Superconductivity and Cryogenics at CERN

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LHC Cryogenics Operation

With valuable input from L. Tavian & A. Perin for their study on similar topic published March2010, EDMS 1063910

IASS POTSDAM

Institute for Advanced Sustainability Studies e.V.

Abstract

Superconductivity and associated cryogenics have been used at CERN since the sixties, with a sharp rise in capacity and size for the LEP200 project and more recently for the LHC.

The actual achievements for LHC will be presented, with the emphasis on the approach used towards efficiency and availability.

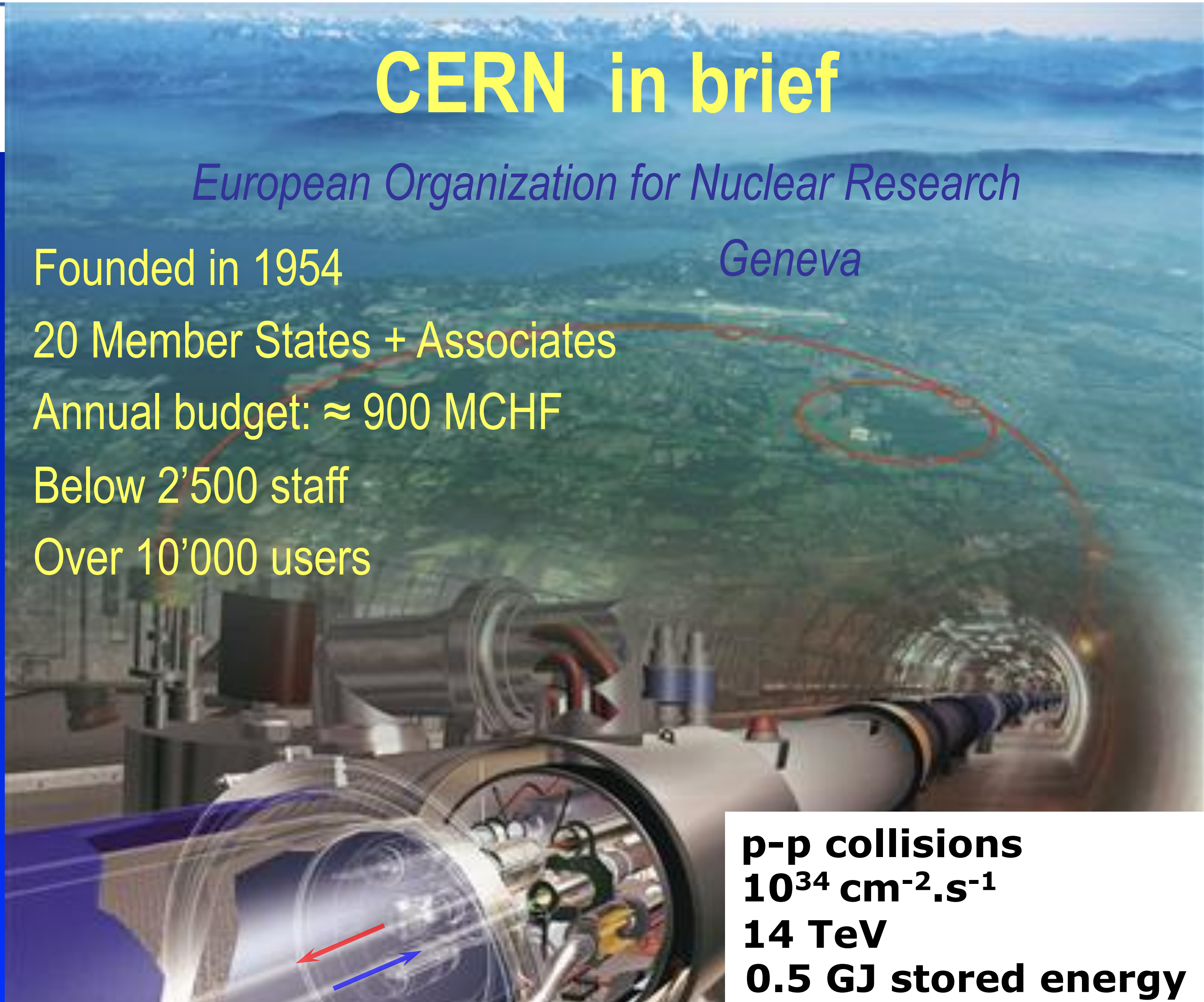
Perspectives for power distribution applications will be proposed, considering operational constraints transposed to long power lines.

Outline

- Introduction to CERN and LHC Cryogenics
- Relevant hardware and key performance
- Operation, maintenance organisation and results so far
- Perspectives for superconducting power lines
- Summary

CERN in brief

European Organization for Nuclear Research

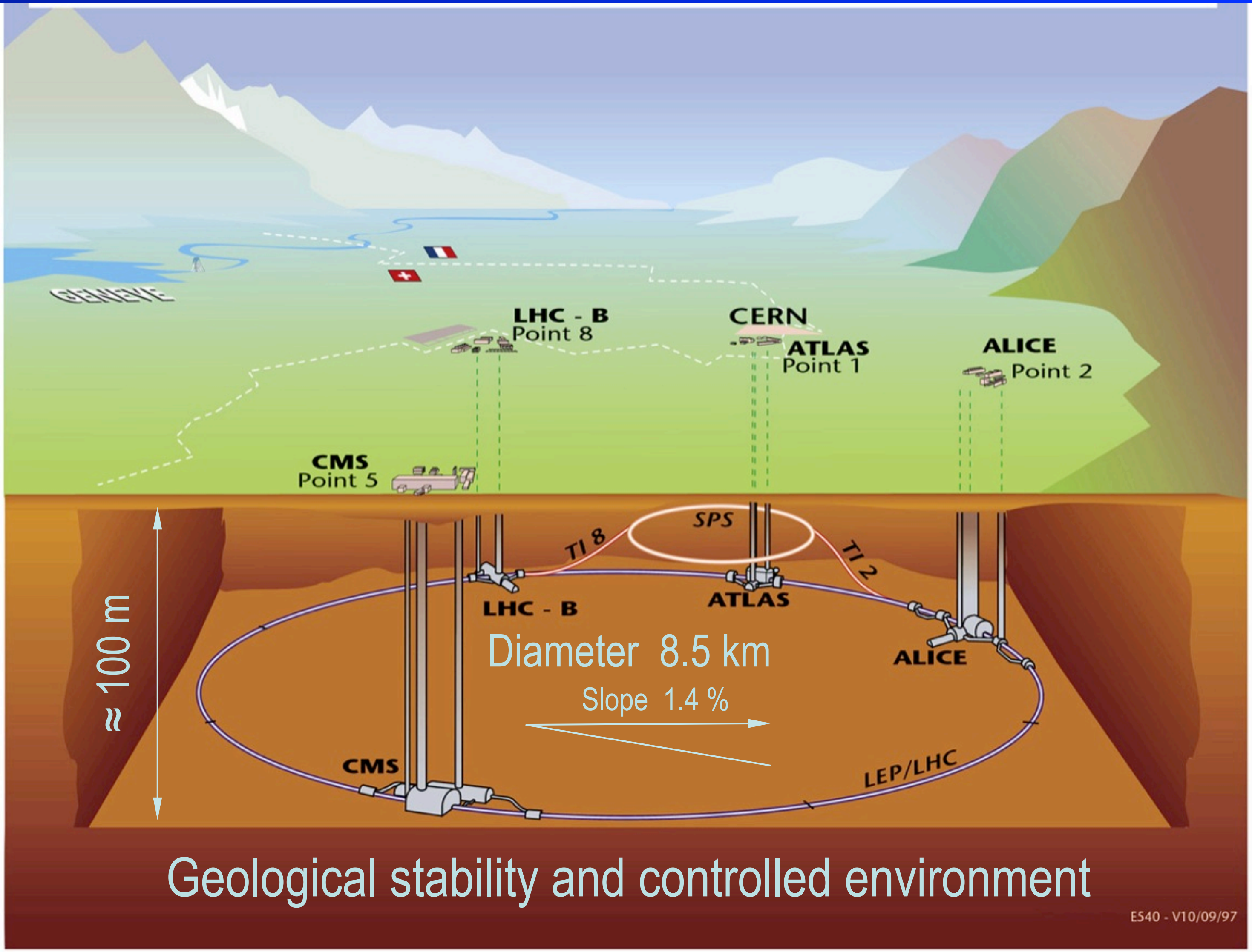


- Founded in 1954
- 20 Member States + Associates
- Annual budget: ≈ 900 MCHF
- Below 2’500 staff
- Over 10’000 users

p-p collisions
10^{34} cm^{-2}.s^{-1}
14 TeV
0.5 GJ stored energy

24 km of superconducting magnets @1.8 K, 8.33 T

Overall layout of LHC and its detectors



Main reasons to superconducting

For accelerators in high energy physics

- Compactness through higher fields

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

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

Capital Cost

Not really the case for power lines

- Saving energy

Electromagnets:

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

Superconducting: $P_{input} \approx Pref$

Acceleration cavities

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

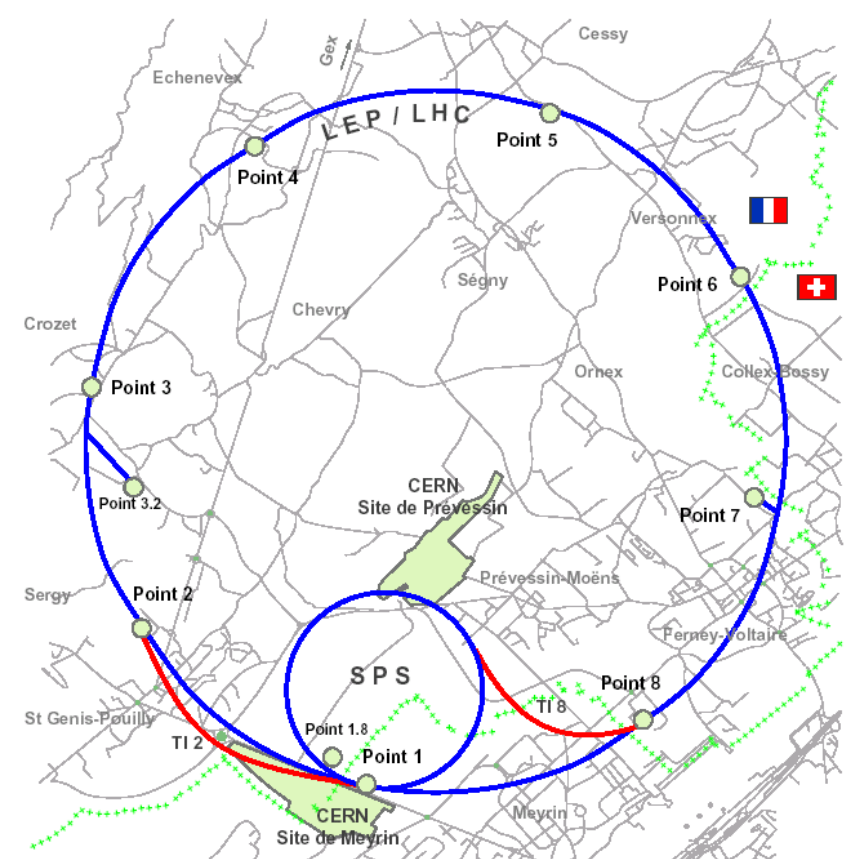
$R_s \approx R_{BCS} + R_o$

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

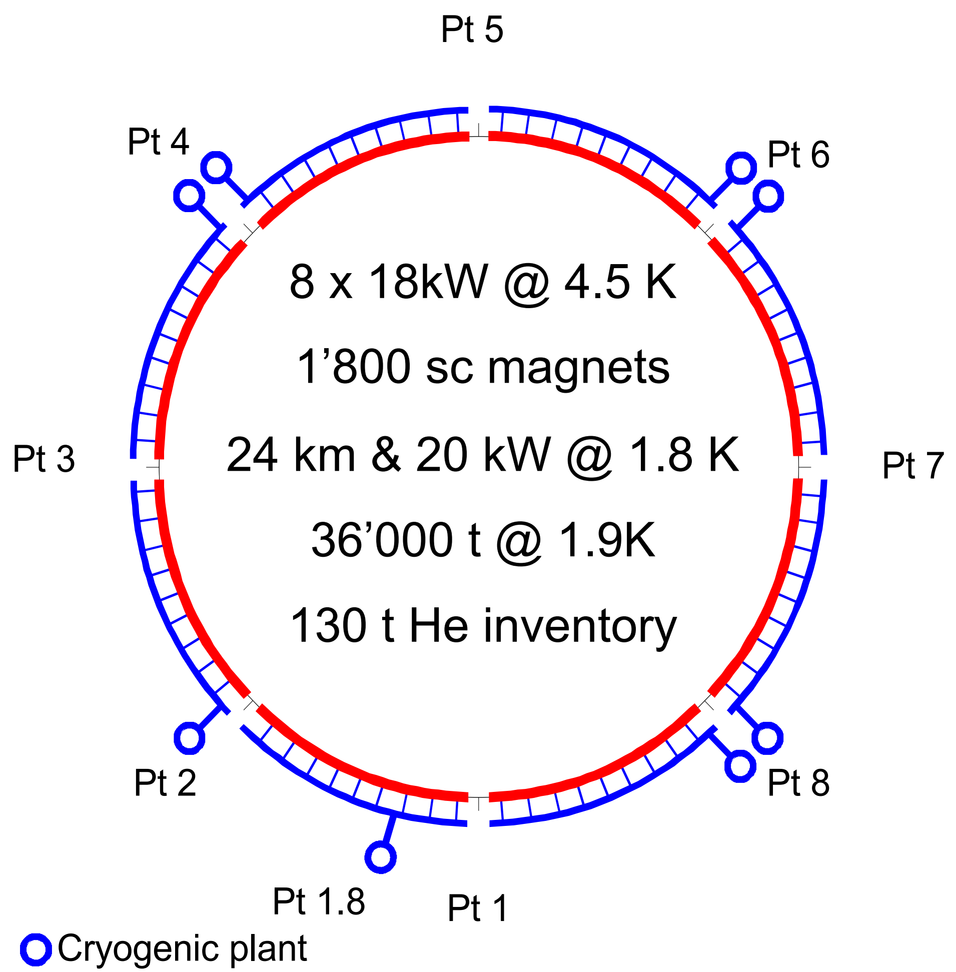
Operating Cost

Clear potential for power lines

Layout of cryogenics

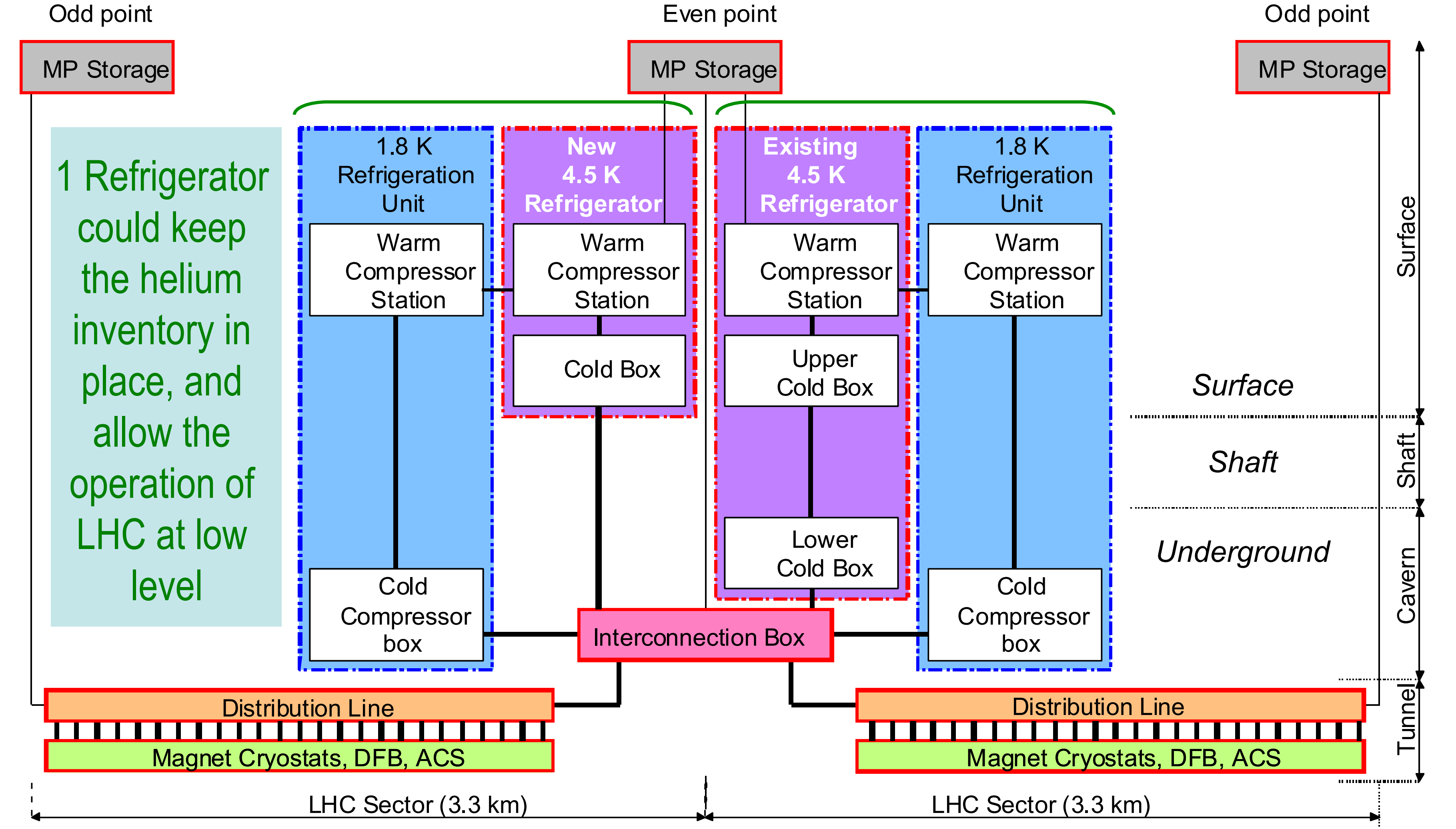


LHC cryogenics is the largest, the longest and the most complex cryogenic system worldwide



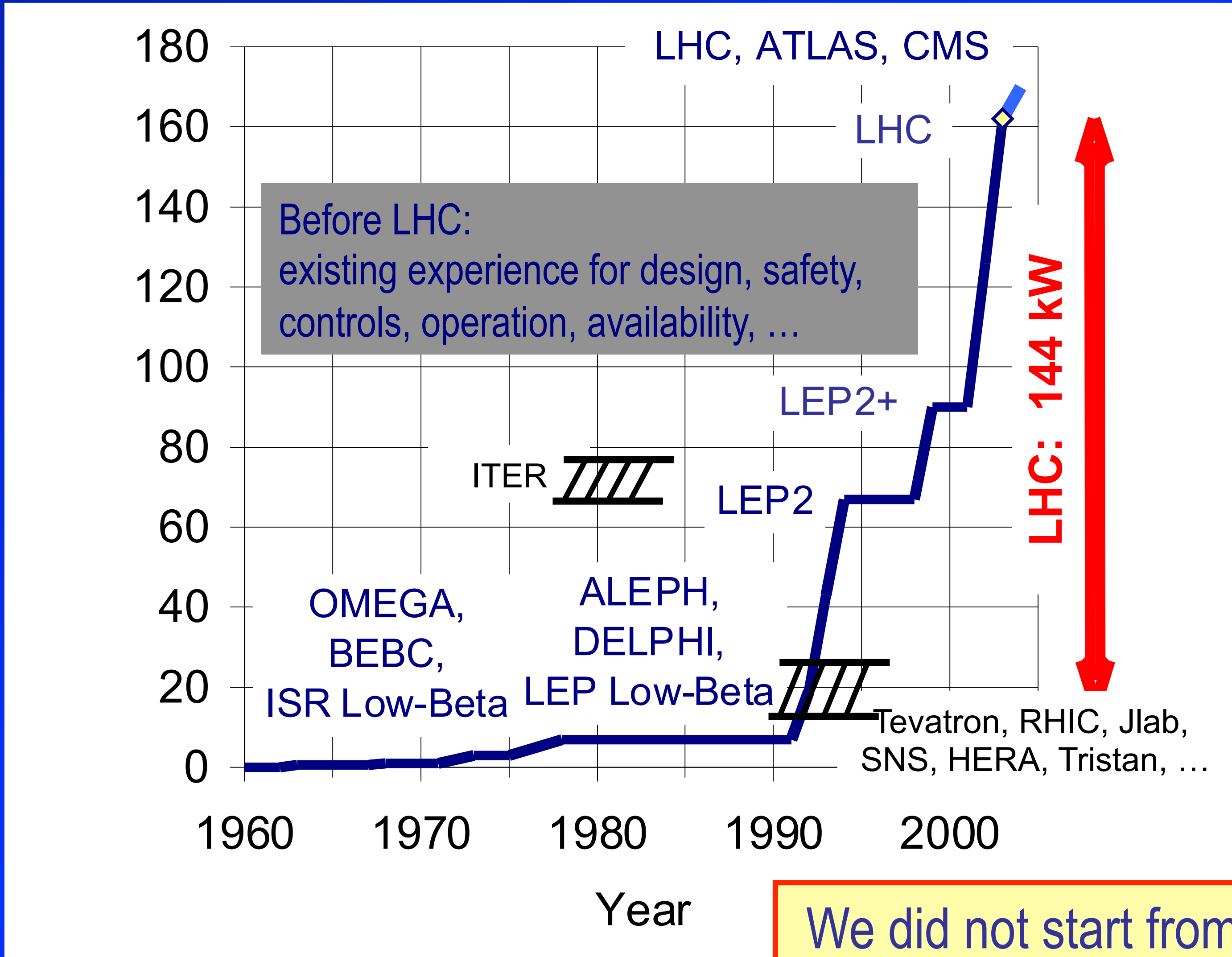
Cryogenic architecture

Typical LHC even point



Evolution of capacity with time

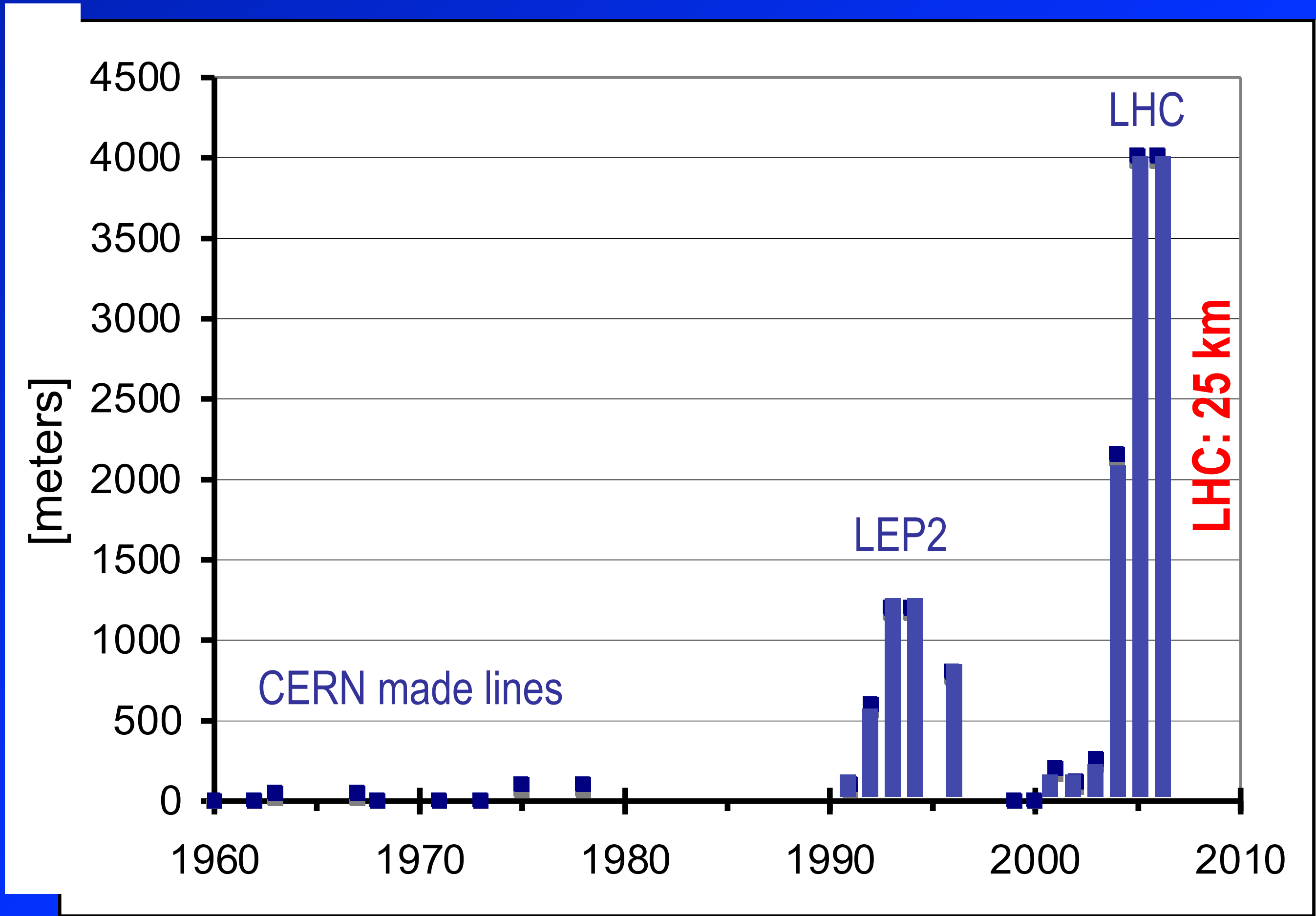
Equivalent cooling capacity at 4.5K, delivered by industry



We did not start from scratch!

