Overview of the LHC cryogenic system

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Overview

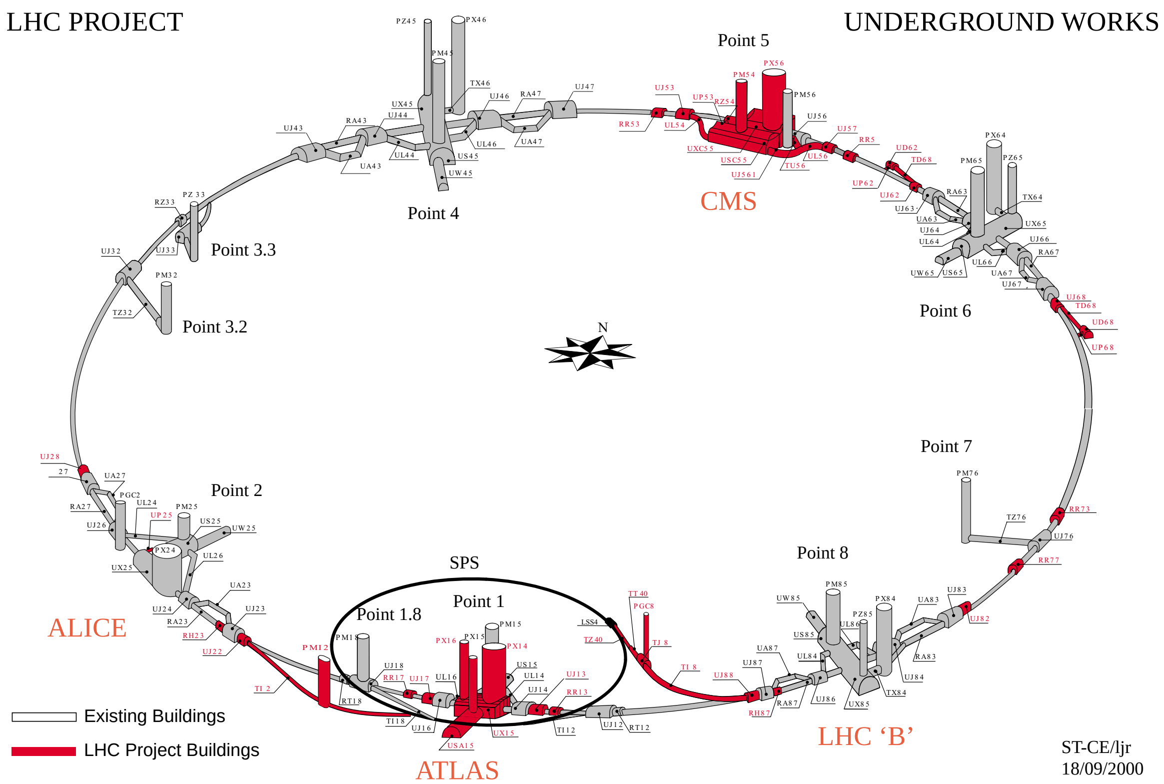
- The LHC accelerator layout
- Functions, constraints, architecture
- Temperature levels
- Heat loads
- Cooling schemes
- Operating modes
- Refrigeration plants
- Instrumentation
- Helium storage and management

The LHC accelerator layout

The 27 km long LHC main accelerator ring is installed underground at a slope of 1.41 % and at depths ranging from 50 m to 150 m.

The accelerator is divided in 8 bending (the ARCs) and 8 straight parts.

There are 8 access points in the straight parts, making for stretches of 3.3 km of accelerator needing to be serviced per access point.

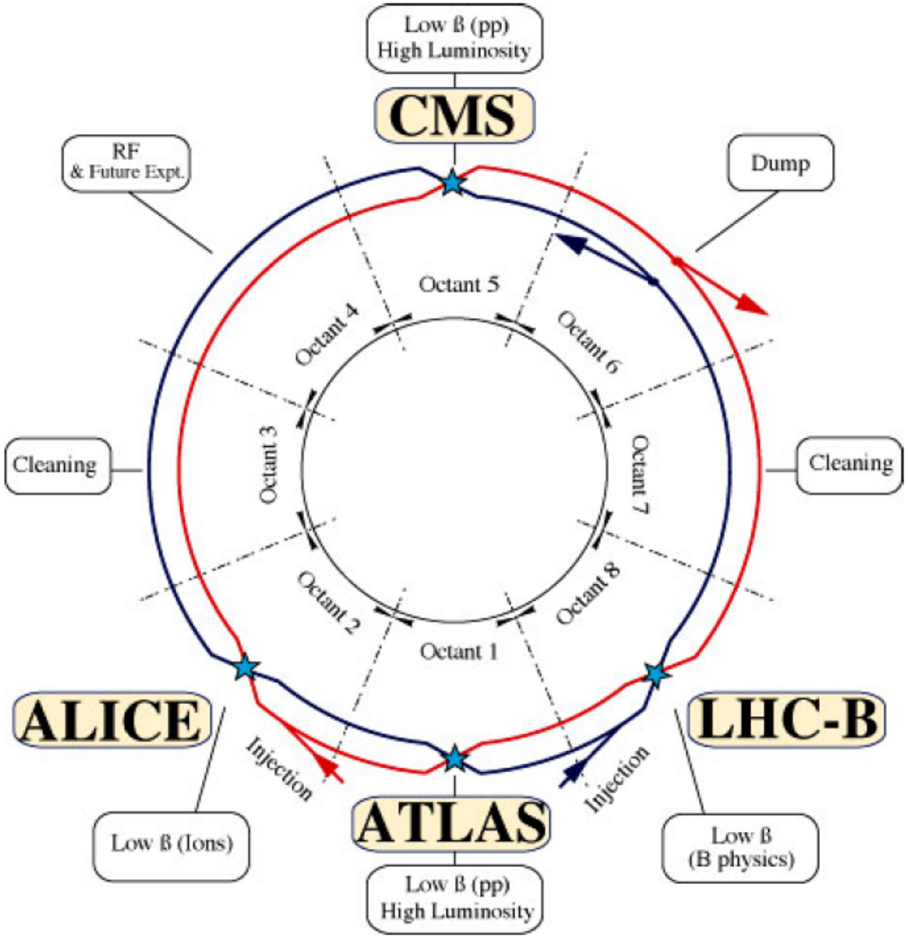


Four particle physics experiments, ATLAS, CMS, ALICE, LHCb, are installed in points 1, 5, 2, and 8.

The LHC accelerator layout

The main dipole and quadrupole magnets, providing the guiding fields for the two counter circulating particle beams (red and blue), occupy the ARCs.

The straight sections of the machine are for the experiments, particle acceleration, final focusing and defocusing of the beams, beam cleaning, beam injection, and beam dump.

