LHC: World's largest vacuum systems being commissioned at CERN

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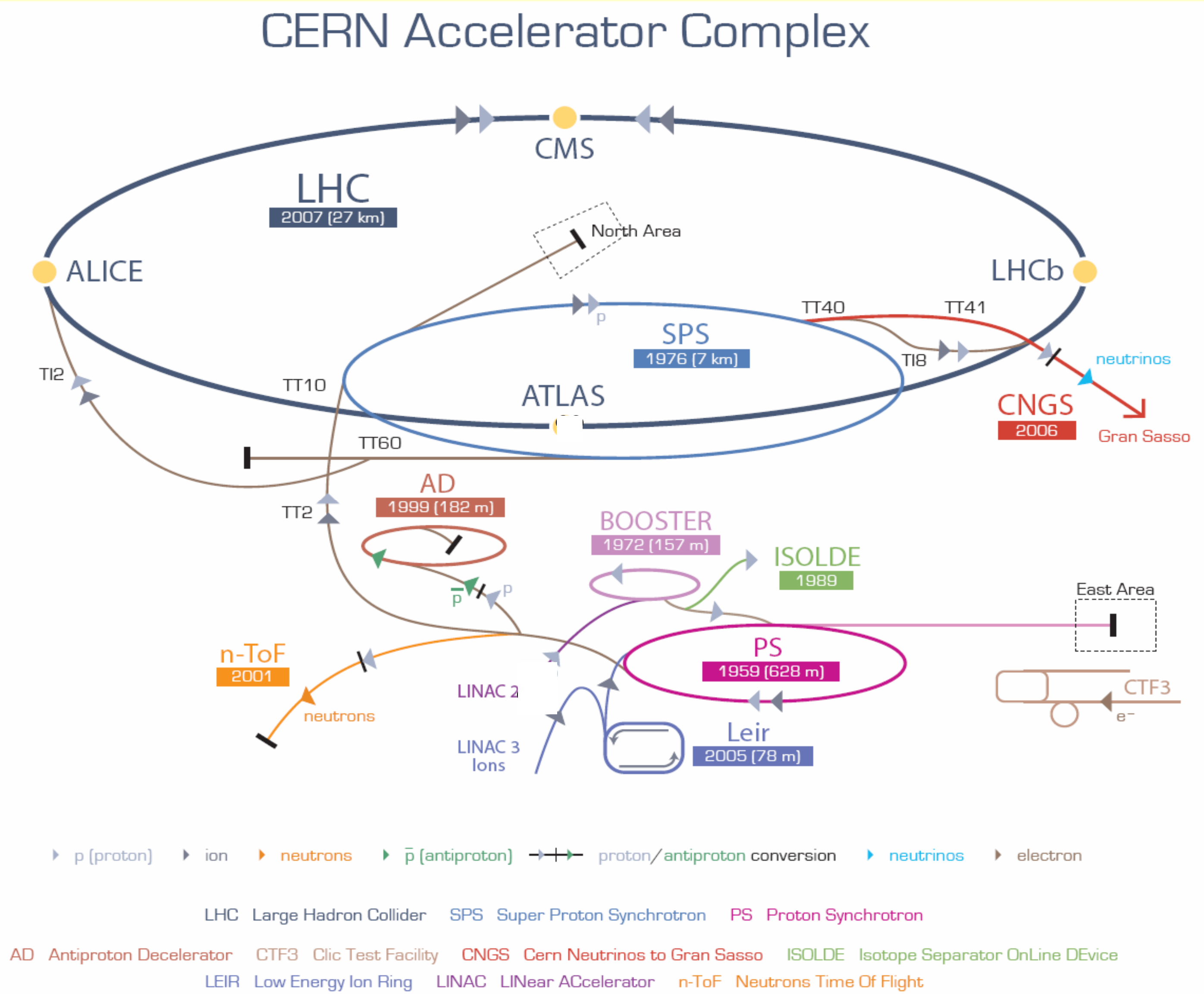
On behalf of Vacuum Group

Accelerator Technology Department

Outline

- **Introduction**
- **The LHC…**
  - Vacuum sectorisation
  - Beam vacuum
  - Insulation vacuum
  - Beam injection and dump transfer lines
  - Controls & Monitoring
- **Closing remarks**

