Cryomodules & Cryogenics – KOM:

Cryogenic experience from CERN LHC

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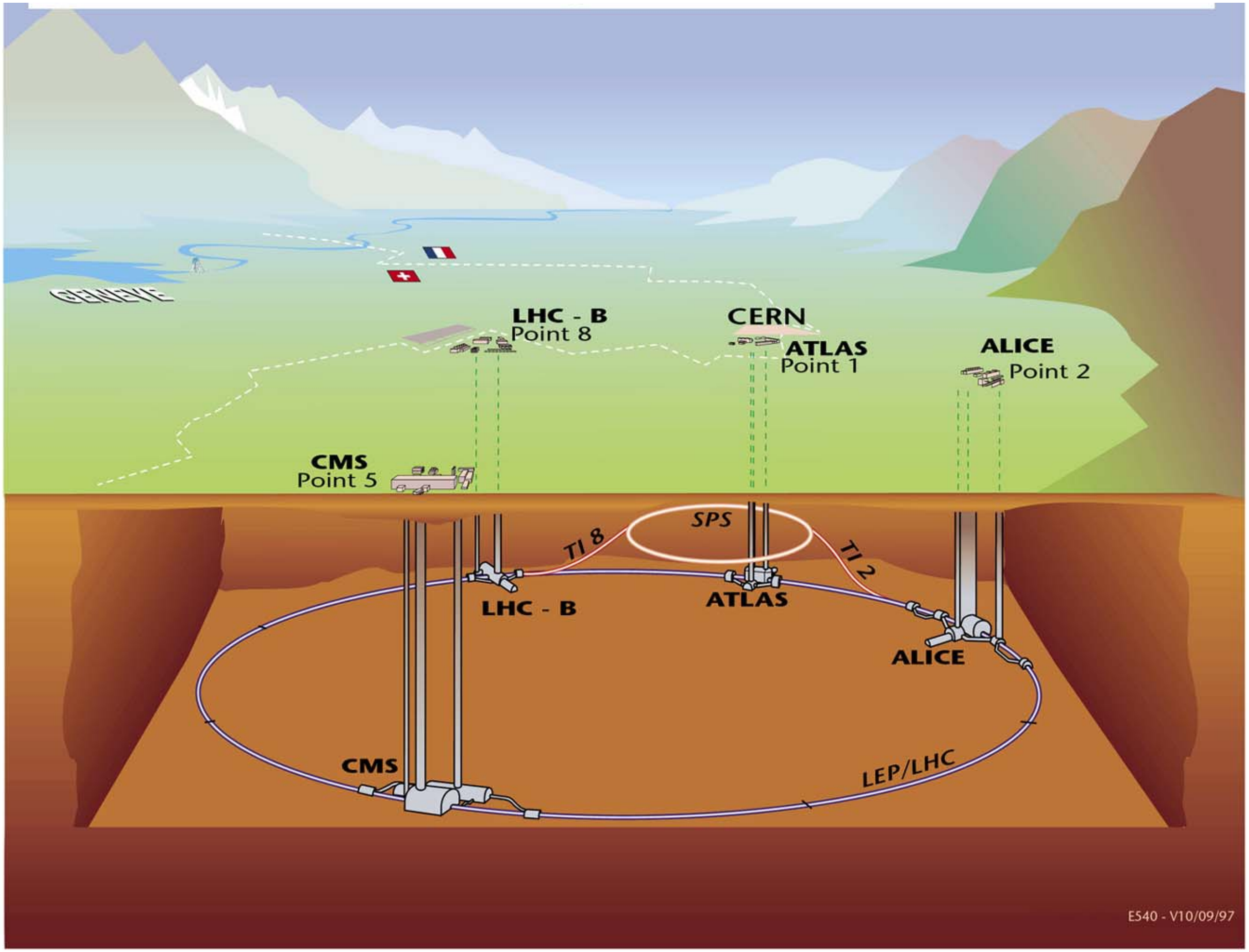
KEK, 13 September 2007

Content

- Overview of the LHC cryogenic system
- Construction experience
- Commissioning / Operation experience
- Preliminary results for measured static heat loads.
- Conclusion

Overall layout of LHC and its detectors

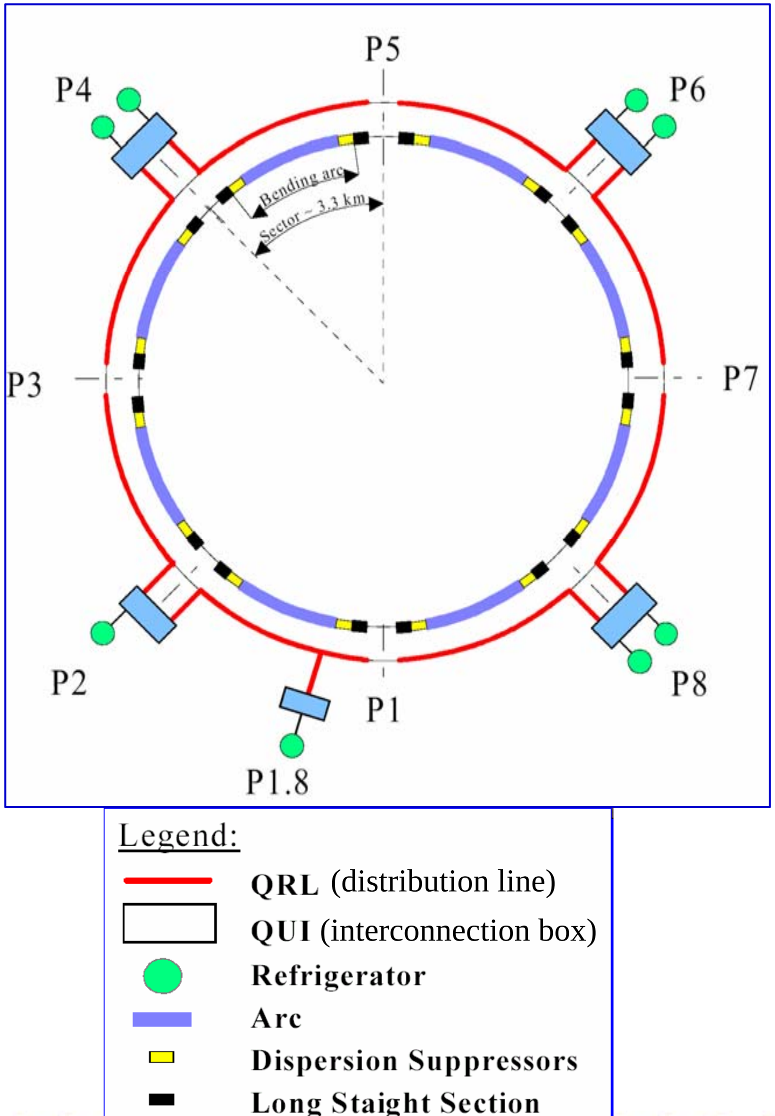


The LHC accelerator in tunnel

p-p collision -> 10^{34} $cm^{-2}.s^{-1}$, 14 TeV c.m., 0.5 GJ stored energy

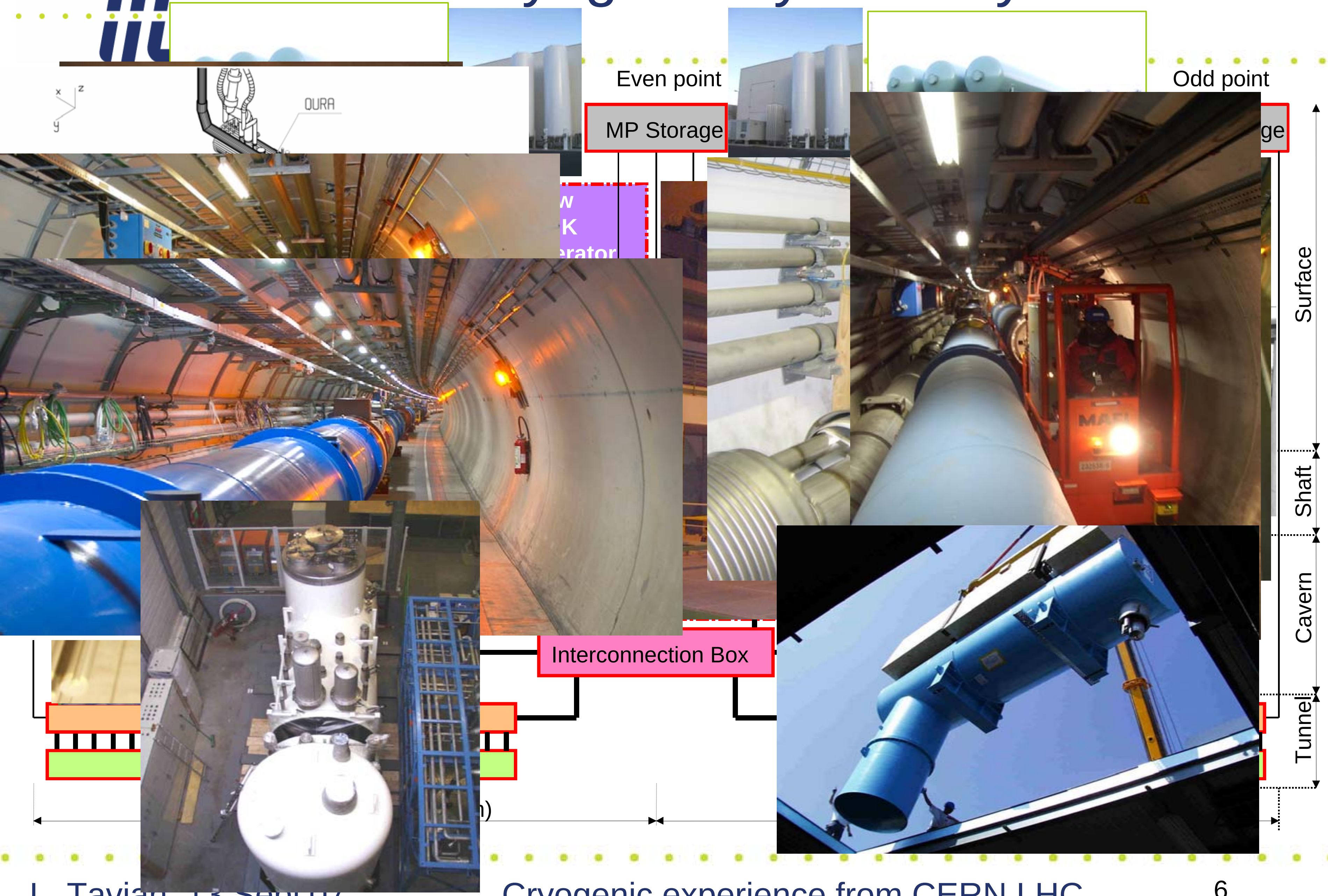
24 km of superconducting magnets @1.9 K, 8.33 T

Cryogenic system layout

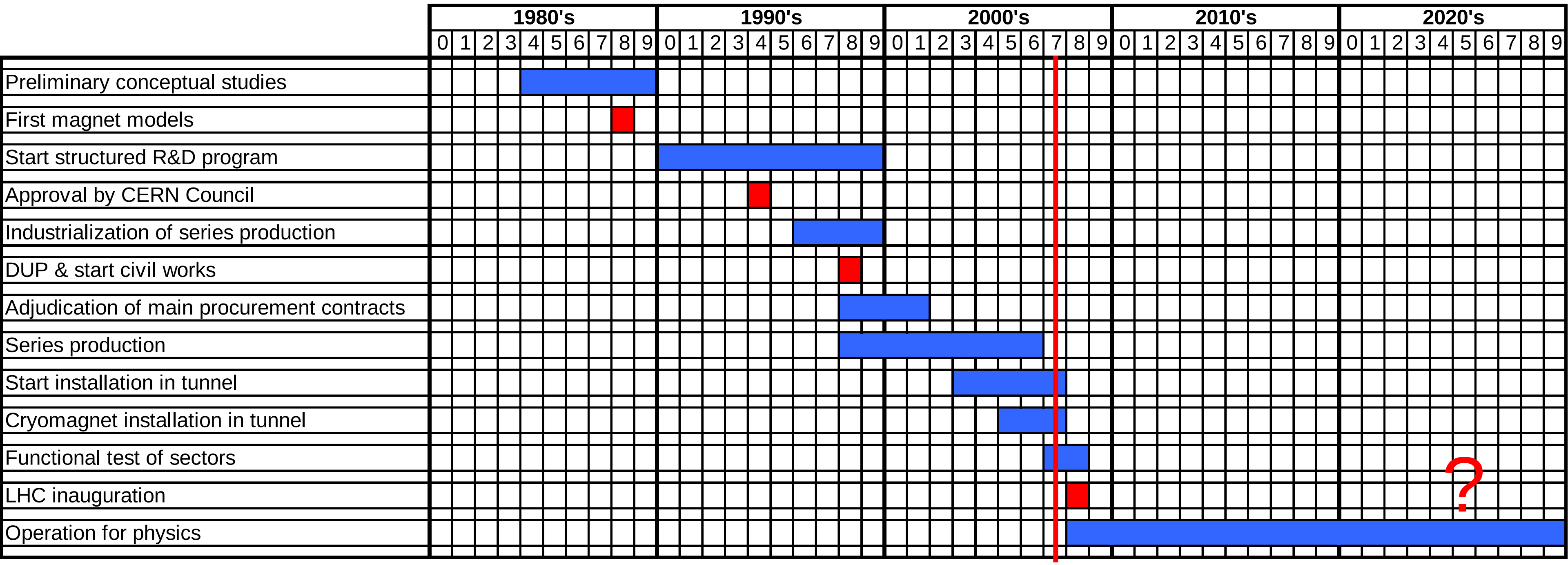


- 5 cryogenic islands
- 8 refrigerators
  - **2 at P4, 6 and 8,**
  - **1 at P2**
  - **1 at P1.8**
- 1 refrigerator serves 1 sector (18 kW @ 4.5 K, 600 kW precooler)
- possibility to couple two refrigerators via the interconnection box ➔ 2 refrigerators for 1 sector

LHC cryogenic system layout 2/2



Historical milestones of the LHC



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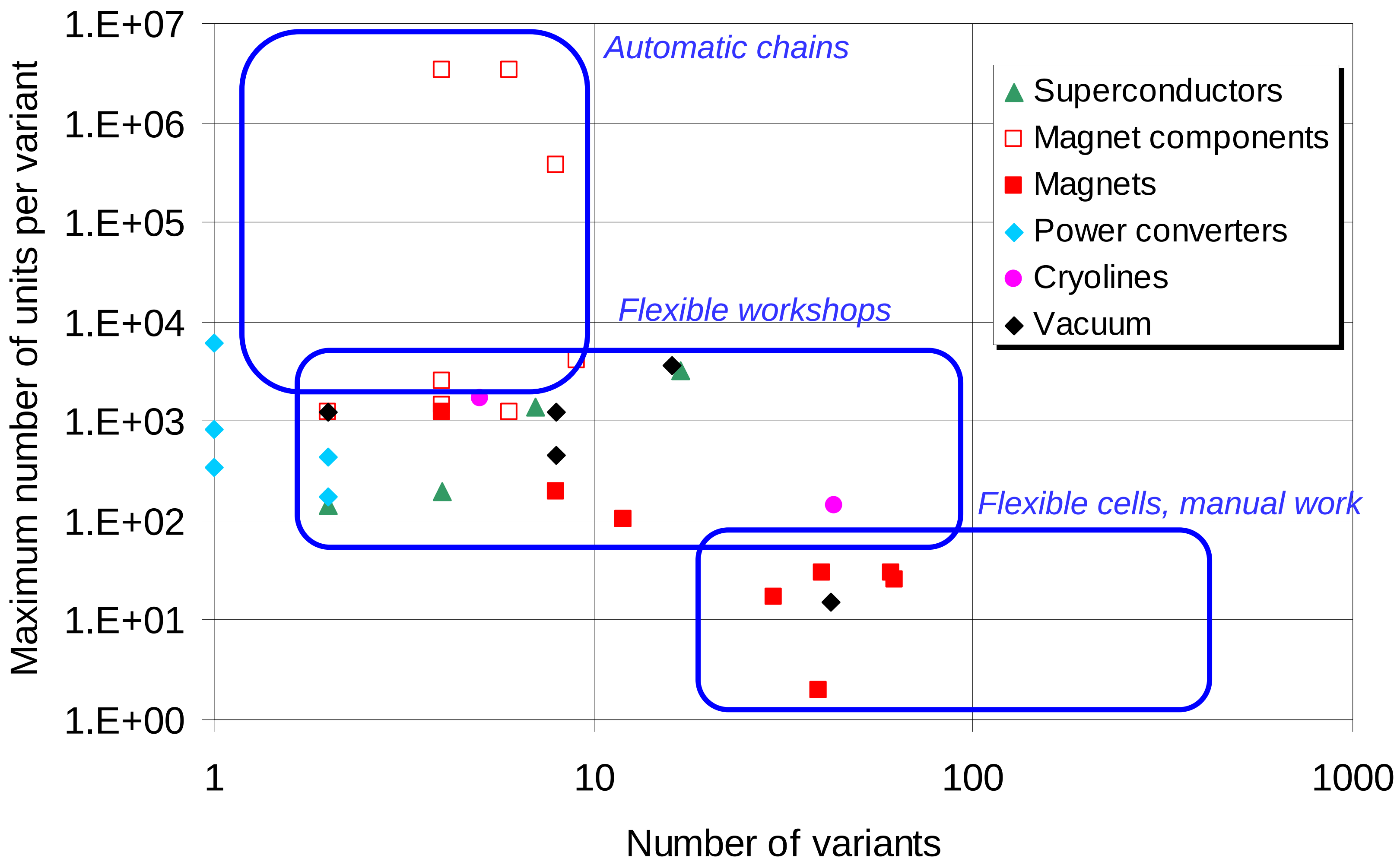
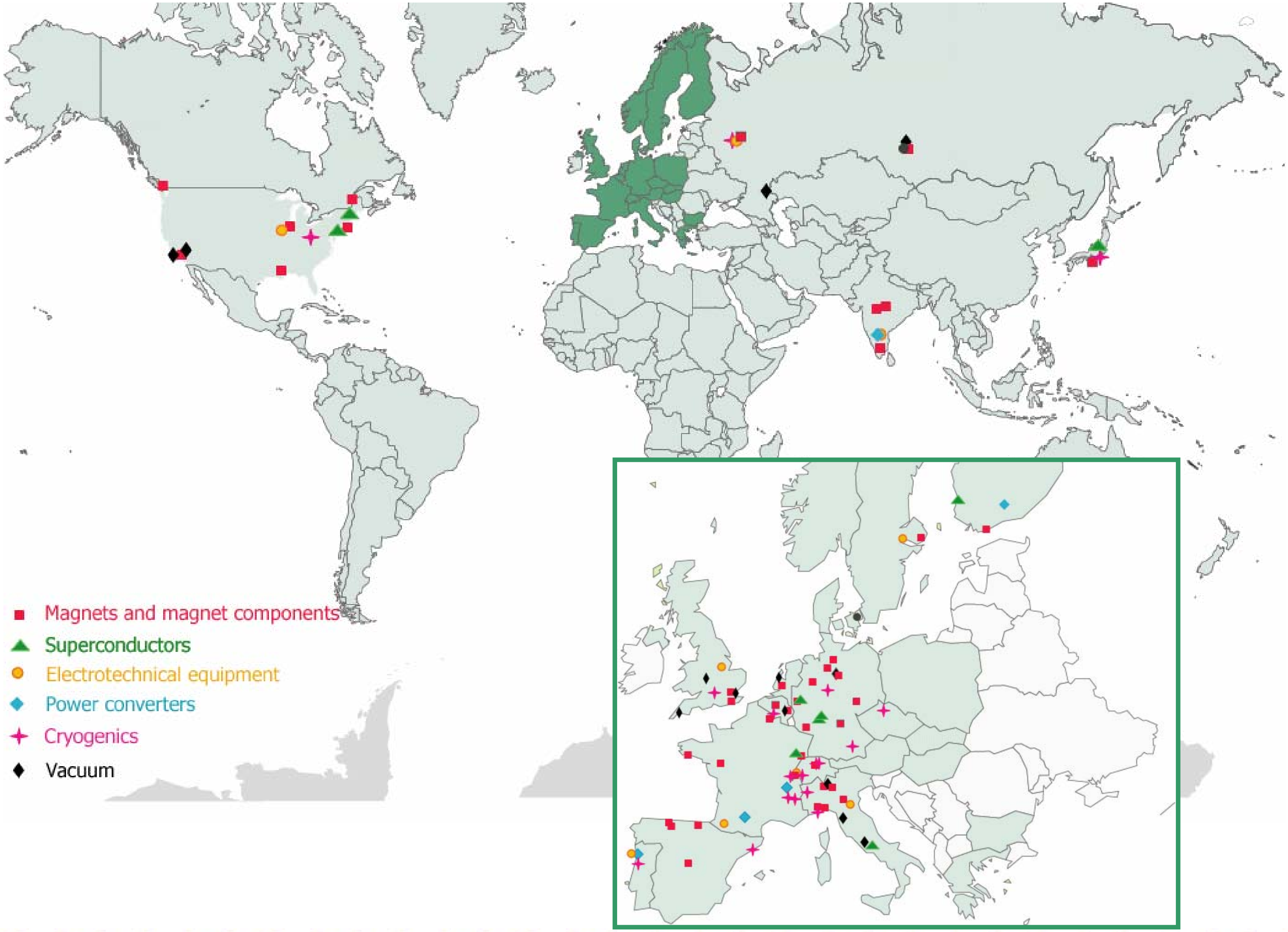
Series production of LHC components



90 main industrial contracts in the world



Production and test rates

- The planned production or test rates were generally reached and often overcome,
  → but always after a "learning" period.