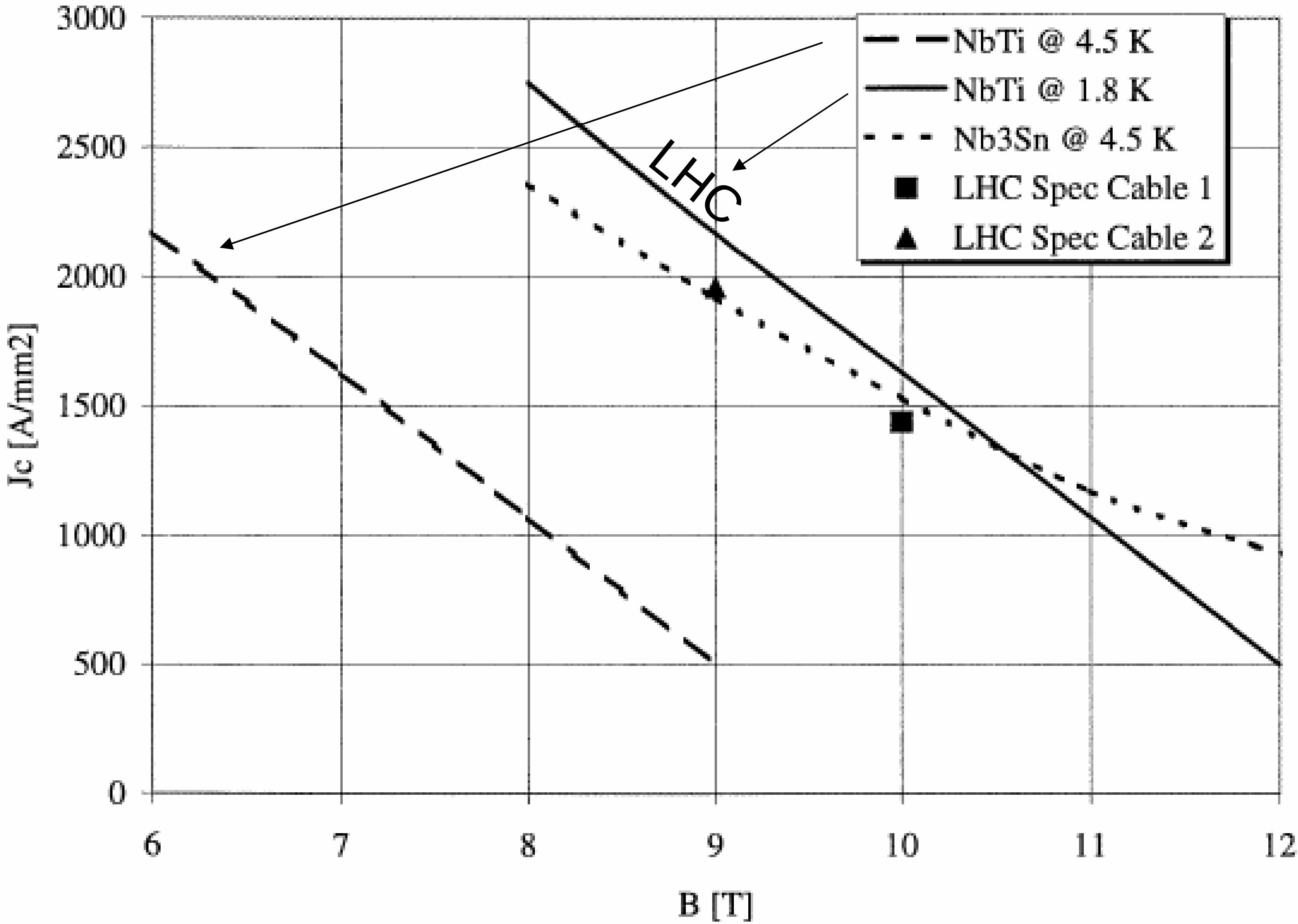


Cryogenics: functional requirements

- The design of the LHC accelerator is based on 25-km of superconducting magnets, the vast majority operating below 1.9 K and using pressurized superfluid helium as coolant.
- The necessity to operate at 1.9 K was given by the high field strength needed and the use of Nb-Ti superconductors, which were the only accelerator grade superconducting cable which could be provided in high quantities.

- Only in the long straight sections, with the exception of the inner triplets and the superconducting dipoles D1, the field strength and heat extraction requirements are such that operation at 1.9 K is not necessary. These magnets will have their superconducting windings immersed in a bath of saturated helium at a temperature of 4.5 K.

Functional requirements: Critical current density of technical superconductors

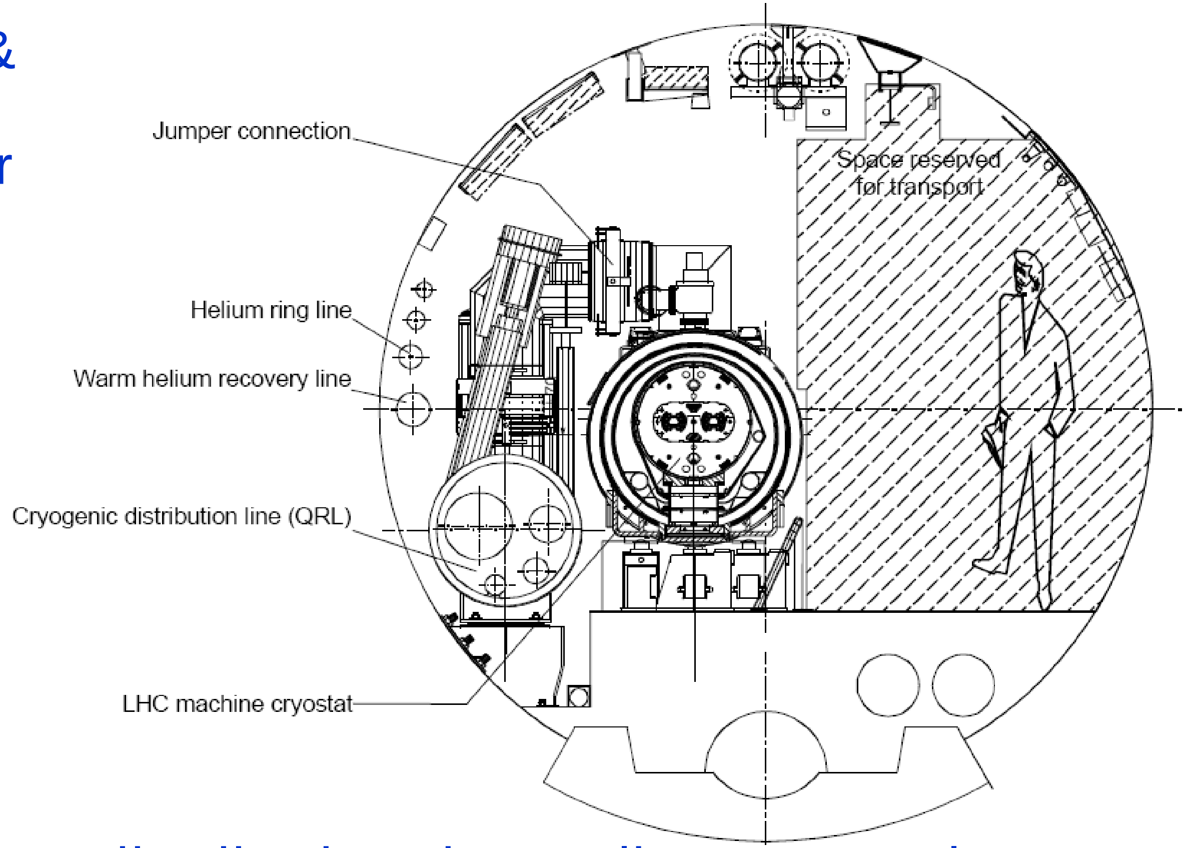


Cryogenics: functional requirements

- *The main magnets must be maintained at temperatures below 1.9 K.* This cooling requirement applies during both ramping and stored-beam operation. In the case of fast current discharge, the temperature excursion may be larger but must still remain below the helium II/helium I phase transition (lambda line).
- *Cope with load variations* and large dynamic range induced by operation of the accelerator.
- *Be able to cool down and fill the huge cold mass of the LHC, 37x10^{6} kg in a maximum time of 15 days while avoiding thermal gradients in the cryo-magnet structure higher than 75 K.* This limit in thermal gradient and time also applies to the forced emptying and warm-up of the machine prior to shutdown periods.
- *Cope with the resistive transitions of the superconducting magnets* while minimizing loss of cryogen and system perturbations.
- In addition to these basic operational duties, the LHC cryogenic system should *allow for rapid cool-down and warm-up of limited lengths of cryo-magnet strings*, e.g. for repairing or exchanging a defective unit.

