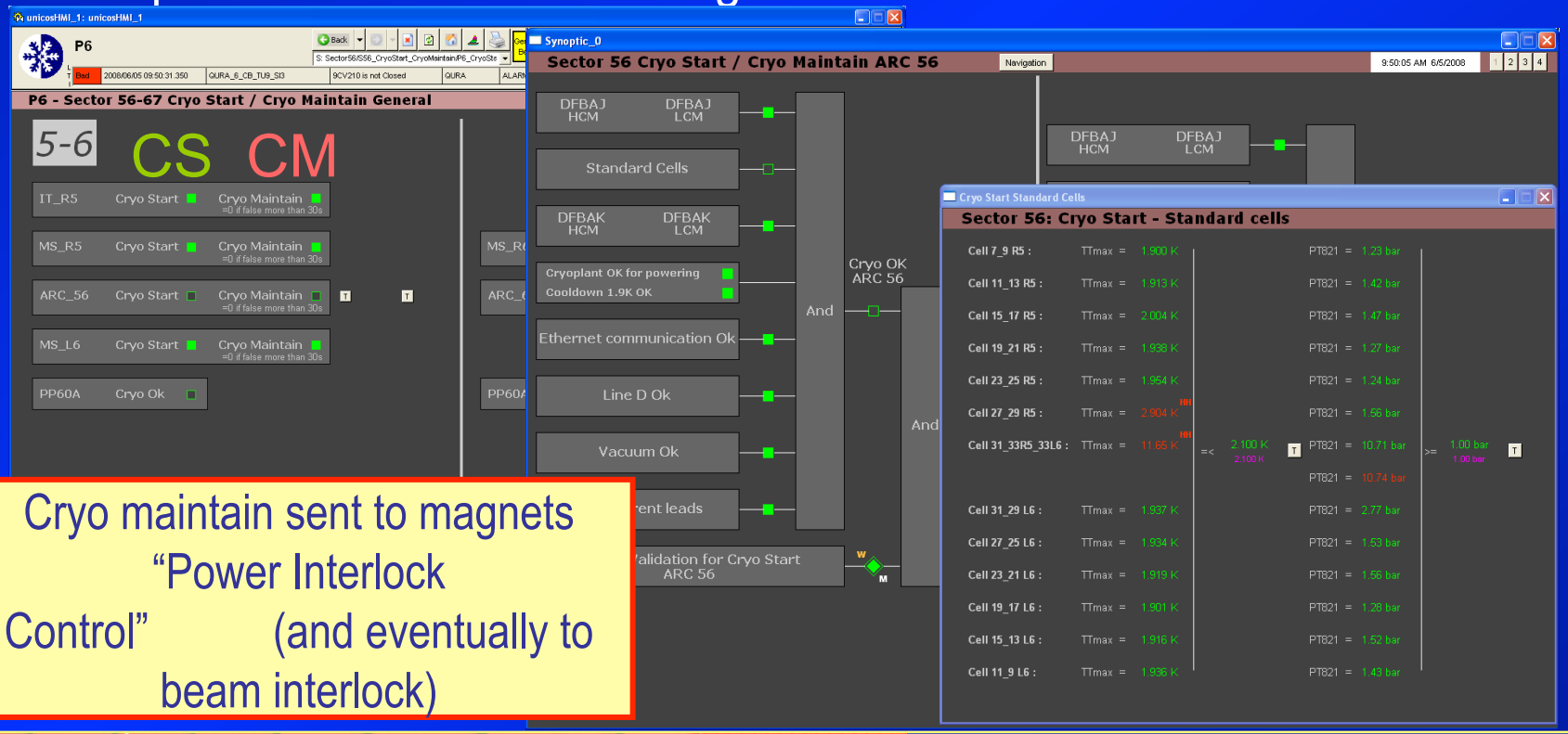
- 6 weeks required per sector in 2008
- 2 weeks OK June 2009 for 1st time
- < 1 week per sector now

- 4.5K stand-alone magnets
  - Cool-down to < 10K
  - Adjust instrumentation LT/EH
  - Control LHe at 50%
  - ⇒ Fill-up and boil-off to determine appropriate set-point
- Electrical Feed Boxes (DFB's)
  - Cool-down shield (if any)
  - Cool-down leads at 150K, then cool-down phase separator
  - Adjust instrumentation LT/EH
  - Control LHe at nominal
  - ⇒ Fill-up and boil-off to determine appropriate set-point
  - ⇒ Tuning of Temp. control loops

Cryo conditions for powering

Cryo Start: set of conditions to allow powering of concerned sub-sector (rather strict = good stability of process)

Cryo Maintain: Few important conditions checking integrity of HW, with slow power abort in case this signal is lost



Cryo maintain sent to magnets "Power Interlock Control" (and eventually to beam interlock)

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Operation structure & approach

Cool-down
Tuning

- Per site, one experienced engineer to guide a local team of operators, with help of support teams (instrumentation, experts, controls)

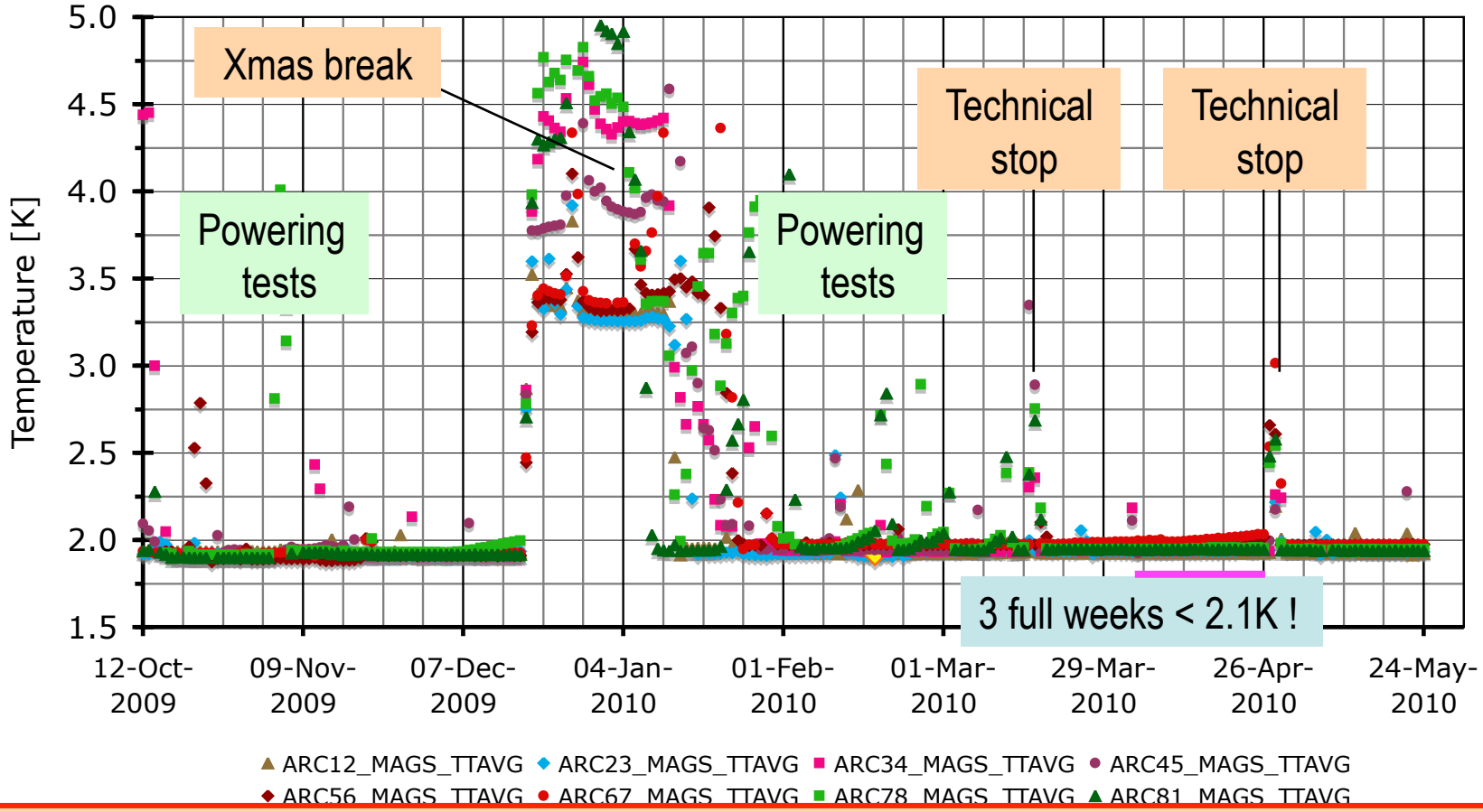
- For machine controls (temperature, level, pressure), basic interlocks and simple PID loops with generic tools for fast orders, now completed with automated sequences