Introduction
CERN accelerator chain



Introduction
CERN accelerator chain

Machine	Type	Year	Energy	Bakeout	Pressure (Pa)	Length	Particles
Linac, Booster, ISOLDE, PS, n-TOF and AD Complex						**2.6 km !**	
LINAC 2	linac	1978	50 MeV	Ion pumps	10^{-7}	40 m	p
ISOLDE	electrostatic	1992	60 keV	-	10^{-4}	150 m	ions: 700 isotopes and 70 (92) elements
REX-ISOLDE	linac	2001	3 Mev/u	partly	10^{-5} - 10^{-10}	20 m	
LINAC 3	linac	1994	4.2 MeV/u	Ion pumps	10^{-7}	30 m	ions
LEIR	accumulator	1982/2005	72 MeV/u	complete	10^{-10}	78 m	pbar, ions
PSB	synchrotron	1972	1-1.4 GeV	Ion pumps	10^{-7}	157 m	P, ions
PS	synchrotron	1959	28 GeV	Ion pumps	10^{-7}	628 m	P, ions
AD	decelerator	?	100 MeV	complete	10^{-8}	188 m	pbar
CTF3 complex	linac/ring	2004-09		partly	10^{-8}	300 m	e
PS to SPS TL	Transfer line	1976	26 GeV	-	10^{-6}	~1.3 km	P, ions
SPS Complex						**15.7 km !**	
SPS	synchrotron	1976	450 GeV	Extractions	10^{-7}	7 km	p, ions
SPS North Area	Transfer line	1976		-	10^{-6} - 10^{-7}	~1.2 km	
SPS West Area	Transfer line	1976				~ 1.4 km	
SPS to LHC TI2/8 Line	Transfer line	2004/2006				2 x 2.7 km	
CNGS Proton Line	Transfer line	2005				~730 m	
LHC Accelerator						***~109 km !***	
LHC Arcs (Beam x2, Magnets & QRL insul.)	collider	2007	2 × 7 TeV	-	< 10^{-8}	2 x (2 x 25 km)	p, ions
LSS RT separated beams				complete		2 × 3.2 km	
LSS RT recombination						~ 570 m	
Experimental areas						~ 180 m	
Beam Dump Lines TD62/68	Transfer line	2006	7 TeV	-	10^{-6}	2 × 720 m	
				High Vacuum		~20 km	**~128 km !**
				UHV w/wo NEG		~ 57.5 km	
				Insulation vacuum		~ 50 km	

Introduction
CERN accelerator chain

- CERN runs a wide range of accelerators
  - Small: LEIR with a circumference of 80 m
  - Very large: LHC with a circumference of 27 km
- The basic vacuum requirements
  - Depend more on beam performance than on size
  - With increasing beam energy and intensity, dynamic effects dominate
    - Exception:
      low energy ion accelerators are also dominated by dynamic effects
- Higher beam energy means larger size
  - Requires a trade-off between performance and cost
  - Higher demand on integration and logistics

Vacuum in the accelerators
Evolution of requirements (1/2)

Vacuum aims to reduce beam-gas interaction which is responsible for:

- Machine performance limitations
  - Reduction of beam lifetime (nuclear scattering)
  - Reduction of machine luminosity (multiple coulomb scattering)
  - Intensity limitation by pressure instabilities (ionization)
  - Electron (ionization) induced instabilities (beam blow up)
  - Magnet quench i.e. transition from the superconducting to the normal state
    - ⇨ Heavy gases are the most dangerous
- Background to the experiments
  - Non-captured particles which interact with the detectors
  - Nuclear cascade generated by the lost particles upstream the detectors

Vacuum in the accelerators
Evolution of requirements (2/2)

Beam vacuum pipes are designed to:

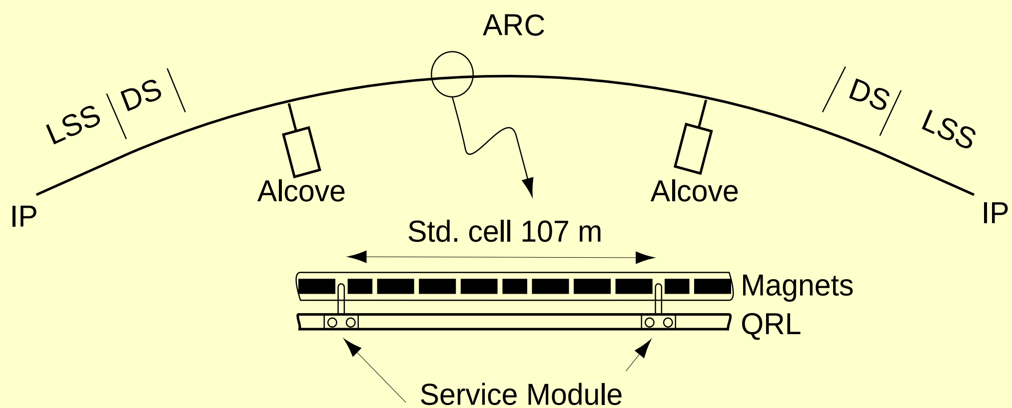
- Minimise beam impedance and HOM generation
- Optimise beam aperture
- Intercept heat loads (cryogenic machines)
  - Synchrotron radiation (0.2 $W.m^{-1}$ per beam)
  - Energy loss by nuclear scattering (30 $mW.m^{-1}$ per beam)
  - Image currents (0.2 $W.m^{-1}$ per beam)
  - Energy dissipated during the development of electron clouds

⇨ Intercept most of the heat load, 1 W at 1.9 K requires 1 kW of electricity

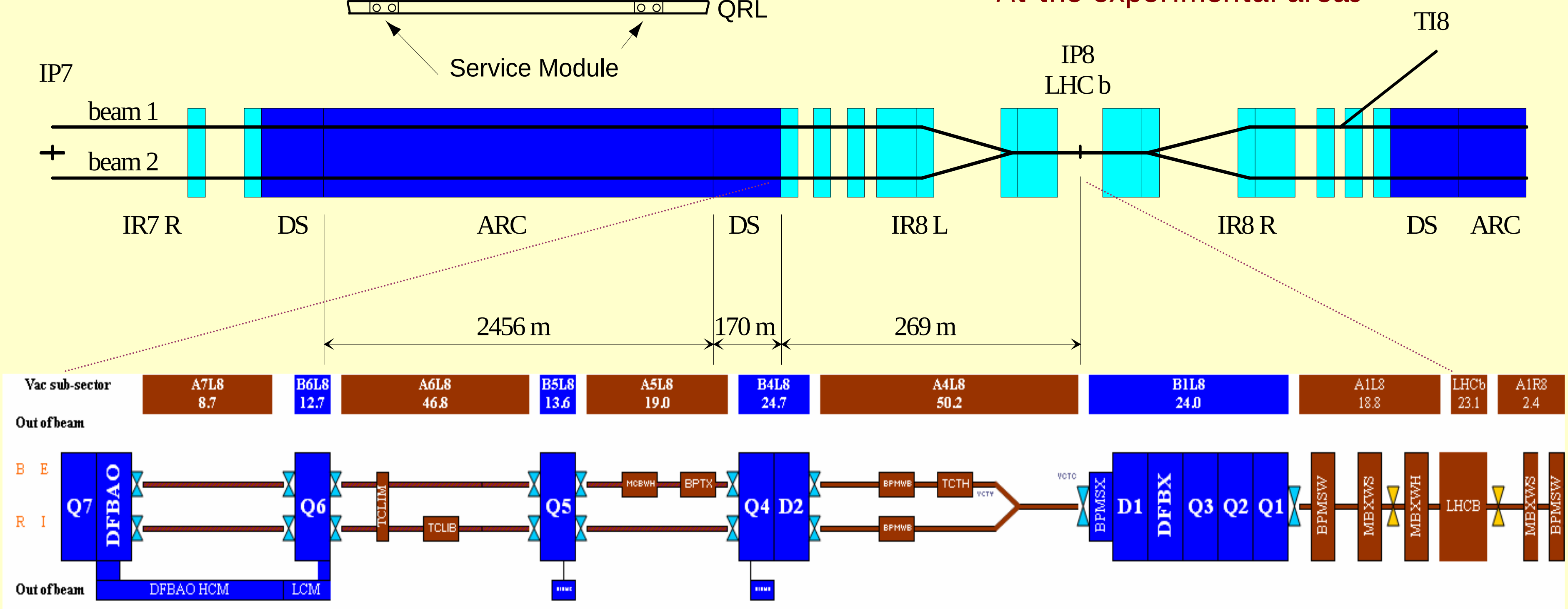
The LHC…
LHC vacuum sectorisation

LHC sectorisation

LHC layout: arcs and LSS



- 8 arcs and 8 straight sections
- Separation of cold and RT vacuum systems
- Create vacuum sectors in long/fragile RT zones
- Equipment which need and ex-situ conditioning
- At the experimental areas