Evolution of length with time

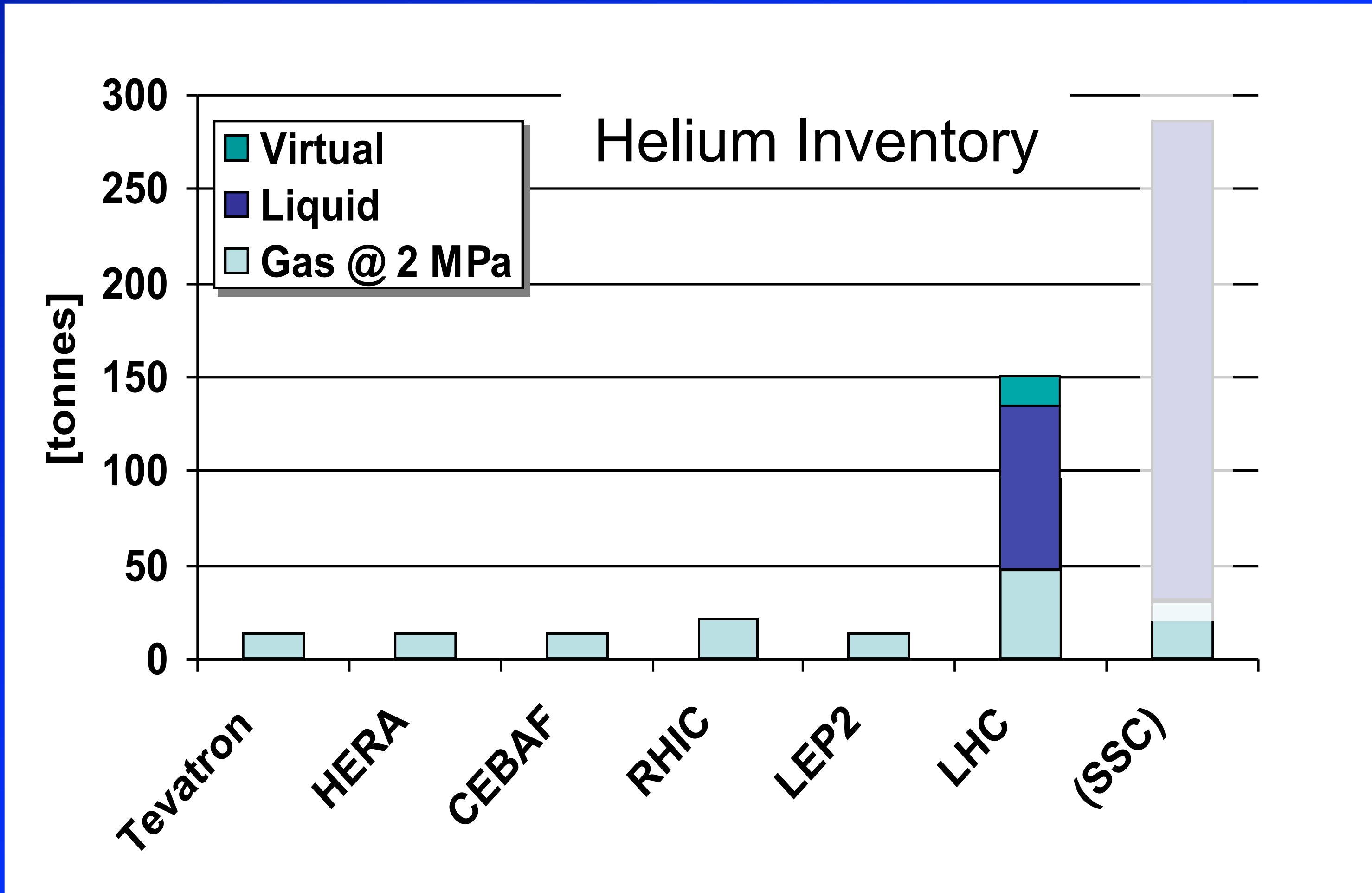
Length of cryogenic distribution lines



From CERN home-made hardware to industry (+ support) for large projects

Evolution of Helium storage with time

Necessary Helium inventory to allow operation



Losses of about 2% per month to be compensated

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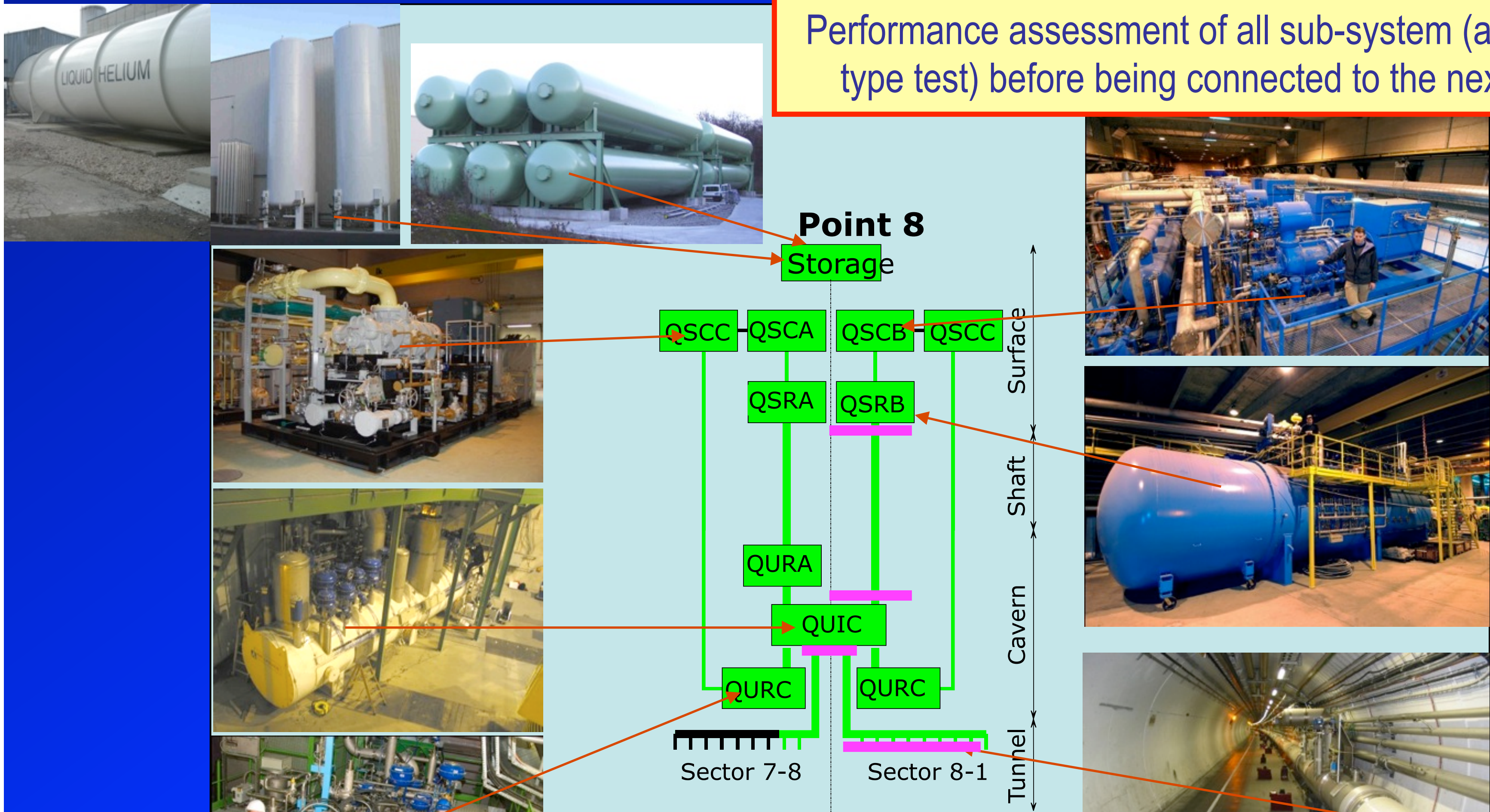
Testing the cryogenic sub-systems

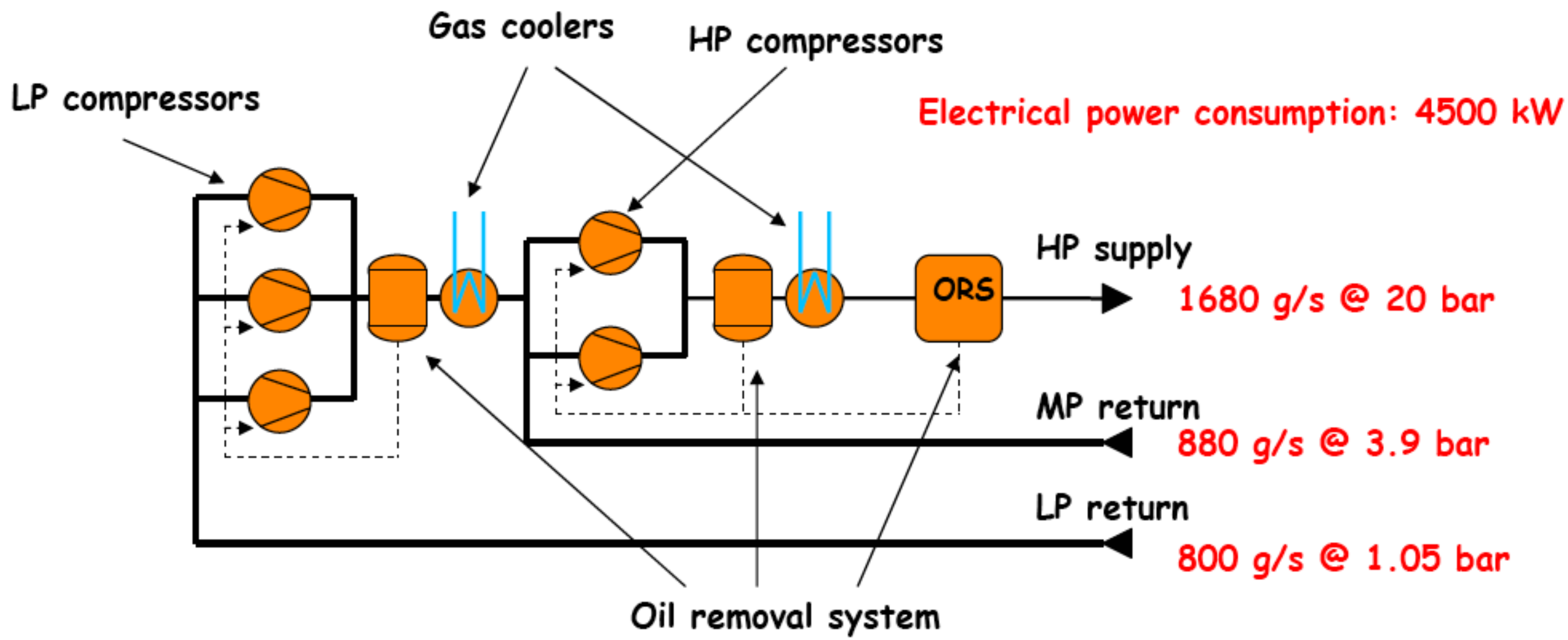
Performance assessment of all sub-system (at least a type test) before being connected to the next one



Large impact of discussions with manufacturers for HW protection settings: they want to protect, we want to operate …