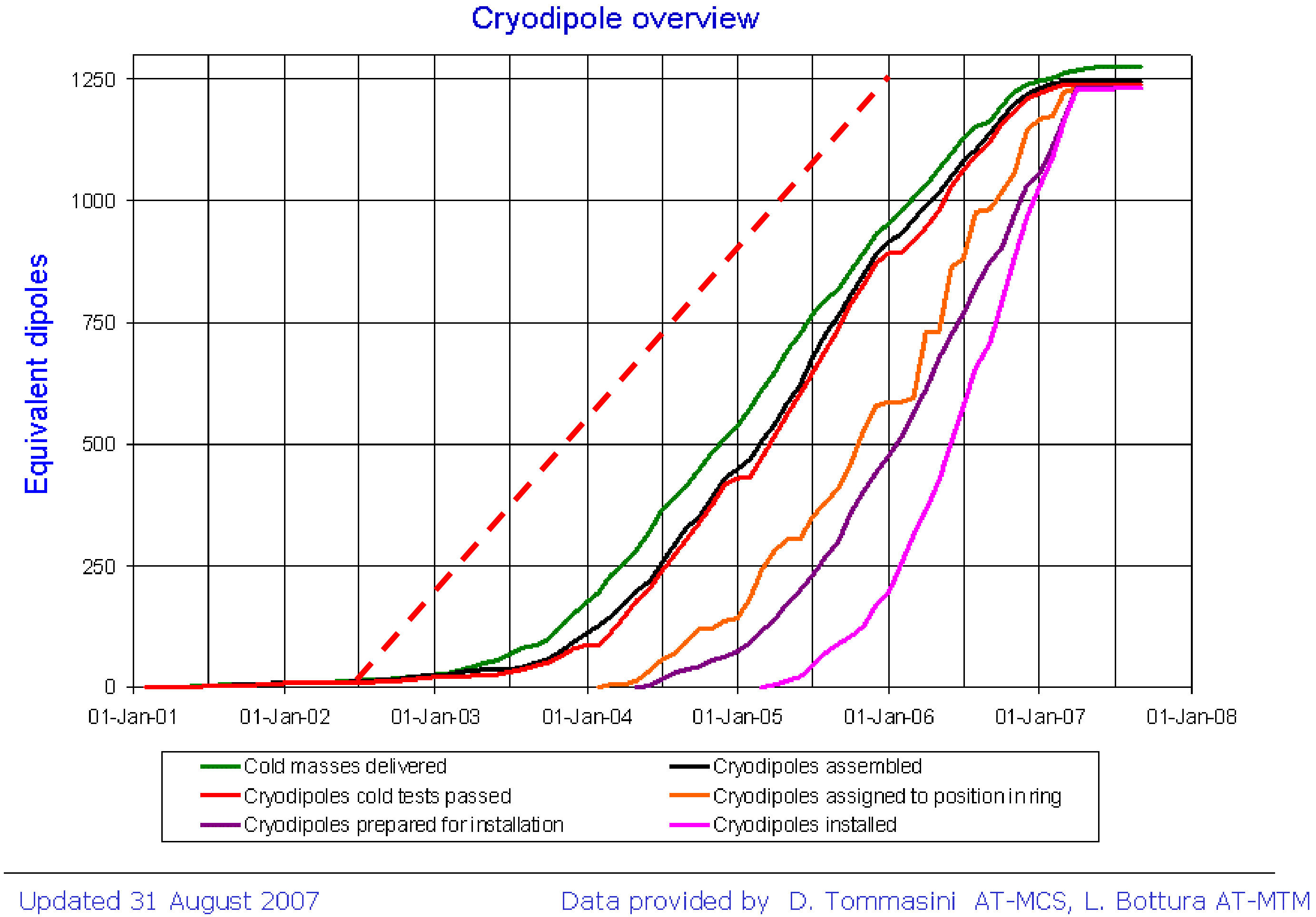
- The main difficulty is to assess the duration of this learning period and to have it agreed by all the stakeholders.

- For the LHC cryogenics, this learning periods were often too optimistic.
  Examples: the cryomagnet cold test, the quench valve production and the cryogenic distribution line (QRL)

Cryomagnet test station

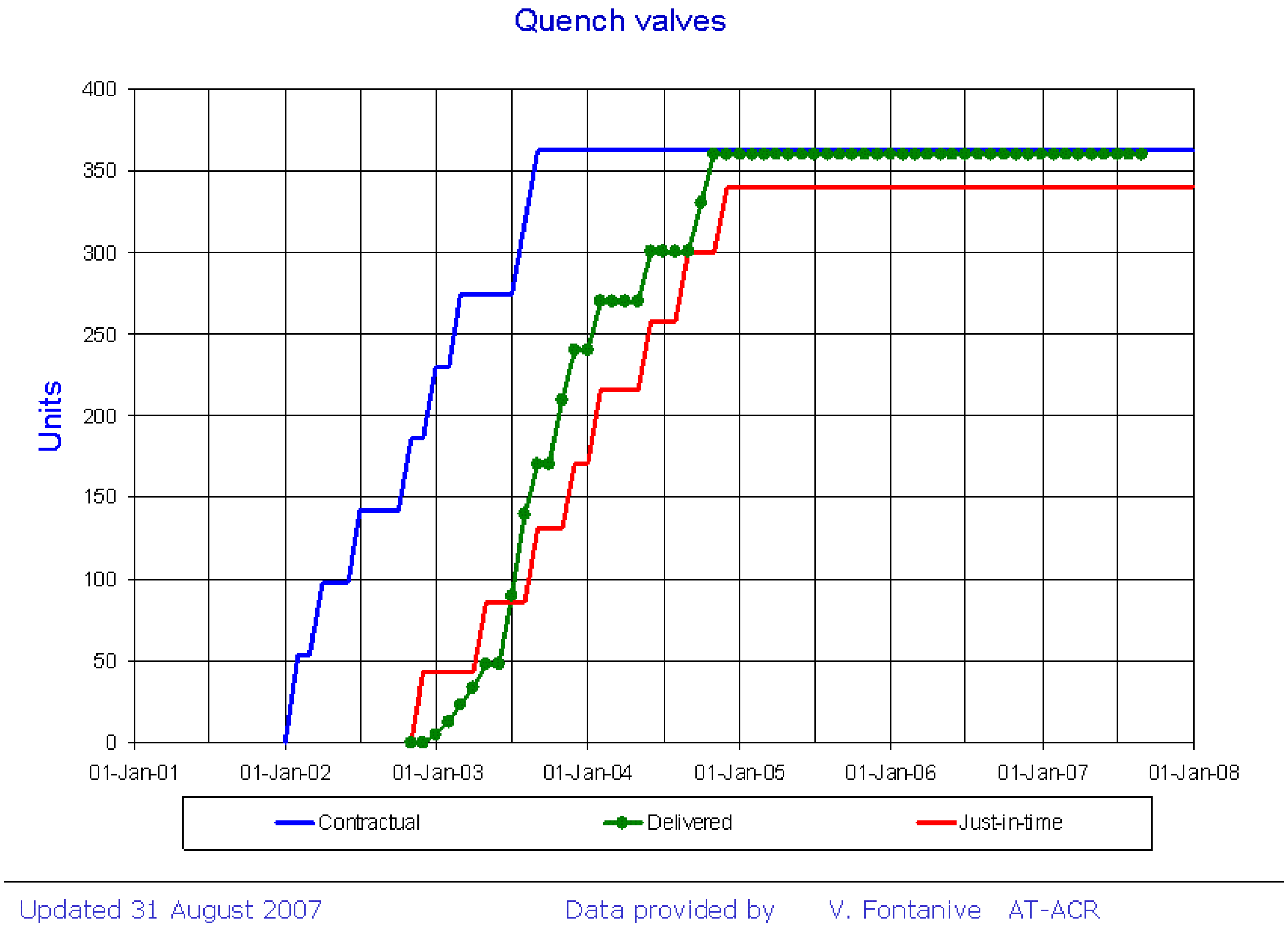
12 benches, rate: ~15 magnets per week

Cryodipole cold tests



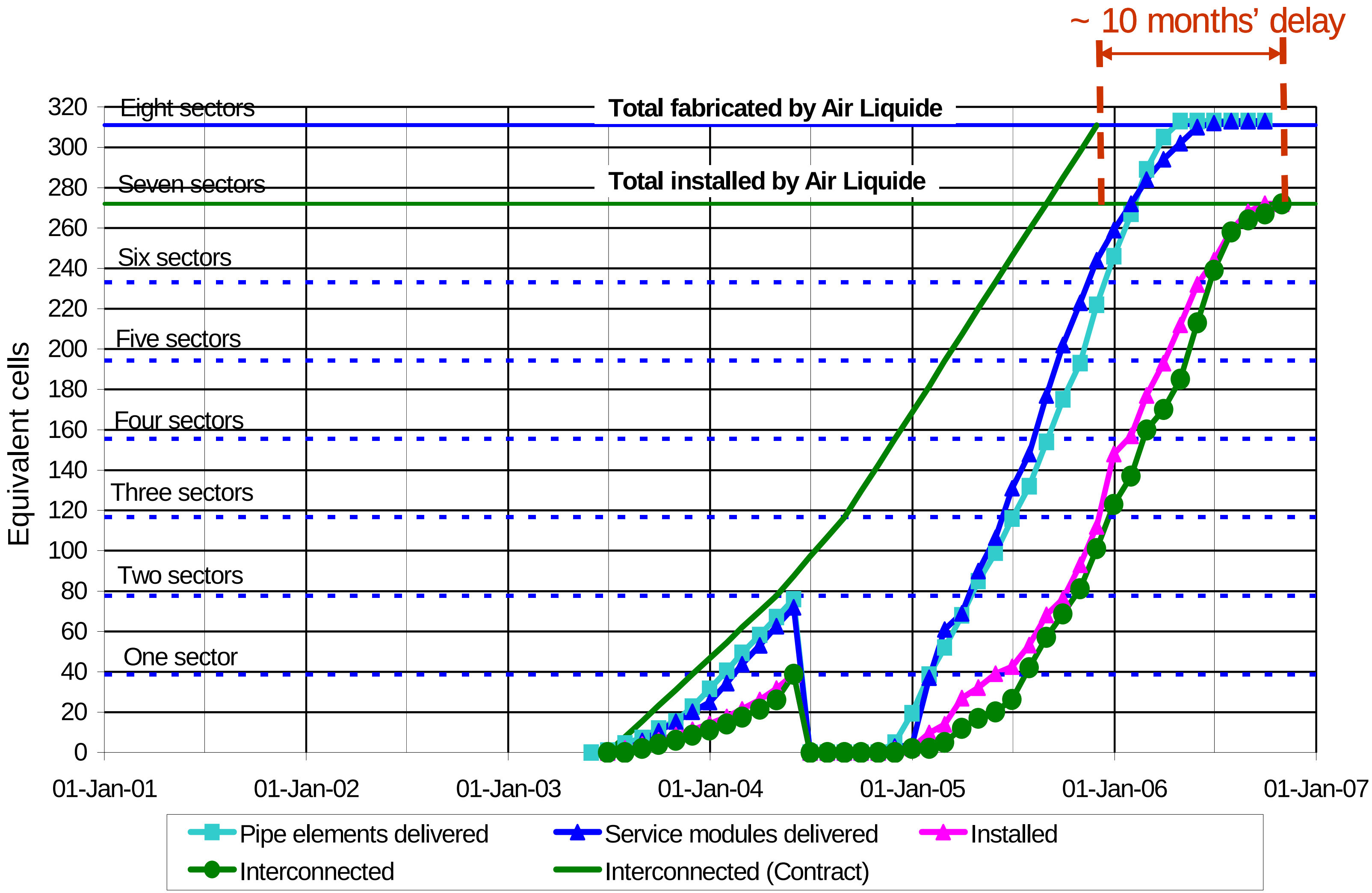
Delays: mixing of sub-contractor insolvency and learning period for efficient test bench operation (cog-wheeling).

Quench-valve dashboard



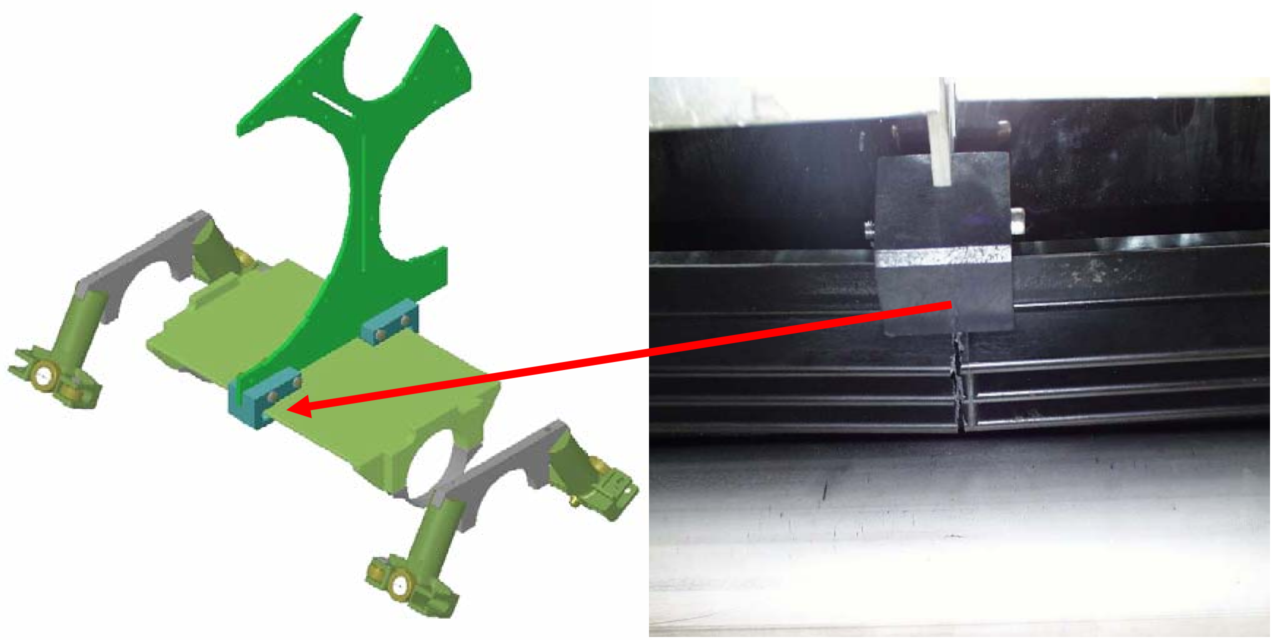
Delays: Finalization of the design

QRL Dashboard



Example of construction problems

The LHC cryogenic distribution line (QRL) problem: Elements equivalent to two sectors to be repaired and one sector to be reinstalled (by CERN).



Composite material (Neonite®) fabricated with short fibers instead of long ones → insufficient resistance to impacts

Example of achieved production rates

Fabrication of QRL modules

	Pipe elements	Fixed points/ Special pipe elements	Service modules	Service modules	Service modules	Steps/ Elbows
	Air Liquide-2C (FR)	Tuboplan (PT)	SIMIC (IT)	FCM (SP)	Air Liquide (FR)	Tuboplan (PT)
Contract (old target) *[element/week]*	15	3	1.5	1	0.1	0.5
Contract (new target) *[element/week]*	25	6	2.5	1.7	1	1.5
Produced (average) *[element/week]*	30	7	2.3	1.8	1	1.85
Produced to-date *[number of elements and %]*	1714	447	168	106	39	66
	100%	100%	100%	100%	100%	94%

How to deal with construction problems?

- For large and ambitious projects, everyone is convinced that, in view of their complexity, some problems will definitely arise.
- But when a problem happen, everyone (except the ones who have to deal with the problem) asks: How is it possible to make such a mistake ?

- General rules to avoid construction issue:
  - Do not specify something for which you have no solutions.
  - Do not mix prototype, pre-series and series production. Be sure that when the series production starts, all developments are completed.
  - Put sufficient independent resources on quality control. (Mandatory for large series). Do not trust the internal quality control of a manufacturer even with ISO qualification.
    - For LHC a contract for quality inspection has been placed with only 2 “itinerant” inspectors foreseen to follow cryo-equipments → 7 inspectors were required to follow correctly the QRL quality inspection.
  - Put sufficient effort to test the critical components, but the difficulty remains in the risk assessment. (Always easier to do after the problem detection).

Splitting or not splitting ?

- Splitting of contract for the procurement of equipment is generally a good decision:
  - To secure the production: If one supplier has difficulties, part or totality of the remaining production can be transferred to the other suppliers.
  - To get some competition within the suppliers (performance, delays…)
  - For political reason (Funding return in several places / countries / continents)
- But:
  - a known splitting before tendering could generate less commercial competition, i.e. higher offer prizes. (In cryogenic refrigeration only two suppliers are on the market)
  - splitting generates more contract follow-up needs which are generally not anticipated in the manpower plan.

Contingency for difficulties: time or money?

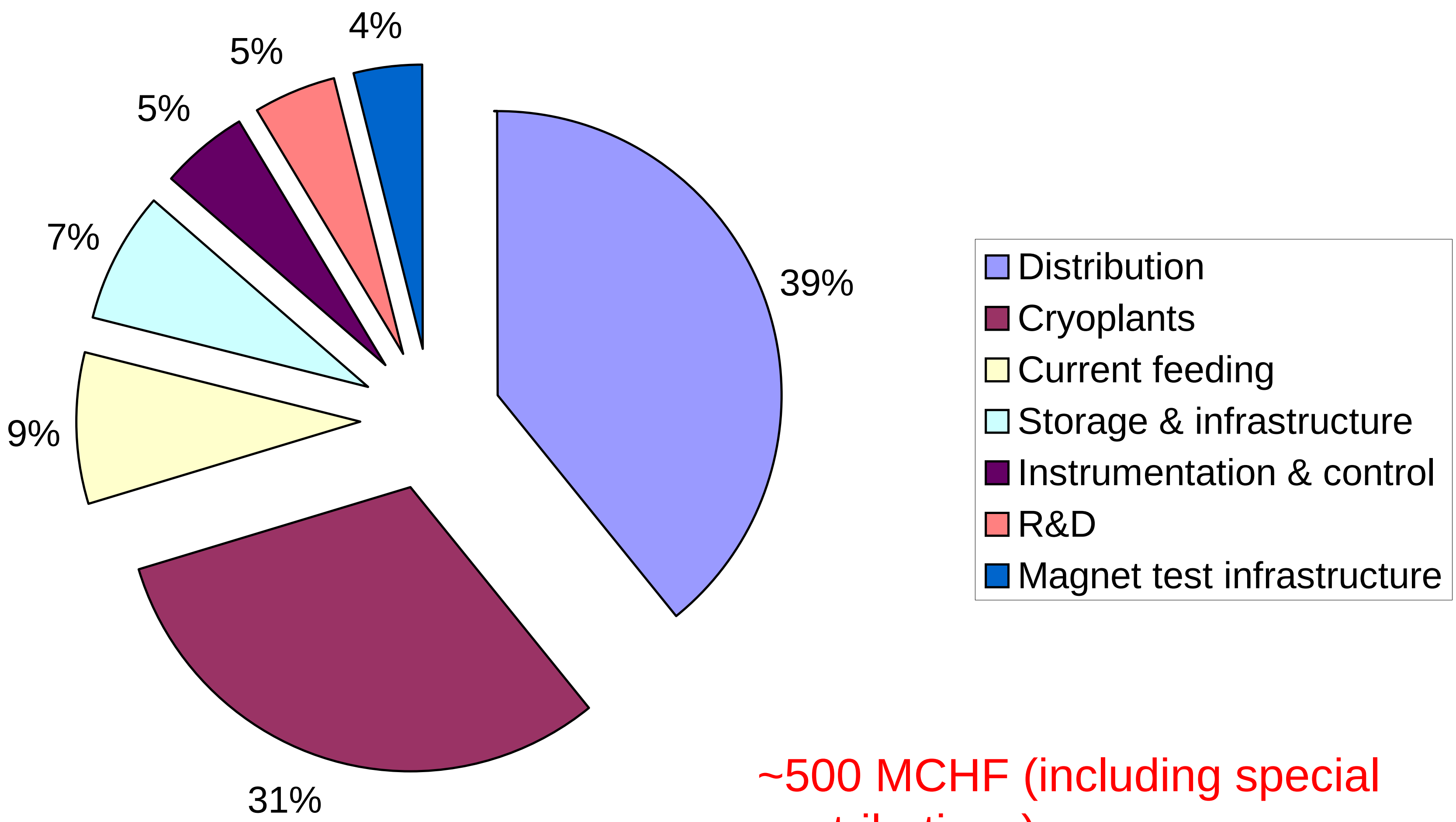
Following difficulties identified on a contract:

- **If time is available:**
  - Ideal case for the project as some pressure can be put on the supplier to fulfill the contractual terms.
    → Time is contingency

- **If no time is available (supply already on the critical path):**
  - In this case, extra resources (i.e. money) have to be allocated by the project to solve the difficulties:
    - Via a second contract in case of splitting of contract
    - Internally in case of re-internalization of part of the supply
    - Directly to the firm via “justified” claims.