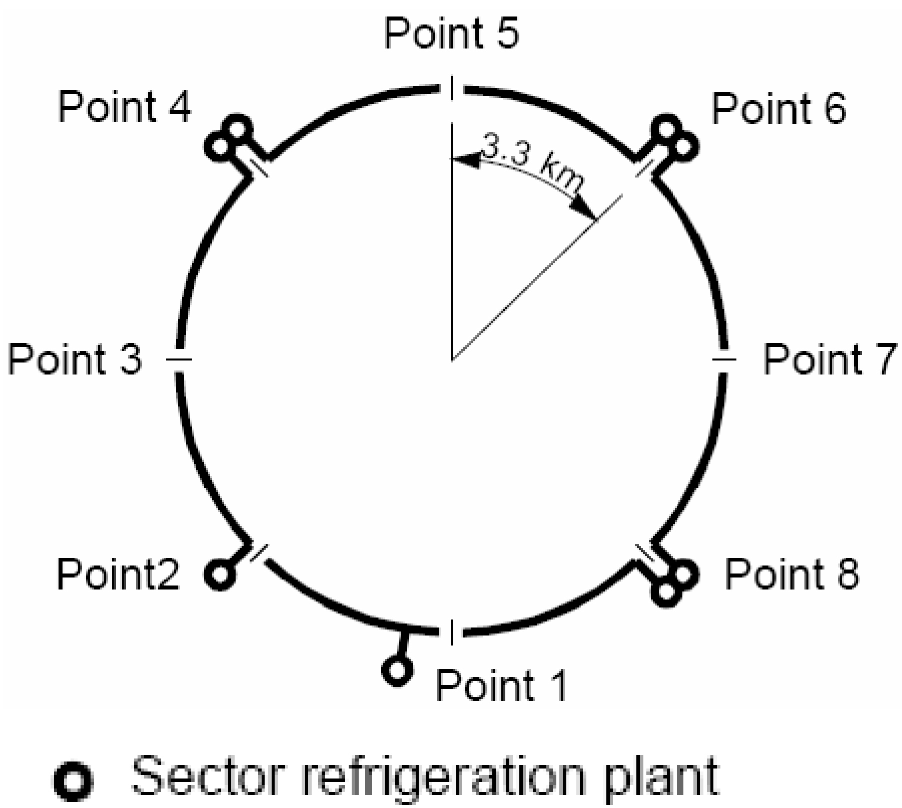
Design constraints: transverse cross-section of the LHC tunnel

- Use of LEP tunnel & infrastructure.
- The limited number of access points to the underground areas.



- The cryogenic headers distributing the cooling power along a machine sector as well as all remaining active cryogenic components in the tunnel are contained in a compound cryogenic distribution line (QRL). The QRL runs alongside the cryo-magnet strings in the tunnel and feeds each 106.9 m-long lattice cell in parallel via a jumper connection.

General architecture: general layout of the cryogenic system



Five cryogenic "islands" at access points 1.8, 2, 4, 6 and 8 where all refrigeration and ancillary equipment is concentrated.

Each cryogenic island houses one or two refrigeration plants that feed one or two adjacent tunnel sectors, requiring distribution and recovery of the cooling fluids over distances of 3.3 km underground.

Equipment at ground level includes electrical substation, warm compressor station (QCS_A,B,C), cryogen storage (helium and liquid nitrogen), cooling towers, cold-boxes (QSR_A,B)

Underground are the lower cold-boxes (QURA), 1.8 K refrigeration unit boxes (QURC), interconnecting lines, and interconnection boxes (QUI_A,B,C).

General architecture: above ground

Liquid Nitrogen storage

Gaseous helium storage

Warm compressor station

General architecture: above ground

4.5 K cold boxes

Pit lines

General architecture: underground

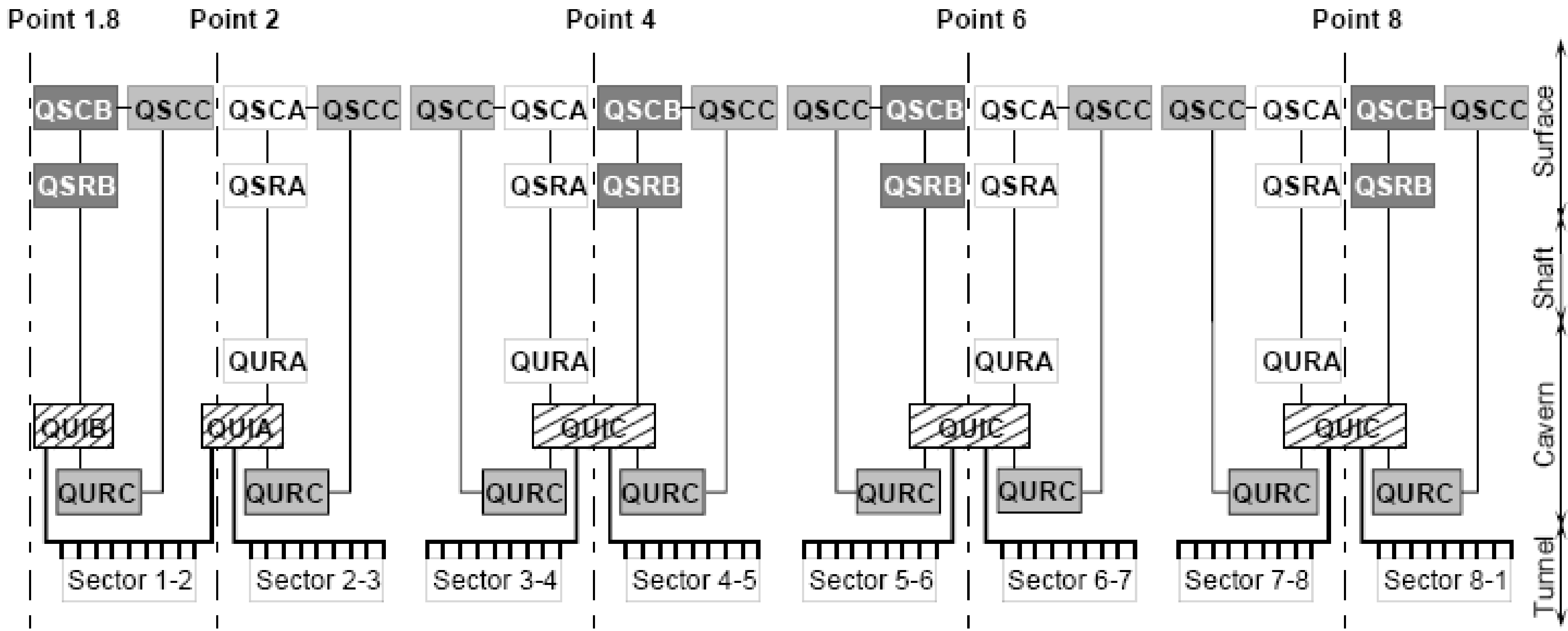
Cryogenic interconnection box

cold compressor elements

QRL (no magnets attached yet)