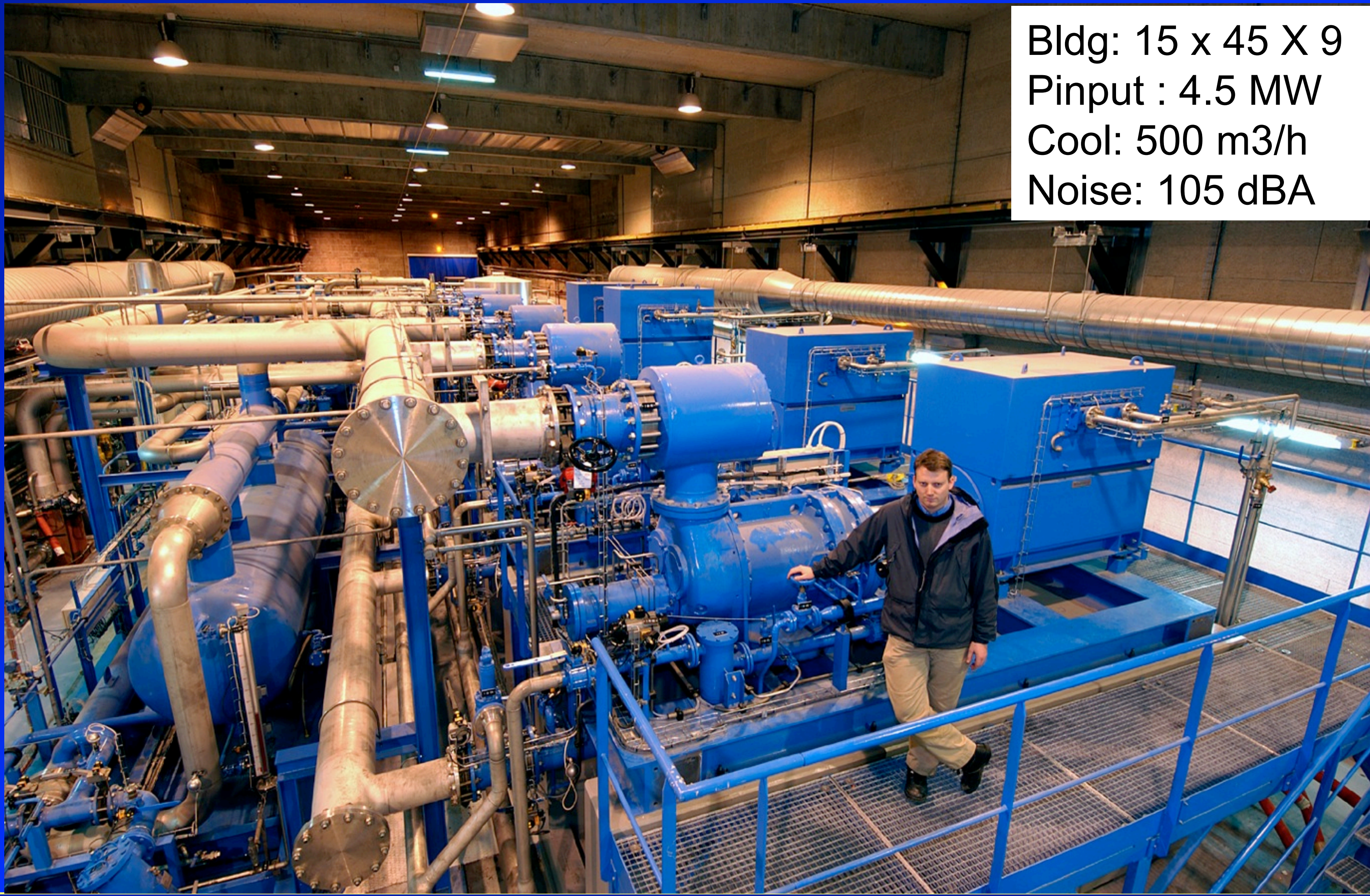
LHC 18 kW @ 4.5 K Helium Refrigerator

Compressor stations



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

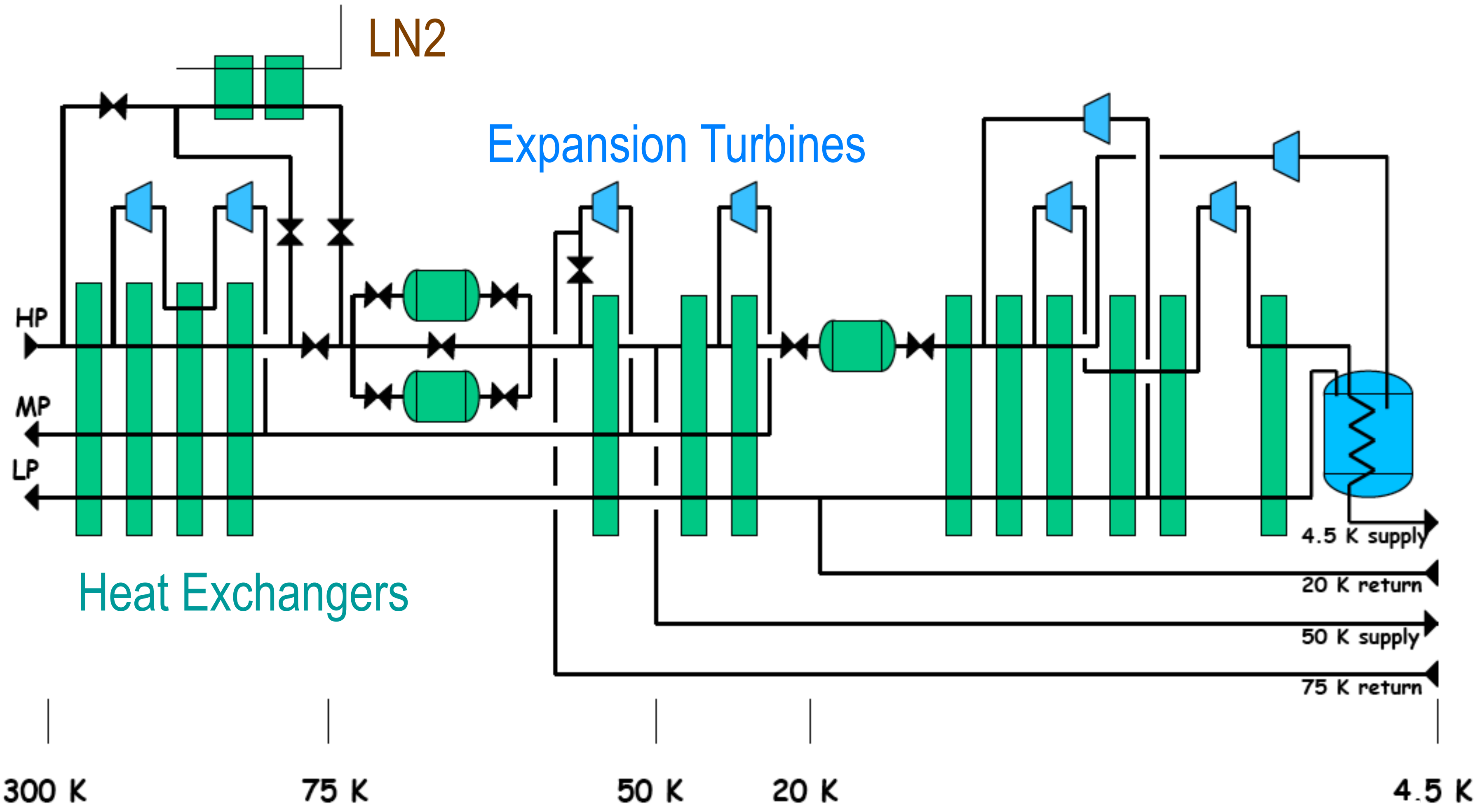
Compressor station of LHC 18 kW@ 4.5 K



Bldg: 15 x 45 X 9
Pinput : 4.5 MW
Cool: 500 m3/h
Noise: 105 dBA

LHC 18 kW @ 4.5 K Refrigerator

Process cycle for Air Liquide



Cold Boxes of LHC 18 kW@ 4.5 K

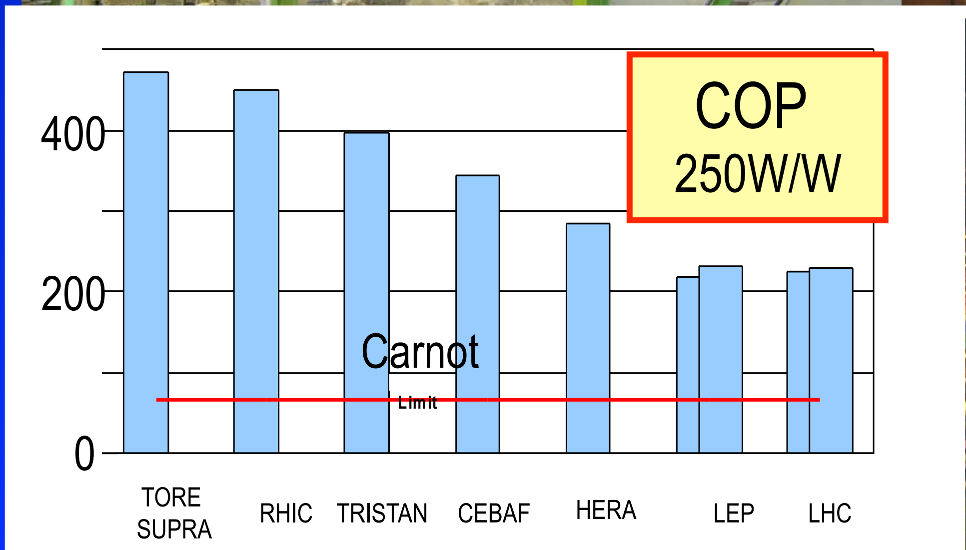
Key components:

Expansion turbines on gas bearings, plate fin heat exchangers, cryogenic valves, vacuum shell

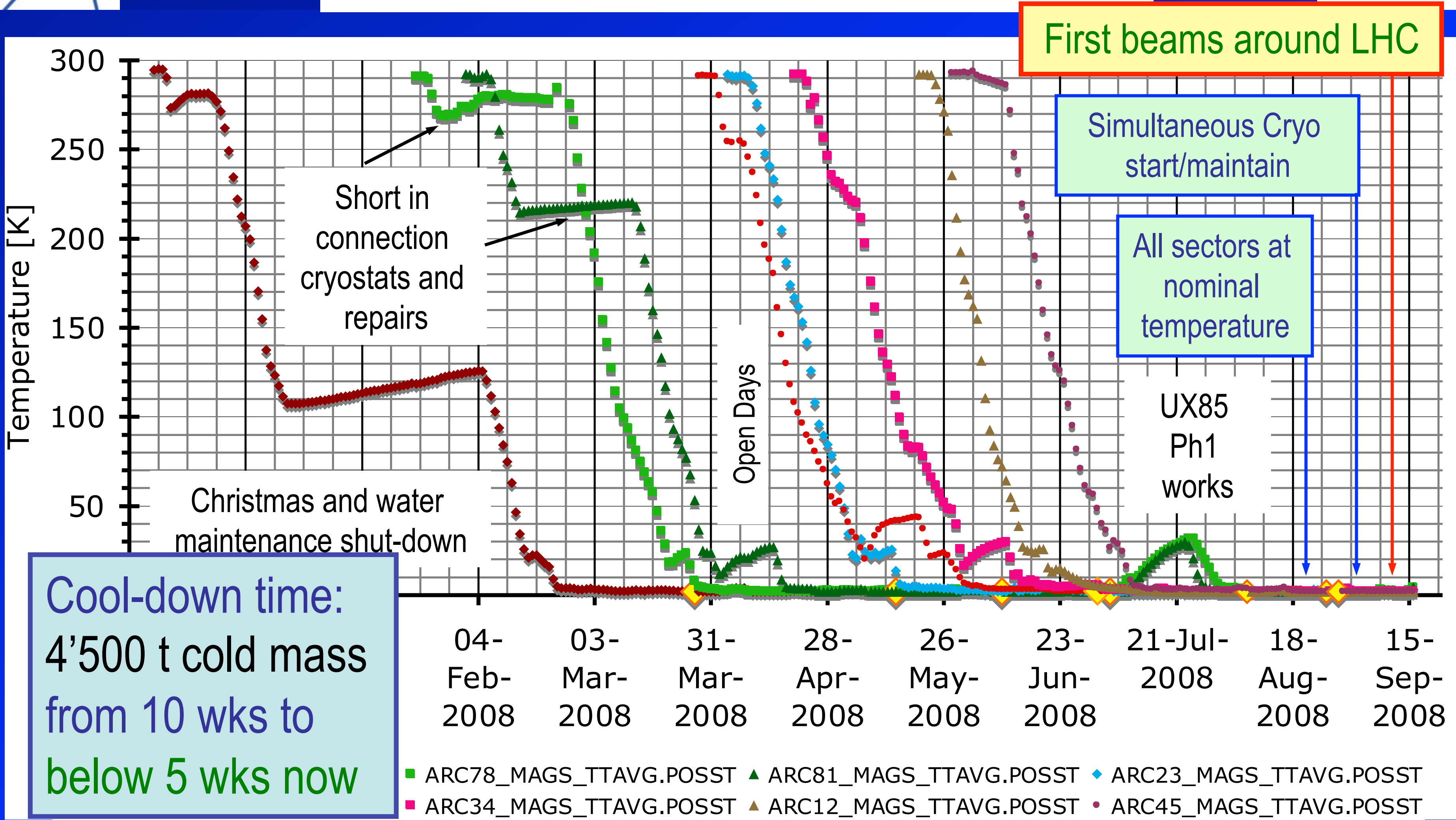
Bldg: 15 x 10 X 10
Pinput : 40 kW
Cool: 20 m3/h
Noise: 85 dBA

18 kW @ 4.5 K Refrigerators performance

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



First cool-down of LHC sectors

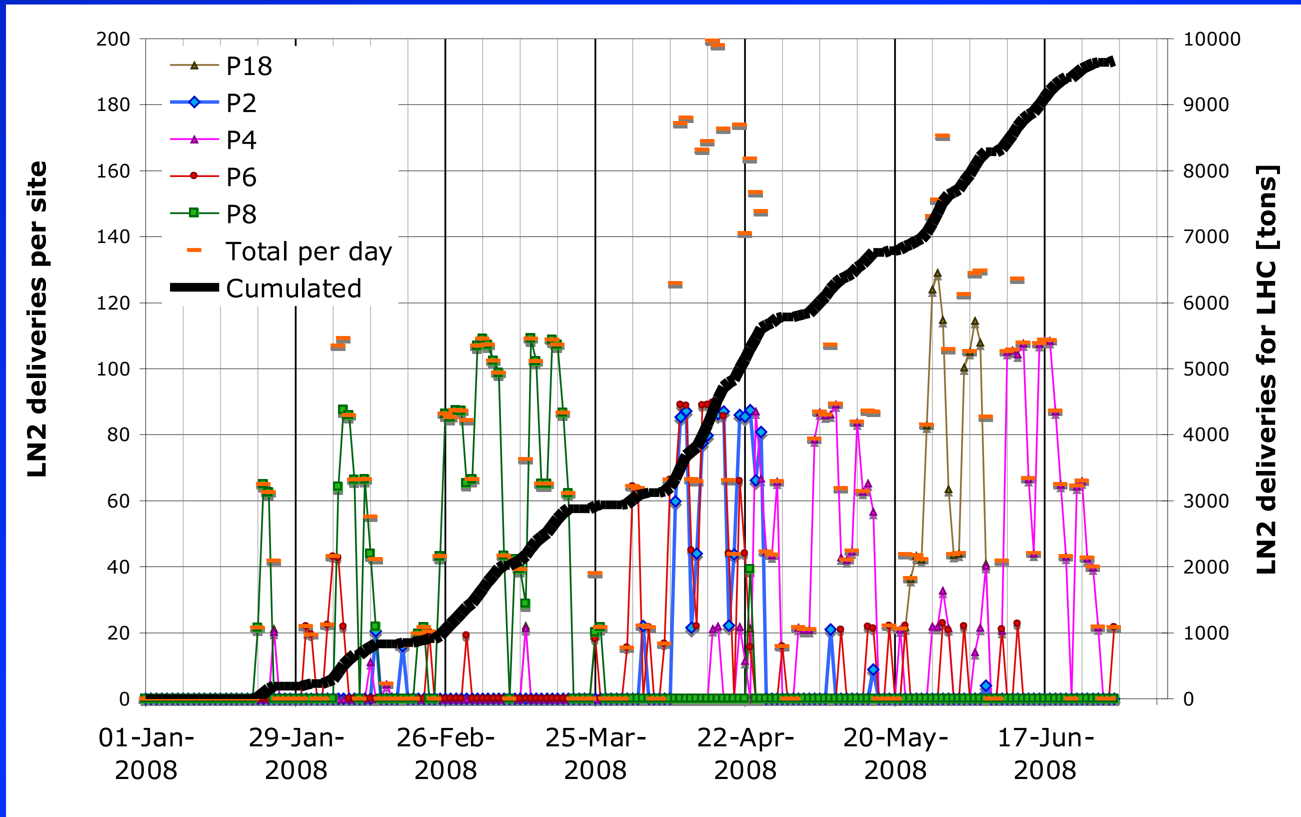


Cool-down time:
4'500 t cold mass
from 10 wks to
below 5 wks now

If 100 kg/m, 45km equals a LHC sector, with cool-down time in weeks !

Pre-cooling to 80K with LN2

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



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

- 2008: 500 trucks (20 tons) for 7 sectors in 5 months
- 2009: 400 trucks (20 tons) for 5 sectors in 3 months

Interconnections in LHC tunnel

Compulsory high level Quality Assurance !!!