    → Money is contingency

Cost breakdown



~500 MCHF (including special contributions)

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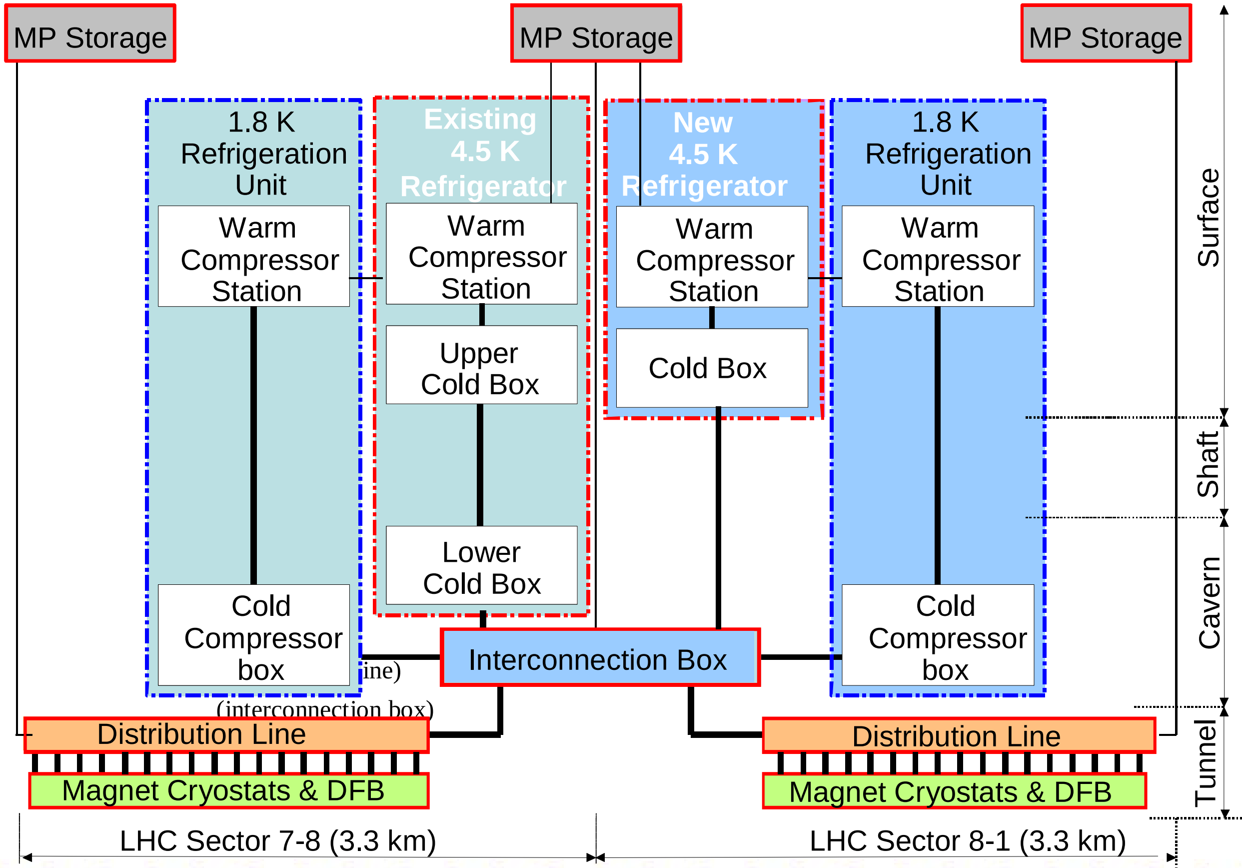
Commissioning / operation strategy

From commissioning to operation staging:
- Starting from surface equipment (4.5 K cryoplants)
- Following by cavern equipment (interconnection box then 1.8 K refrigeration units)
- Finishing by tunnel equipment (QRL, machine)



Commissioning of the first LHC sector

- The 1st LHC sector, sector 7-8, began to be cooled down for the first time on Jan. 15th, 2007
- After about 2 months, the temperatures of all the magnets were below 2 K, i.e. more than 10 tons (70’000 liters) of pressurized superfluid helium distributed along 3 km have been produced (about 20 times higher than Tore Supra).
- Nevertheless, to reach this successful milestone, several problems were encountered:
  - Unbalanced cool-down
  - Unexpected long cool-down
  - Problems with ex-LEP cryoplant
  - Problems with 1.8 K refrigeration units
  - Longer tuning of the tunnel cryogenics

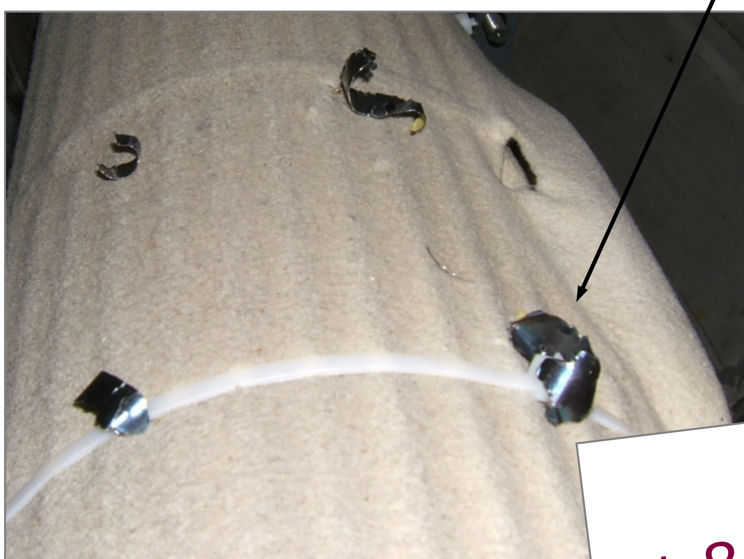
Machine flushing Wk 2 Jan'07

Before

After

Kapton bits

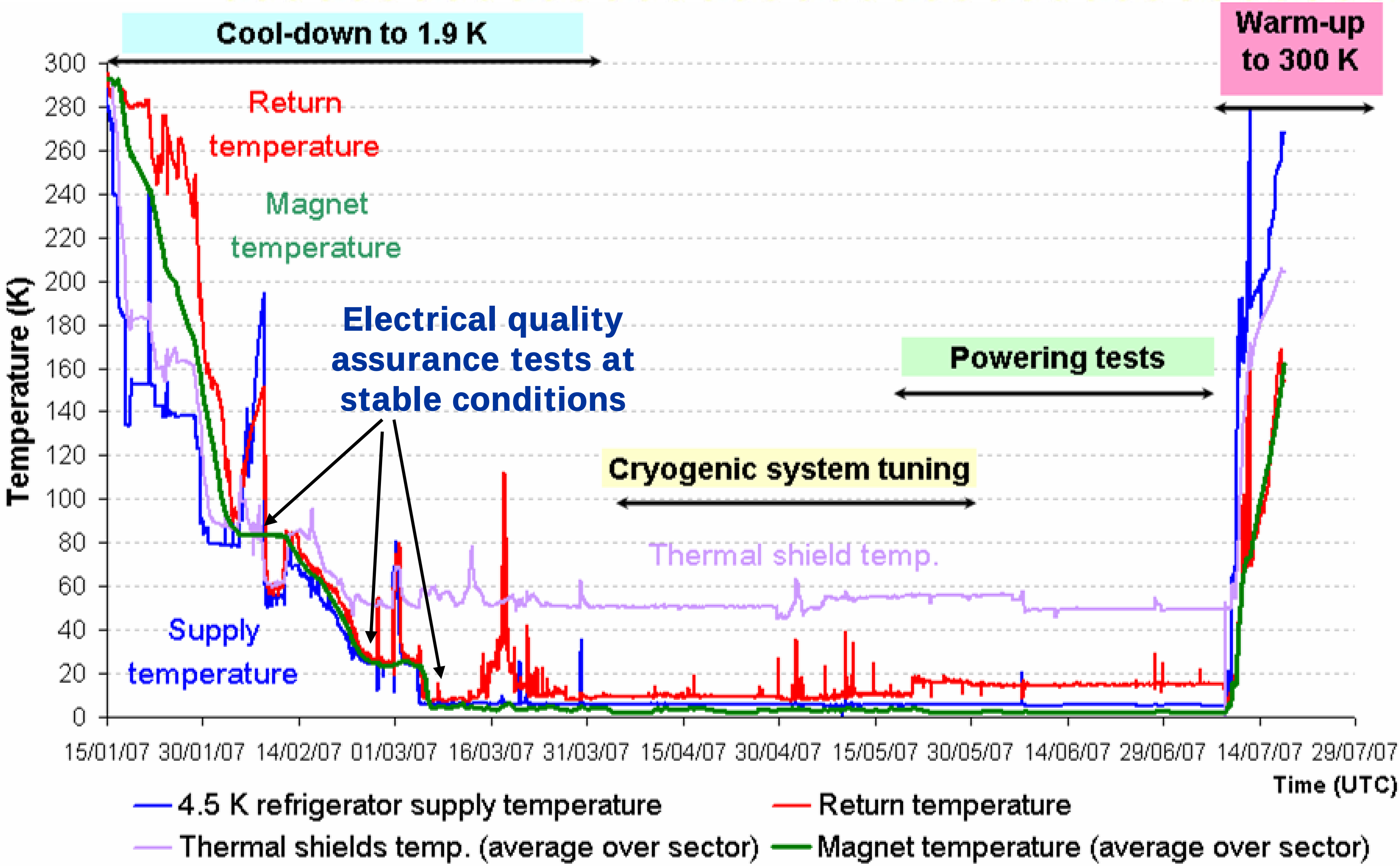
Metal strips



≈ 50 h

+ 8 L of Water

First sector (S7-8) commissioning



Cooldown of first sector (4625 t over 3.3 km)

Unloading of LHe & LN2

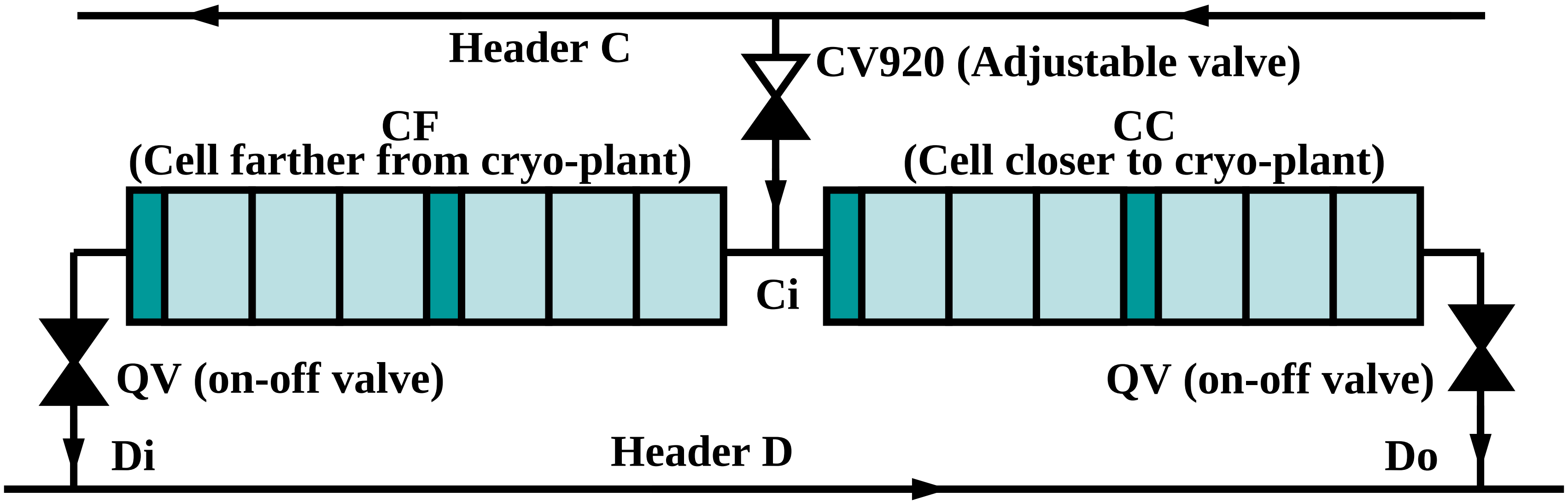
600 kW precooling to 80 K with LN2:

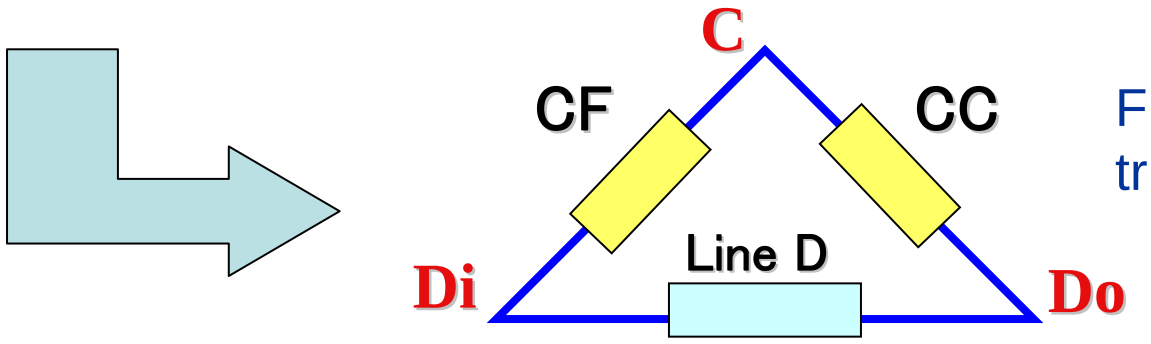
- up to ~5 t/h

- 1250 t of LN2 in total

- 6 LN2 trailer per day during 10 days

Cool-down generic flow scheme

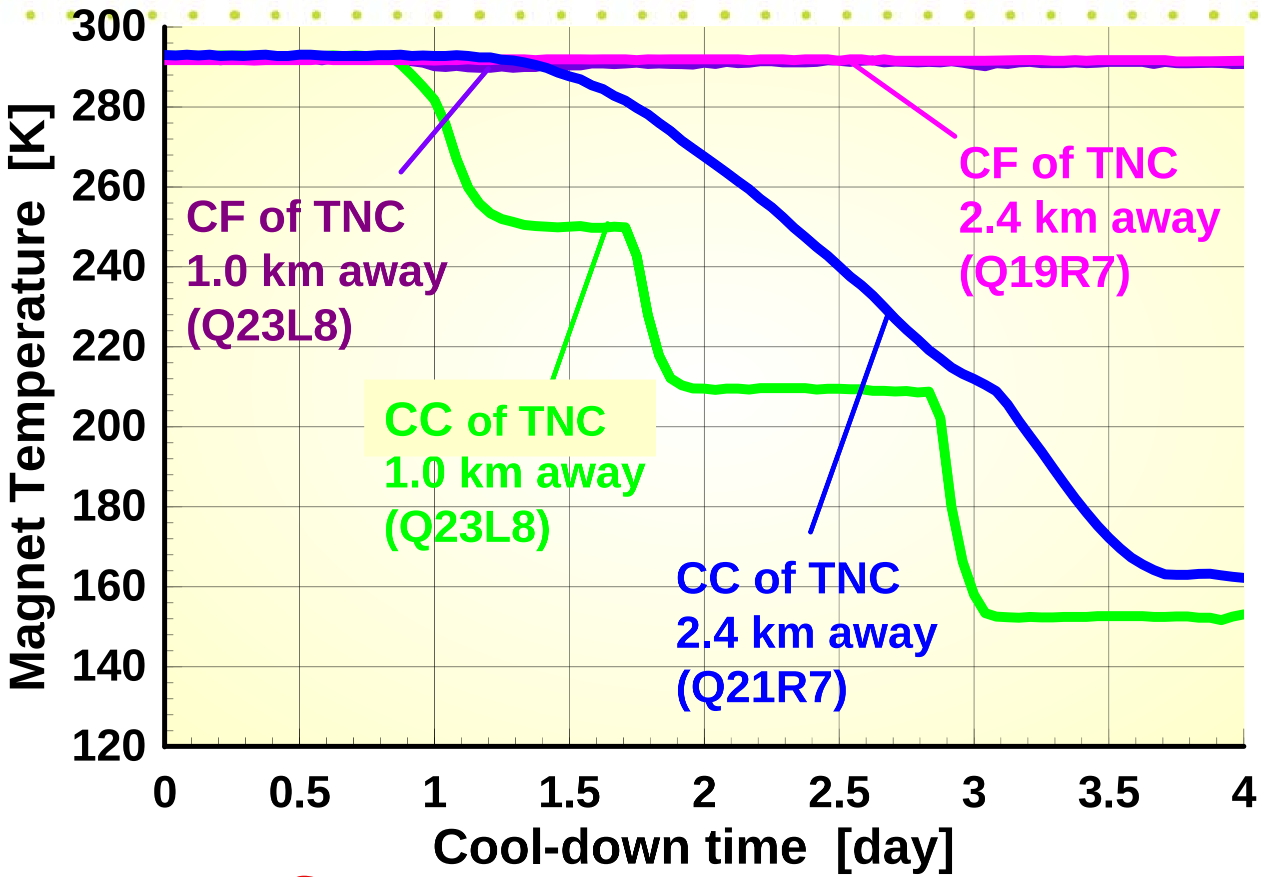


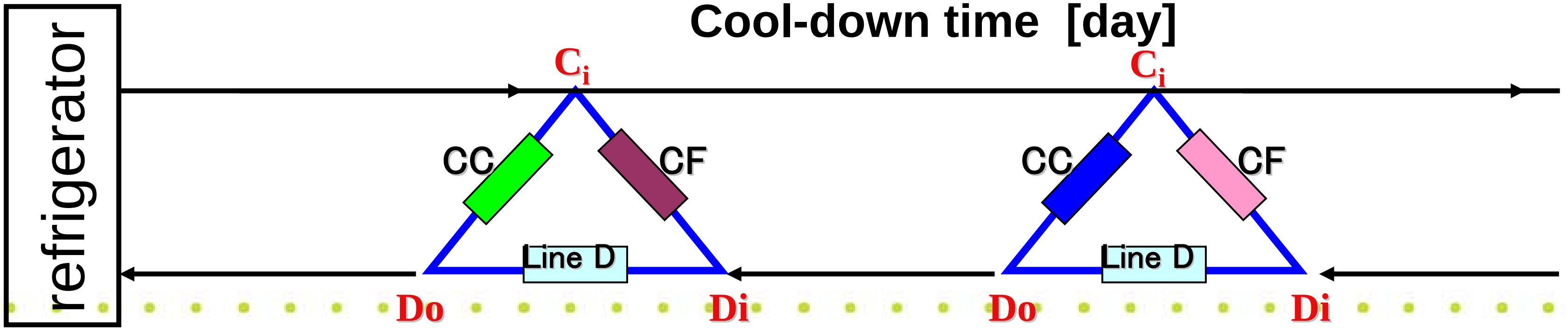


Flow resistance triangle

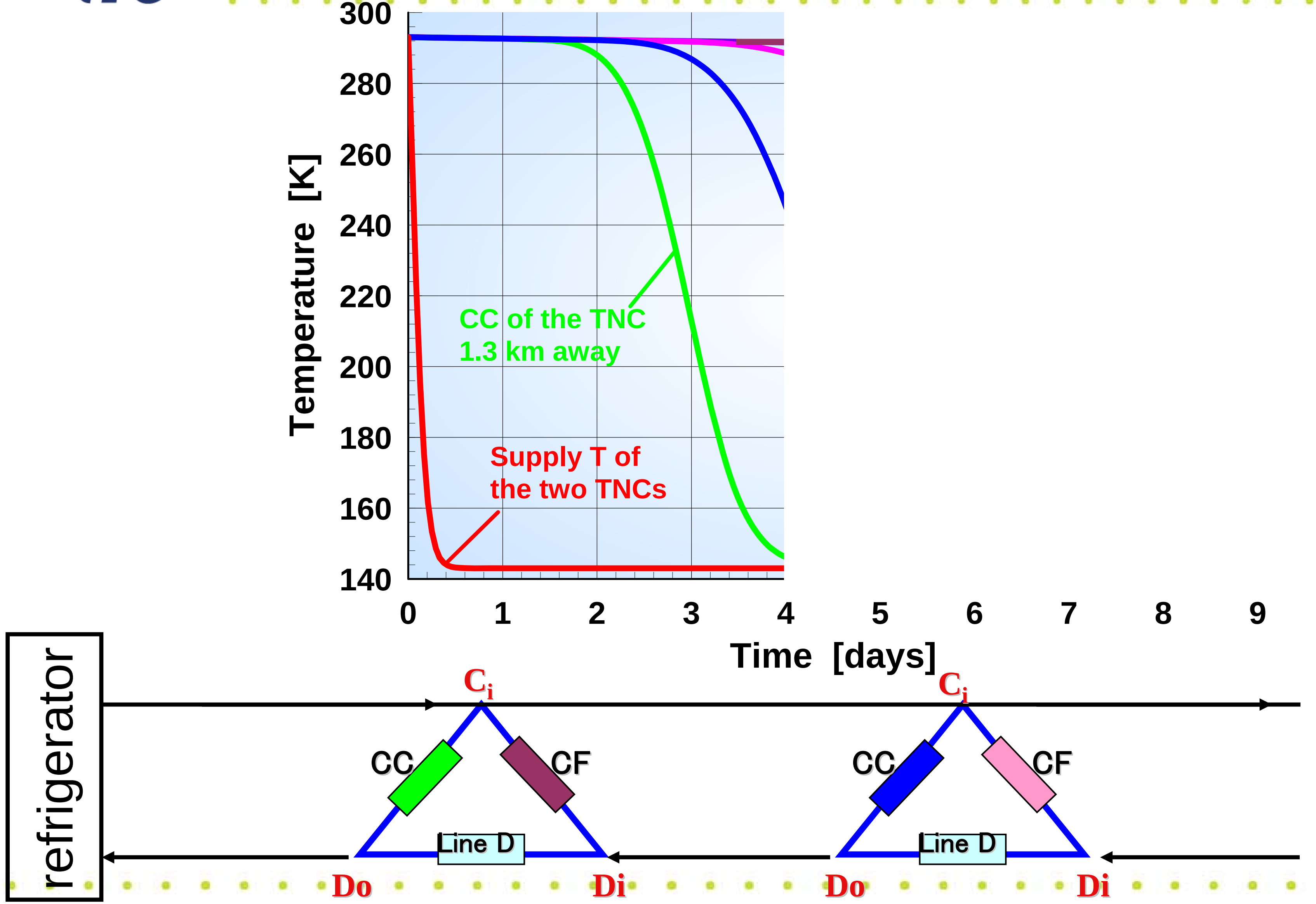
Two neighboring standard cells supplied by one valve