ARC magnets

General architecture: general layout of the cryogenic system



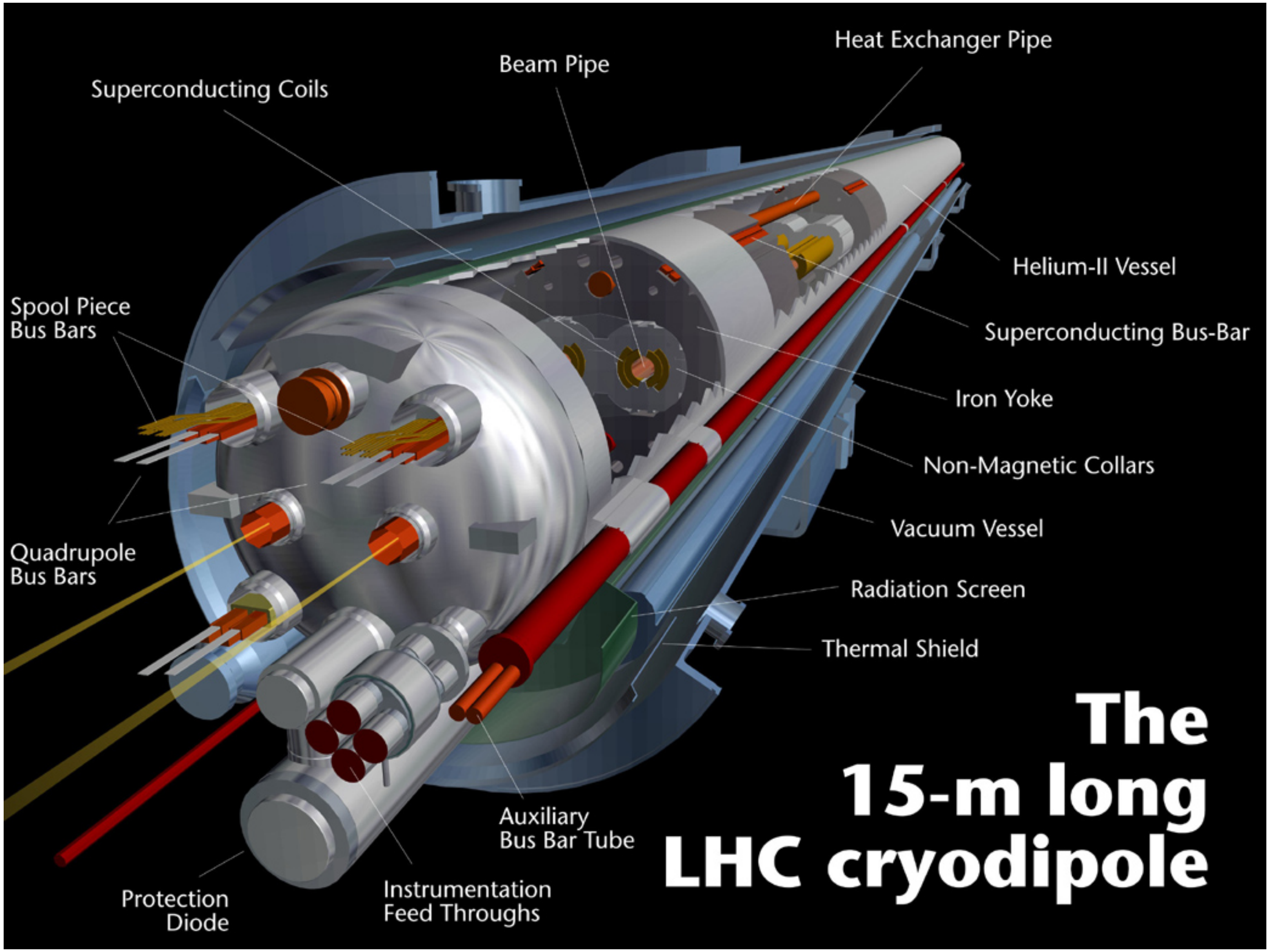
Legend

Cryogenic Distribution Line

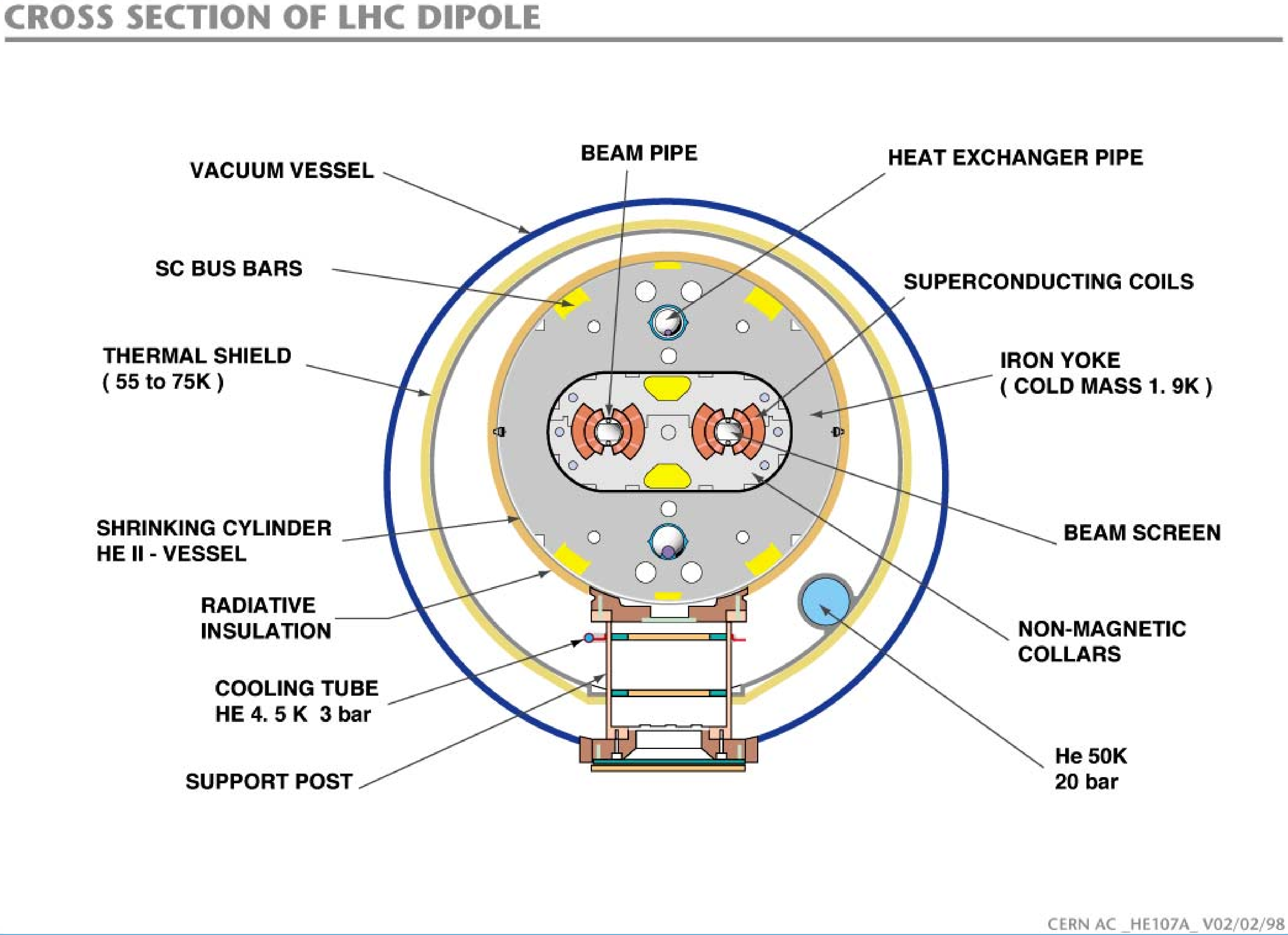
QSC_(A,B,C): Warm Compressor Station
QSR_(A,B): Surface 4.5 K Refrigerator Cold Box
QURA: Underground 4.5 K Refrigerator Cold Box
QURC: 1.8 K Refrigeration Unit Cold Box
QUI_(A,B,C): Cryogenic Interconnection Box