Once experienced

- Since 2009, one operator in shift 24h/7d, more transverse structure site/CCC, procedures

Stability of temperature, 8 sectors

Getting closer to stable and "longer" periods below 2K

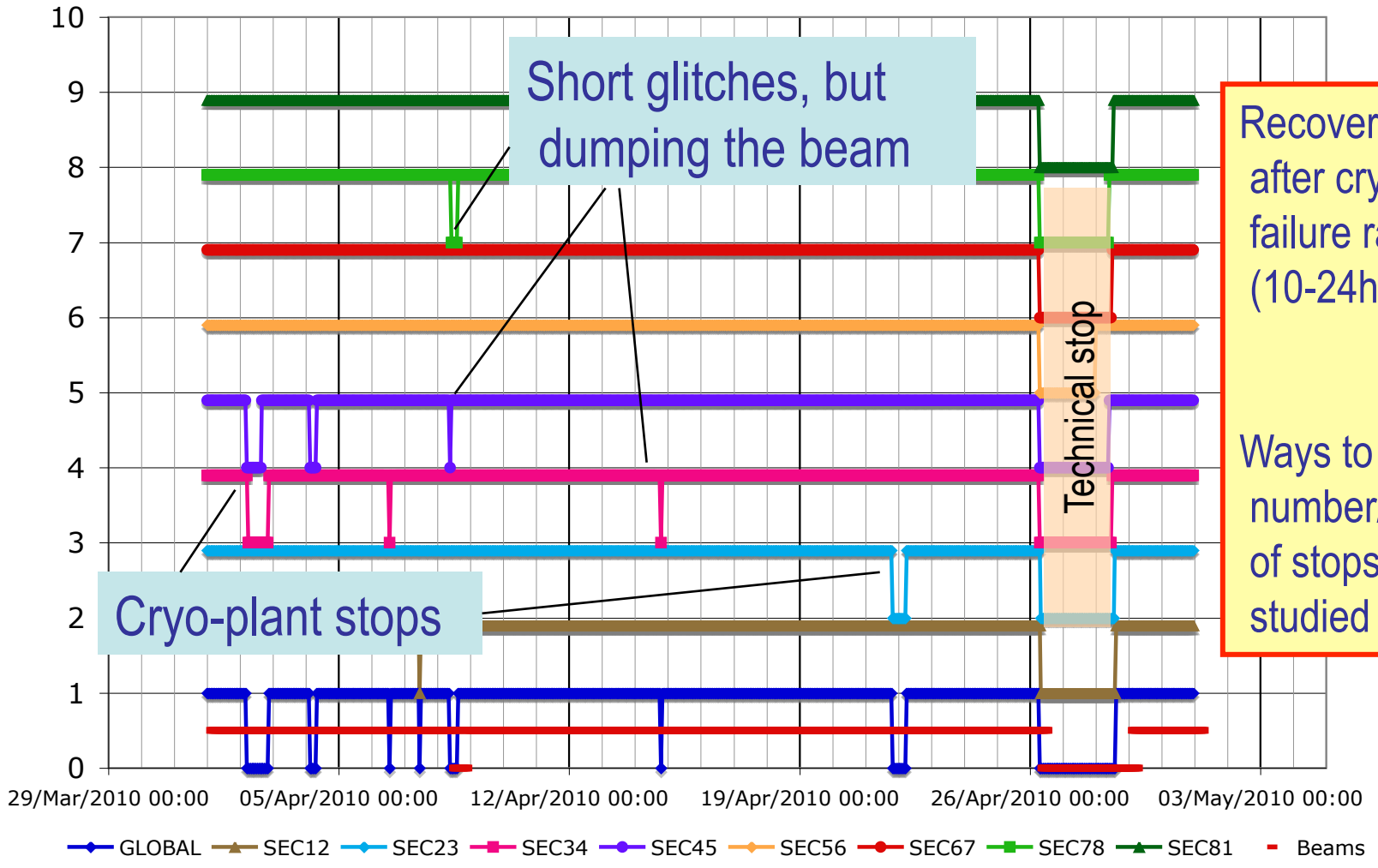


Terminating efforts to get air leak tight sub-atmospheric circuits (last one!)

Readiness for powering and beams

April 2010

(single stops < 10min not yet reported here)