Unbalanced Cool-down (Measurement)

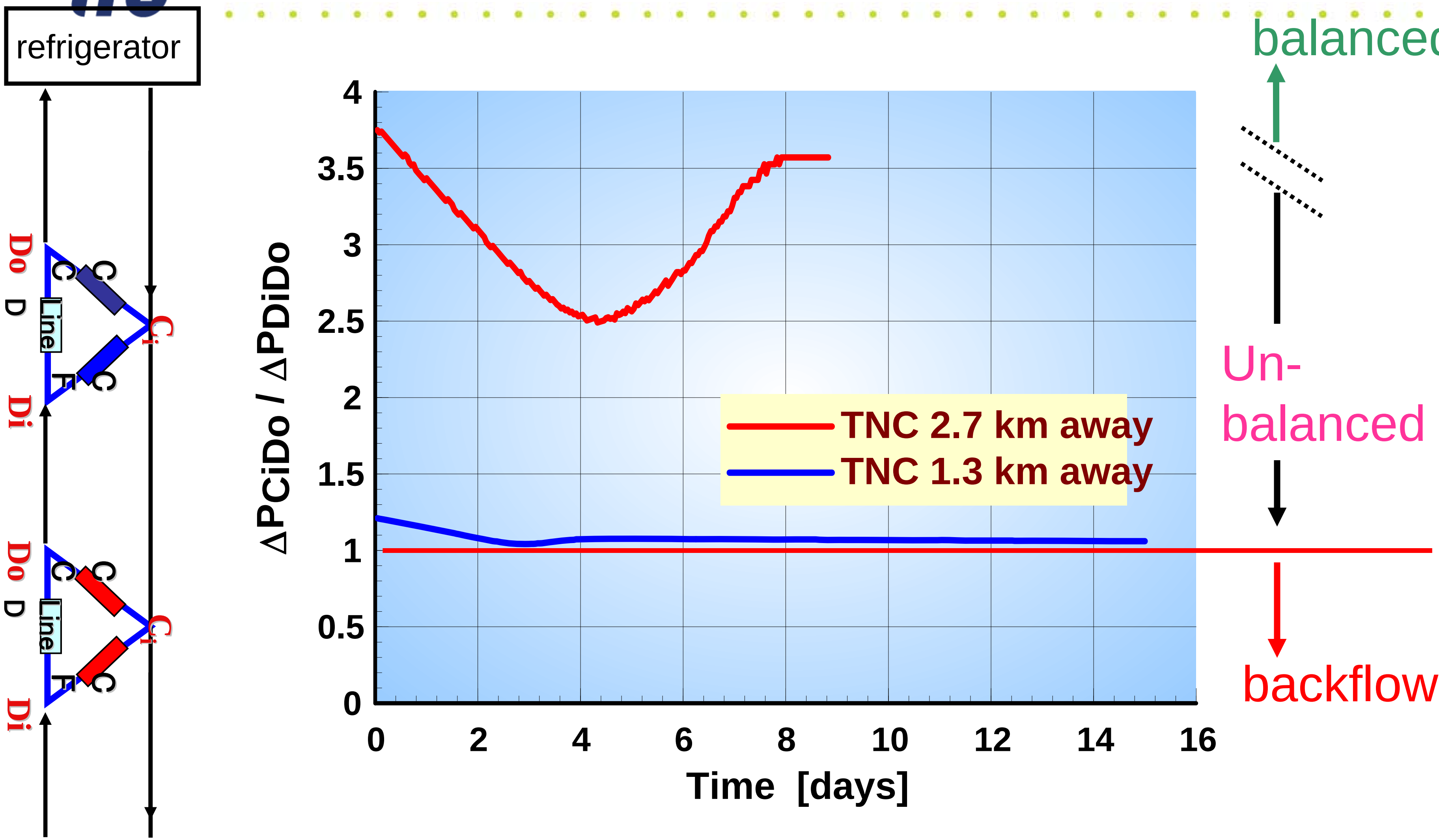




Unbalanced Cool-down (Simulation)

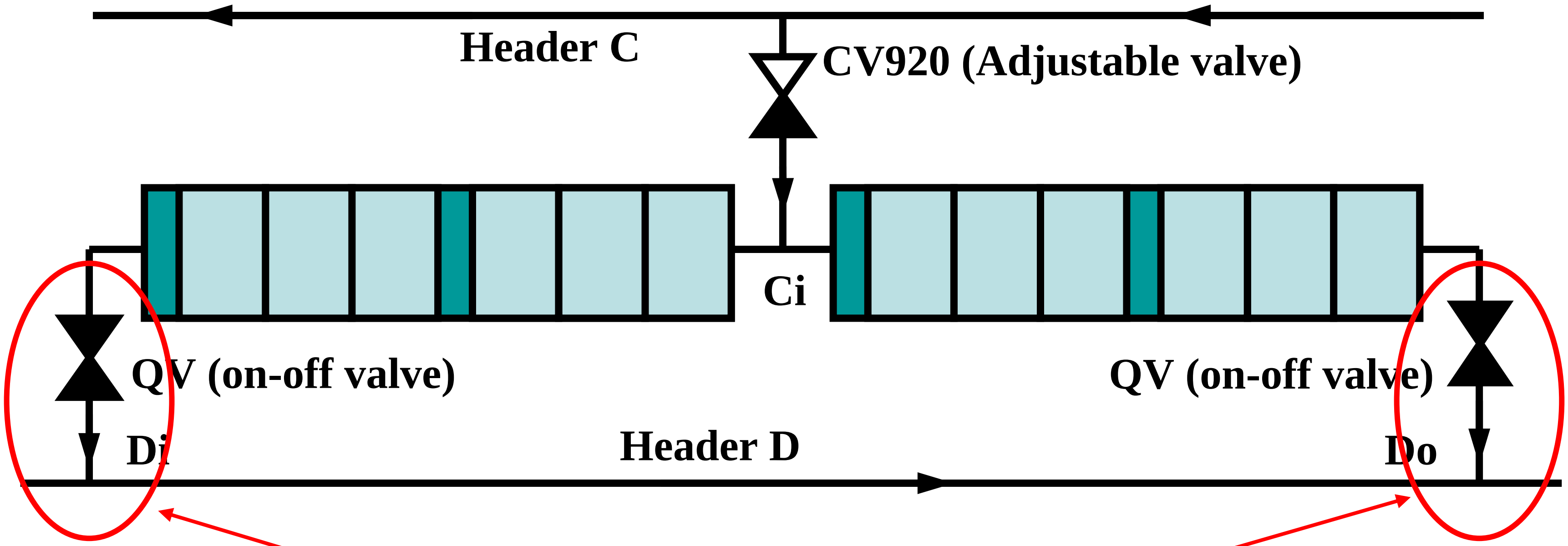


Unbalanced Cool-down (Analysis)



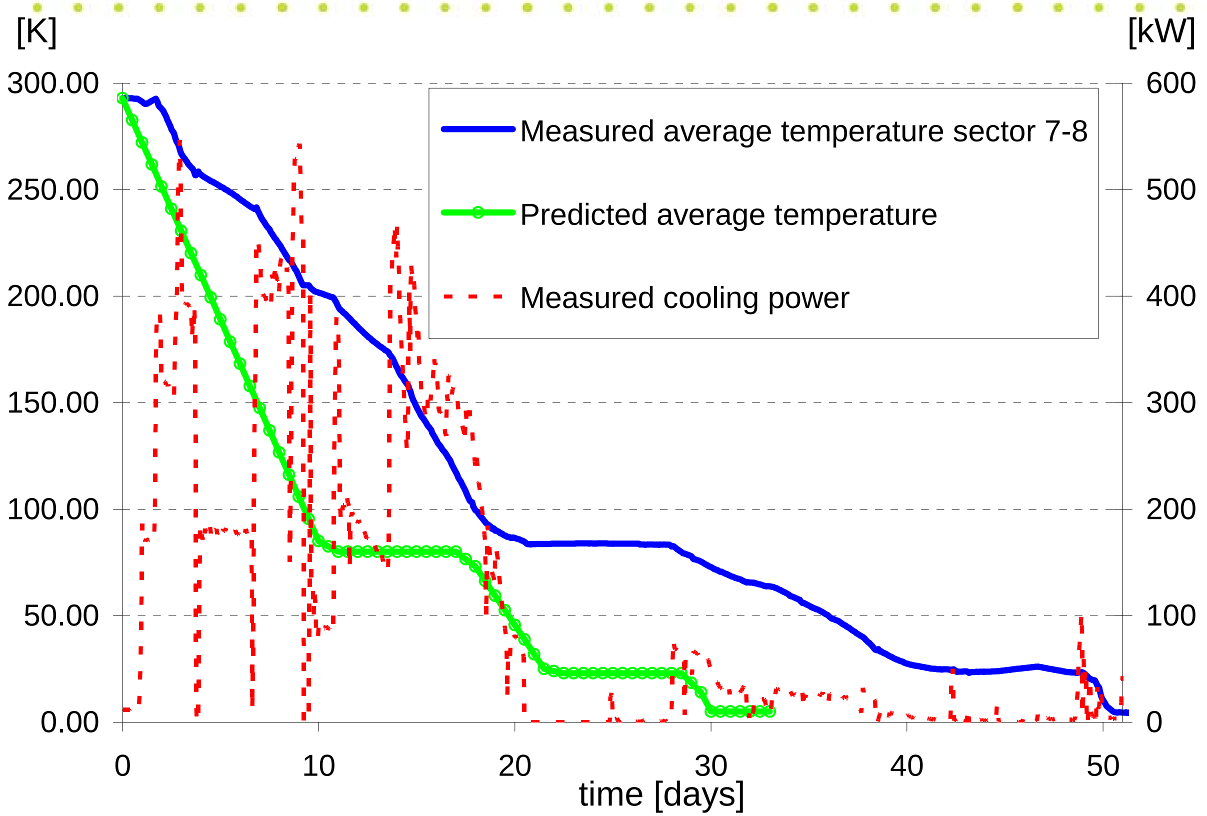
Evolution of ratio of ΔP of TNC at different positions

How avoiding unbalanced cool-down ?



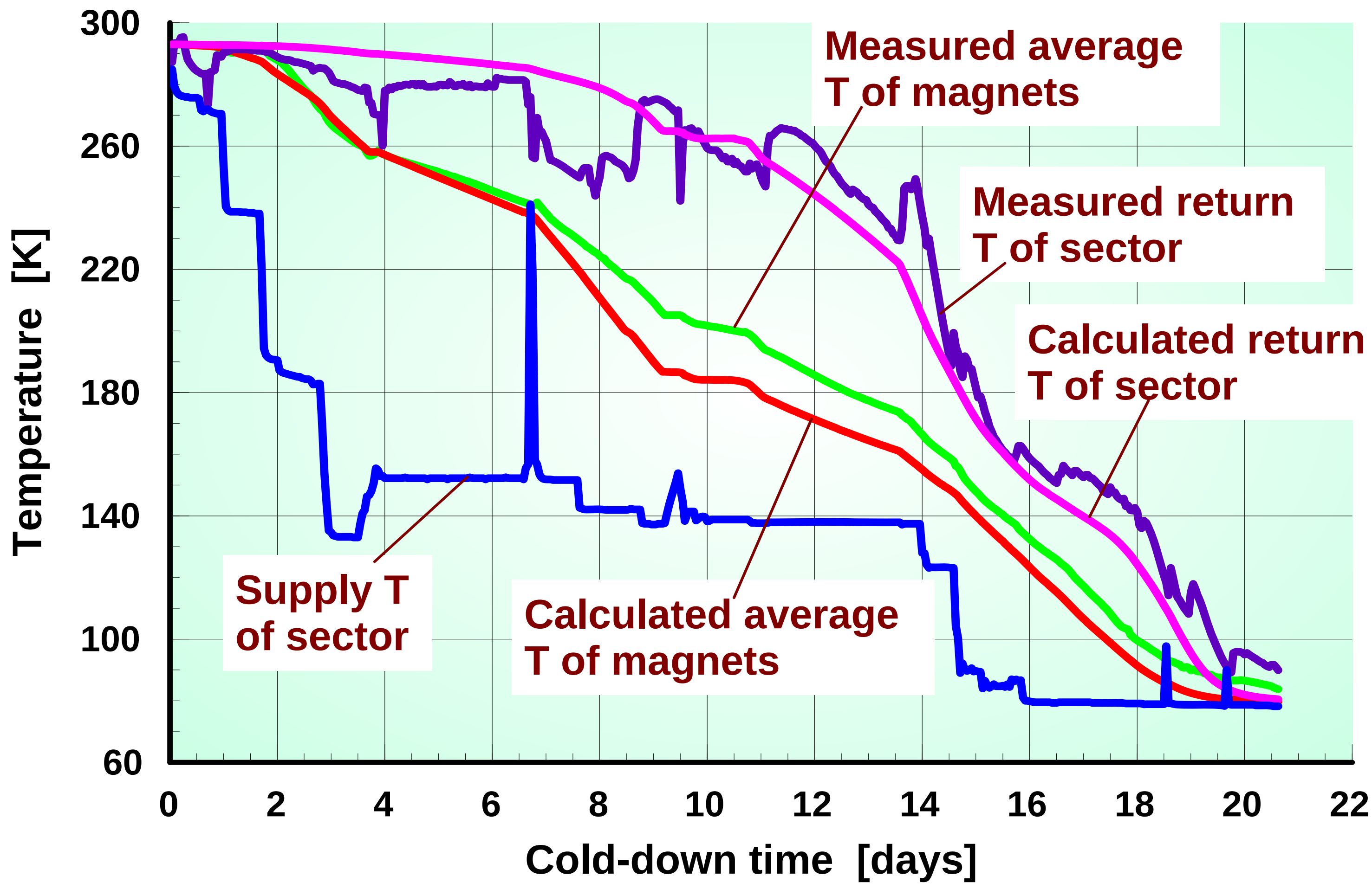
Periodic switch-over (every 12 hours) of QV valves:
The available cool-down flow goes in one cell, then in the other with no increase of the total cool-down time.

Unexpected long sector cool-down



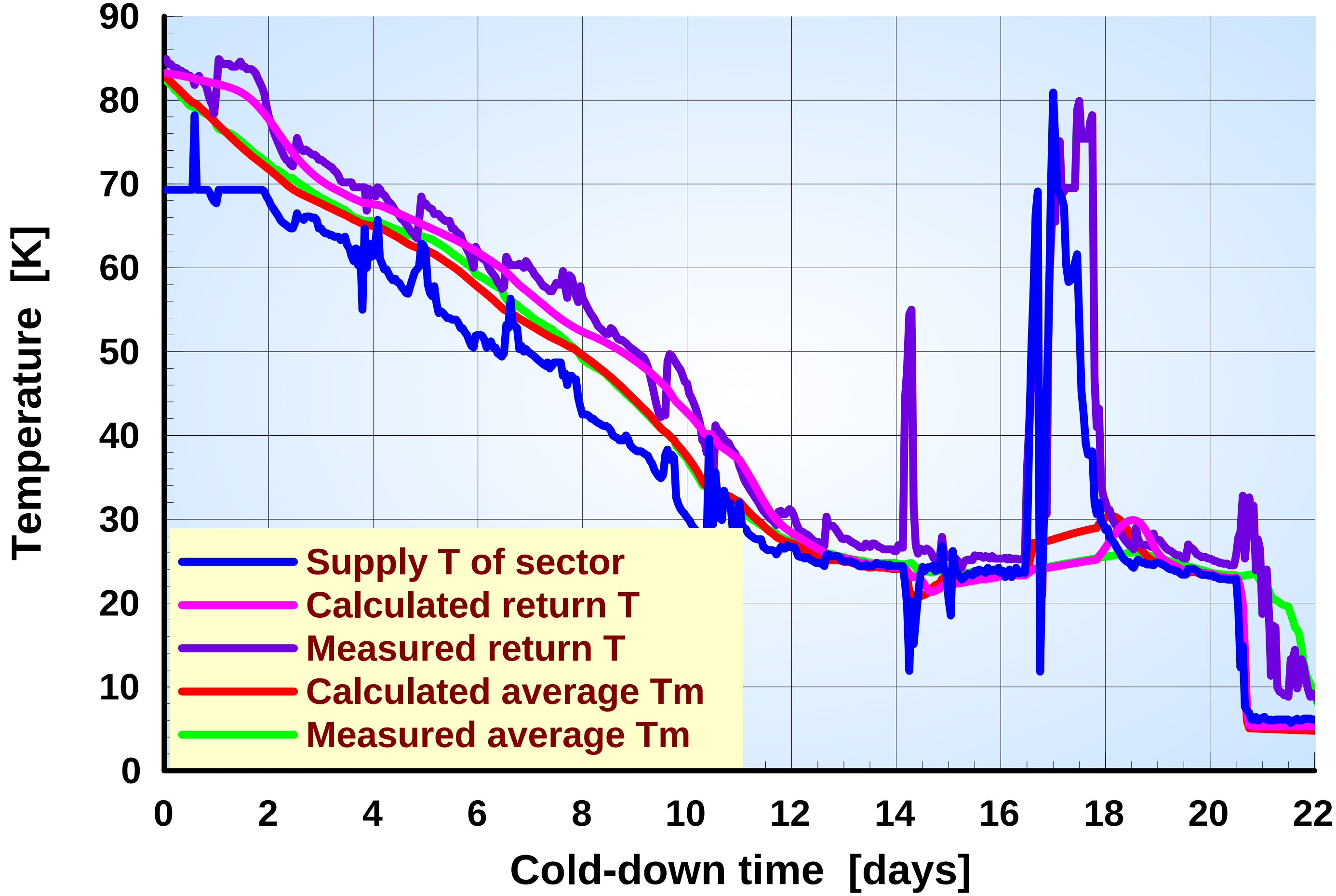
- Longer cool down time: 36 days instead of 15 days (without electrical QA plateaus)
  - Learning and tuning of the process (unbalance, …)
  - Reduced available cooling power:
    - LN2 logistic during nights and week-ends
    - Limitation on turbo-expanders not working at nominal conditions
    - Flow restriction in the cold part of the 4.5 K refrigerator