65'000 electrical joints

Induction-heated soldering

Ultrasonic welding

Very low residual resistance

HV electrical insulation

Design issue, to be cured in 2013

40'000 cryogenic junctions

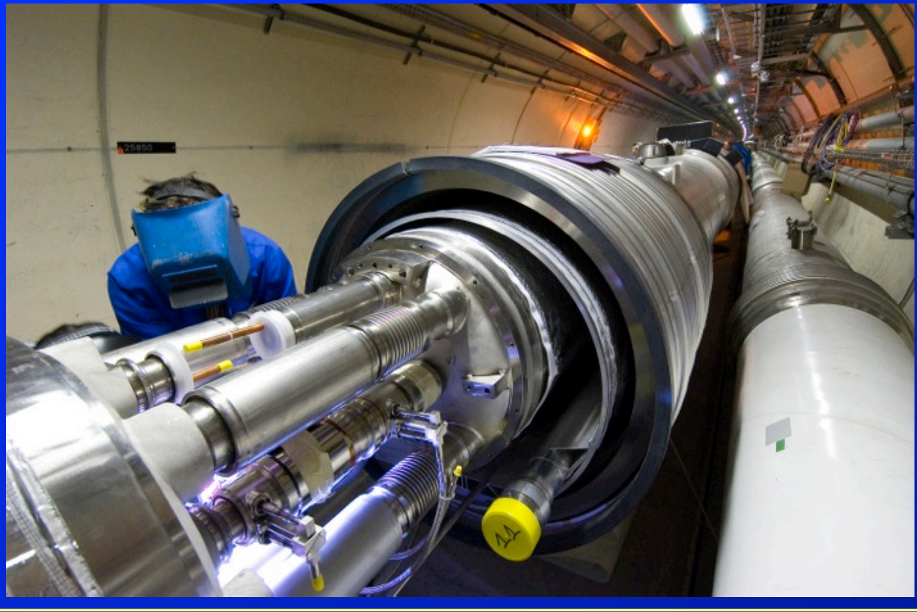
Orbital TIG welding

Weld quality

Helium leaktightness

0.2% to 1% in-situ leaks

19 left as "acceptable"
6 appeared (4 cured)

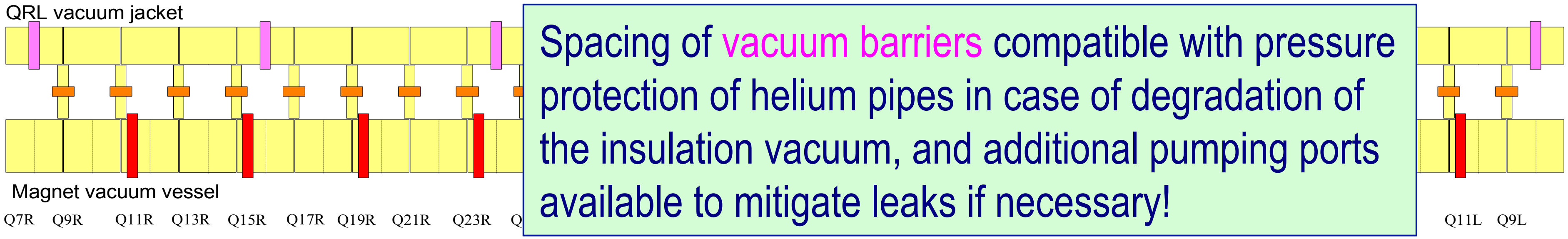


Present LHC baseline (1/3)

LHC Arc: Cryogenic and Insulation Vacuum Baseline design

Insulation Vacuum sectorization:

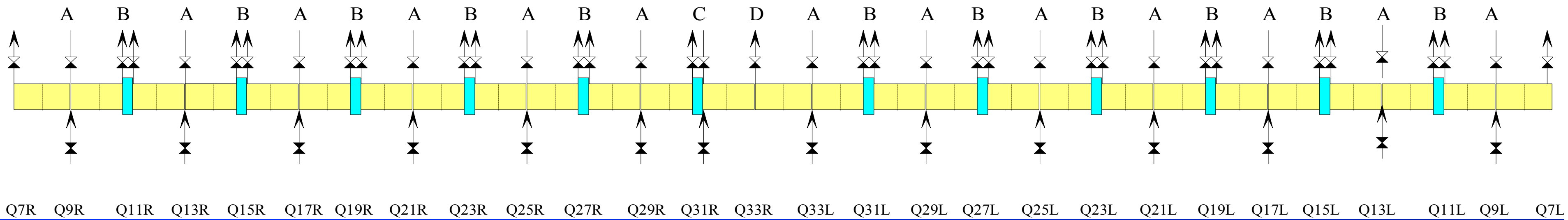
Magnet vacuum barriers — Jumper vacuum barriers — Cryogenic line vacuum barriers



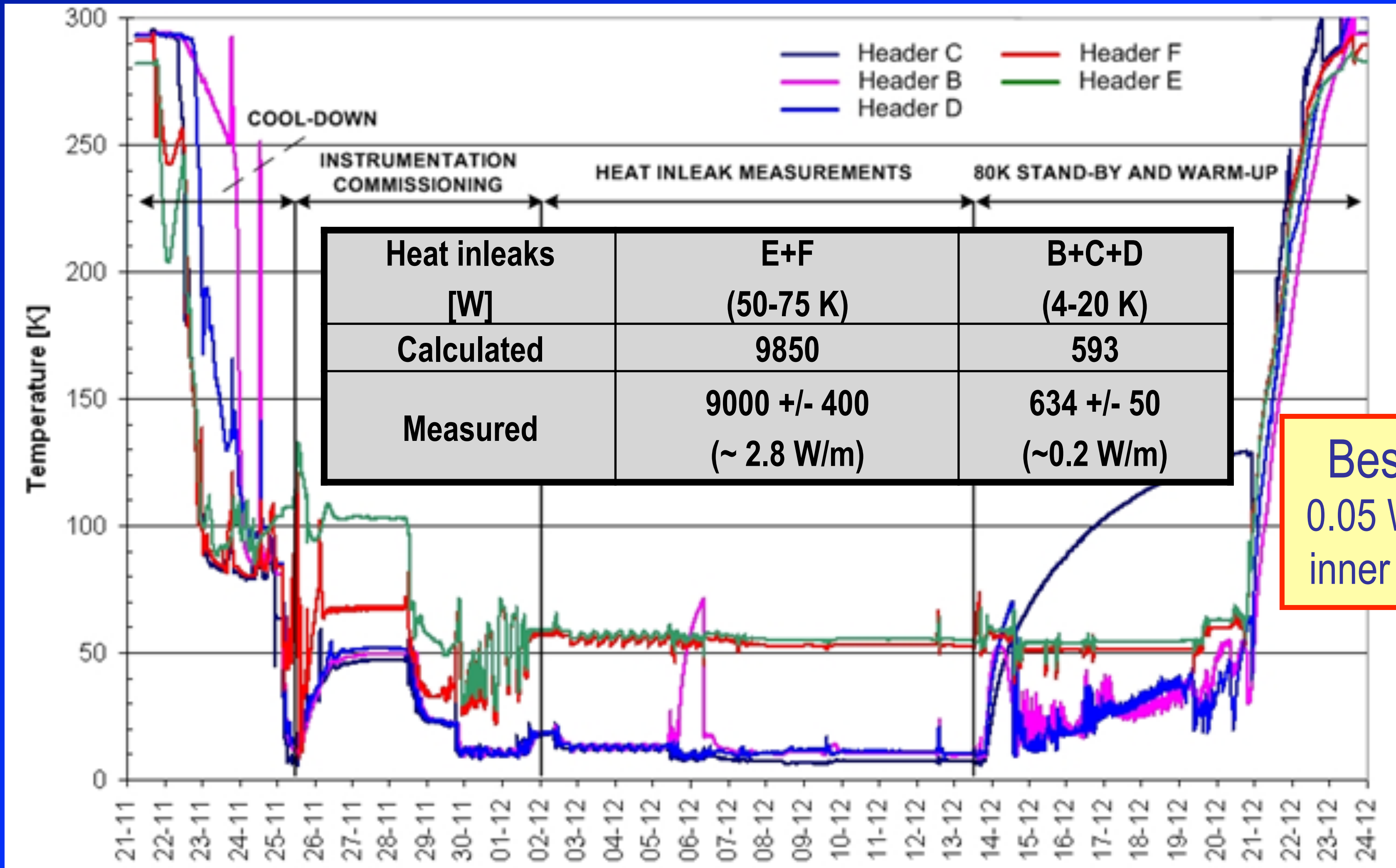
Spacing of vacuum barriers compatible with pressure protection of helium pipes in case of degradation of the insulation vacuum, and additional pumping ports available to mitigate leaks if necessary!

Cold-mass sectorization:

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



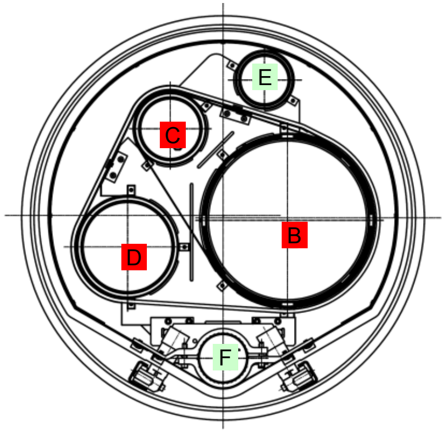
Main cryogenic line performance



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)

Best:
0.05 W/m
inner pipe

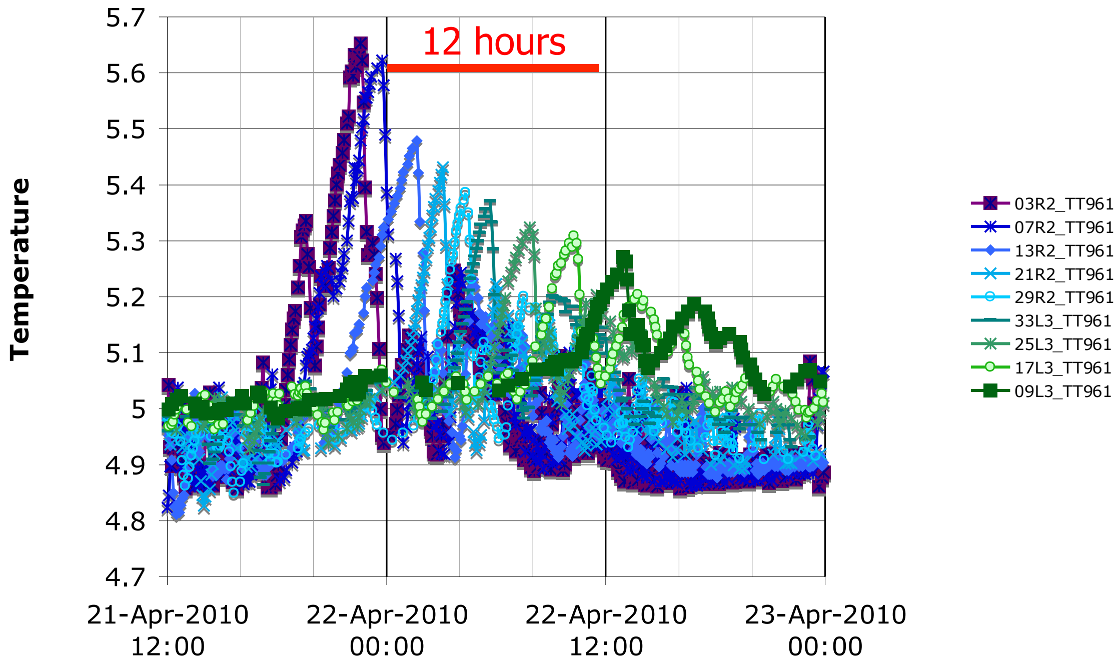
Control logic must handle long time delays



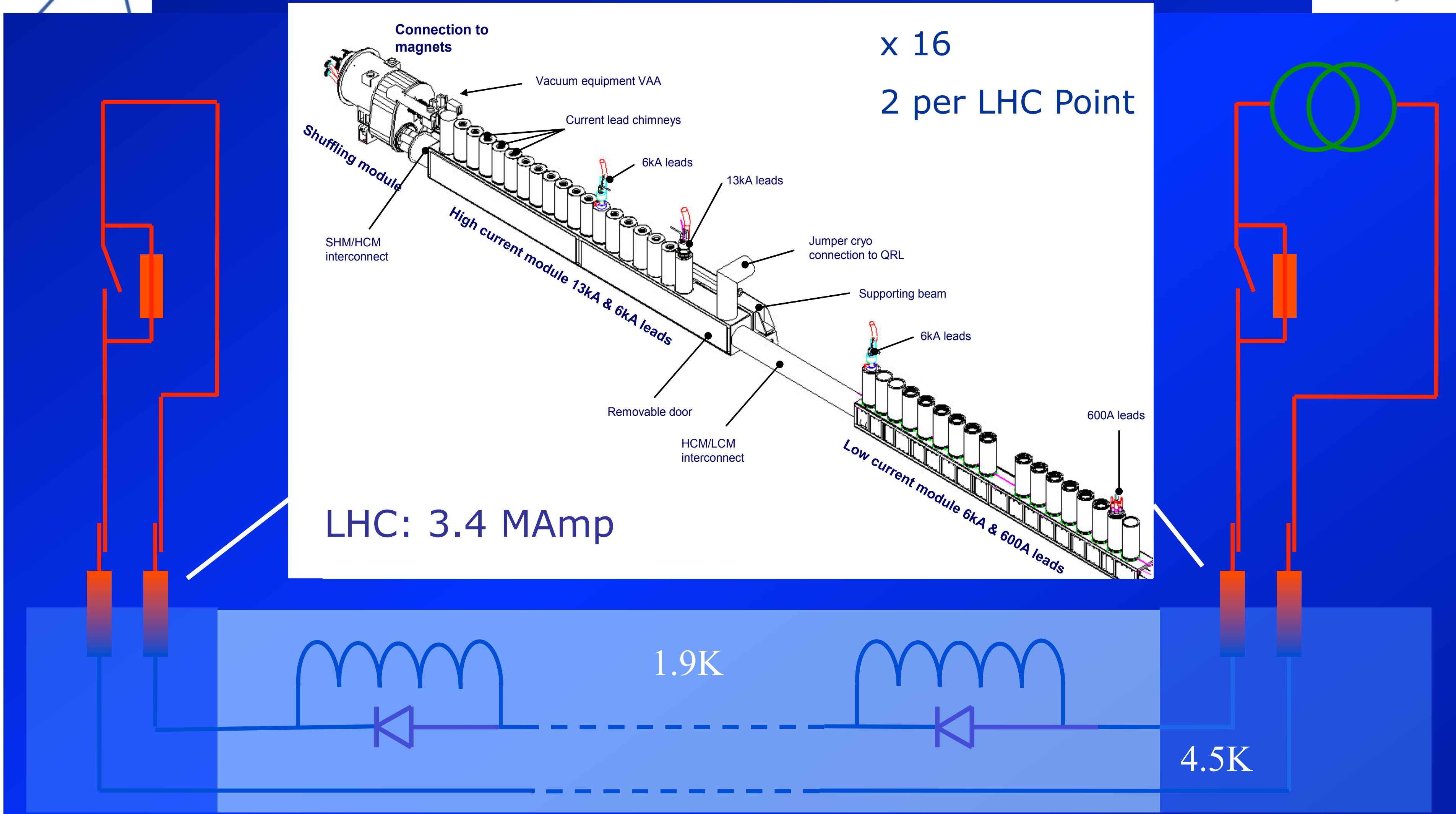
	Density [g/l]	Mass [kg]	Time flight
C [3B, 5K]	118	3058	5 - 12h
D [1.3, 8K]	8	467	1 - 4h
B [0.015, 4K]	0.18	29	4 - 12'