New 4.5 K refrigerator
Ex-LEP 4.5 K refrigerator
1.8 K Refrigeration unit

Temperature levels



Temperature levels

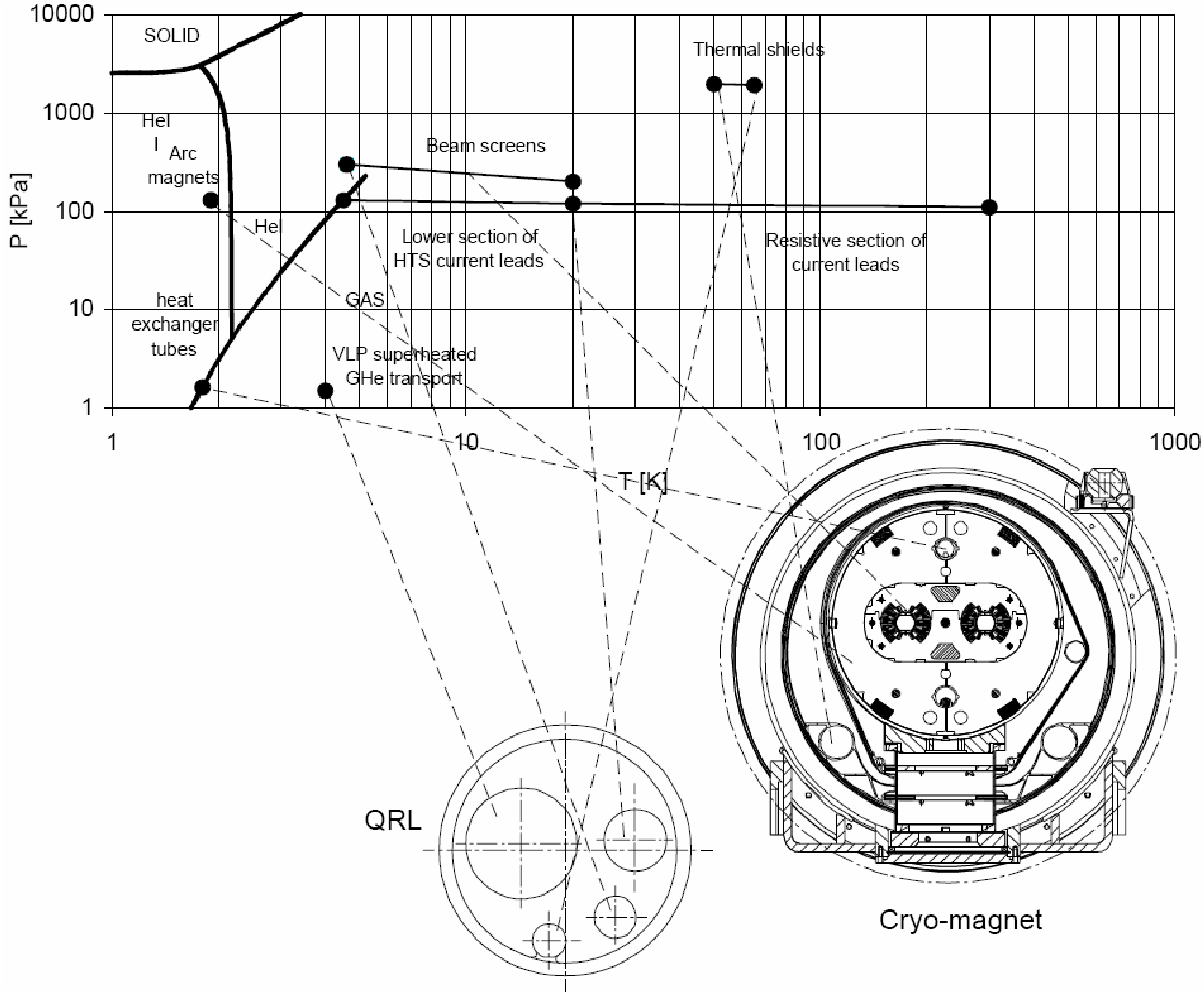


Temperature levels

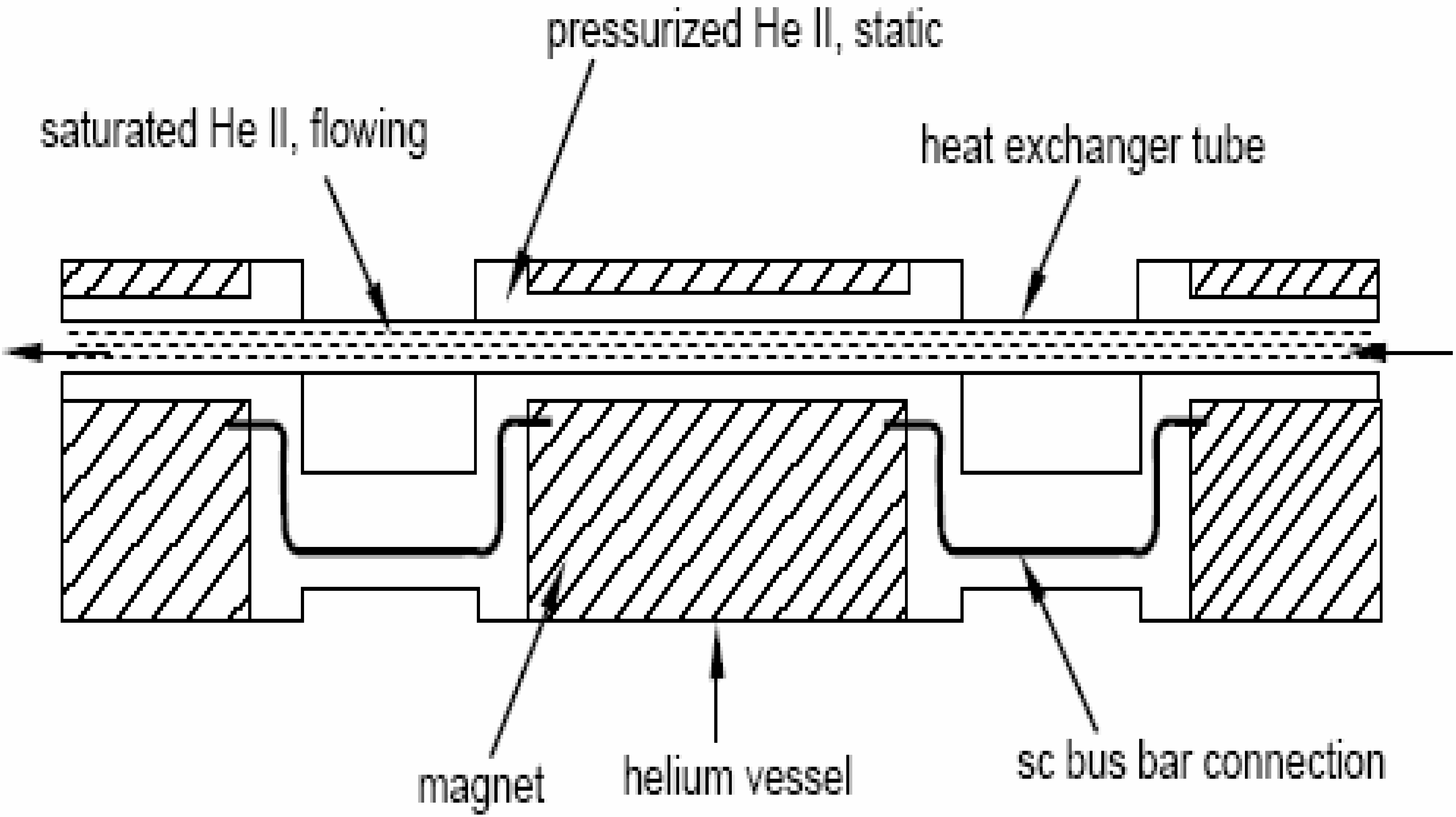
To minimize the cost of refrigeration the thermal design of the LHC cryogenic components aims at intercepting the largest fraction of applied heat loads at the highest temperature possible, hence the multiple, staged temperature levels in the system:

- *50 K to 75 K for thermal shield* as a first major heat intercept, sheltering the cold mass from the bulk of heat in-leaks from ambient.
- *4.6 K to 20 K* for lower temperature heat interception and for the cooling of the beam screens which protect the magnet cold bore from beam-induced loads.
- *1.9 K quasi-isothermal superfluid helium* for cooling the magnet cold mass.
- *4 K at very low pressure (VLP)* for transporting the superheated helium flow coming from the distributed 1.8 K heat exchanger tubes across the sector length to the 1.8 K refrigeration units.
- *4.5 K normal saturated helium* for cooling special superconducting magnets in insertion regions, superconducting acceleration cavities, and the lower sections of high temperature superconductor (HTS) current leads.
- *20 K to 300 K cooling* for the resistive upper sections of HTS current leads.