Simulation of 300-80 K cool-down



Calculated and measured results of the 1st normal CD from 300 K to 80 K

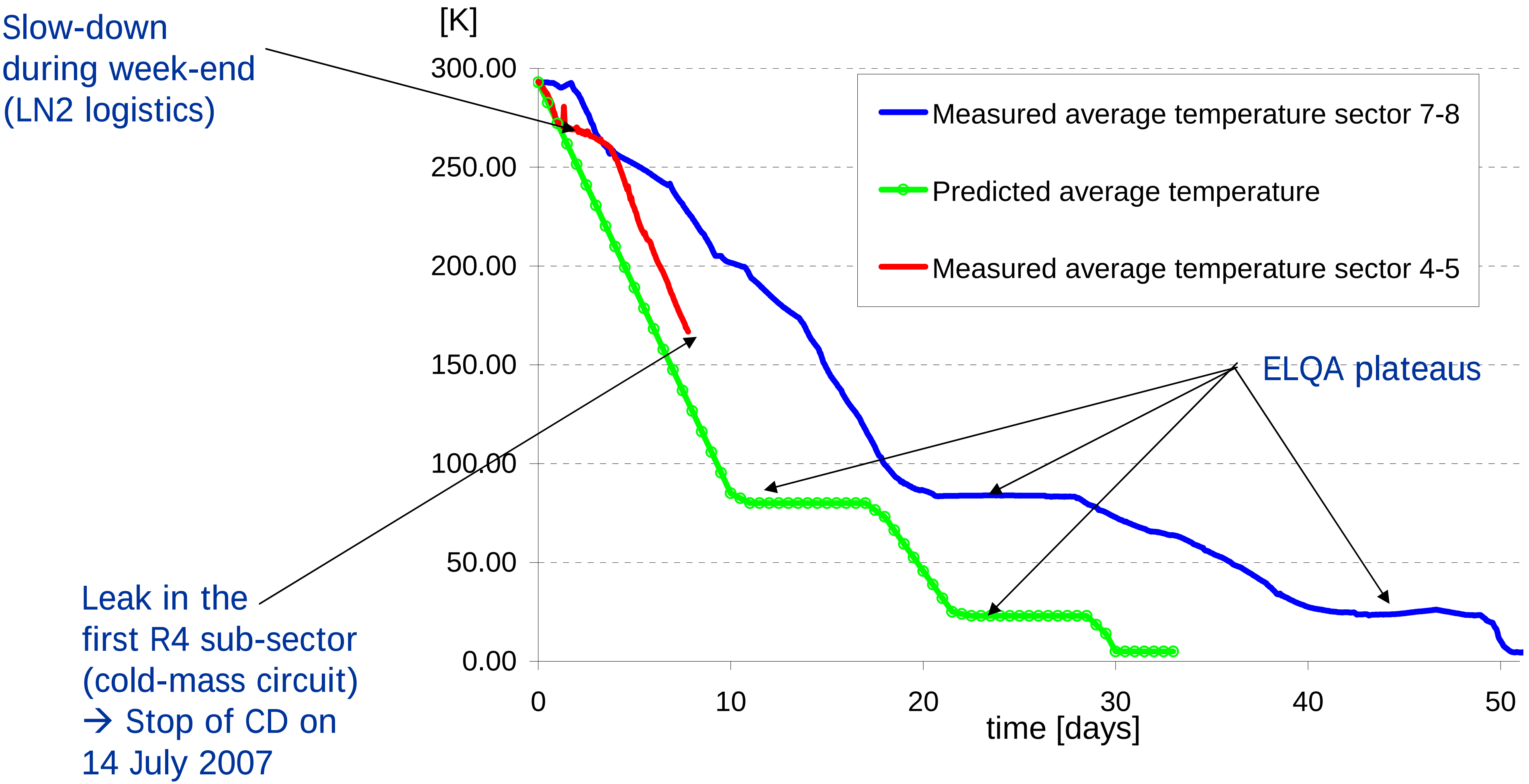
Simulation of 80-4 K cool-down



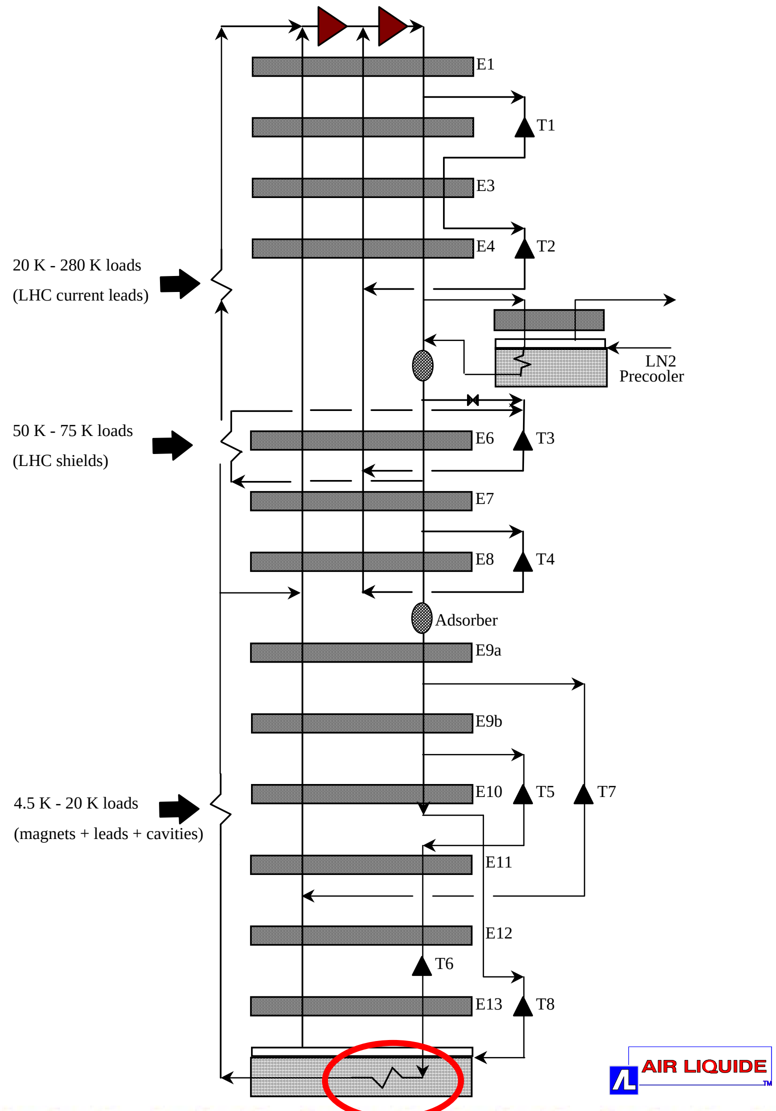
Calculated and measured results of the 1st normal CD from 80 K to 4.5 K

Learning process: better agreement for 2nd sector cool-down

- Effective cool-down started on Thursday 5 July 2007

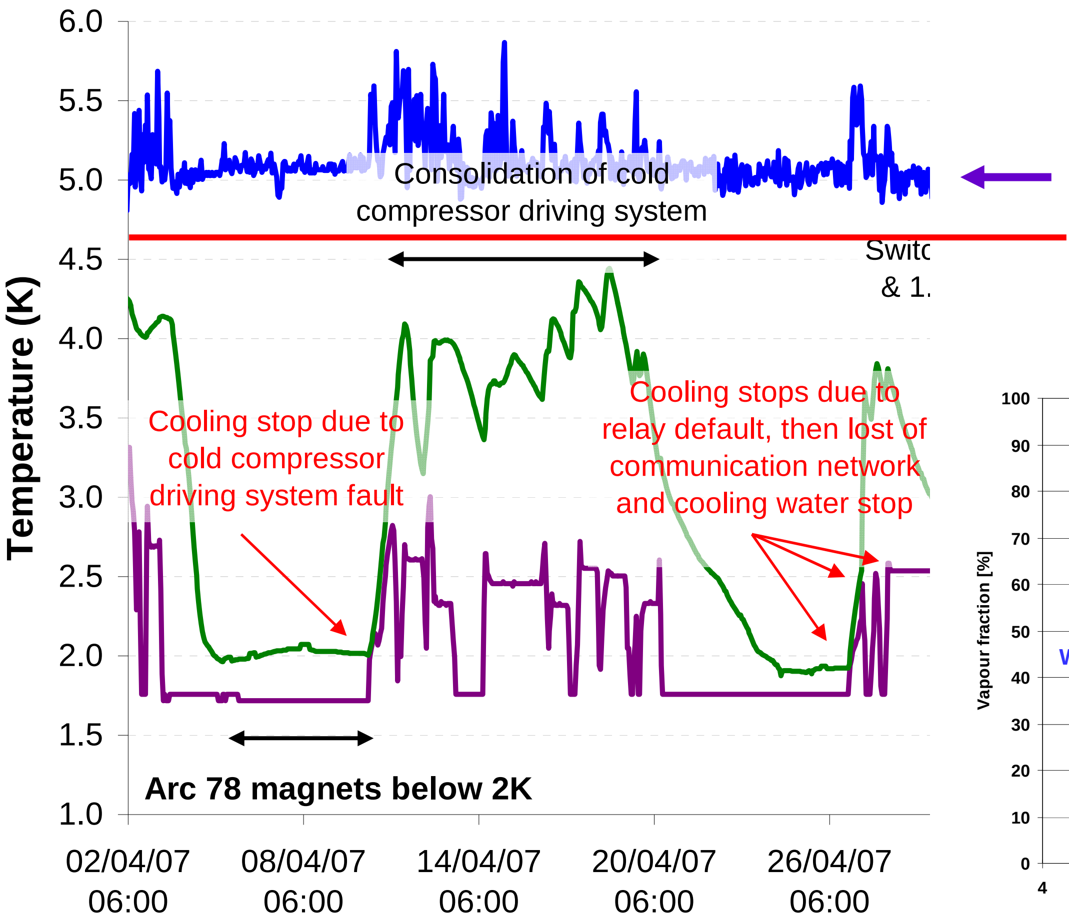


Problem with Ex-LEP cryoplant



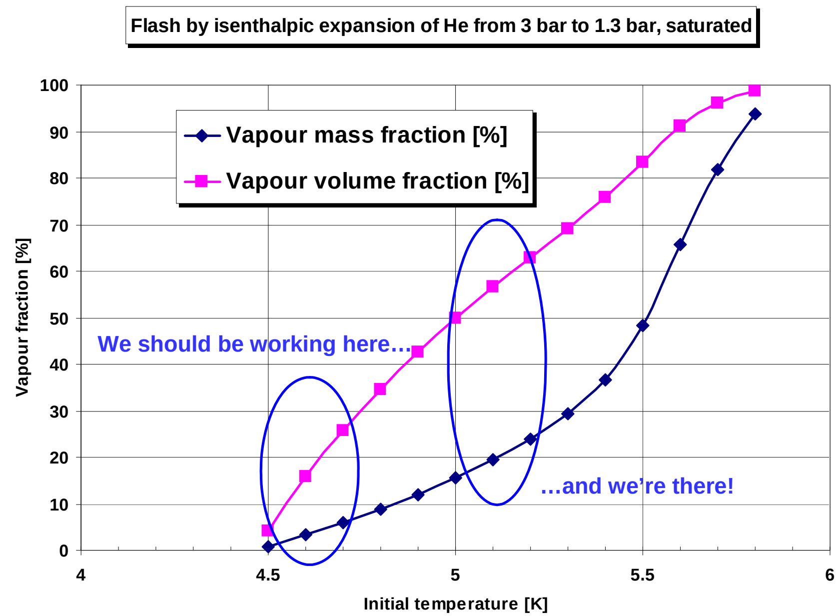
Sub-cooler recovered from LEP undersized:
→ too high tunnel supply temperature

Problem with Ex-LEP cryoplant



Too high temperature w/r to specification:

→ Important gas fraction in final expansion

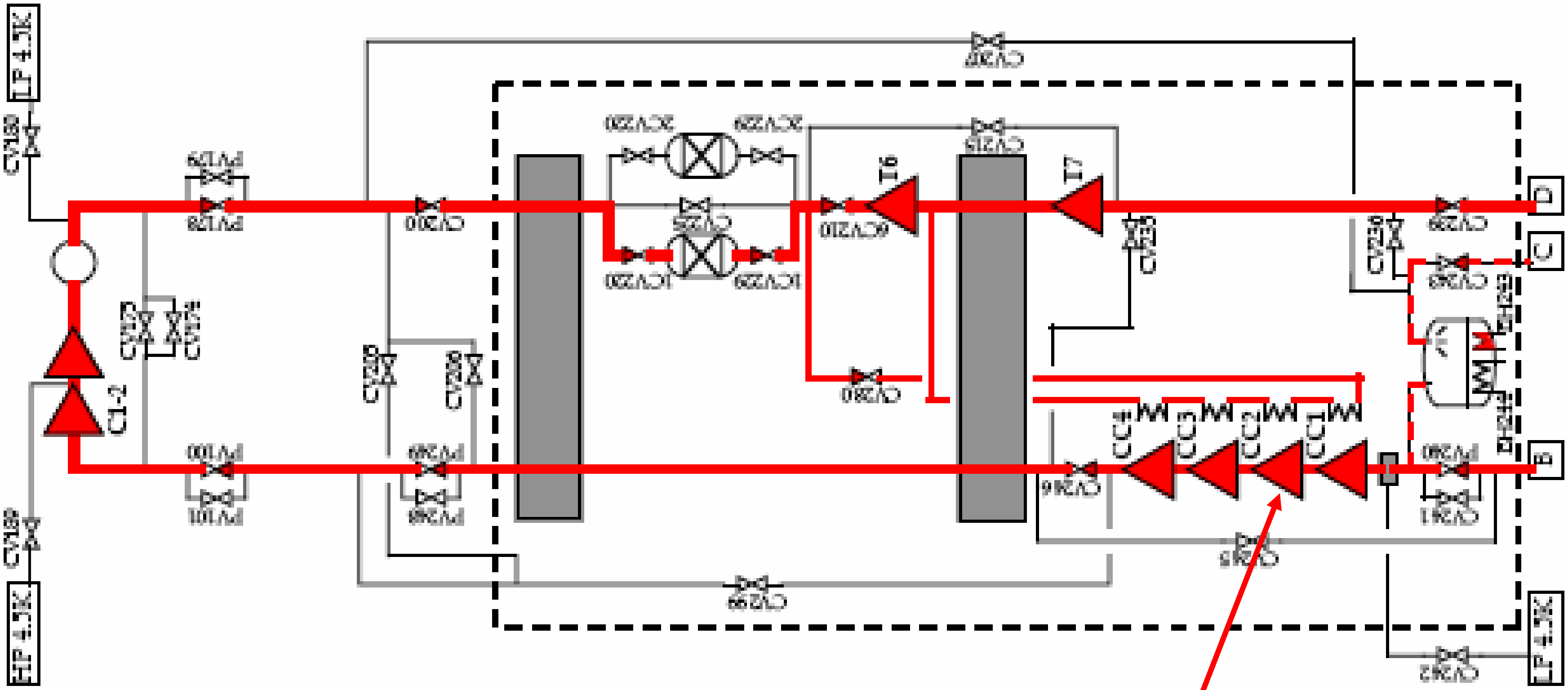


4.5 K refrigerator supply temperature

Magnet temperature (average over sector)