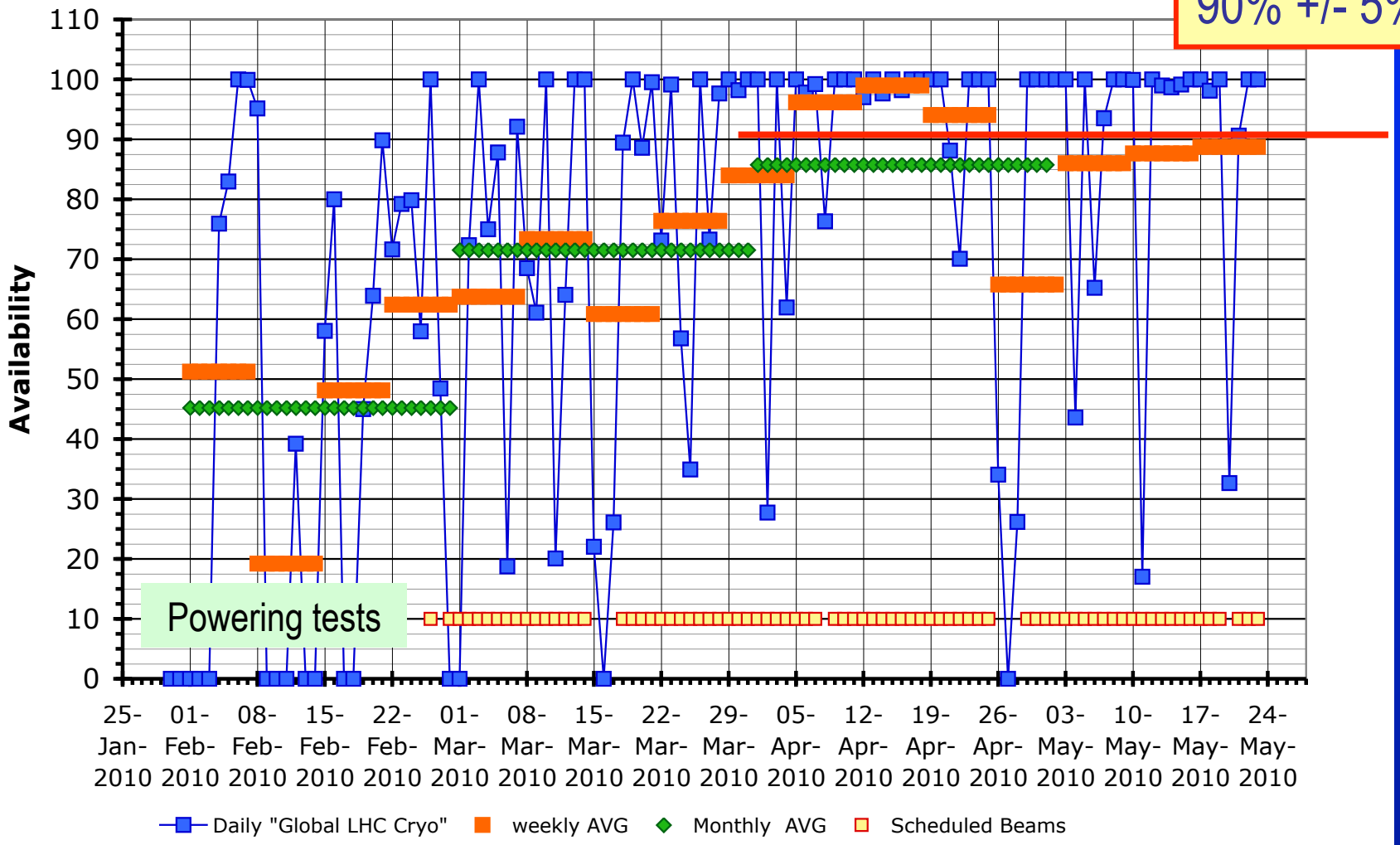
Recovery time after cryo-plant failure rather long (10-24hs)