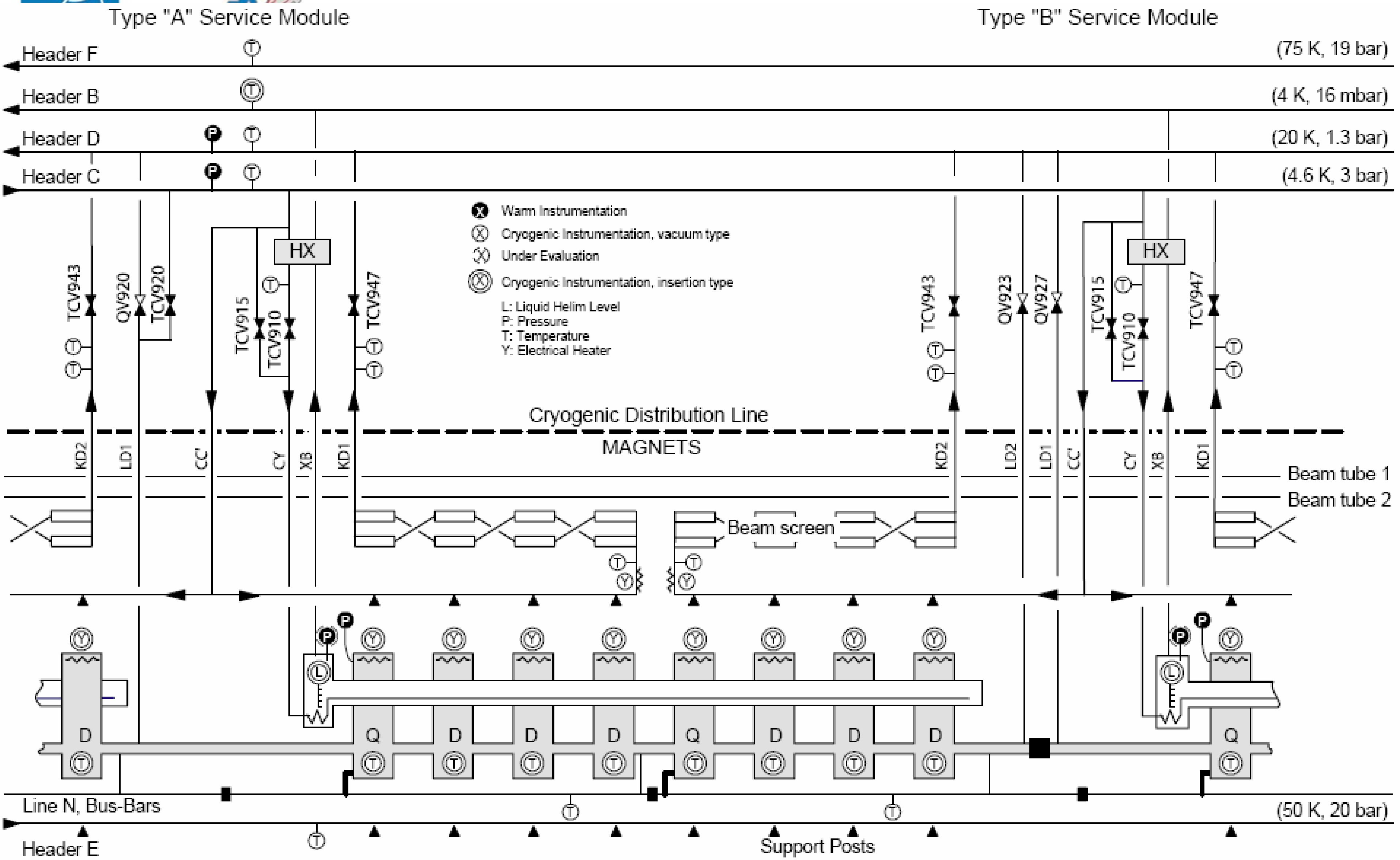
Temperature levels



Cooling schemes: 1.9 K principle



Cooling schemes: ARC and dispersion suppressor



Heat loads: sources

- *Static* due to heat from ambient (cryostat design)
- *Resistive* heating due to non-superconducting sections of magnet circuits
- *Beam-induced* heat loads which are deposited in the cryo-magnets through several processes and by the circulating and colliding proton beams themselves. They depend strongly on the energy, the bunch intensity, number and length of the circulating bunches as well as on the luminosity in collision
- *Transient* due to eddy currents when ramping the magnetic fields up and down

Heat loads: static

➢ Typical magnet-side static heat in-leaks are:

T-level	50-75 K [W]	4.6-20 K [W]	4.5 K LHe [W]	1.9 K LHe [W]	20-300 K [g/s]
Cell (107 m)	482	14.0	-	20.4	-
ARC (23 cells)	11090	323	-	470	-
1/2-Straight Section	700	14	80, 313 at Point 4 (RF)	40	9

Heat loads: static

- Typical distribution-side static heat in-leaks are:

T-level	50-75 K [W]	4.6-20 K [W]	4.5 K LHe [W]	1.9 K LHe [W]	20-300 K [g/s]
Sector: QRL	10000	245	12	45	300
Sector: interconnection boxes and transfer lines	600	190	-	-	35

Heat loads: beam-induced

➢ Typical (nominal/ultimate) magnet-side beam induced heat in-leaks are:

T-level	4.6-20 K [W]	4.5 K LHe [W]	1.9 K LHe [W]
Cell (107 m)	169/466	-	6-10/9-14
ARC (23 cells)	3880/10740	-	211/284
DS	320/910	-	40/100
Straight: Low-luminosity	40/100	6/12	40/95
Straight: High-luminosity	45/120	10/22	193/440
Straight: RF	31/87	214/529	2/2

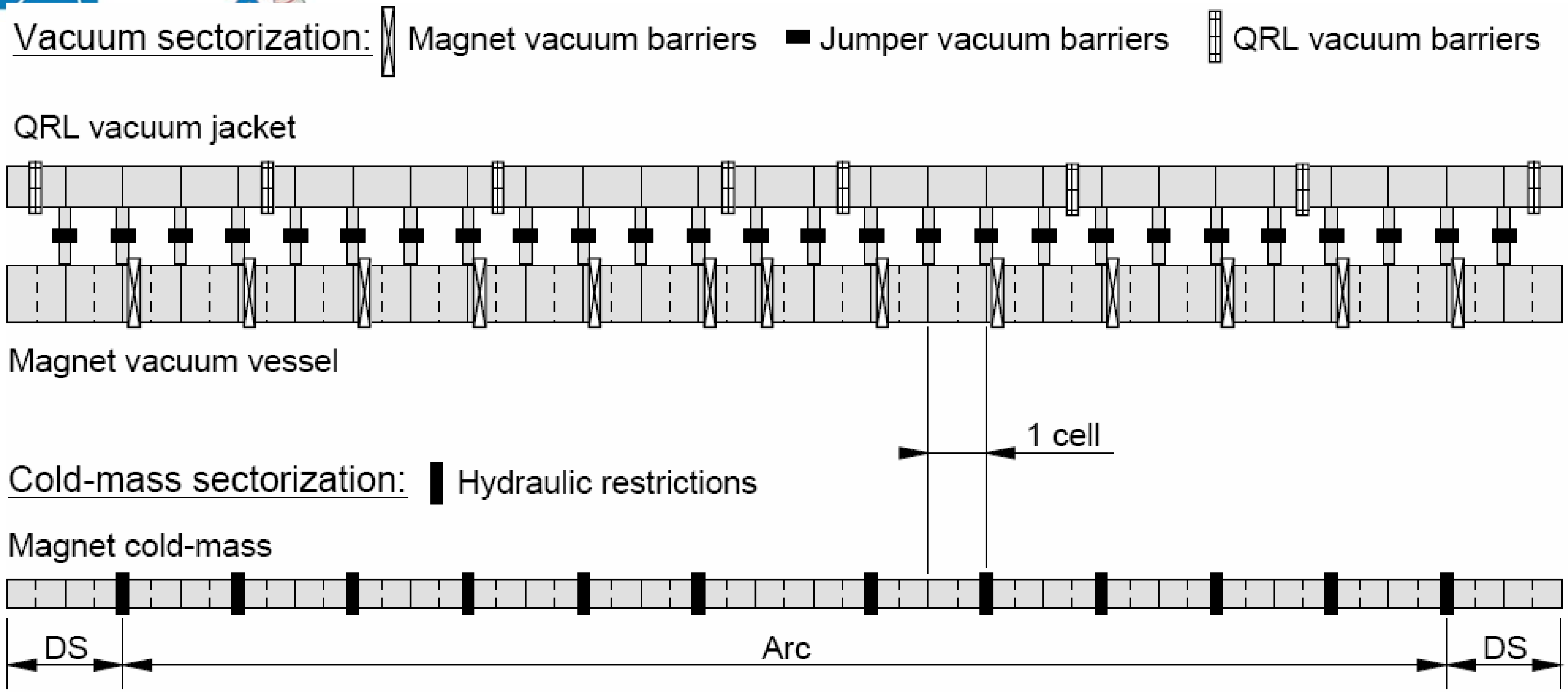
Refrigeration plants

- Installed refrigeration capacity in the LHC sectors

Temperature level		High-load sector	Low-load sector
50-75 K	[W]	33000	31000
4.6-20 K	[W]	7700	7600
4.5 K	[W]	300	150
1.9 K LHe	[W]	2400	2100
4 K VLP	[W]	430	380
20-280 K	[$g.s^{-1}$]	41	27