1.8 K refrigeration unit cooling temperature

Problem with the driving system of one cold compressor

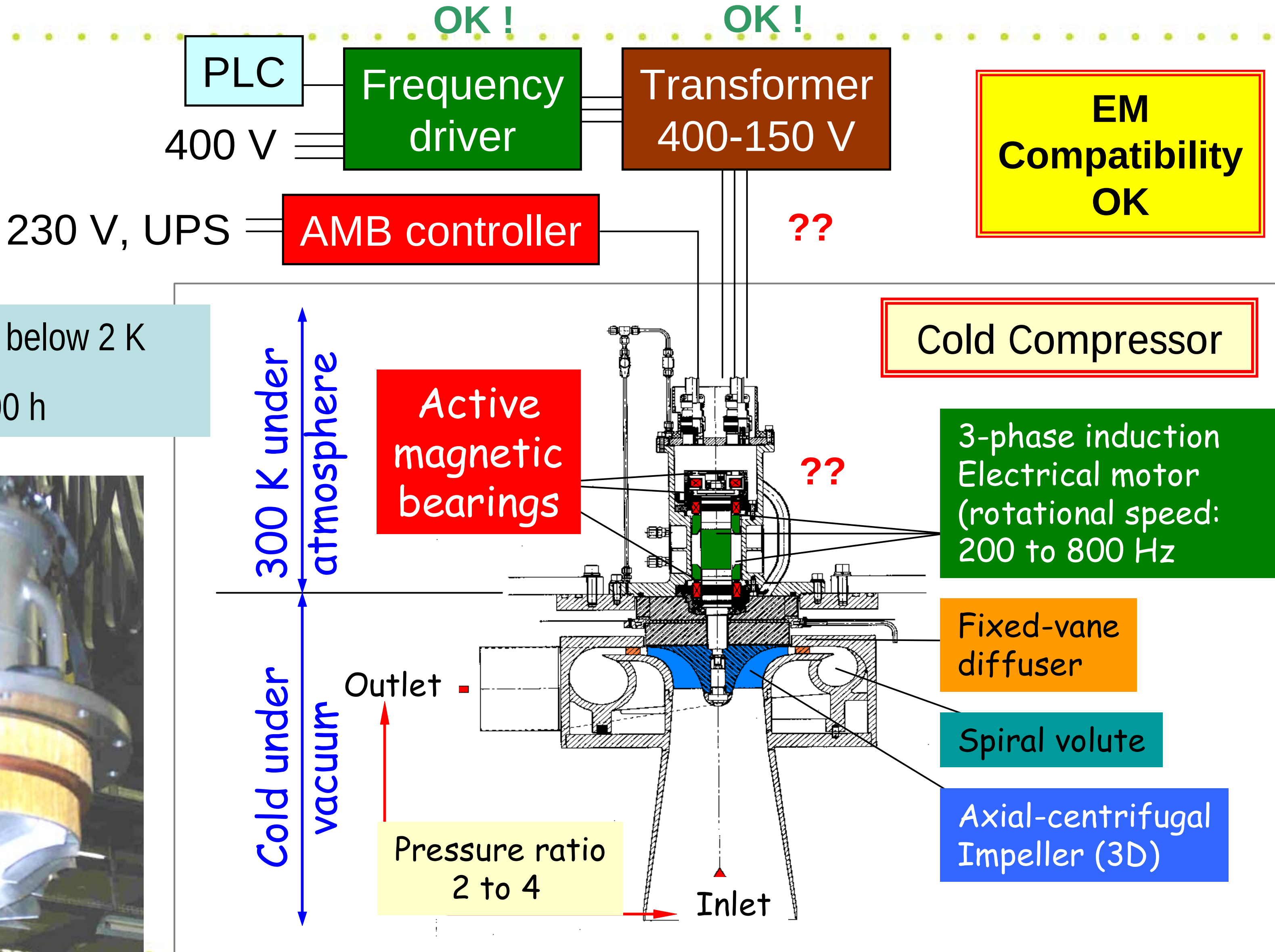


CC2 frequency-drive stops on « overload » after some time above some load

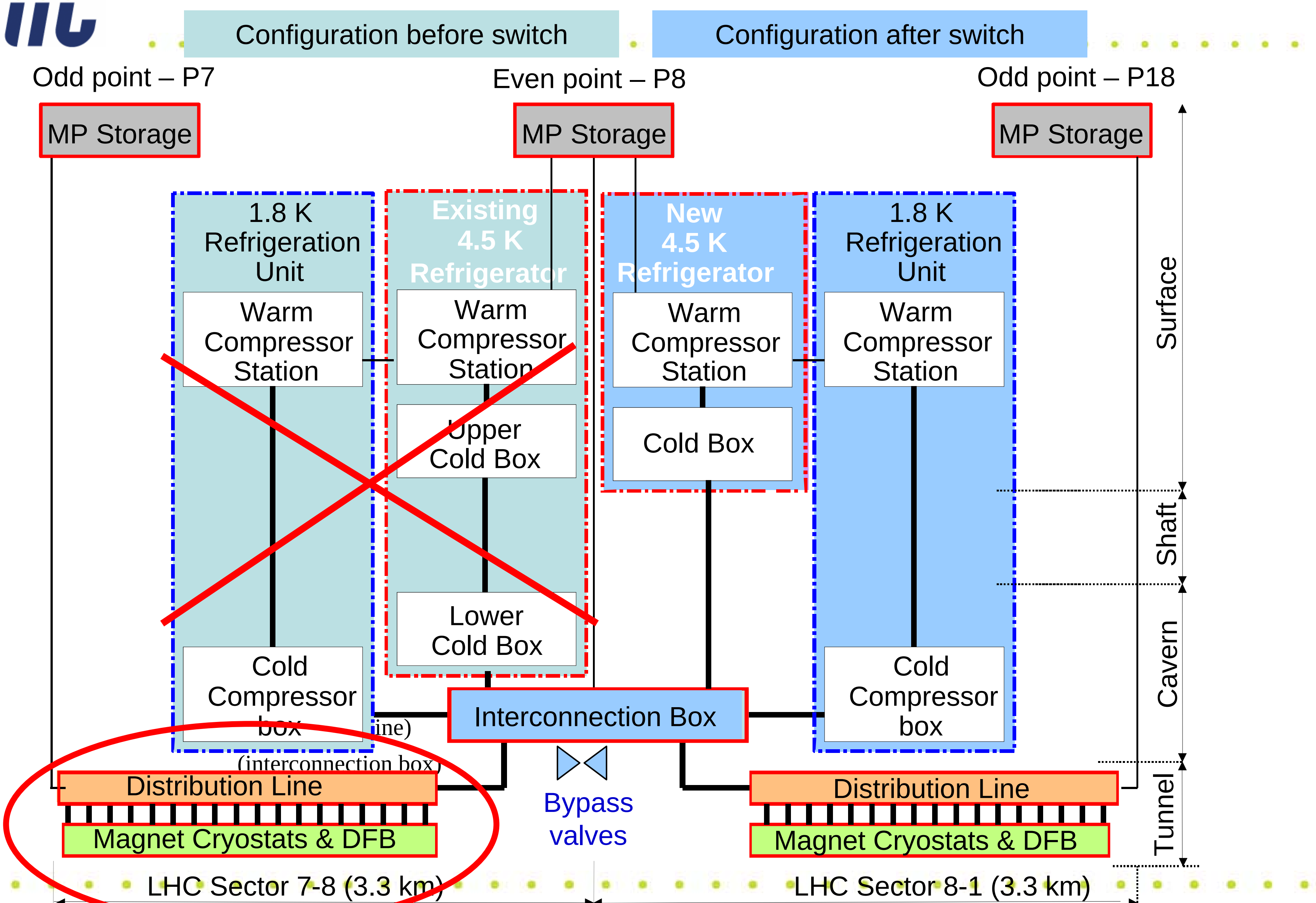
Cold compressor cartridge

Series: ≥ 1’000 h below 2 K

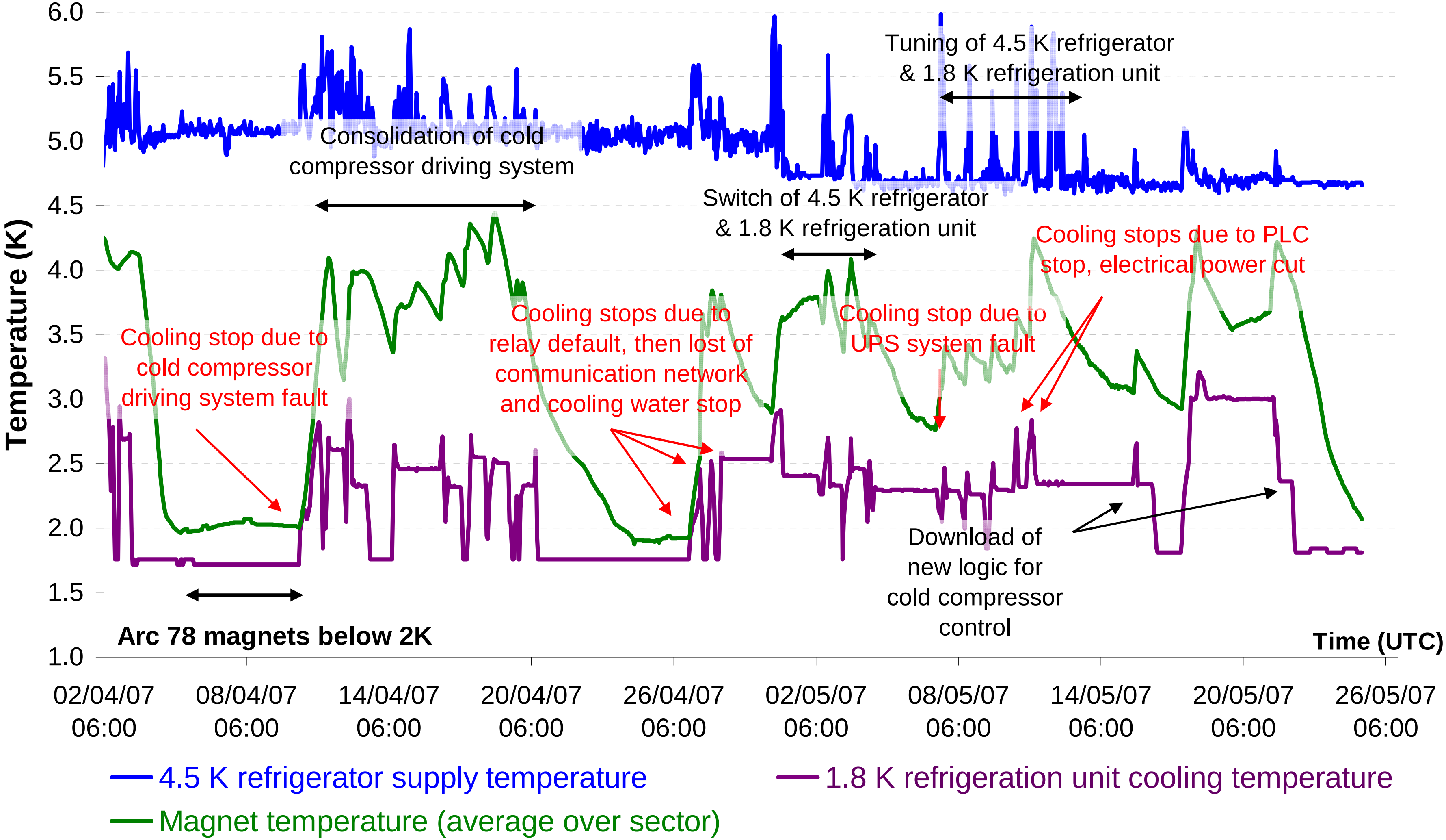
Loaded over 2’800 h



Switch of refrigerators: Validation of redundancy



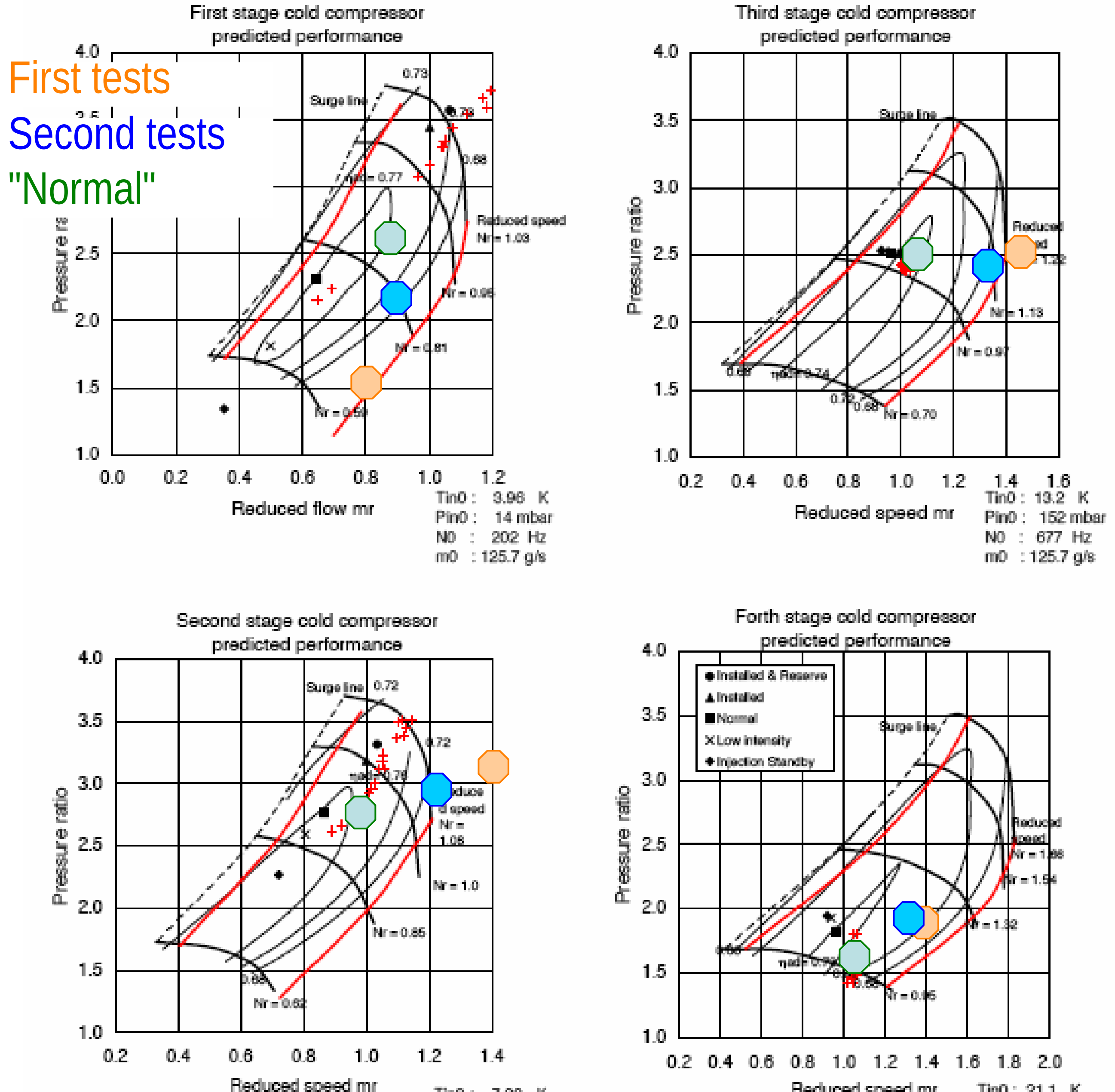
Improvement after refrigerator switch



2.3 - Cold compressor tuning

Problem with control algorithms which have to be adjusted to deal with faulty instrumentation (inlet temperature).

The use of mixing chamber and phase-separators to adjust the flow and the temperature was mandatory



$$Mr = \frac{M}{Mo} \times \frac{Po}{P} \times \sqrt{\frac{T}{To}}$$

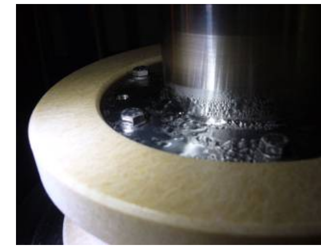
$$Nr = \frac{N}{No} \times \sqrt{\frac{To}{T}}$$

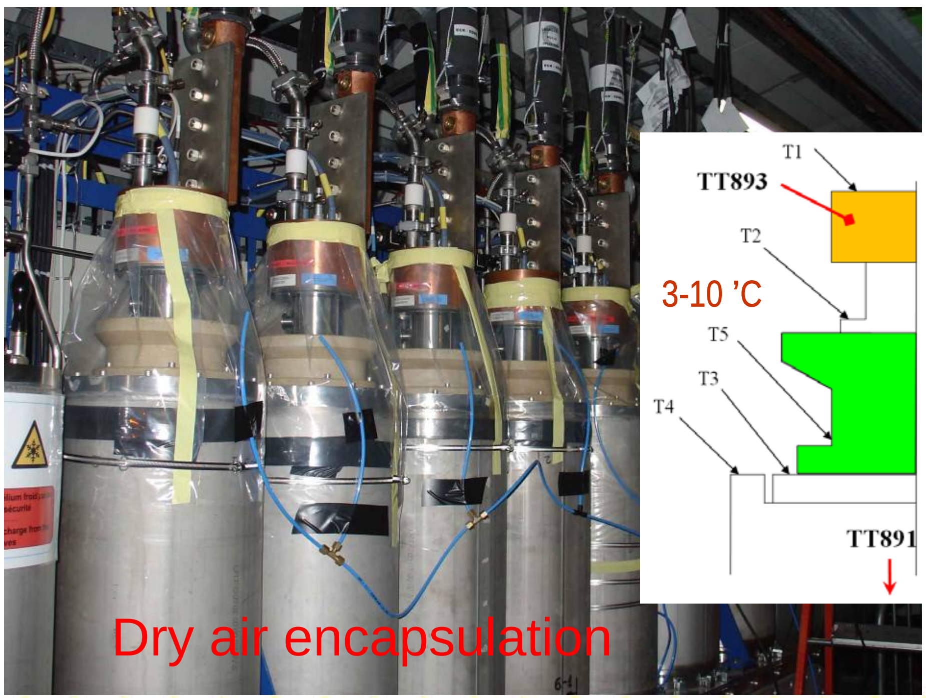
Machine tuning: Current feed boxes

- **No cold tests of these boxes before sector commissioning (skipped for time and resource saving).**

- **Condensation problems at the top of chimneys (very humid condition in tunnel).**

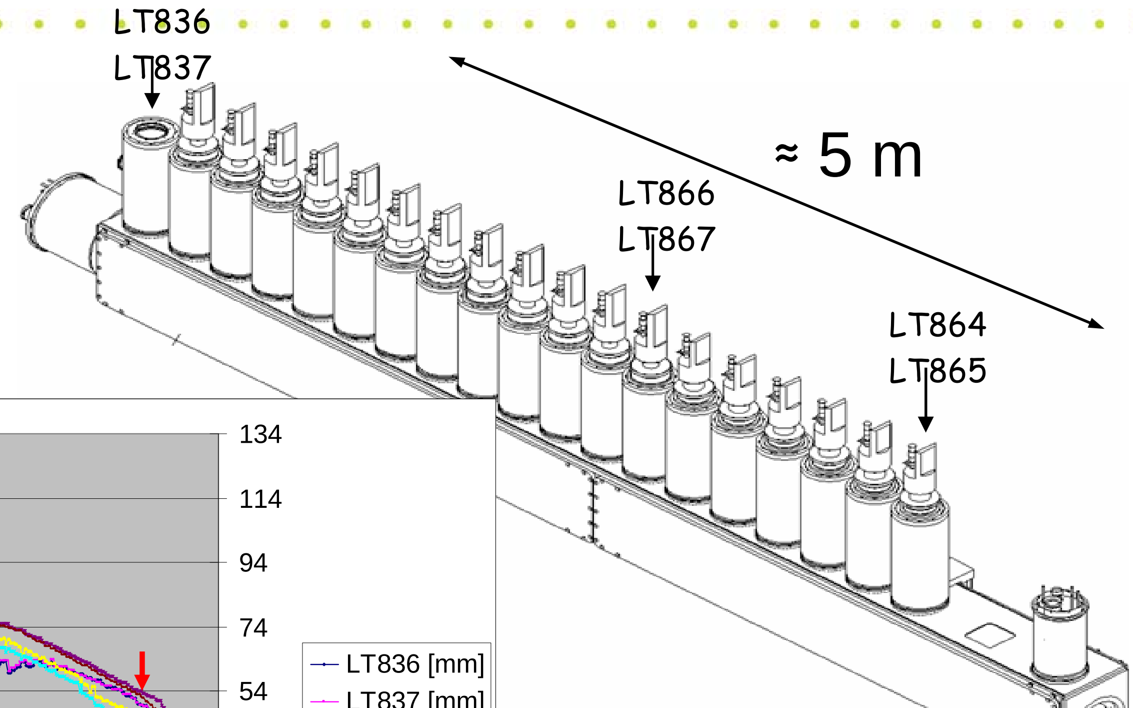
- **Identical problem for the 60 A leads distributed in the tunnel**

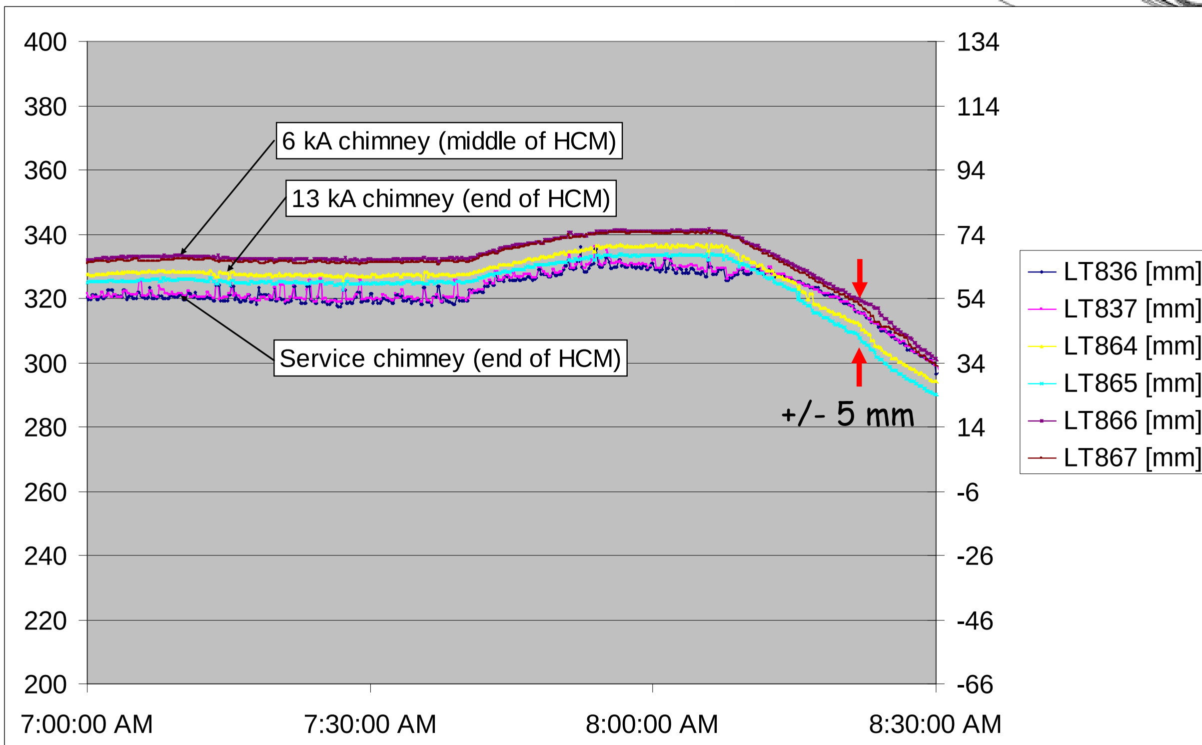


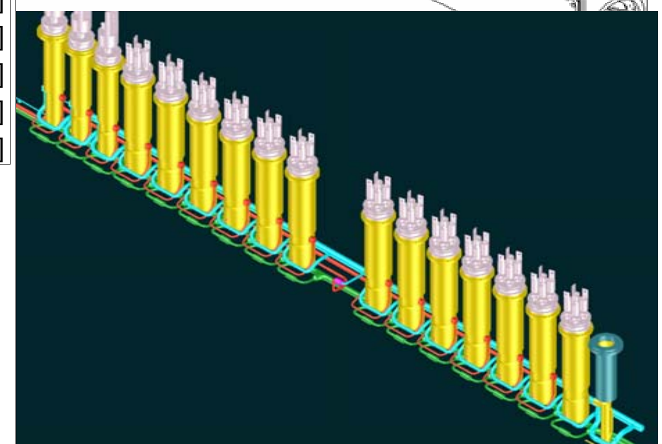


DFB Commissioning – level validation

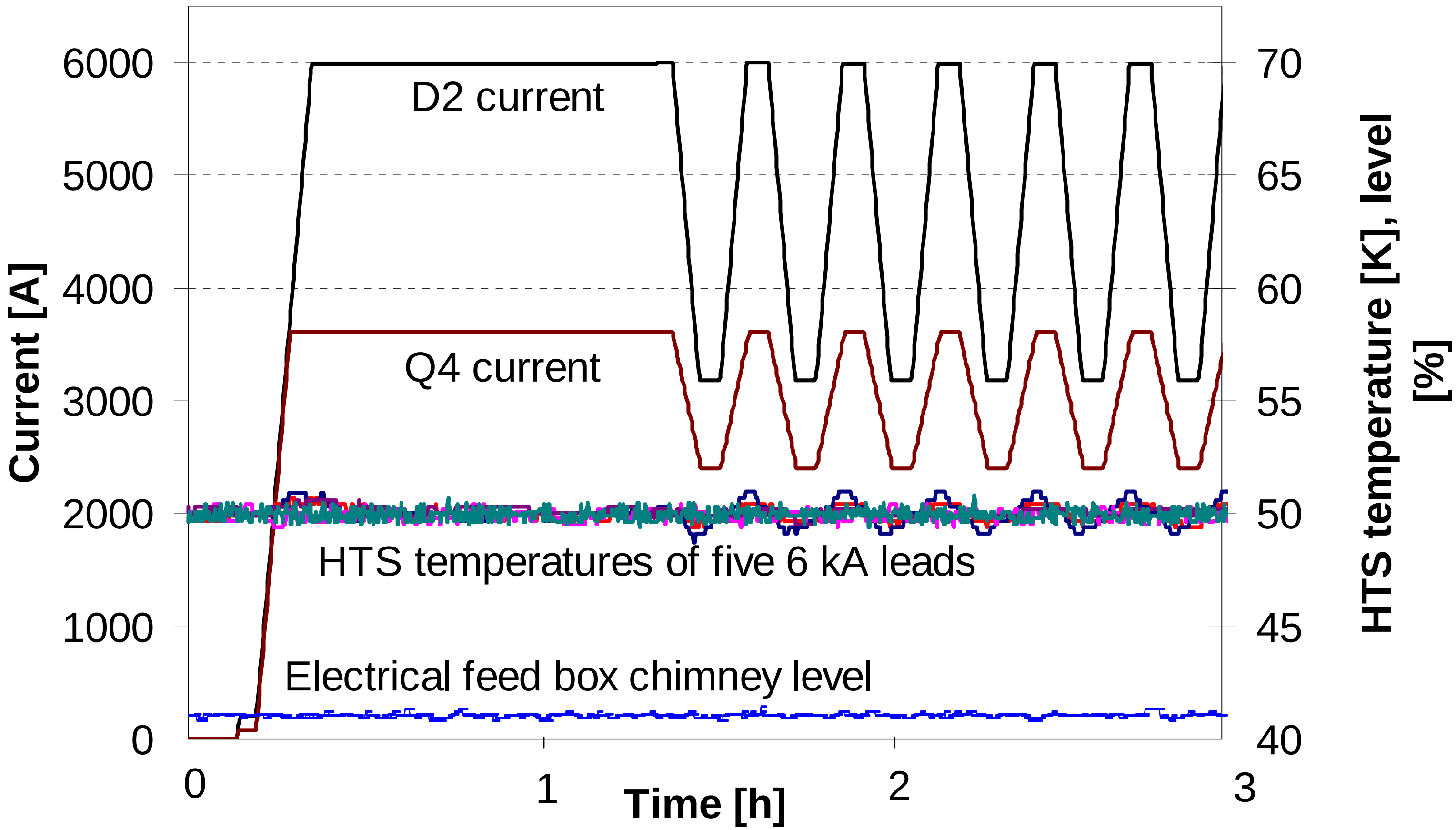
Good global behaviour of level sensors DFBAO