along 3.3 km sector

Slow propagation of « warm bump » along the sector



Electrical Feed Boxes



Global electrical protection system (quench detection) mandatory

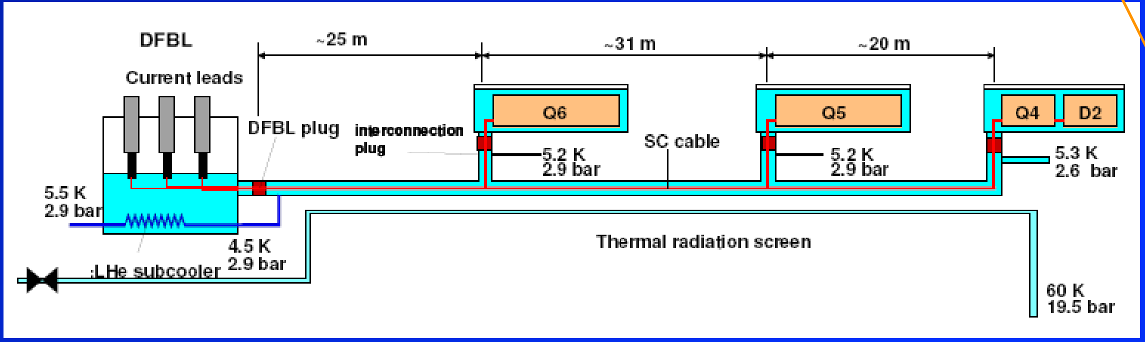
Electrical feedbox with current leads

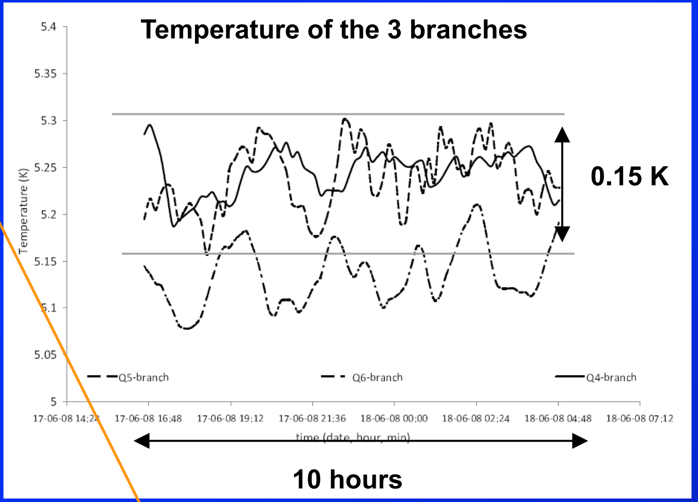
LSSL2 of the LHC

Superconducting Links

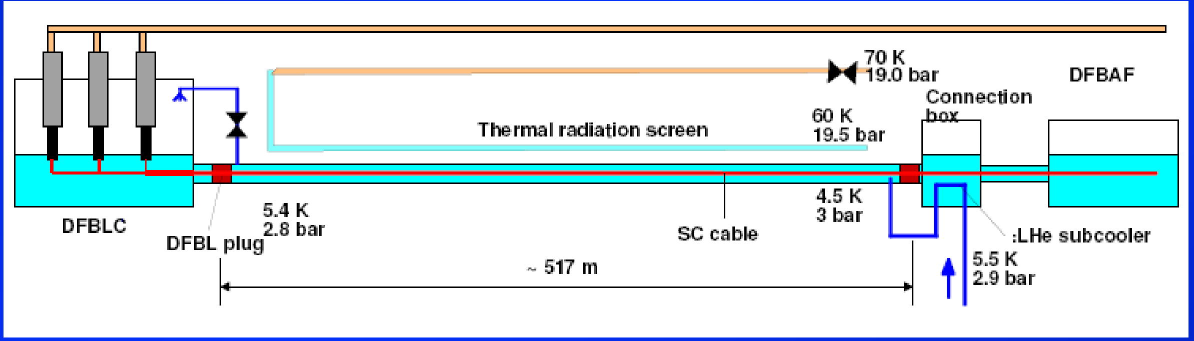
A kind of power line built in low-load rigid cryogenic transfer line

76 m with 3 branches, 11 x 6 kA + 12 x 600 A



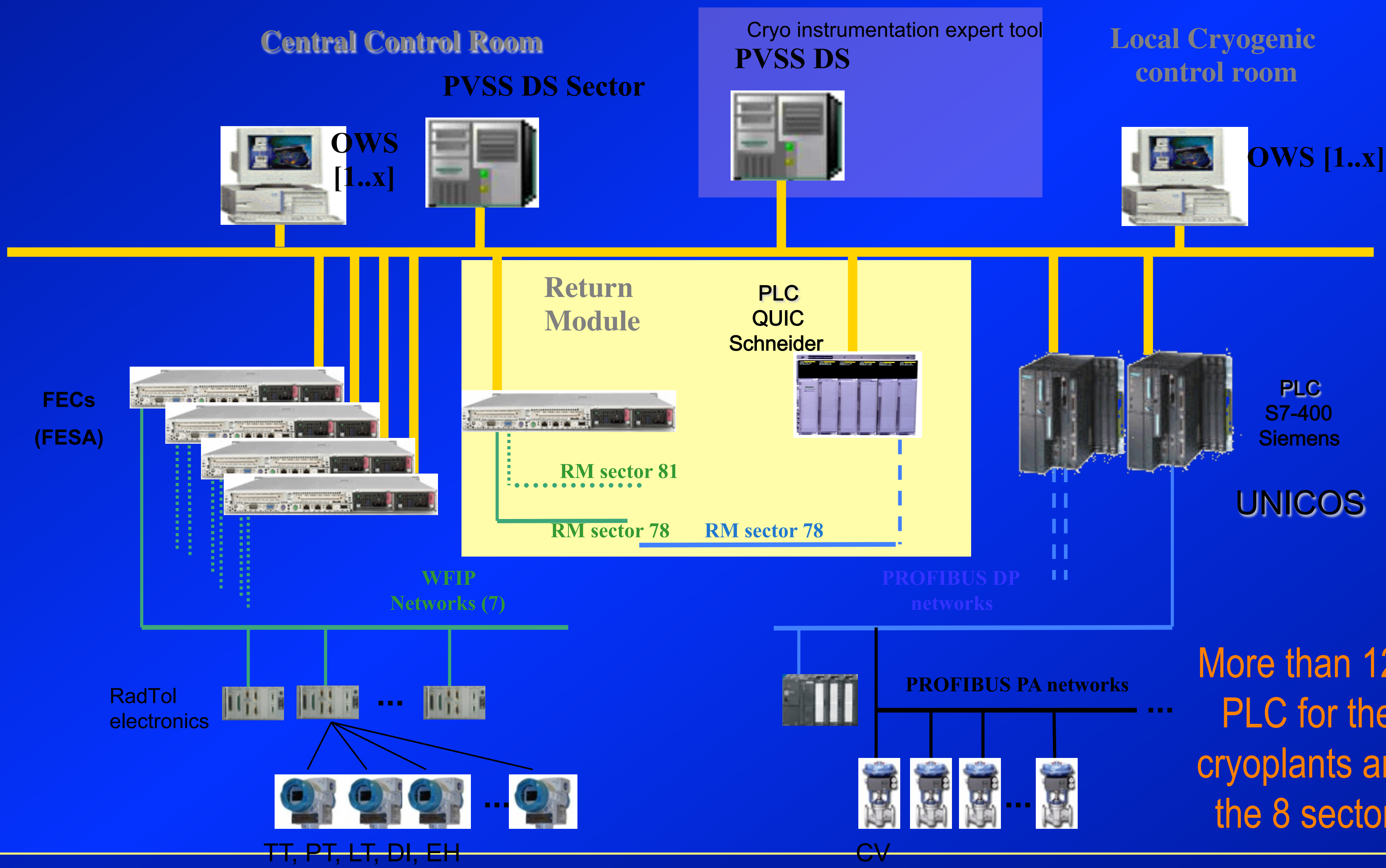


517 m , 44 x 600A



Controls for LHC cryogenics

21300 AI, 7000 AO, 18400 DI, 4200 DO, 4000 analog control loops



More than 120 PLC for the cryoplants and the 8 sectors

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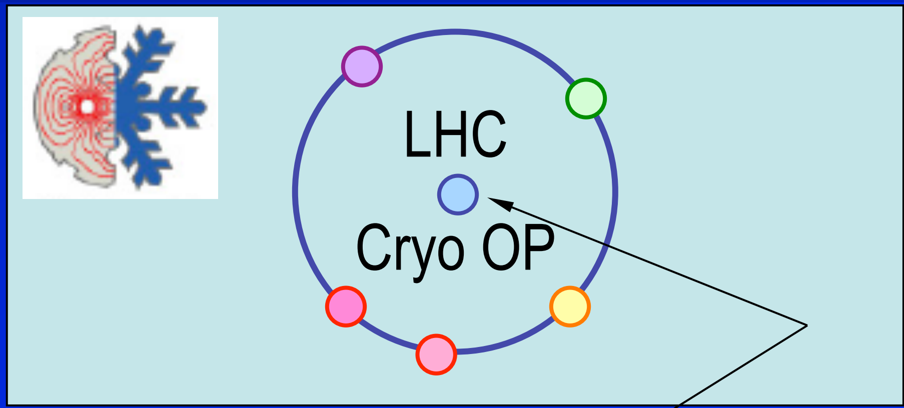
Affectations LHC Cryo CRG-OA



Structured alarms
eLogbook
Procedures
Documentation …

4	*Ing. OP référents* *academic experts*
4	*Ing. production* *Site management*
12	*Opérateurs* *Sites + Shifts*

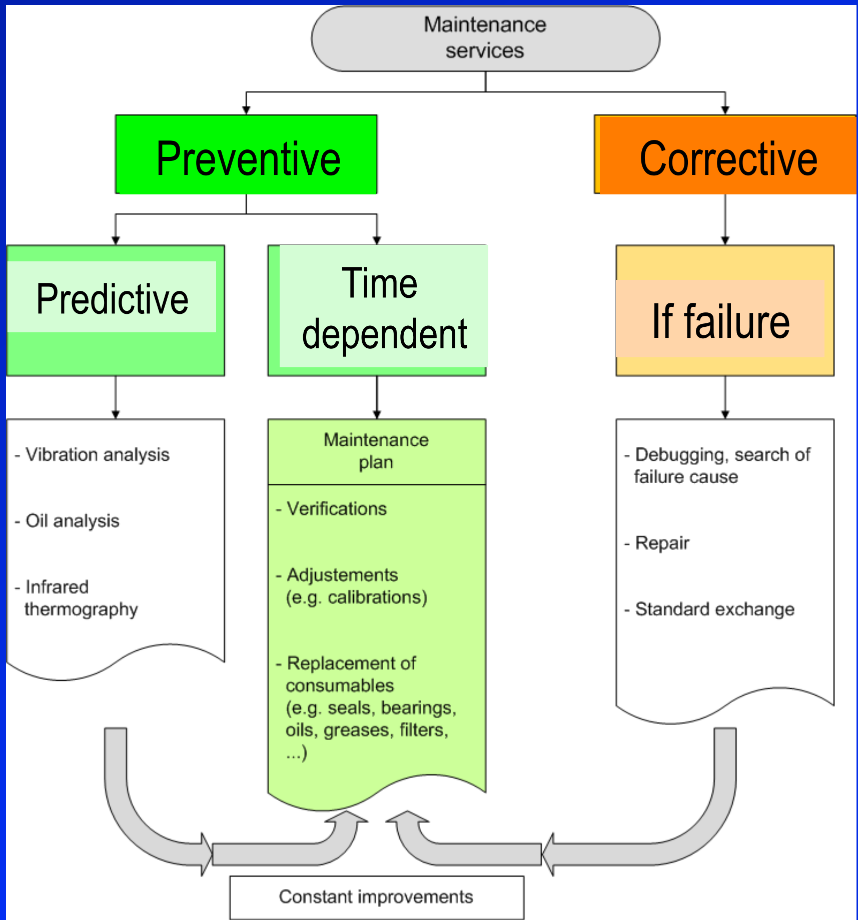
Cern Control Center: Monitoring on shift 24/7

Site control rooms: periodic checks, 1st line intervention

+ Industrial partner teams in local control rooms (≈ 15 personnes Serco)

High level recruitment, training (academic - on the job - shadowing), certification for operation (10months), join & leave about to work

Maintenance principles



Simply applying standardised methods!