- The 4.5 K refrigerators and 1.8 K cold compressor units will be addressed in the talk by S. Claudet

Cooling schemes: sub-sectorization



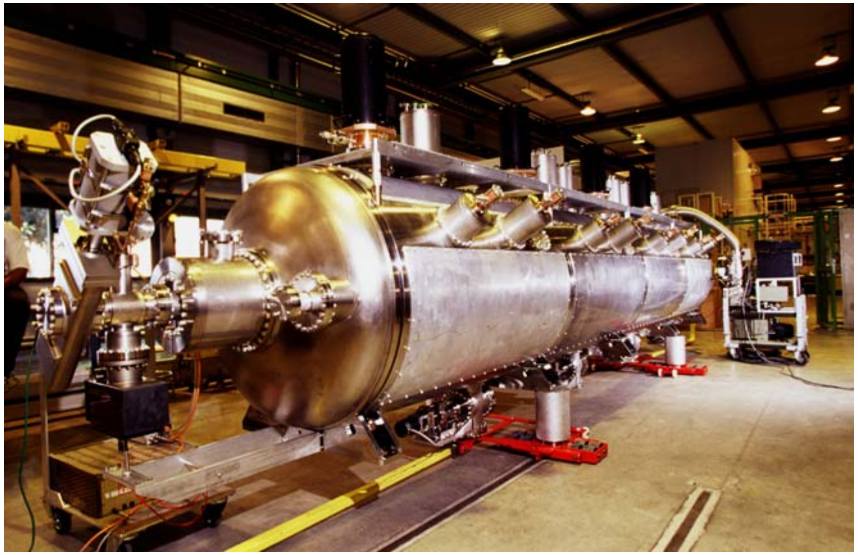
- ➢To avoid parts of the cold mass going sub-atmospheric due to hydrostatic head (1.41 % tunnel slope), the cold mass volume within a sector has been sub-sectorised by adding hydraulic restrictions every two or three cells
- ➢The cryogenic vacuum is also sub-sectorised in order to limit the extent of a degraded vacuum zone created by a possible helium leak of the internal circuit. On the cryo-magnet side, every two cells. On the cryogenic distribution line side, every four cells. The jumper connection between QRL and magnet cryostats always contains a vacuum barrier.

Cooling schemes: Matching sector and special equipment

- The special magnets of the matching section, which do not require cooling at 1.9 K for field strength and heat extraction, operate in baths of saturated helium I at 4.5 K.
- The inner-triplet quadrupoles in the insertion regions are subject to dynamic heating from secondaries of up to 10 W/m at each of the high luminosity insertions 1 and 5 and up to about 2 W/m at the low luminosity insertions 2 and 8 from the particle interactions. Although this represents a much higher heat load than the magnets in the arc and DS receive, they can be cooled by a scheme similar to the standard cell.

Cooling schemes: special equipment

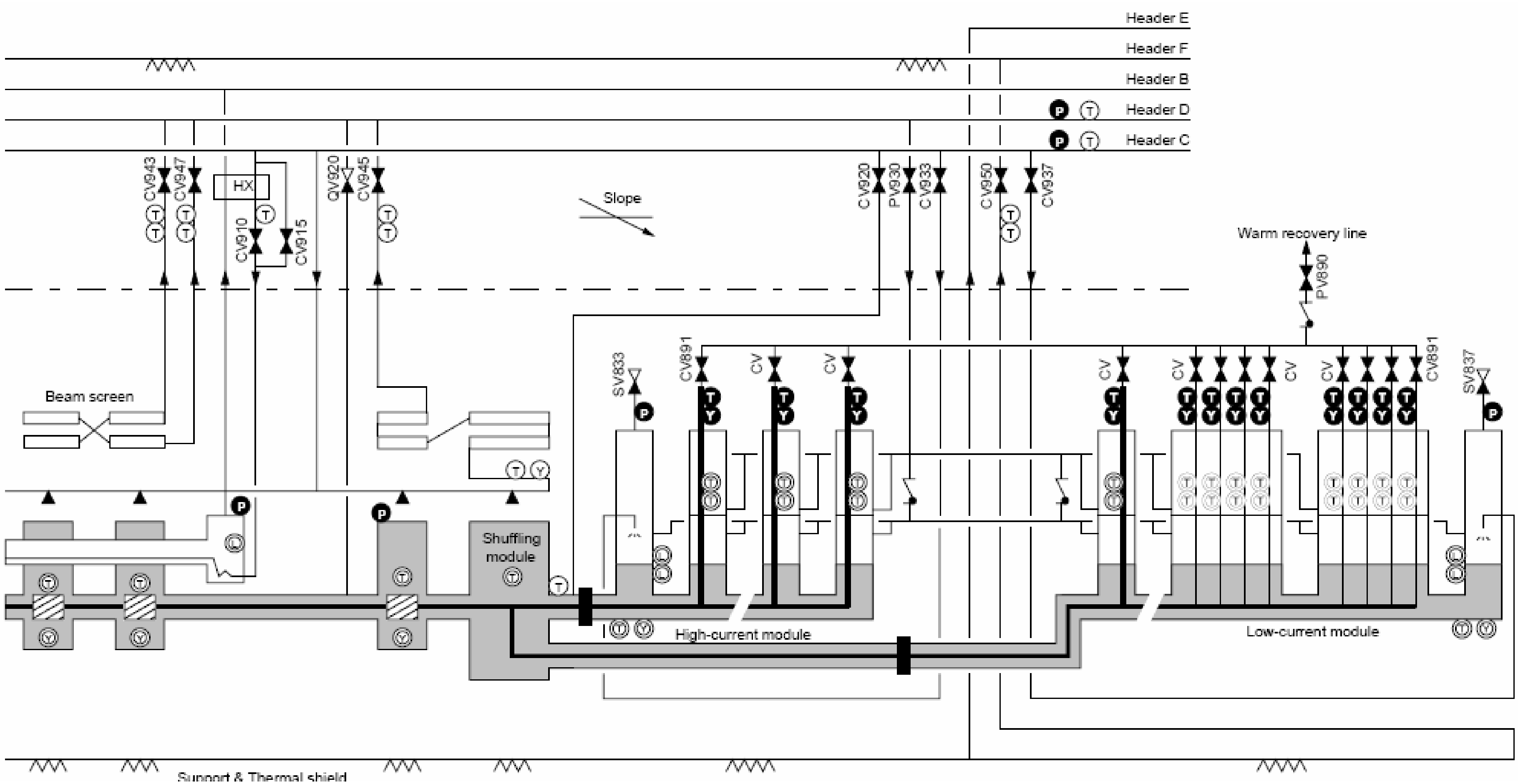
Electrical current feed box, housing HTS current leads



RF cavities

- The electrical distribution feed boxes which are the equipments interfacing the room-temperature powering and the superconducting magnet busbars, as well as the RF cavities are low design pressure equipment (0.35 MPa for the DFBs and 0.25 MPa for the RF cavities) connected to high design pressure (2 MPa) equipment and cryogen supplies. This peculiarity has specific consequences for their cryogenic implementation.