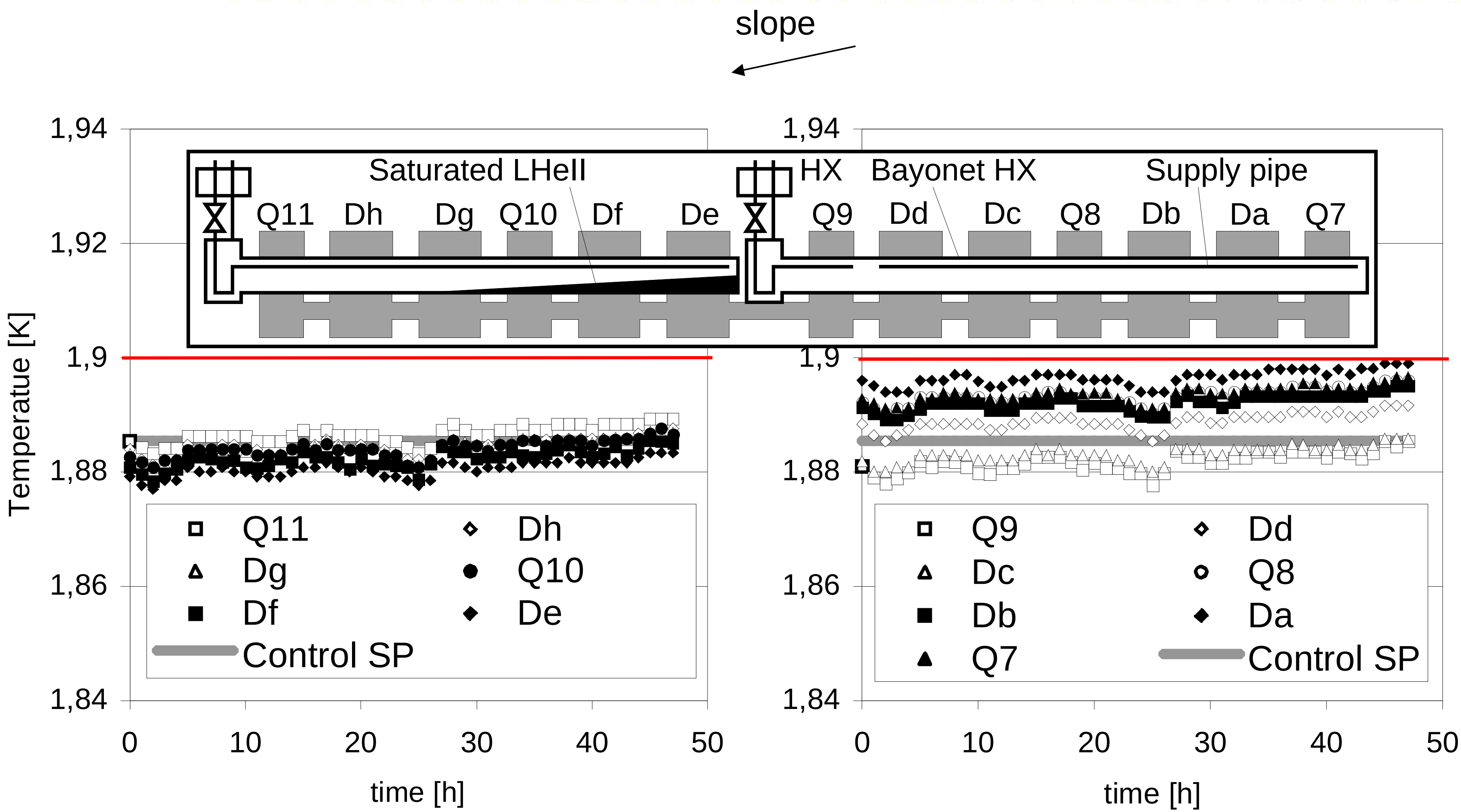


Steady-state: current leads



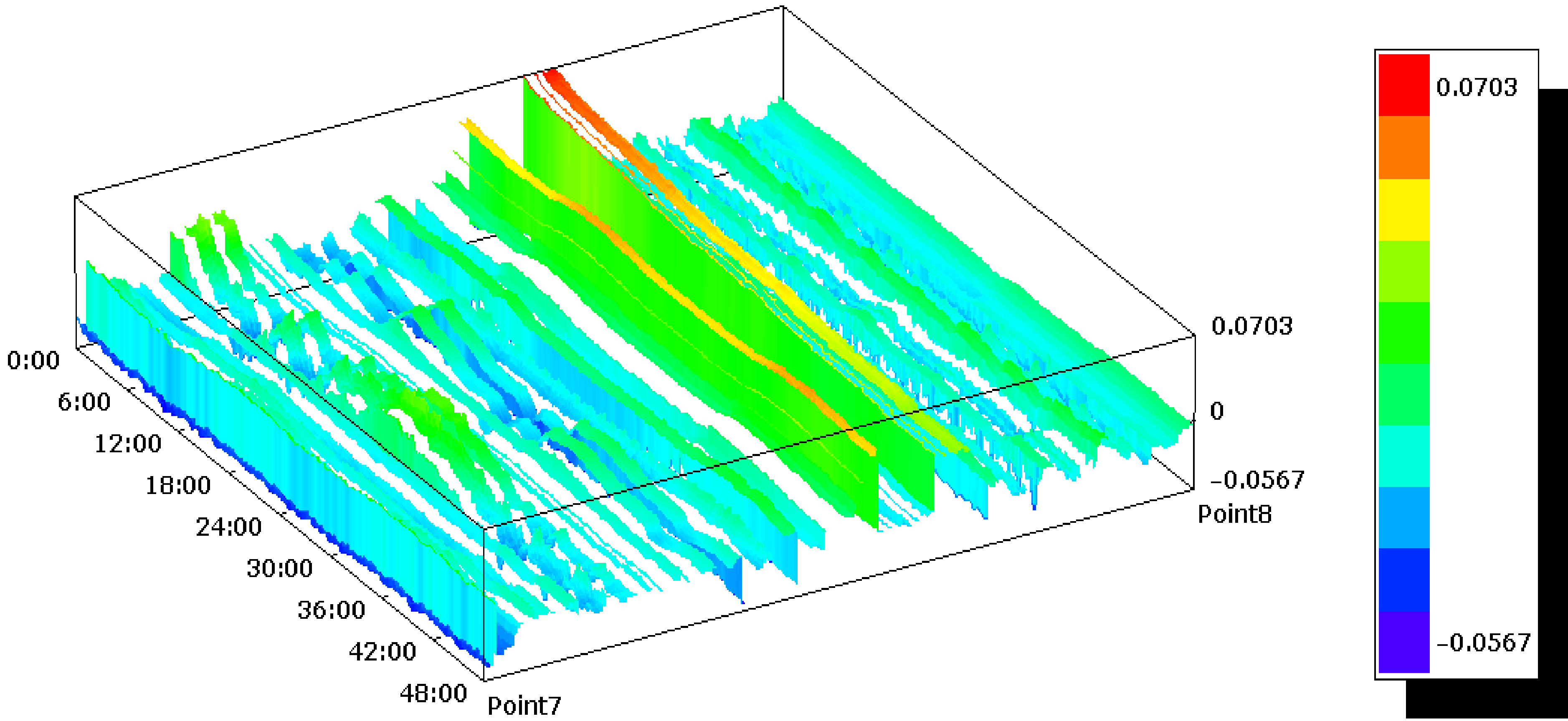
- Extensive calibration program for the liquid helium level gauges
- Once commissioned, successful operation at nominal conditions

Steady-state cold-mass temperature

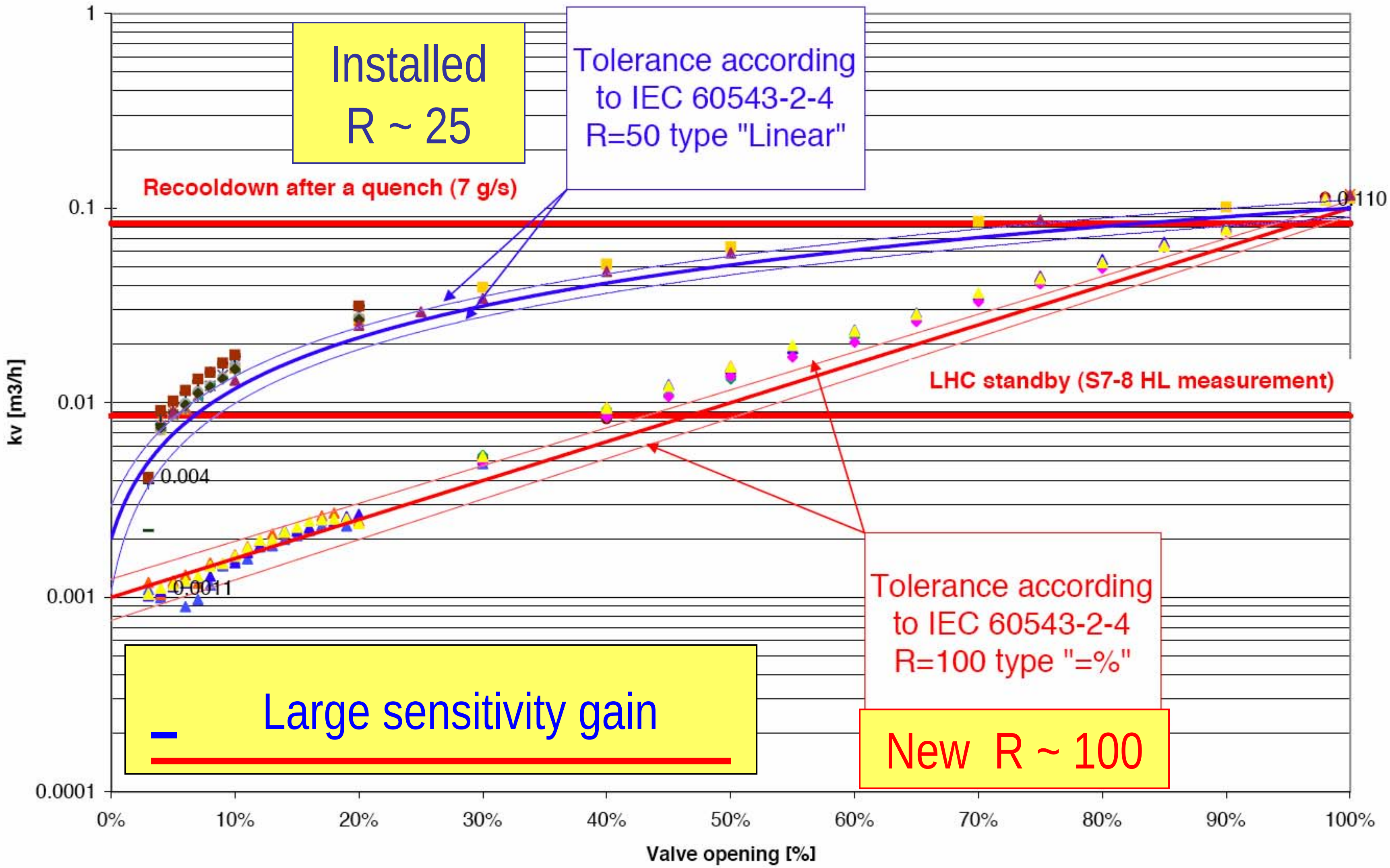


Validation of cell cooling redundancy !!

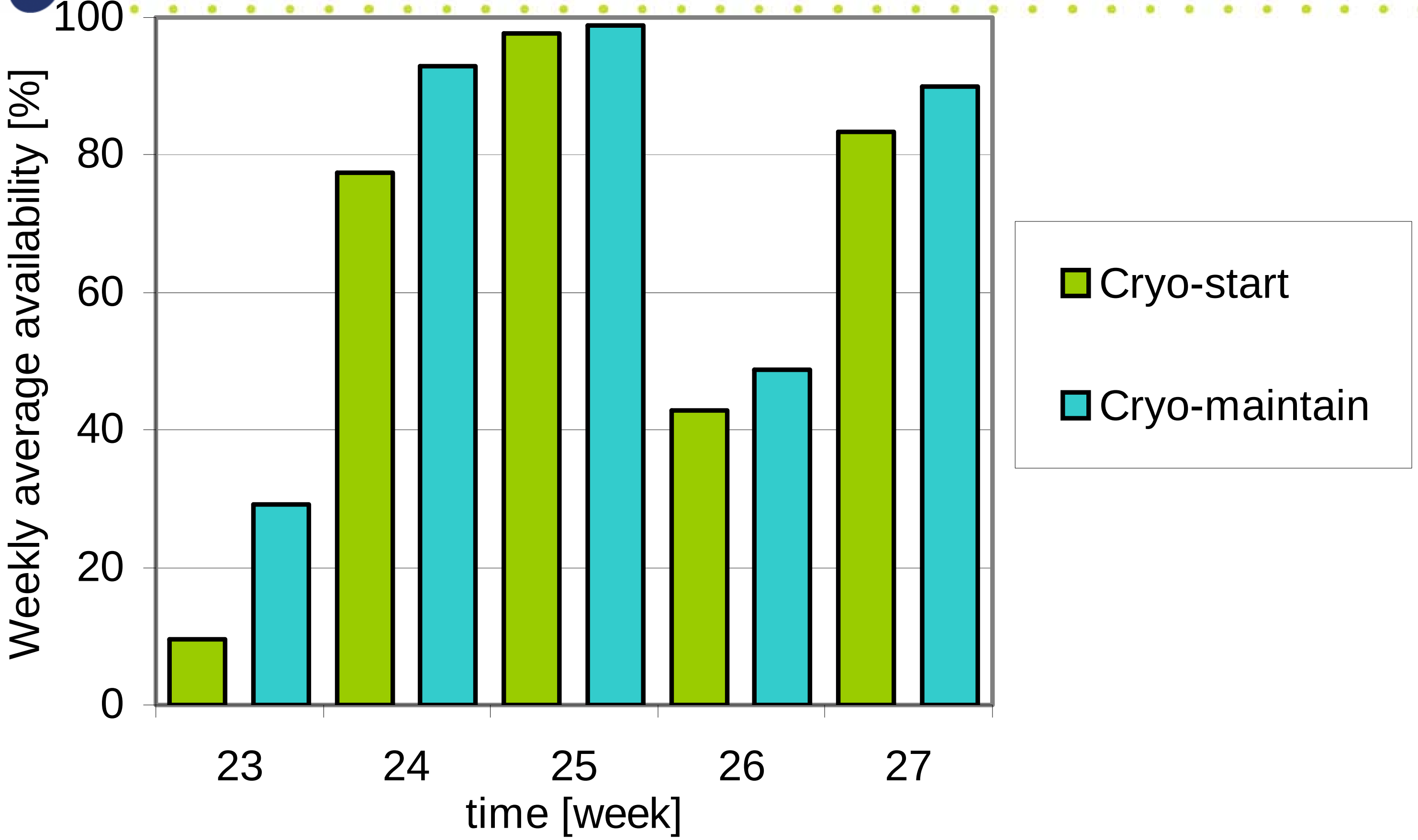
Steady-state: magnets cooling



JT valves: Flow caracteristics

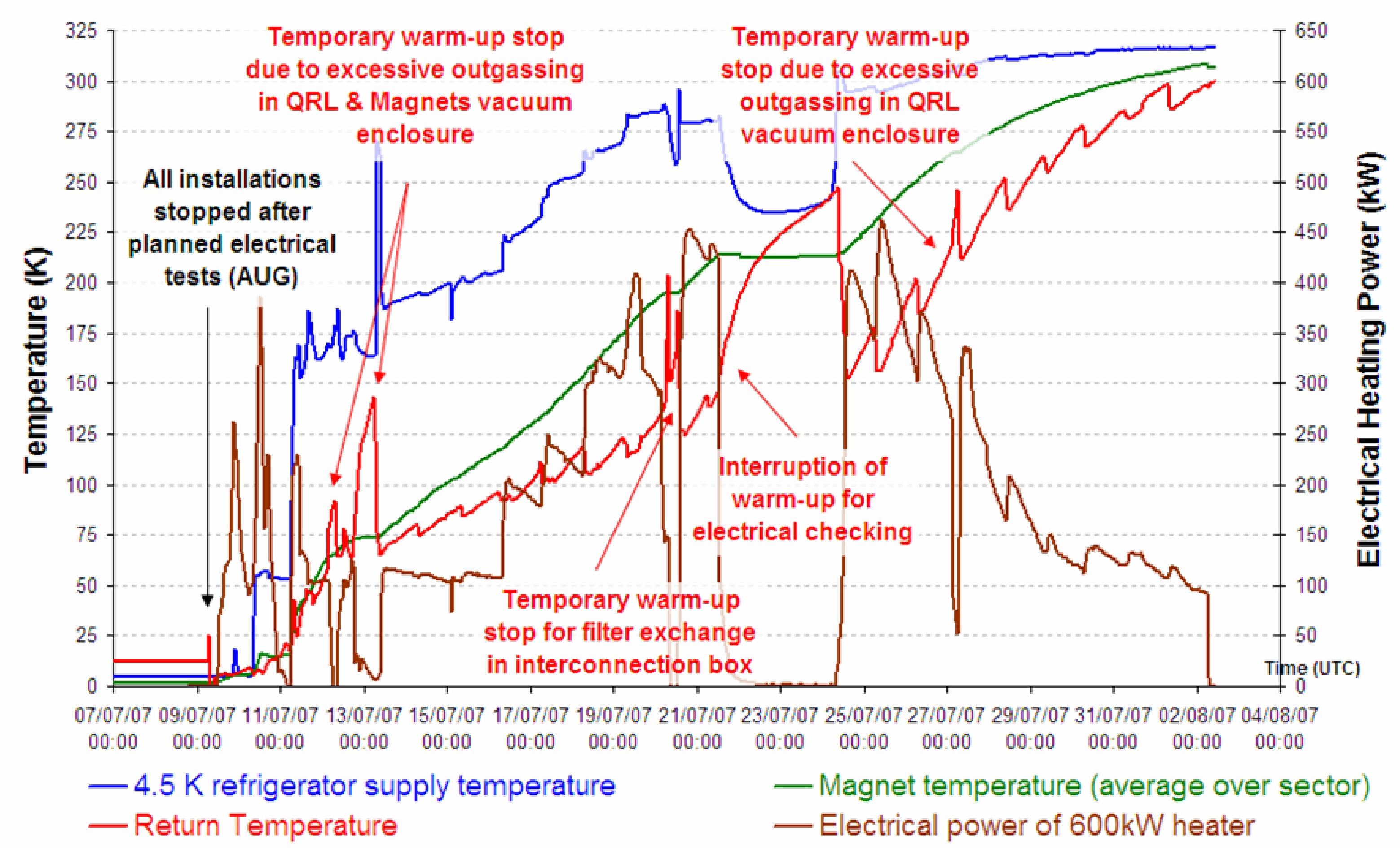


Availability during arc powering test



CW23: Deactivation of Cryo-start during the night and instrumentation (heater) problem
CW24 & 25: Mainly ELQA and powering w/o quenches
CW26: Problem with electrical supply on the PLC of the 4.5 K refrigerator
CW27: down-time due to quench recovery