Ways to improve number/duration of stops to be studied

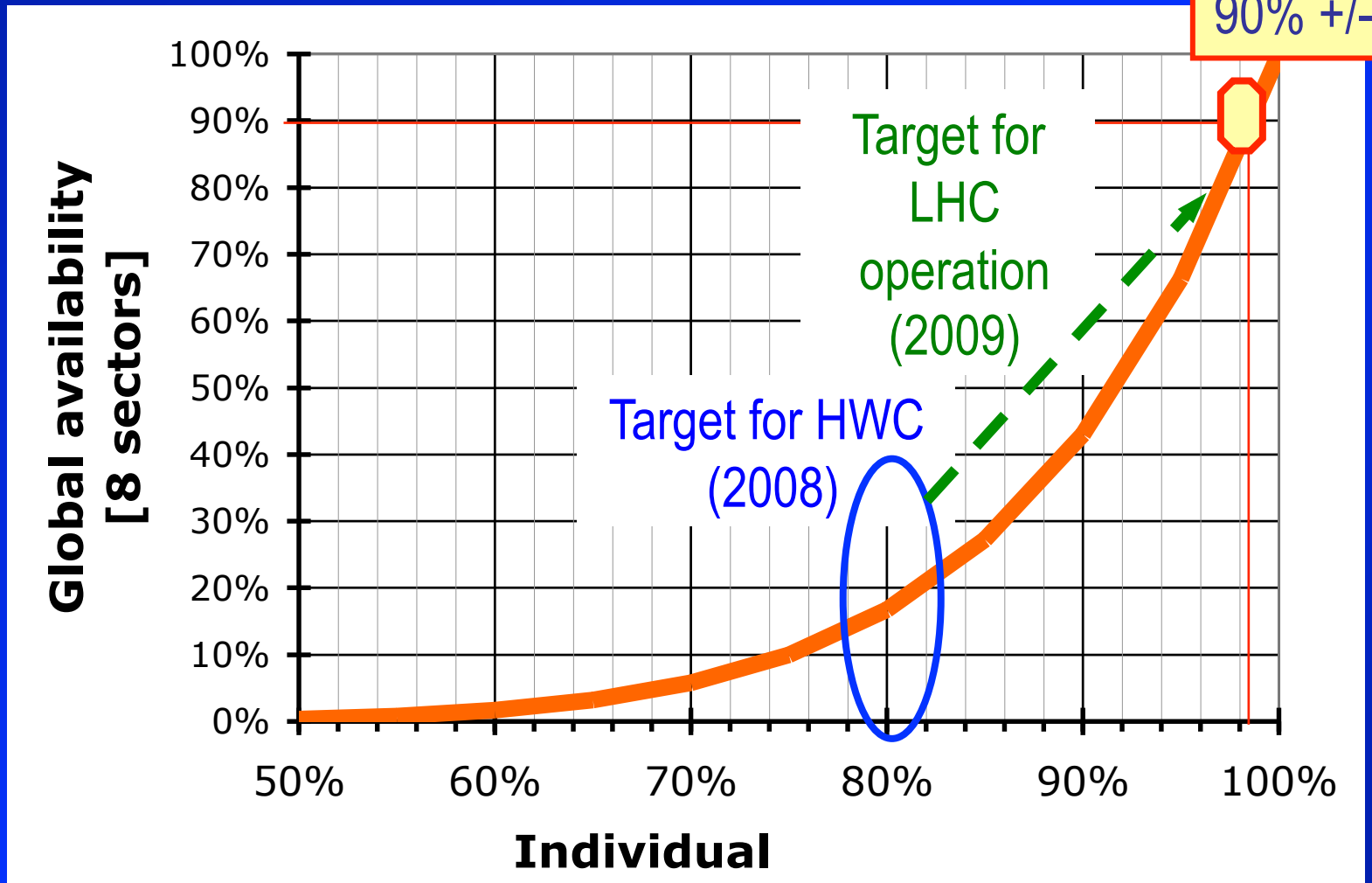
Availability

Based on LHC_Global_CryoMaintain signal per unit of time

90% +/- 5%



Availability



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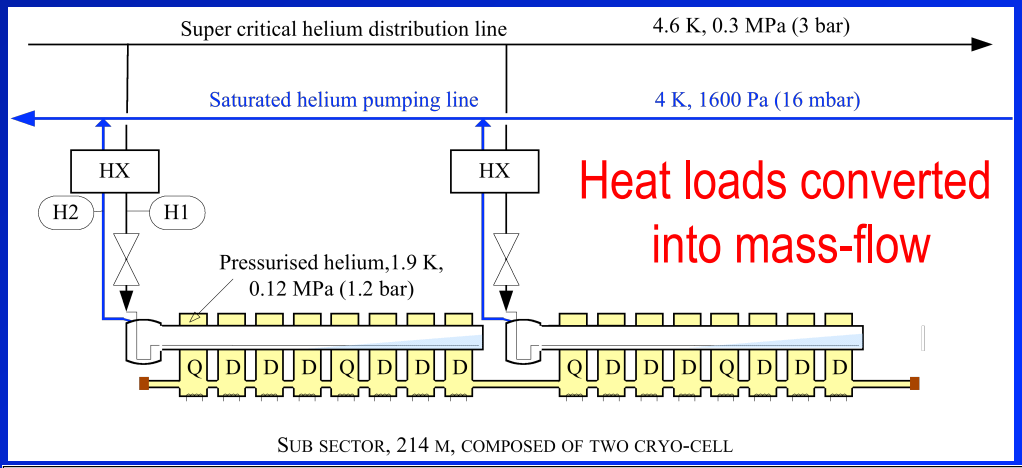
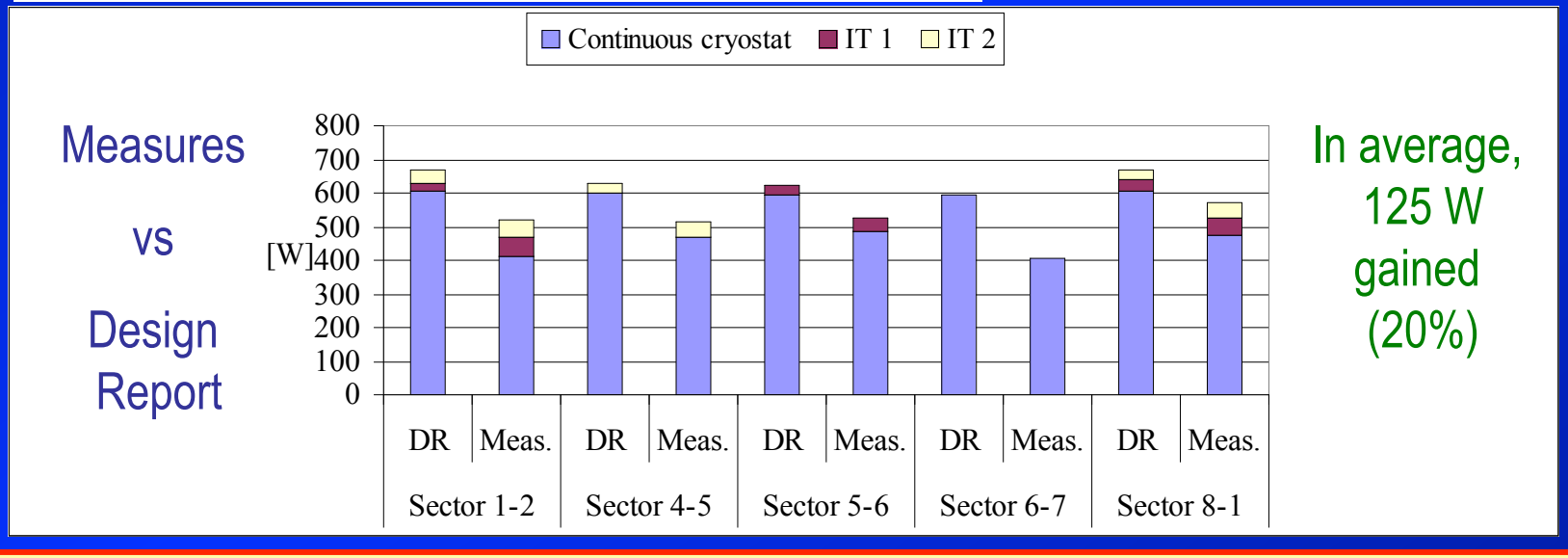
Static heat leaks measurements



SUB SECTOR, 214 M, COMPOSED OF TWO CRYO-CELL

Heat loads converted into mass-flow

Measurement campaign on 5 sectors, Autumn 2008

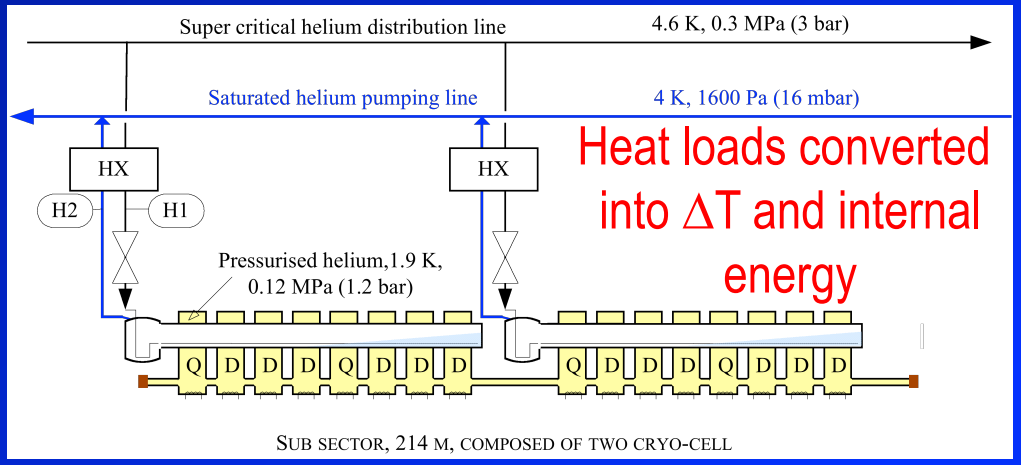


Measures vs Design Report

In average, 125 W gained (20%)