A	**Simple adjustments** foreseen by the component, equipment or installation supplier by the means of components that are accessible without disassembly and opening of the component. and/or The replacement of consumables that can be accessed safely as bulbs, filters, oils, etc.	Operators
B	**The repair** or maintenance **by standard exchange** of elements foreseen for this type of repair and/or Minor operations of preventive maintenance.	Contractor
C	**The identification and diagnostics of the failure** which may be followed by the replacement of components. and/or The global adjustment and calibration of the equipment/ component.	Contractor
D	**Complex tasks of corrective and preventive maintenance**, in particular the disassembly of a system, exchange and/or repair of components, reassembly and adjustment of the system, but it is excluding the rebuilding of components. and/or The replacement of an assembly of electrical components.	Contractor or CERN
E	**Extensive repair, renovation and rebuilding tasks.** Rebuilding means in this context the manufacturing of components on the basis of a manufacturing drawing (examples are the manufacturing of a rotor screw, the rewinding of a large motor winding and the manufacturing of a cooler).	CERN

Software tools

Spares: 6'000 - Number of assets: 32'000

>1MCHF: 0

50k<<1M: 1

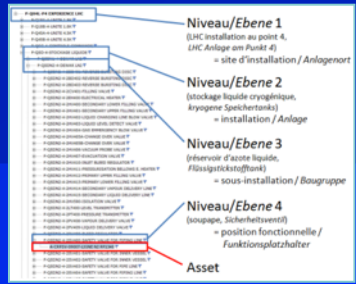
5k<<50k: 2+

<5kCHF: 2 to n

Data Base (Oracle)

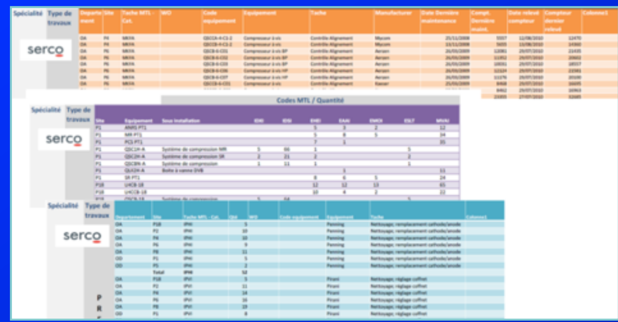
CAMMS Infor EAM

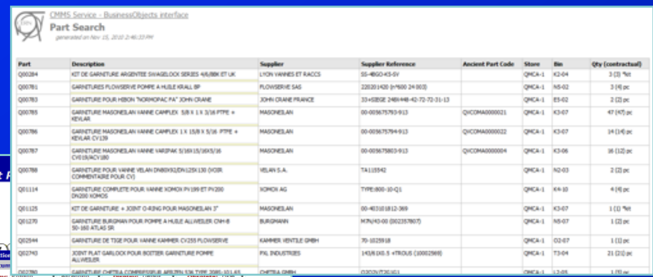
- Gestion des biens *Asset-Management*
- Ordres de maintenance *Arbeitsaufträge*
- Gestion du magasin de pièces de rechange *Ersatzteillagerverwaltung*



Reporting Business Objects

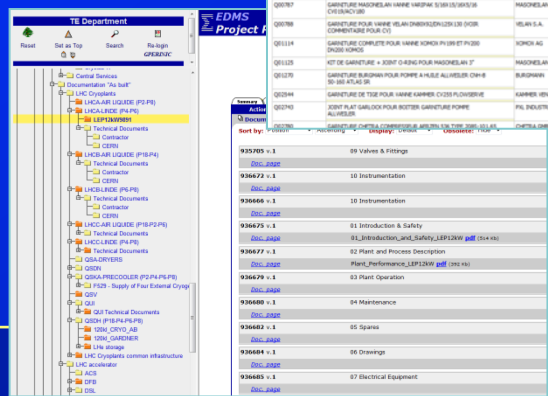
- Affichage/impression simplifiés *einfache Anzeige-/ Druckfunktionen*
- Analyse de données *Datenanalyse*
- KPIs





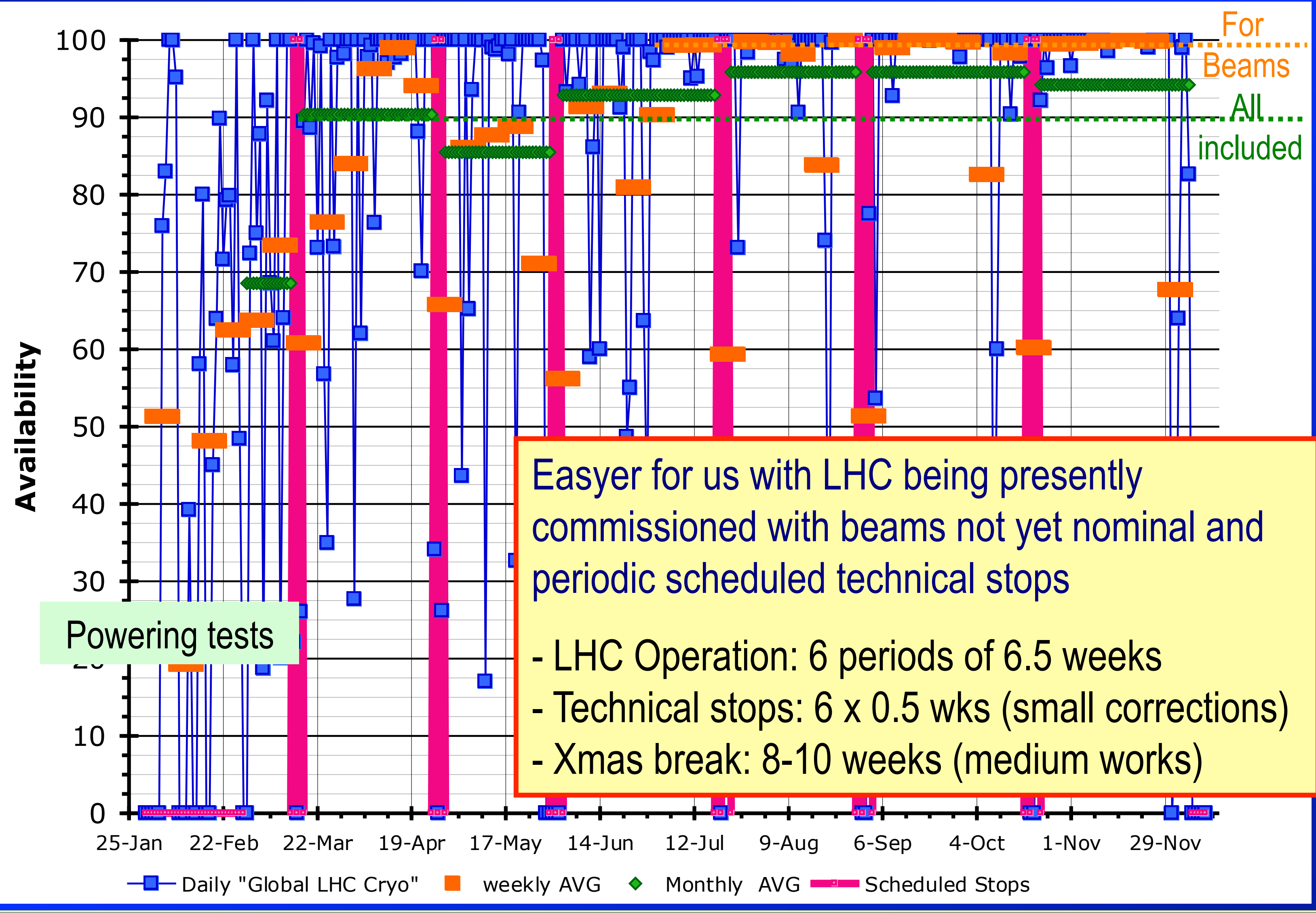
Documents EDMS (based on Agile PLM)

- Documentation *Dokumentation*
- Dessins *Zeichnungen*
- Rapports ... *Berichte ...*



LHCCryo Availability 2010

Based on LHC_Global_CryoMaintain signal per unit of time

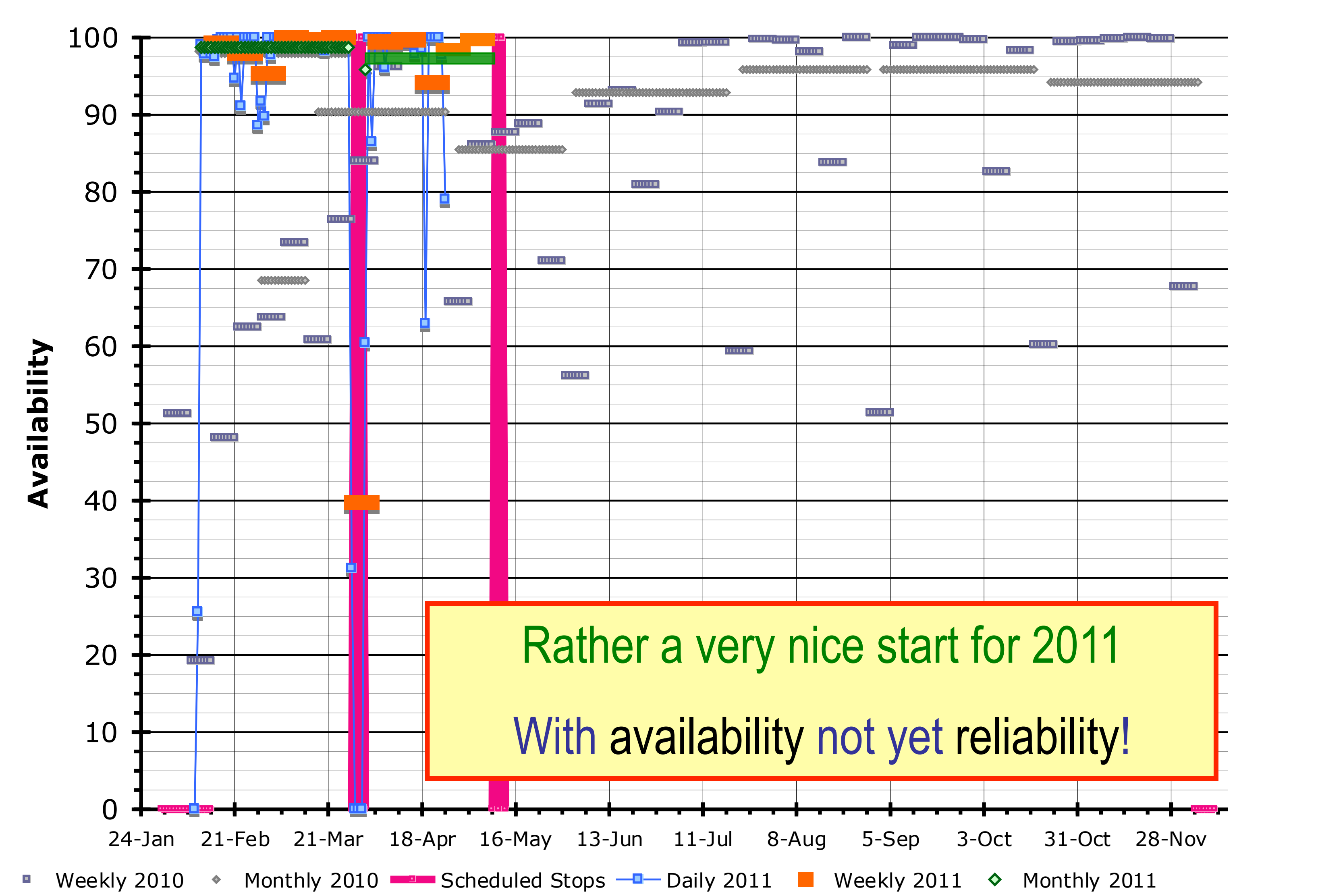


Easyer for us with LHC being presently commissioned with beams not yet nominal and periodic scheduled technical stops