First sector warm-up



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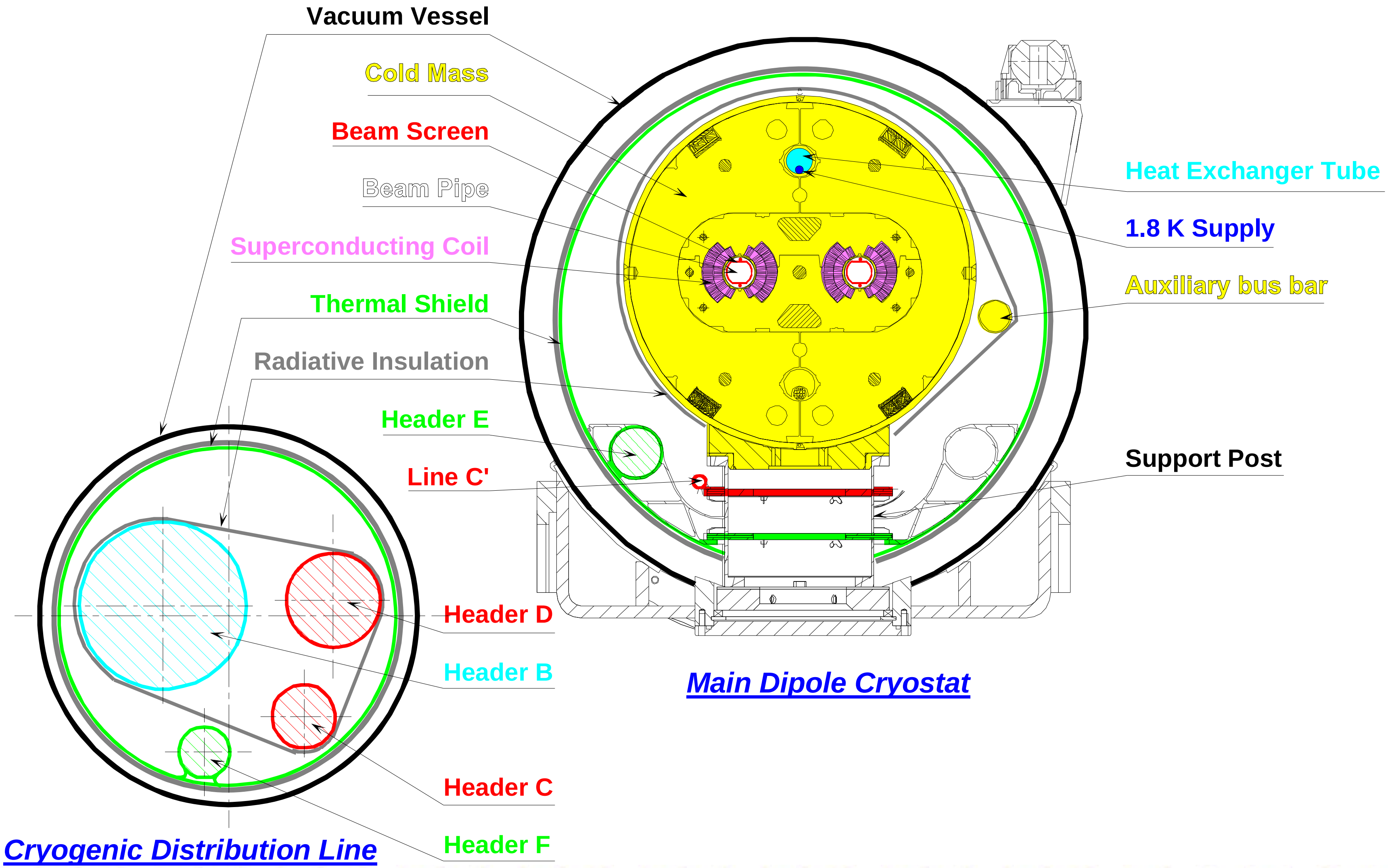
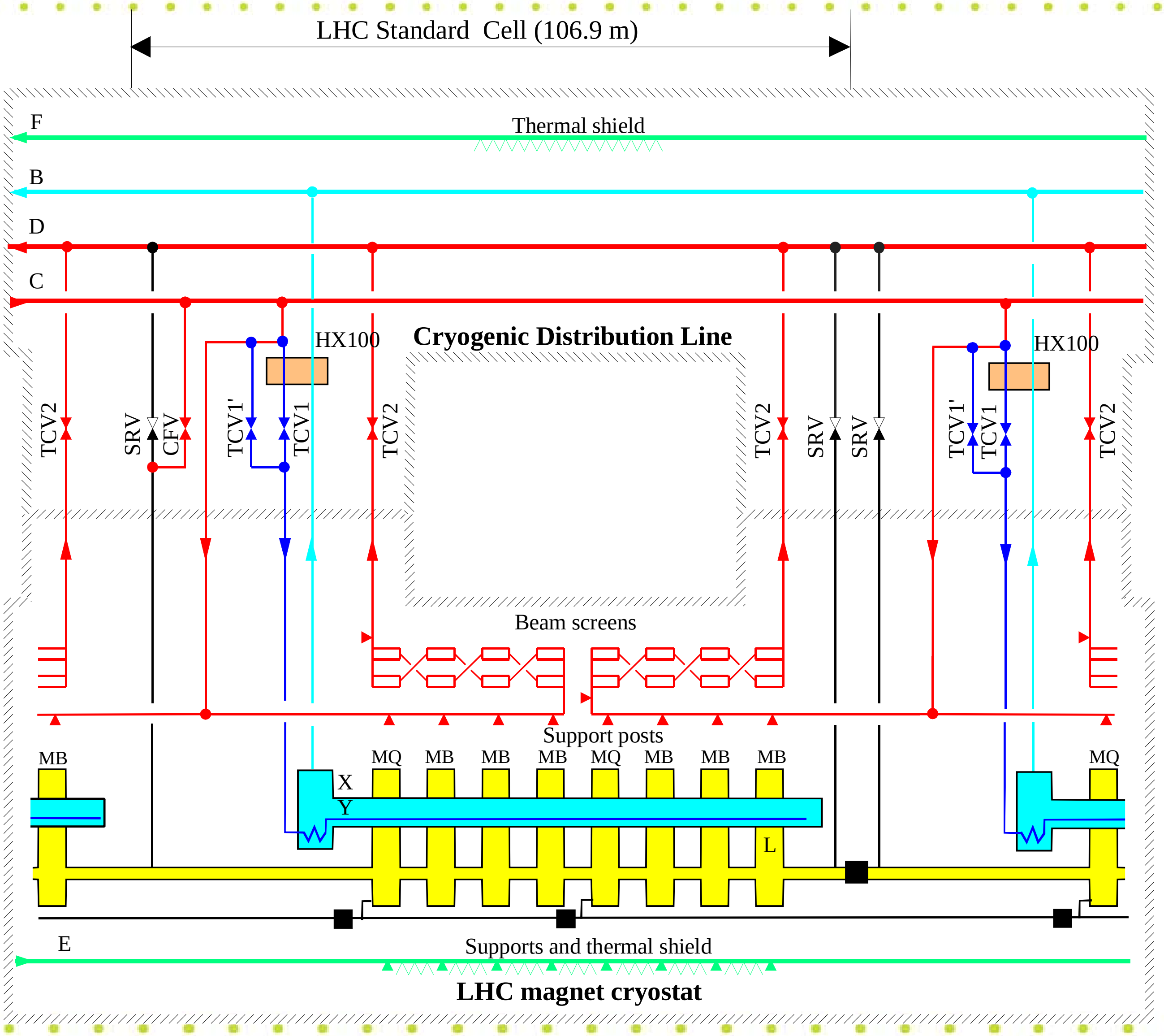
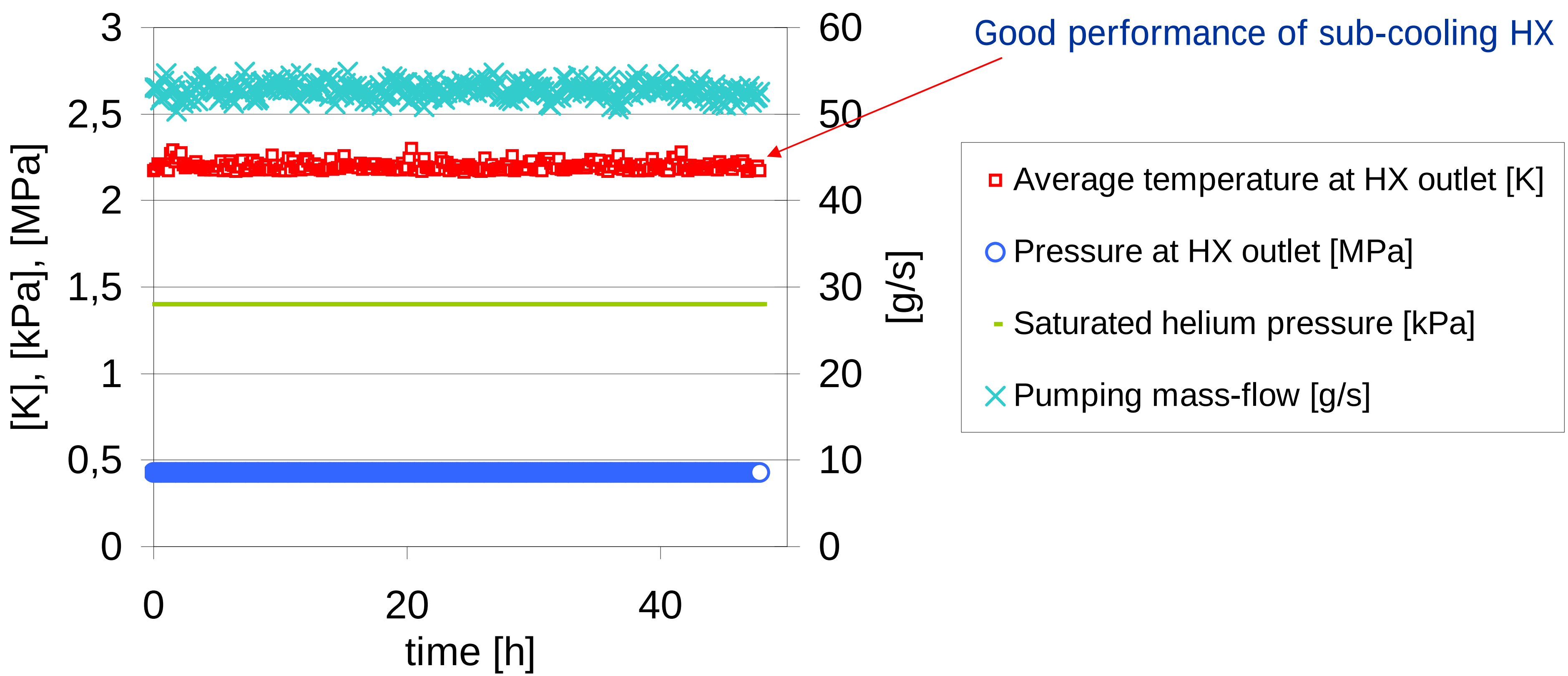
Typical LHC cross-section



LHC cooling flow-scheme



Heat inleaks on cold-mass circuits Measurement by global assessment

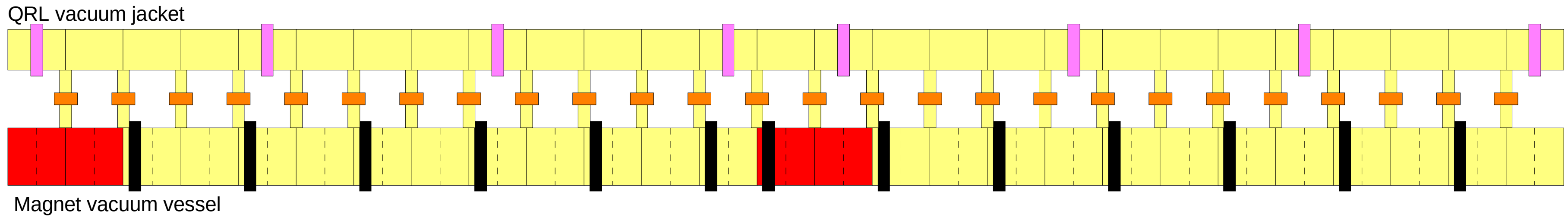


Total heat load 961 W including 401 W of additional electrical heating
→ 560 W of heat inleaks at 1.9 K, i.e. 0.2 W/m (0.21 W/m calculated w/o contingency for a standard cell by the Heat Load WG)

Vacuum & cold-mass sub-sectorization

Vacuum sectorization:

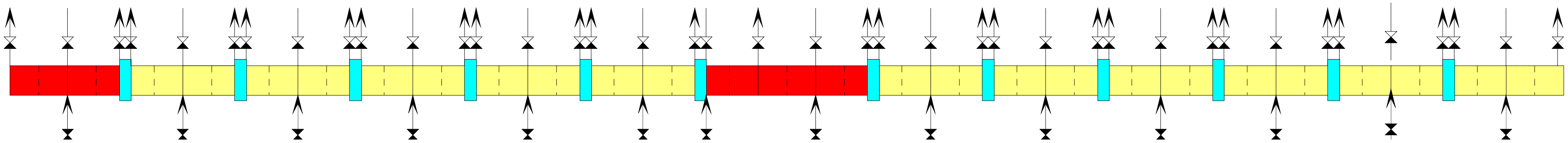
Magnet vacuum barriers — Jumper vacuum barriers — Cryogenic line vacuum barriers



Cold-mass sectorization:

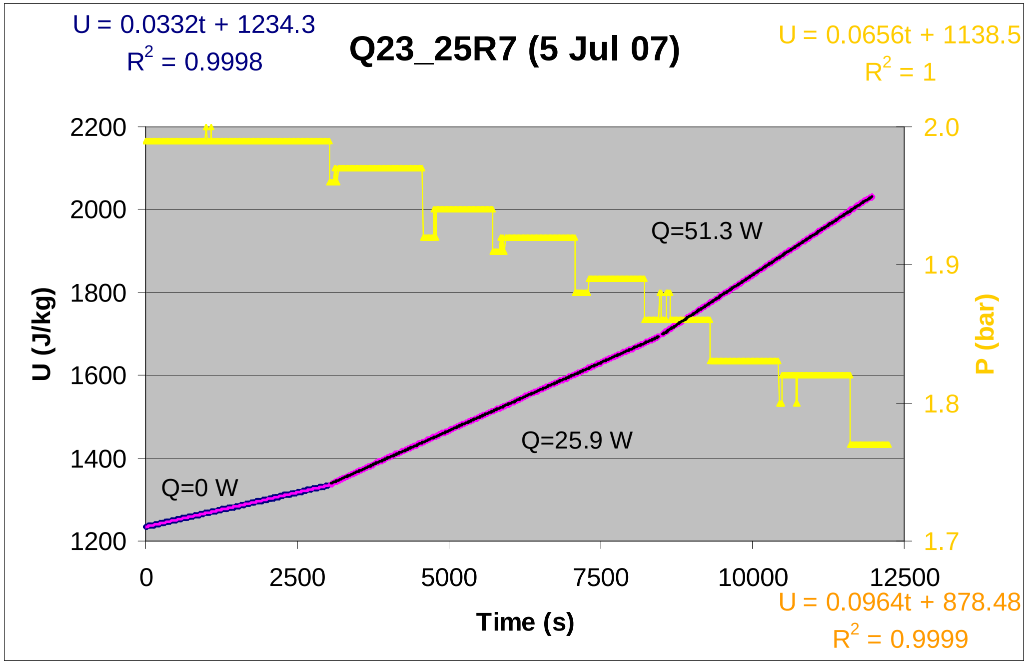
Bad vacuum (Helium leaks)

Bus-bar plugs — Safety relief valves — Cooldown and fill valves



20 % of the sector was not operating at nominal insulation vacuum creating extra heat inleaks (factor 2 to 3 according to valve opening), i.e. nominal sub-sectors have probably smaller heat inleaks than expected by the HLWG.

Heat inleaks on cold-mass circuits Local measurement on sub-sectors



Measurement by variation of internal energy during a natural warm-up of a sub-sector in superfluid state.

Applying a known power allows to assess also the He content

Sub-sector	Q [W]	q [W/m]	V [l/m]
Q27_29 R7	27.0	0.13	24.8
Q23_25 R7	26.9	0.13	25.4
Q15_17 R7	27.9	0.13	24.3

Uncertainty: +/- 2 %

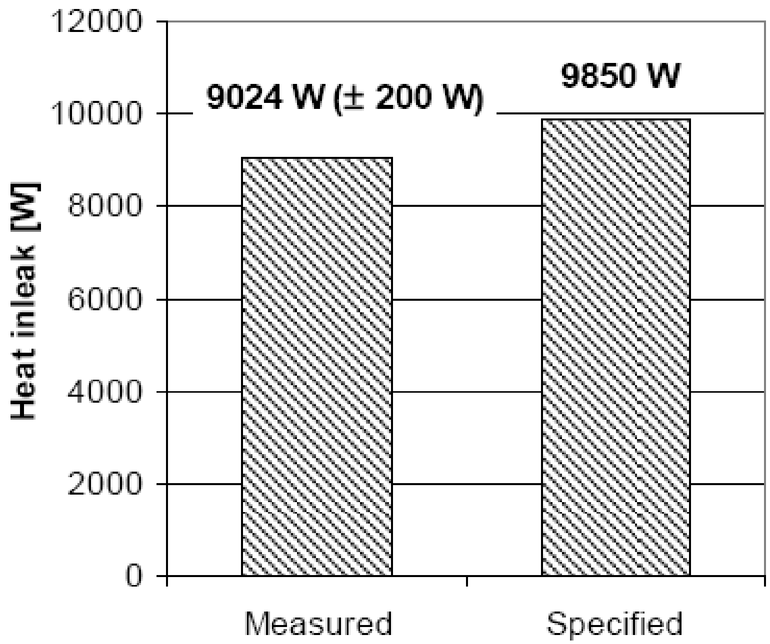
- He content: in accordance with the calculation and warm measurements
- Distributed heat inleaks: 33 % lower than expected by HLWG (but the shields were colder in average by about 5 K)

Heat inleaks on thermal shield circuit

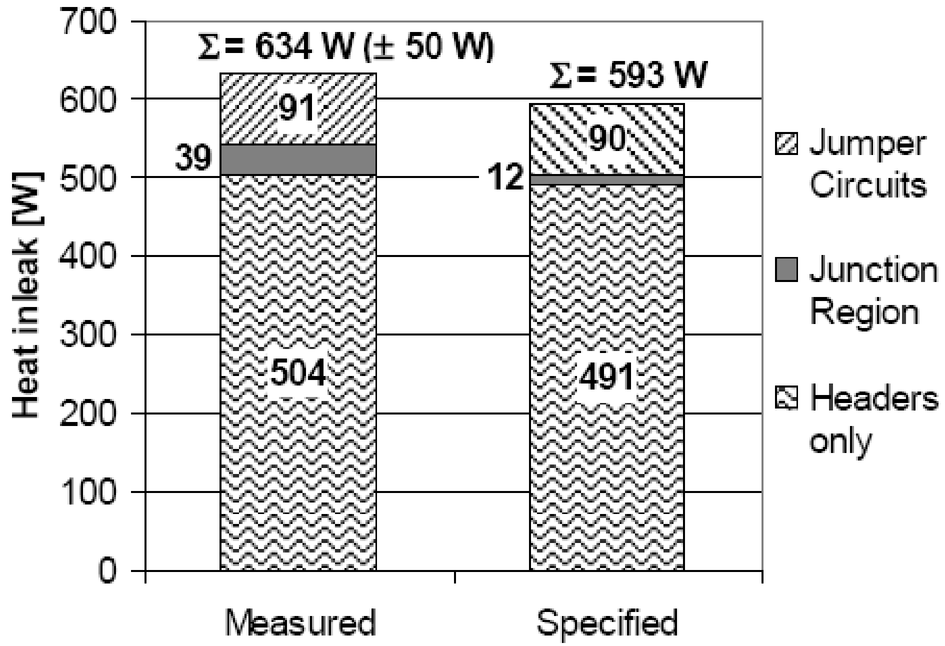
- Global measurement by enthalpy balance at the cryoplant interface:
  - 19.8 kW measured to be compared to the 23.5 kW assessed by the HLWG.
  - i.e. 6.6 W/m measured to be compared to 7.7 W/m assessed by the HLWG (15 % lower than expected)

QRL heat inleaks measurement

Measured done on a QRL sector (S8-1) without magnets



Thermal shields
About 2.7 W/m



Cold headers
About 0.19 W/m

Distributed static heat in-leaks in a standard cell [W/m]

Temperature level	50-75 K		4.6-20 K		1.9 K LHe		4 K VLP GHe	
	C	M	C	M	C	M	C	M
Magnet side	4.5	3.9	0.14	?	0.19	0.13*	N/A	N/A
QRL side	3.2	2.7	0.09	0.09	0.02		0.11	0.10
Total	7.7	6.6	0.23	?	0.21	0.13*	0.11	0.10

C: Calculated (HLWG)
M: Measured

*: with colder thermal shield temperature

Very good agreement between calculations and measurements.

- But a lot of effort in component testing (thermal model, pre-series, string tests…)
- And a global management in a Heat Load WG (2 years of active work)

Conclusion

- LHC enters its last exciting commissioning phase.
- The construction phase confirms that contingency are mandatory to deal with the learning process and problems. Do not forget quality inspection and contingency.
- Cryogenic commissioning of the first LHC sector done:
  - **No “big” surprise / mistake, but some “small” consolidation identified.**
  - **Tuning of cryogenics of this complex system takes more time than foreseen/allowed**
- Heat inleaks are as expected thank to the preliminary work on the thermal validation.
  - **Waiting for dynamic heat load measurement to have the complete picture. (e-clouds remains a big uncertainty)**