Confirmation of valid design, fabrication, installation and quality control

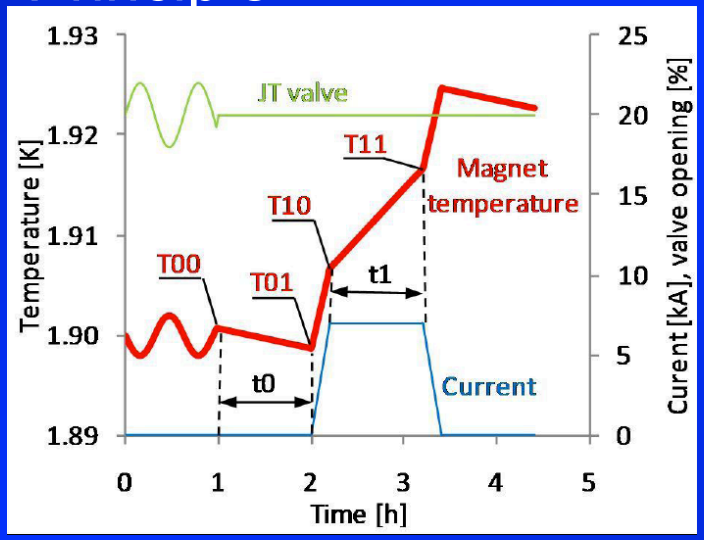
Calorimetry, principle



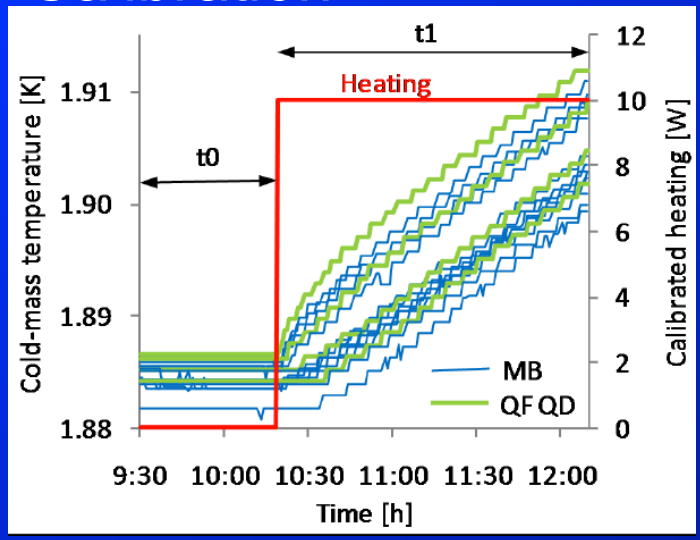
Heat loads converted into ΔT and internal energy