Cooling schemes: electrical distribution feed boxes



Lower parts of current leads in pool boiling helium with dedicated feed at 20 K, exit at room temperature, hydraulic plugs between feed boxes and magnets.

Operating modes

- Steady state

-Nominal: 7 TeV beam energy, 2×0.582 A beam current and 10^{34} cm^{-2} s^{-1} luminosity

-Ultimate: 7 TeV beam energy, 2 × 0.86 A beam current and $2.5x10^{34}$ cm^{-2} s^{-1} luminosity

-Low beam intensity: full beam energy but low beam-induced heat loads

-Injection standby: negligible resistive dissipation and beam-induced heat loads in the magnets.

Operating modes

- Four transient modes are considered (see talk by L. Serio, CERN):
- cool-down from 300 K to 4.5 K (the aim is to cool down the cold mass of a LHC sector in a maximum time of 15 days),
- magnet filling and cool-down from 4.5 K to 1.9 K,
- resistive transition (see spot by M. Chorowski, WUT)
- warm-up from 4.5 K to 300 K (the aim is to warm-up the huge cold mass of a sector in a maximum time of 15 days).

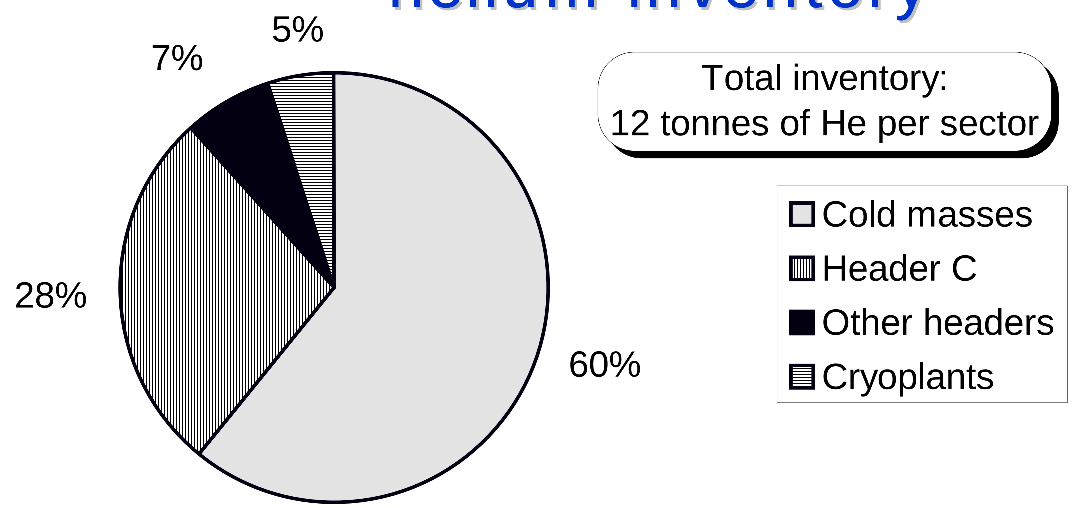
Instrumentation and process control

- The cryogenic operation of the LHC requires a large number of sensors, electronic conditioning units and actuators, most of which are located inside the machine tunnel and must therefore withstand the radiation environment.

Sensor type	Quantity	Redundancy	RadTol quantity
Temperature CX	4,500	1,153	3,347
Temperature Pt100	2,400		450
Pressure Low	230		230
Pressure Mod/High	900		900
Level Gauges	300		300
Electrical Heater	2,500		2,000

- The instrumentation issues and process control will be specifically addressed in the talk by J. Casas-Cubillos.

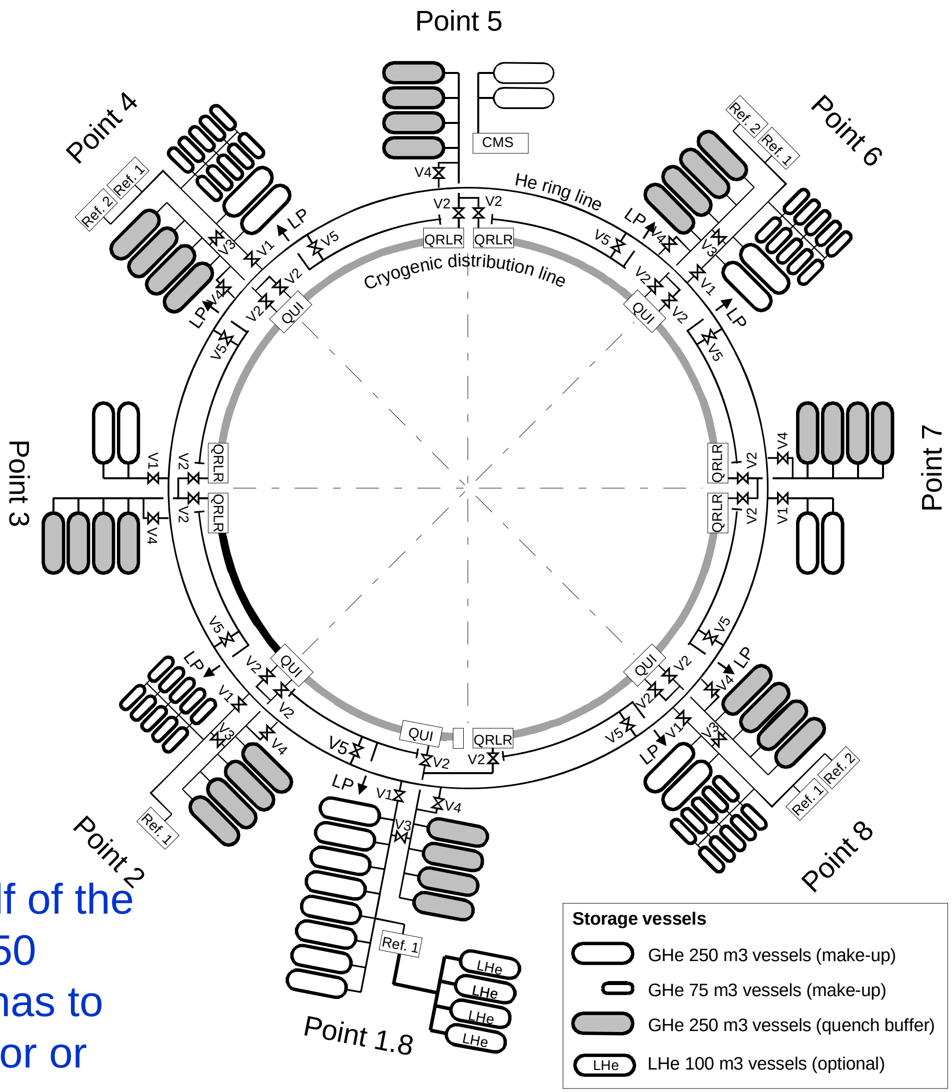
Cryogen storage and management: helium inventory



- Helium is mainly contained in the magnet cold masses which require a minimum filling ratio of 15 l/m of superfluid helium for enthalpy buffering (measured cold masses filling ratio is about 26 l/m) and in the header C of the cryogenic distribution line.
- The total helium inventory of the whole machine is about 96 $\times 10^3$ kg. To limit costs and reduce the environmental impact, it was decided to provide gas storage for only half of the inventory.

Cryogen storage and management: helium inventory

- The gaseous helium is stored at a maximum working pressure of 2 MPa (20 bar) and ambient temperature.
- At each point, four 250 m3 vessels are used as buffer in case of resistive transition of multiple magnets during operation.
- The remaining vessels will be used as make-up gas storage for the cryogenic system.
- A helium line interconnecting the different storage areas will is installed in the tunnel and the access shafts



- "Virtual" or liquid storage

As the gas management allows storing only half of the inventory, during winter shutdown the excess (50 tonnes or about 400000 litres of liquid helium) has to be either “virtually” recovered by a gas distributor or stored in liquid state in a central storage.

Conclusions

- Largest distributed superfluid helium system in the world is on its way to become operational and to function according to design!