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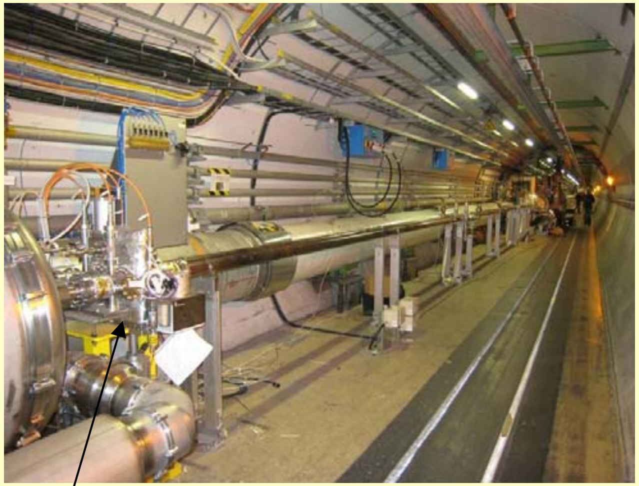
LHC sectorisation
LSS vacuum sectorisation



70% of the sector valves isolate a cold sector from a warm one

303 sector valves in the LHC

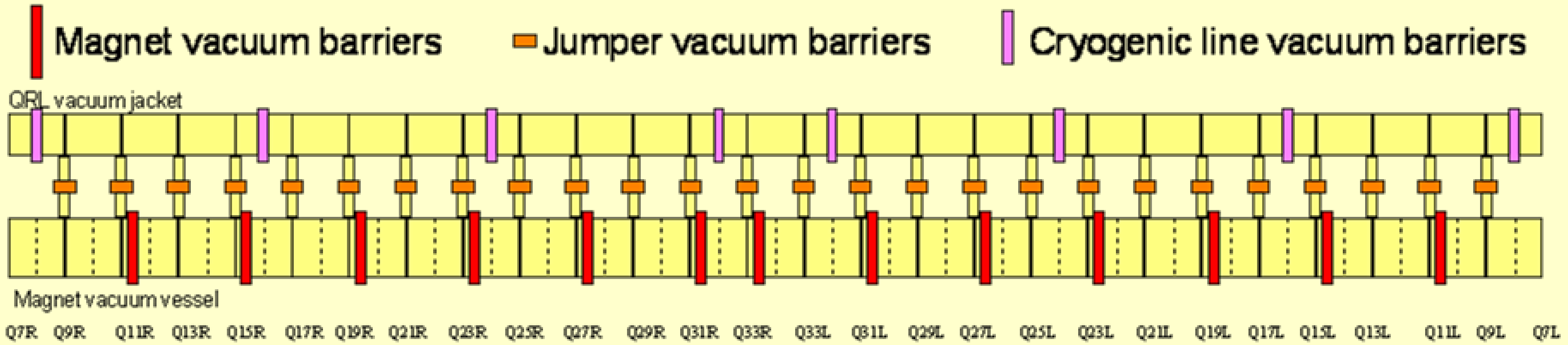
Vacuum instrumentation

Sectorisation modules

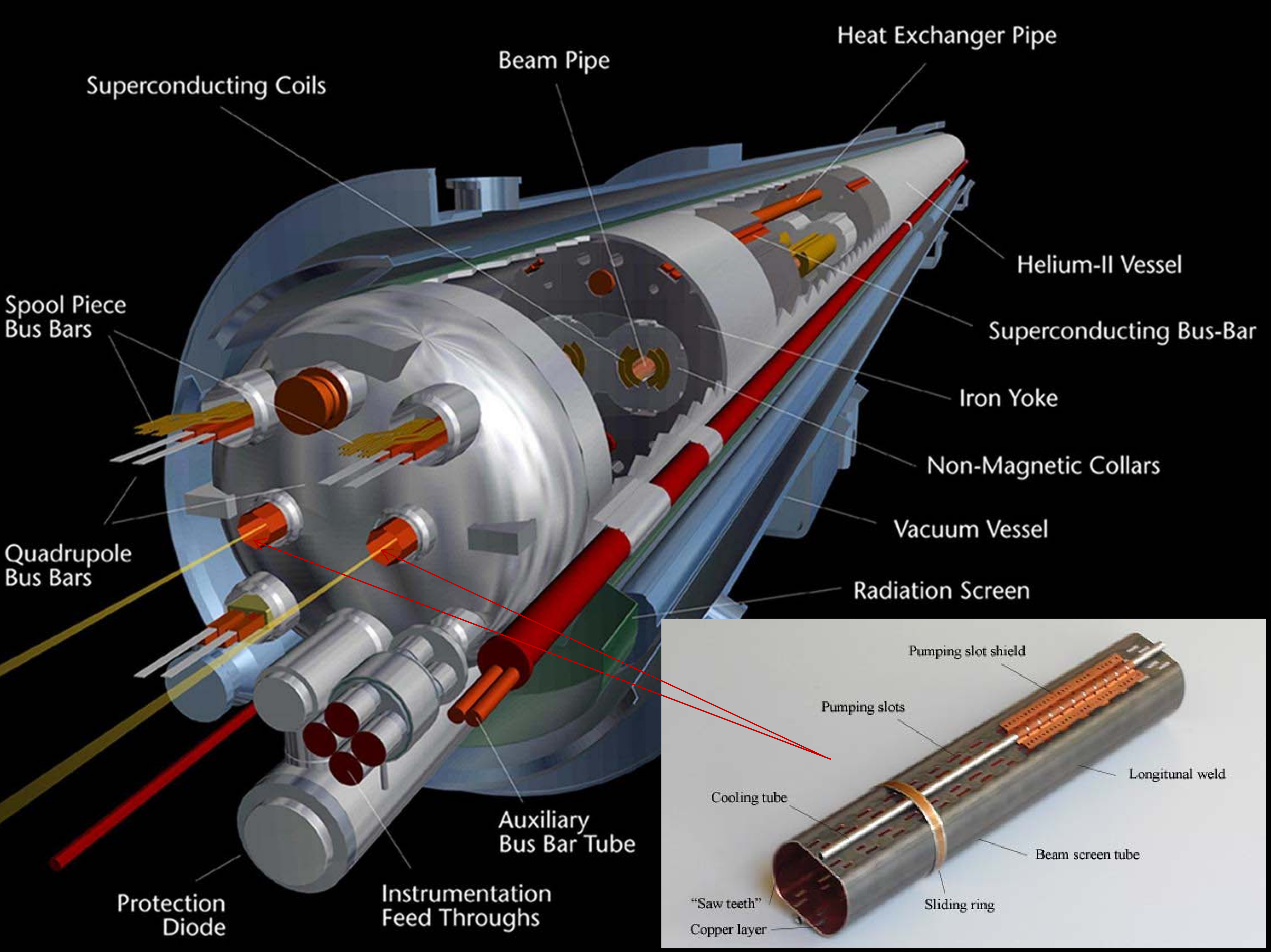
Mobile turbo molecular pumping station

LHC sectorisation