Measurement campaign on 5 sectors, Autumn 2008

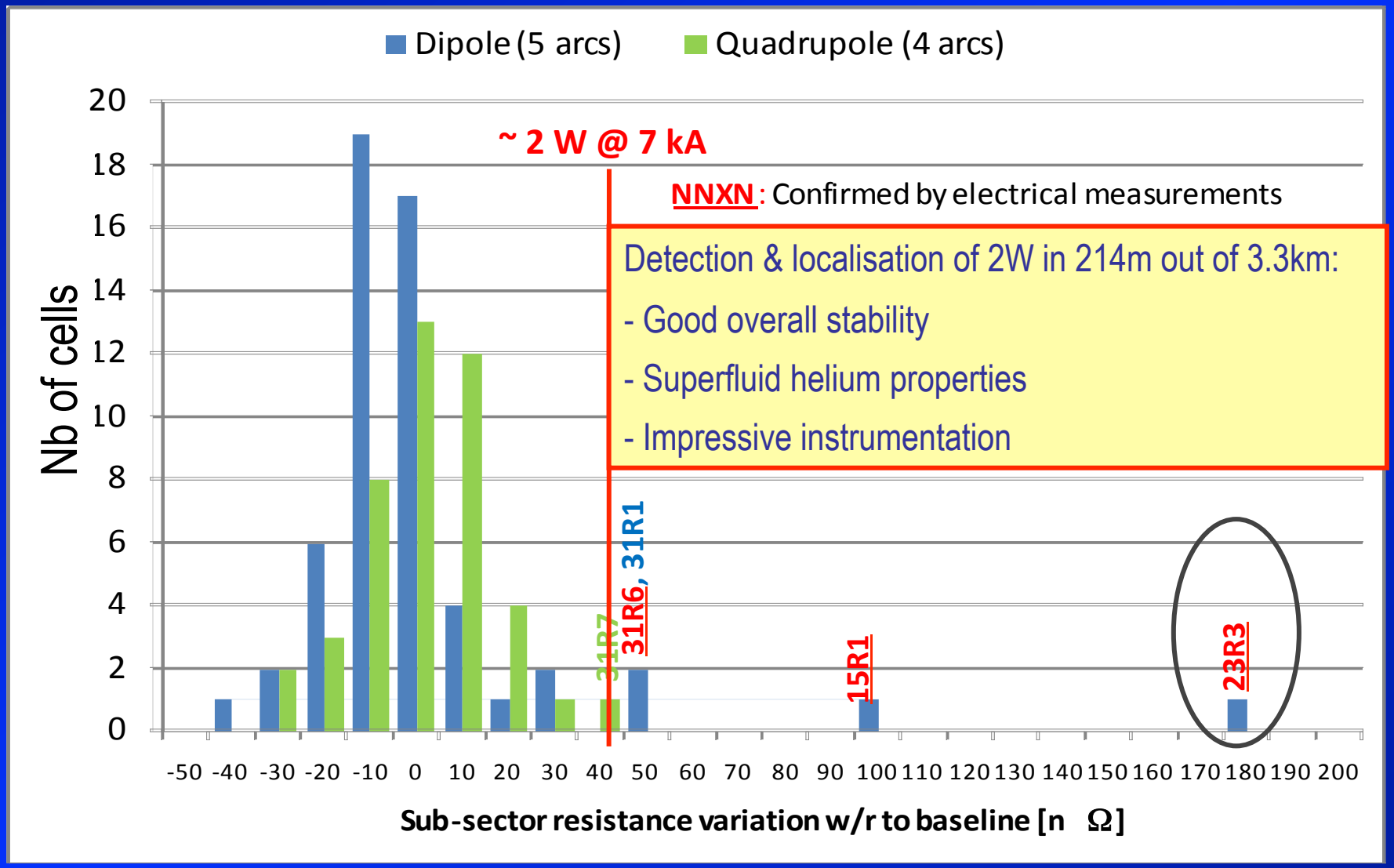
Principle



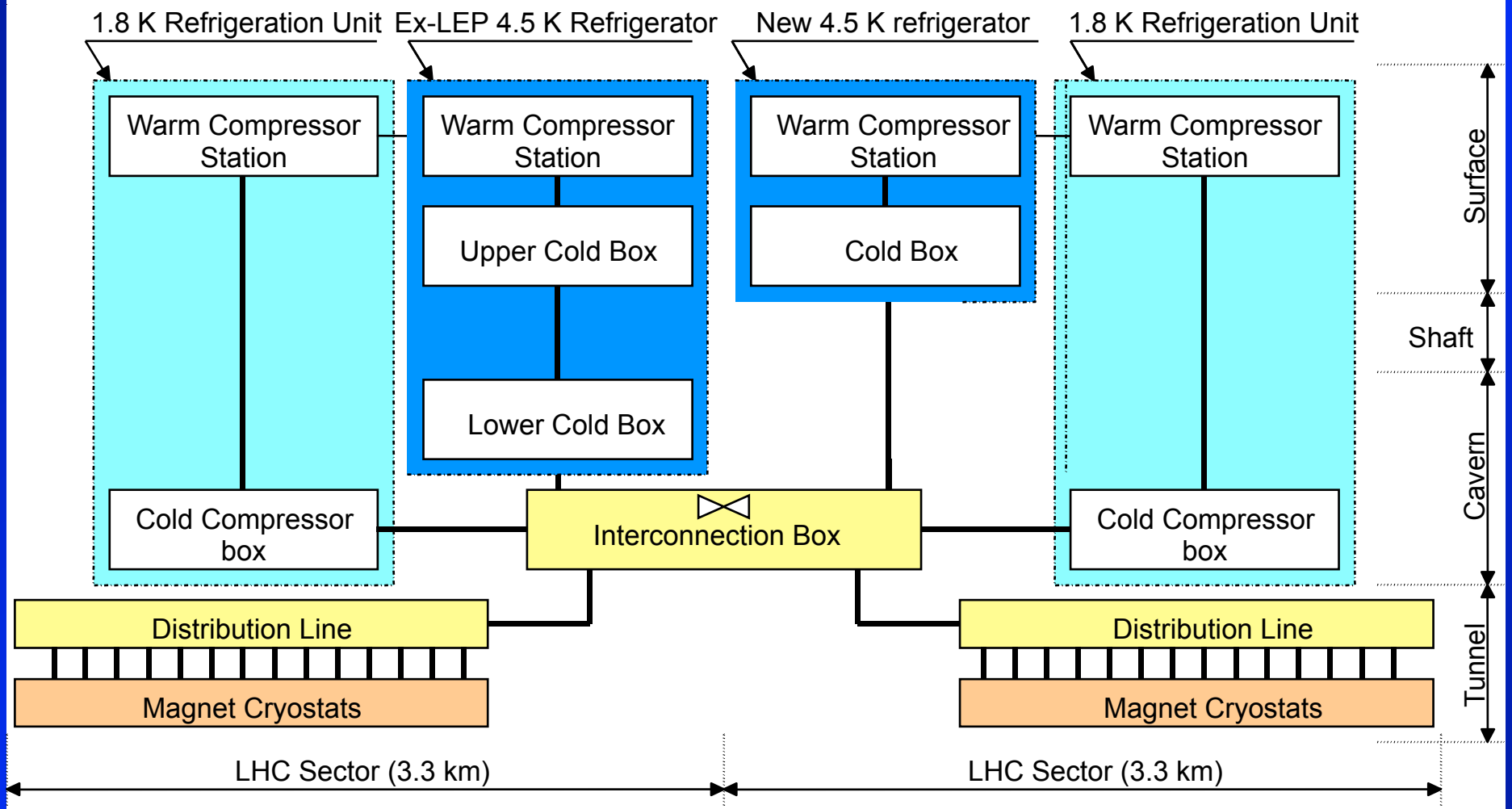
Calibration



Calorimetry, results



One cryoplant for two sectors

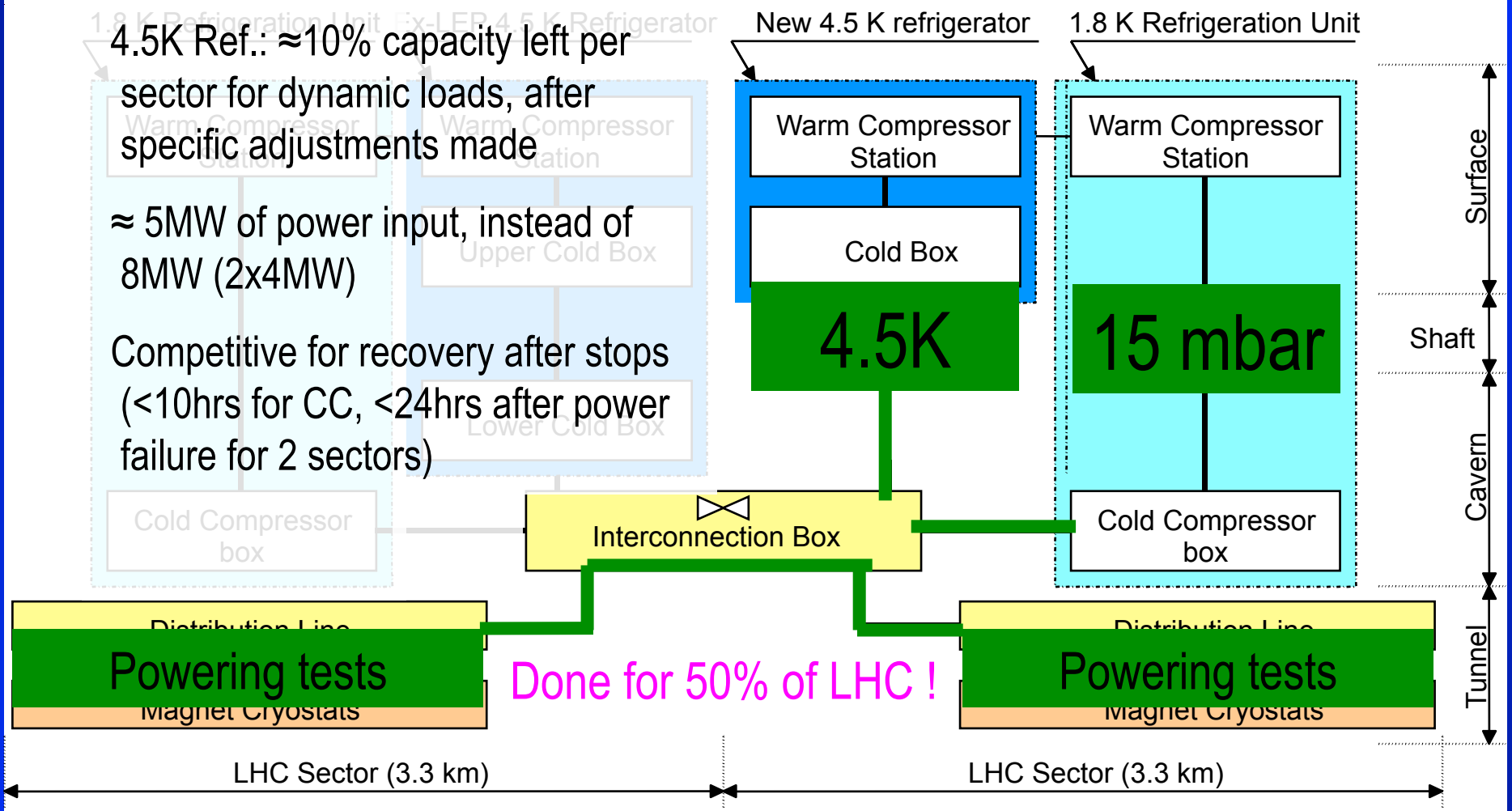


One cryoplant for two sectors

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