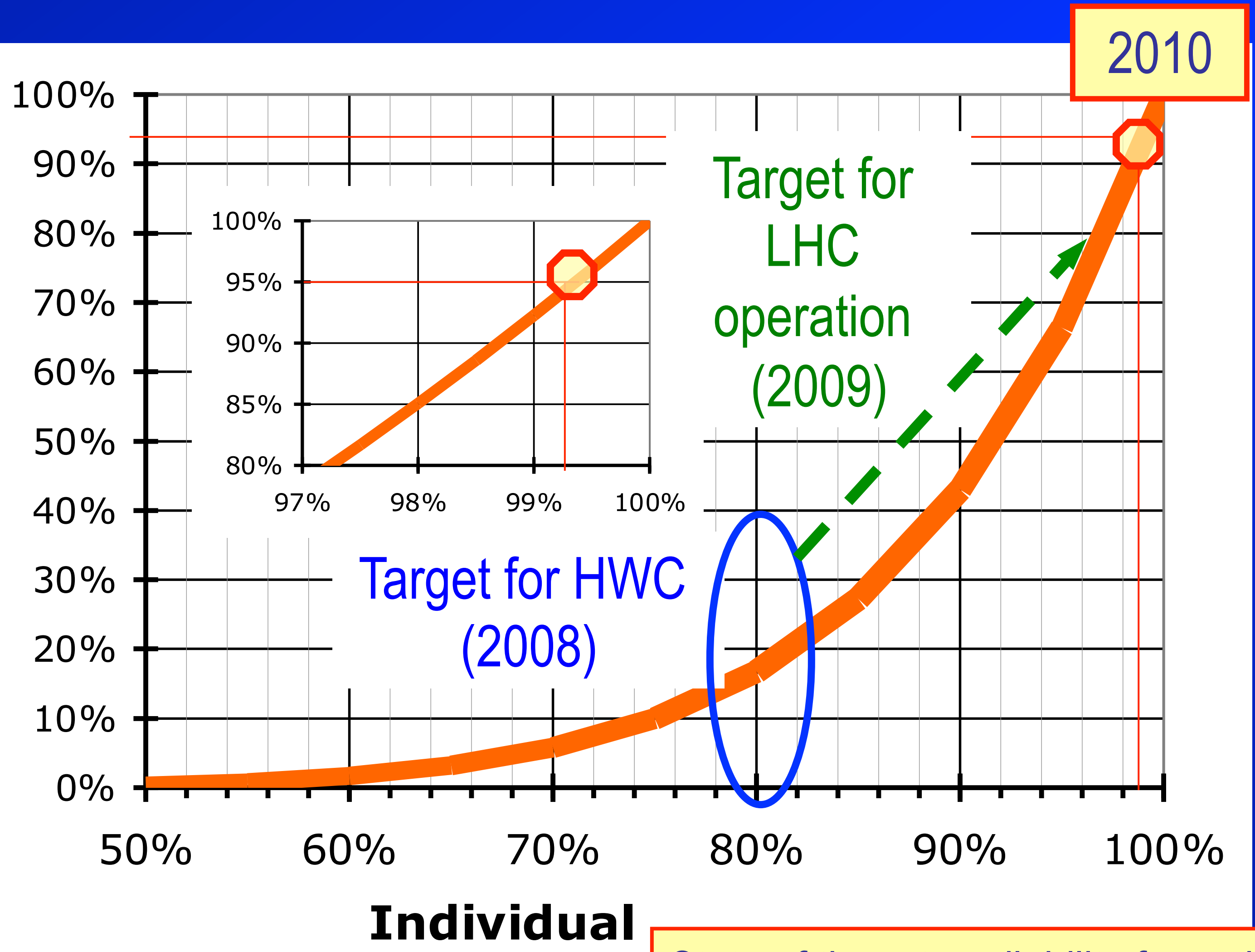
- LHC Operation: 6 periods of 6.5 weeks
- Technical stops: 6 x 0.5 wks (small corrections)
- Xmas break: 8-10 weeks (medium works)

LHCCryo Availability 2011

Based on LHC_Global_CryoMaintain signal per unit of time



Availability, key performance



State of the art availability for a single cryoplant: 99.5% with 12 weeks maintenance / 4 years (2+2+2+6)

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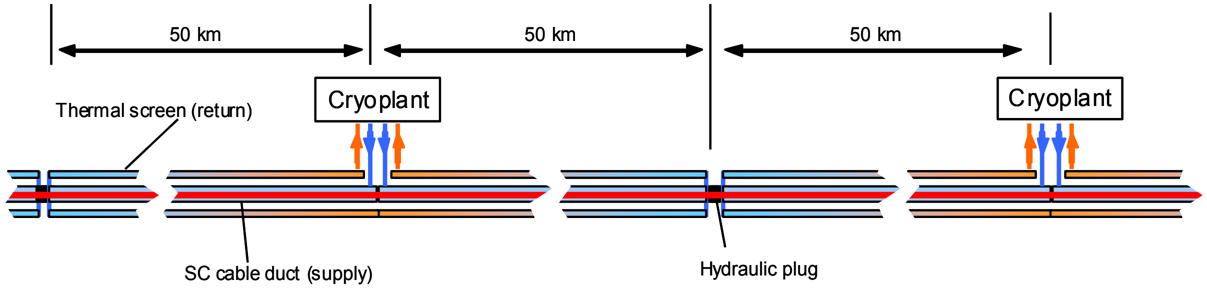
Context



1000 km:
10 plants
every
100 km

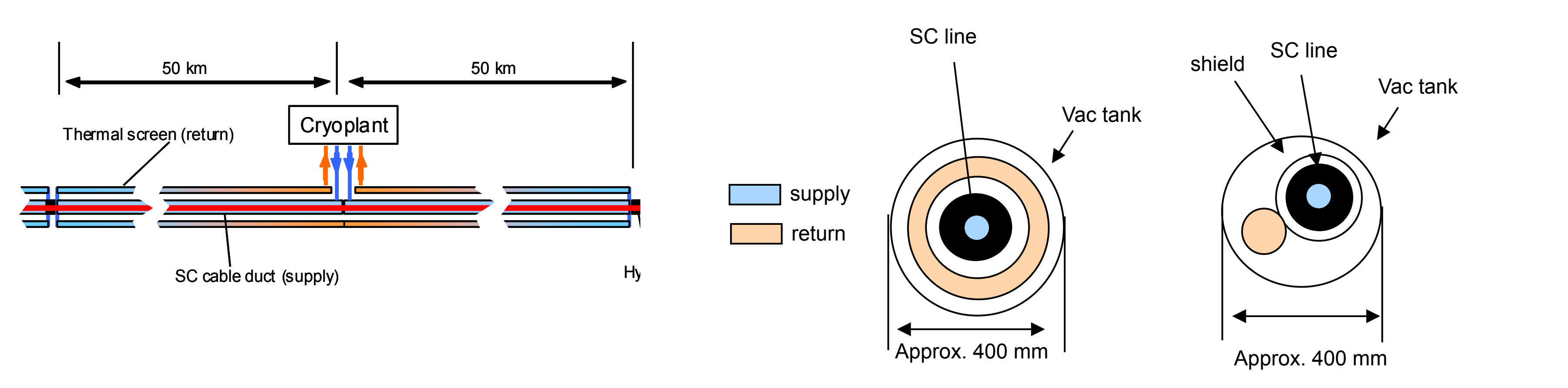
Configuration of a long sc power line system is a tradeoff between:

– Minimised number of cryoplants to reduce capital costs, complexity and increased operational efficiency. Large flow rate to be circulated would require large diameter to match acceptable pressure drops, therefore larger helium inventory

– Minimised dimensions of the cryogenic piping to ease installation and limit the quantity of cryogenic fluids

Distribution over unprecedented distances (50km) to be engineered !

Very low heat loads long lines



Heat loads distribution:

- Dominated so far by static heat (x5 w.r.t dynamic loads from cable)
- 0.05 W/m considered as static heat on inner pipe, which is ultimate achievement with rigid pipes welded every 12-18m …
- Obvious need to get hundreds meters prefabricated elements (flexible or semi-rigid) to ease installation and Quality Assurance
- So far, these lines have a heat load x5 larger than considered

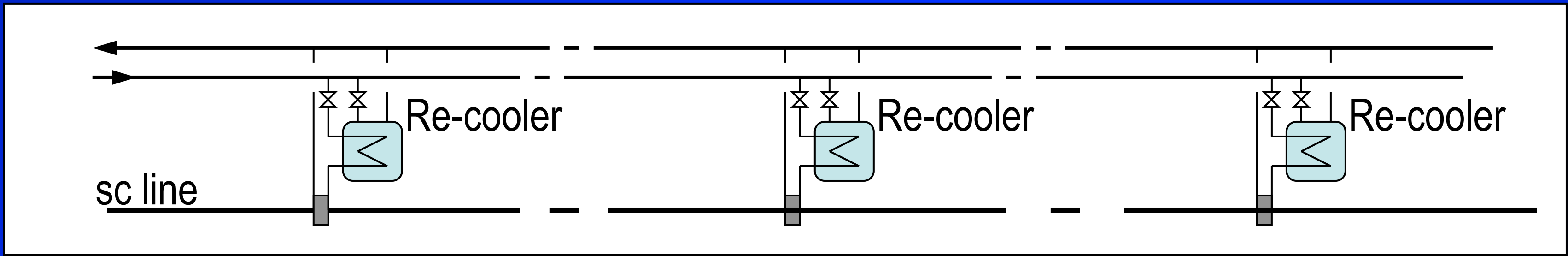
Significant progress required in this field !

Sectorisation and altitudes

Effects linked with change of altitude:

- Pressure difference (Ro.g.z) due to gravity (1.2 bar for 100m for LHe)
- Temperature difference (g.z) due to increased enthalpy (10% for 100m)

=> Usual turnaround implies re-coolers with valves, instrumentation …



Pro/Cons associated with sectorisation:

- Increased complexity

+ Pressure protection: Safety valves (helium pipes and insulation vacuum)
+ Re-cooling time: Significant gain as each loop will be treated in parrallel

Dedicated engineering required to address these serious physical and technical issues !

Cryoplant efficiency & availability

	Efficiency
Conventional	0.97
Superconducting	0.995

Obvious efforts to be made on global availability:

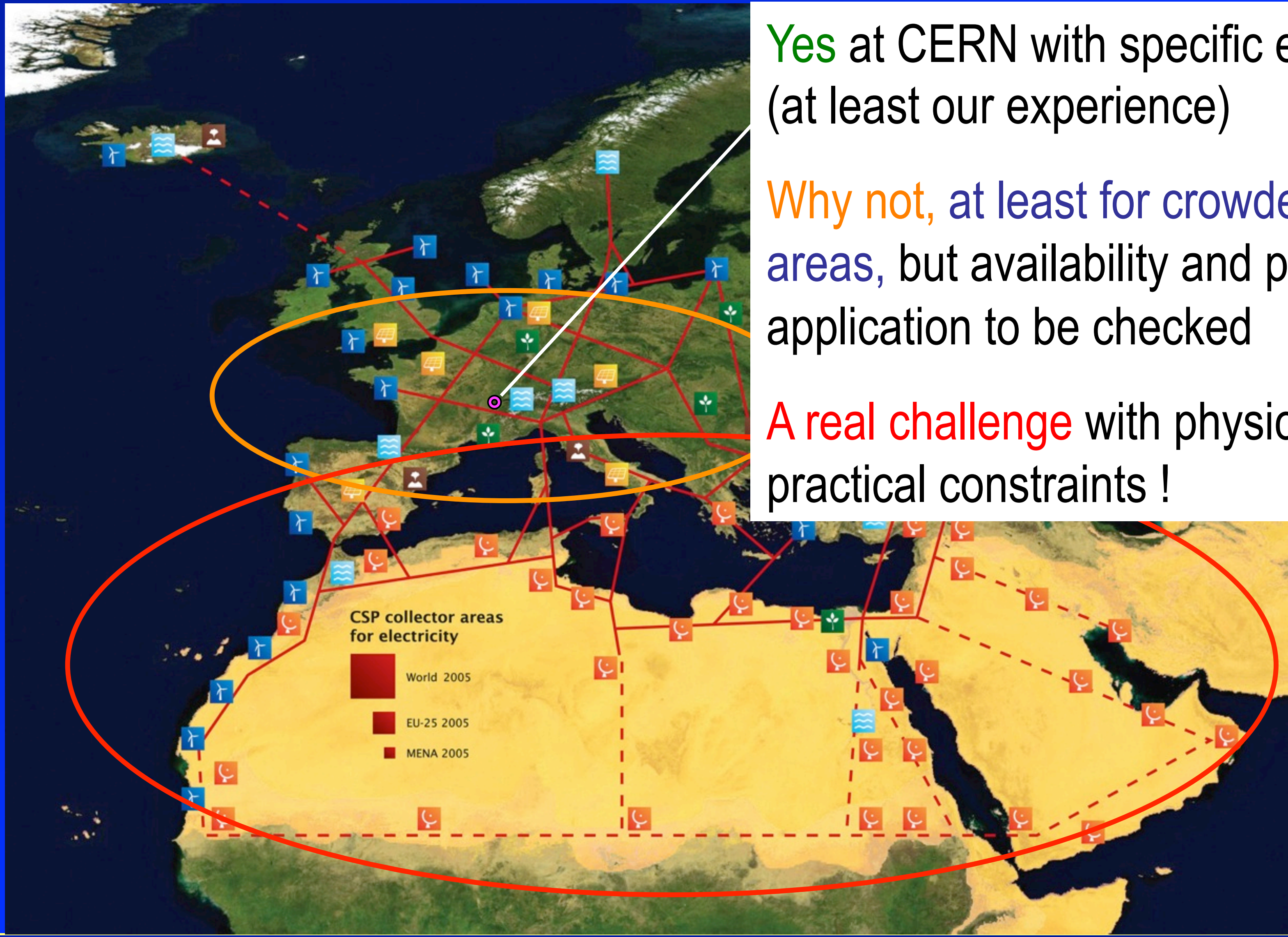
- Not realistic to consider 15 days of downtime + maintenance per year!
- Obvious need of redundancy for cooling capacity, implying an interconnection box between cryoplants and power lines, and potentially a loss of efficiency (hot running spare for automatic switch!)
- Direct impact on investment costs !

Dedicated engineering required to address these serious global issues !

Summary

- LHC cryogenics is the largest, the longest and the most complex cryogenic system worldwide. We could achieve a reasonable availability (around 95%) so far with beams. This demonstrates that there are no big issues in concept, technology or global approach for operation, within LHC environment, schedule and boundary conditions.
- If one could think of applying such technology to GW power lines of 1'000km long, some efforts should be invested in:
  - Very-low heat leaks cable in flexible line design of several 100m modules
  - Sectorisation over long distance and acceptance of moderate altitude variations
  - Assembly and safety valve concept for reliability in outdoor environment
  - Cryoplant reliability (and efficiency)
- For the time being, we have difficulties to apply this concept with significant altitude changes (1000m) and in no-man's land areas …

Summary



Yes at CERN with specific efforts (at least our experience)

Why not, at least for crowded areas, but availability and practical application to be checked

A real challenge with physical and practical constraints !