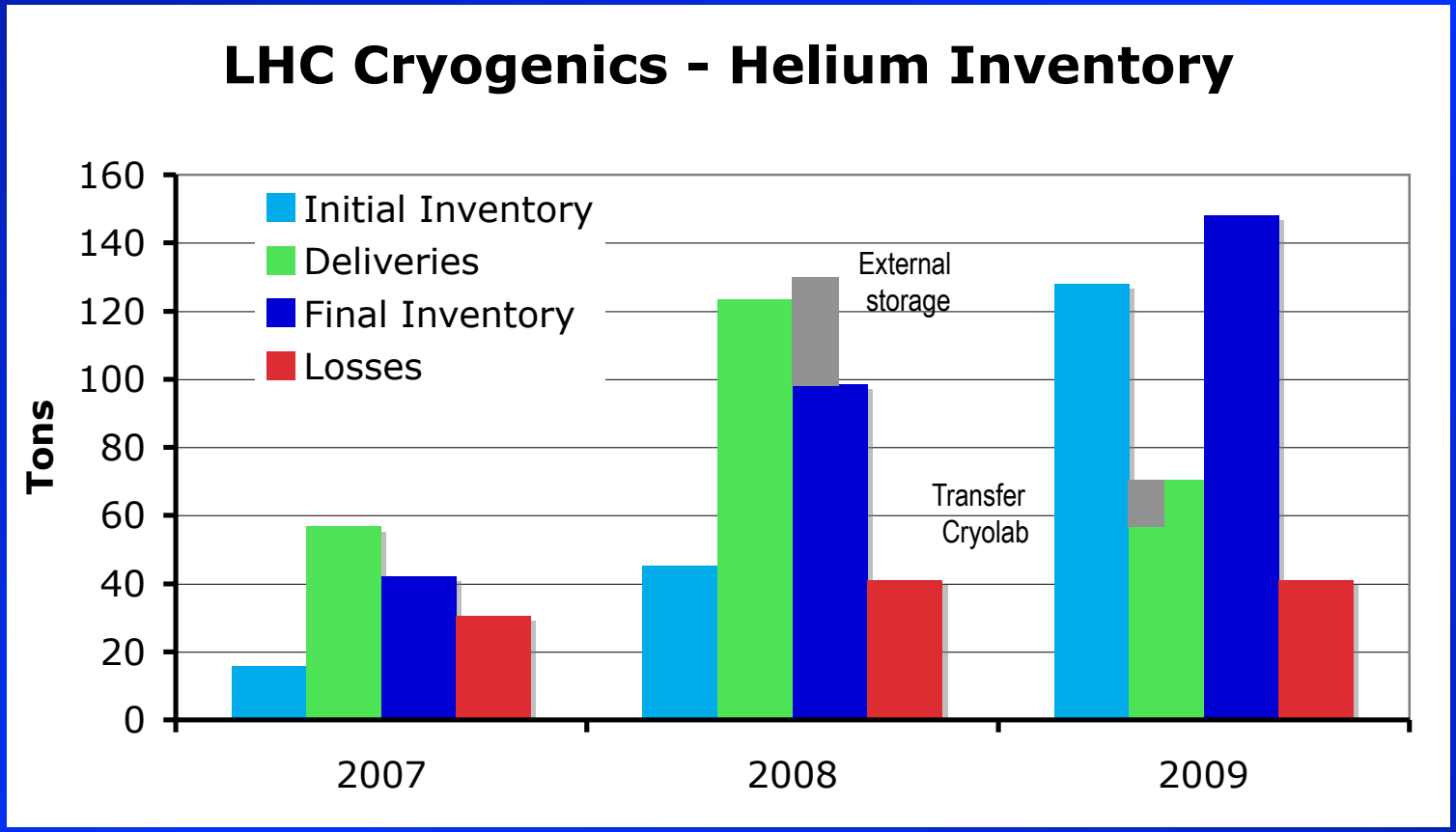
≈ 5MW of power input, instead of 8MW (2x4MW)

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



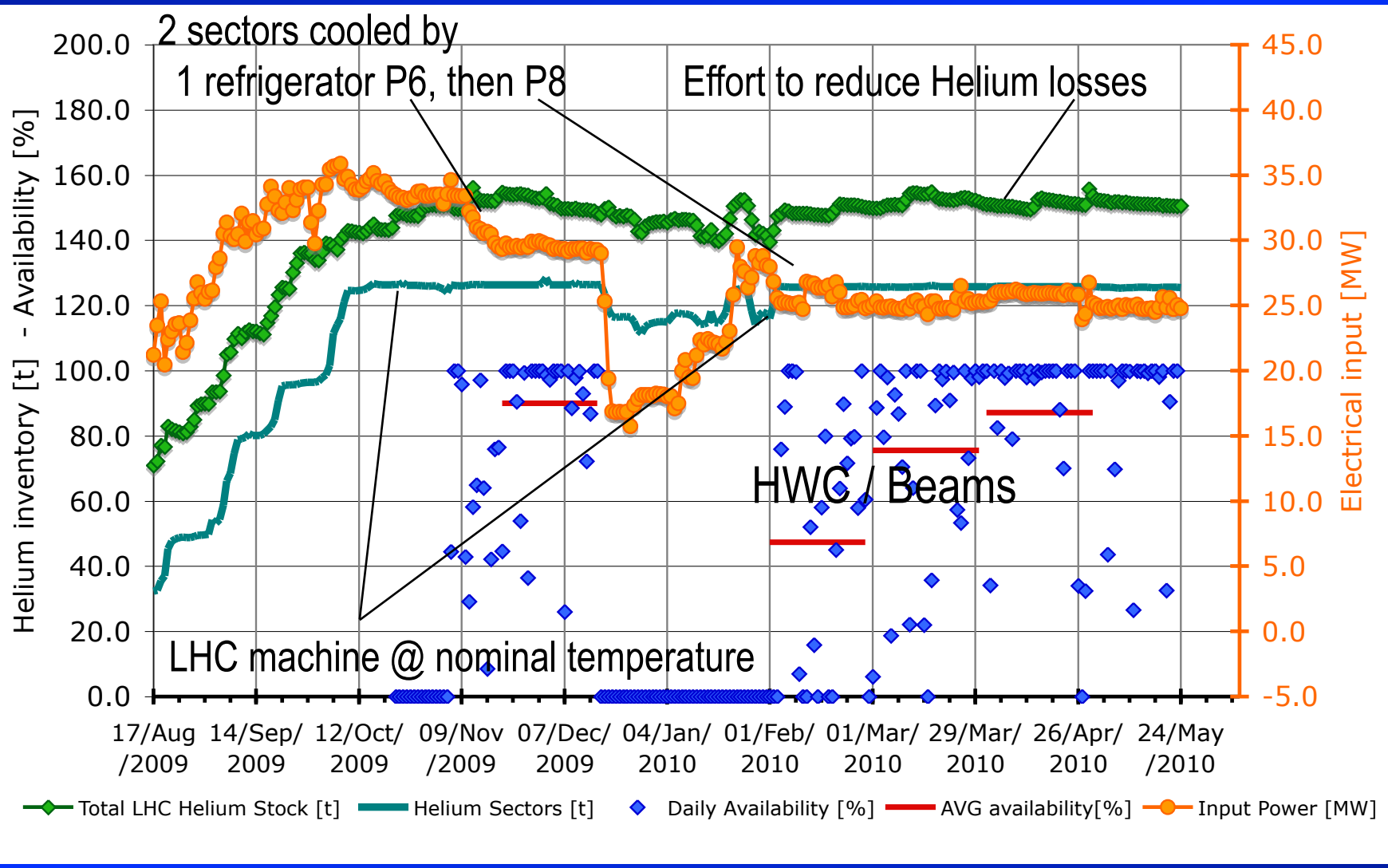
Not valid for large transients, but an interesting feature for low beam loads, or validated fall-back scenario if serious problems with a refrigerator

Follow-up of Helium inventory



Around 30% yearly losses,
with efforts to identify and treat dominant effects

Global performance monitoring



Outline

- Introduction
- Cool-down
- Tuning
- Operation
- Nice features !
- Consolidations
- Summary

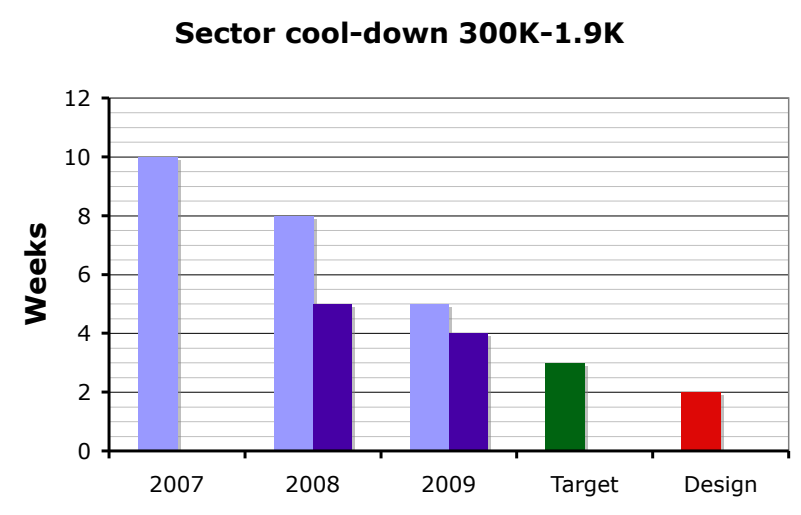
Consolidations

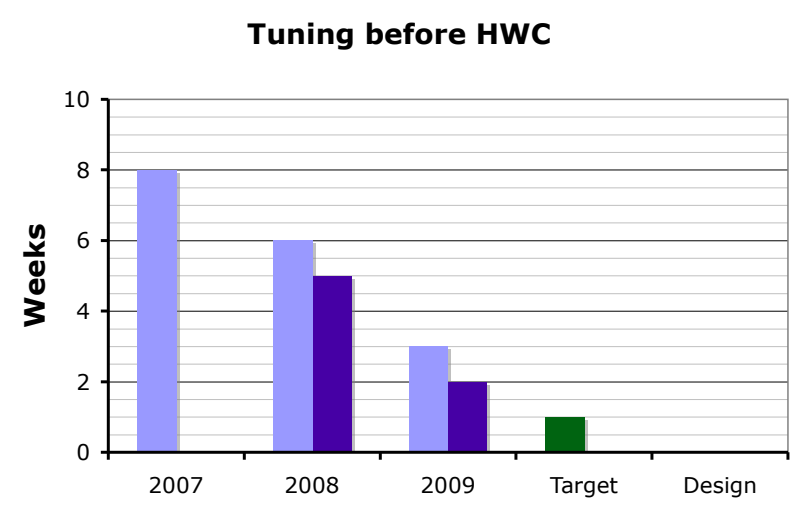
- Done before beams:
  - Electrical feedboxes: condensation, valves (continued)
  - Cryogenic control valve plugs (10% most critical)
  - Cryogenic instrumentation capillary for some magnets (80%)
  - Software simplification and tuning
- Launched, for increased operational reactivity:
  - Liquid helium storage capacity, to reach 110% of inventory
  - Critical spares (screw compressor casings, some turbines)
- Being considered:
  - Possibility to fully decouple adjacent sectors
  - Terminate correct (phase separation) and LHe measurements

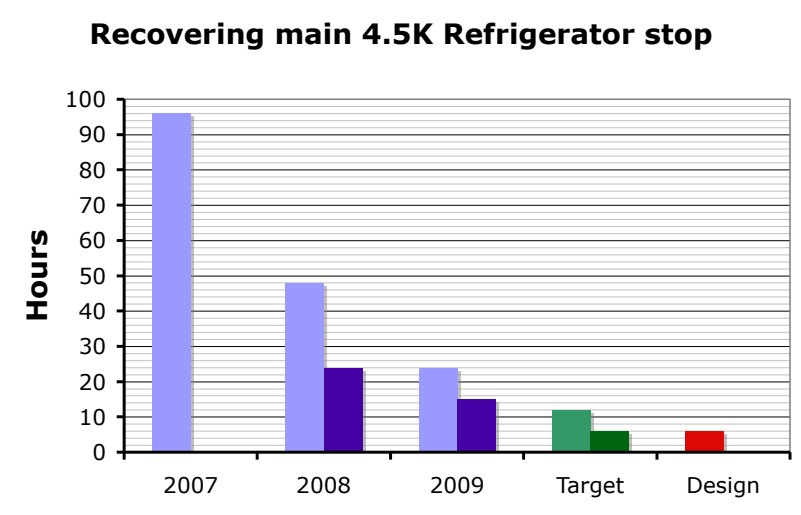
+ *Additional safety relief valves on magnet cryostats*

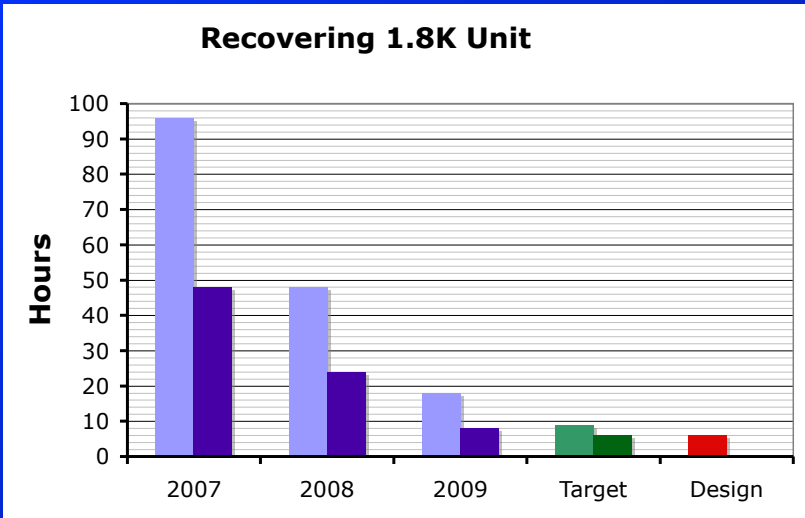
Conclusion: Learning curves

Once understood, easyer to set automatisms and procedures !









Summary

- LHC cryogenics is the largest, the longest and the most complex cryogenic system worldwide. We could achieve a reasonable availablity (around 90%) so far with beams. This demonstrates that there are no big issues in concept, technology or global approach.
- Despite a step by step methodical approach and great involvement of key design/project engineers with experience, we had very hard time and lengthy commissioning to learn how to tune all these sub-systems together while permanently consolidating what was not conform. Could it be done differently, more smoothly (tests, simulators, software)?
- Cryogenics operation is now integrated in central control room with LHC main systems, but operated/supported independently (about 70 people)
- Few specific consolidations are foreseen in 2012, mostly for faster reactivity. And we have to prepare for continued gain in availability!