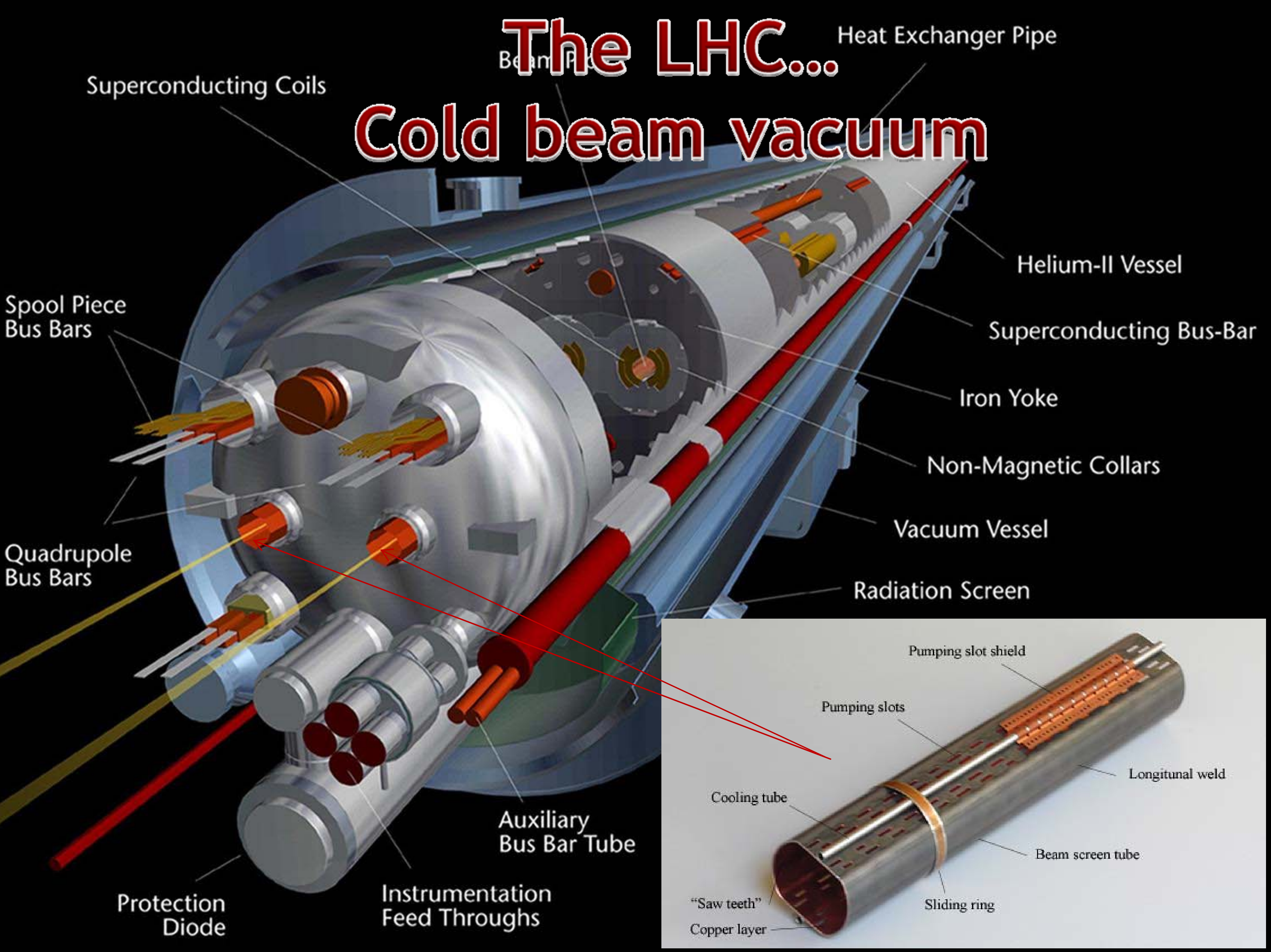
Insulation vacuum sectorisation



- **Vacuum barriers**
  - **104 for the magnets**
  - **64 for the cryogenic lines**
  - **272 for the jumpers (link between QRL and magnets)**

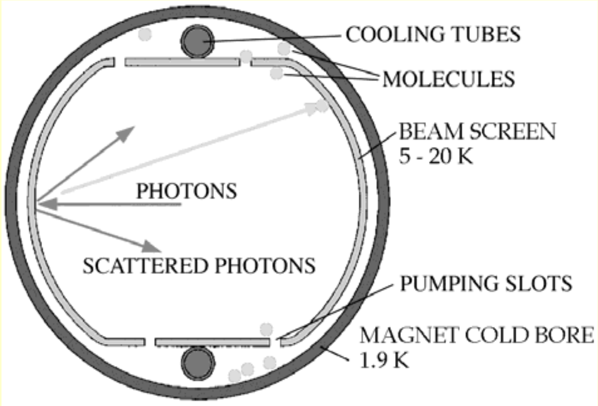

Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs
Pumping slot shield
Pumping slots
Longitunal weld
Cooling tube
Beam screen tube
"Saw teeth"
Sliding ring
Copper layer

The LHC…
Cold beam vacuum



LHC beam vacuum
Cold beam vacuum

- Cold beam vacuums (1.9 K)
- 2 x 2.8 km x 8 (arcs) and in all LSS standalone cryo-magnets
- Non-baked beam vacuum
  - ⇨ 2-3 weeks pumping time (10^{-4} Pa) before cool down
- Pressure lower than 10^{-10} Pa after cool down @ 1.9 K
- Innovating conceptual design with a "beam screen"
  - Radically different design between the arcs and the RT sections
  - Beam screen operated between 5 and 20 K

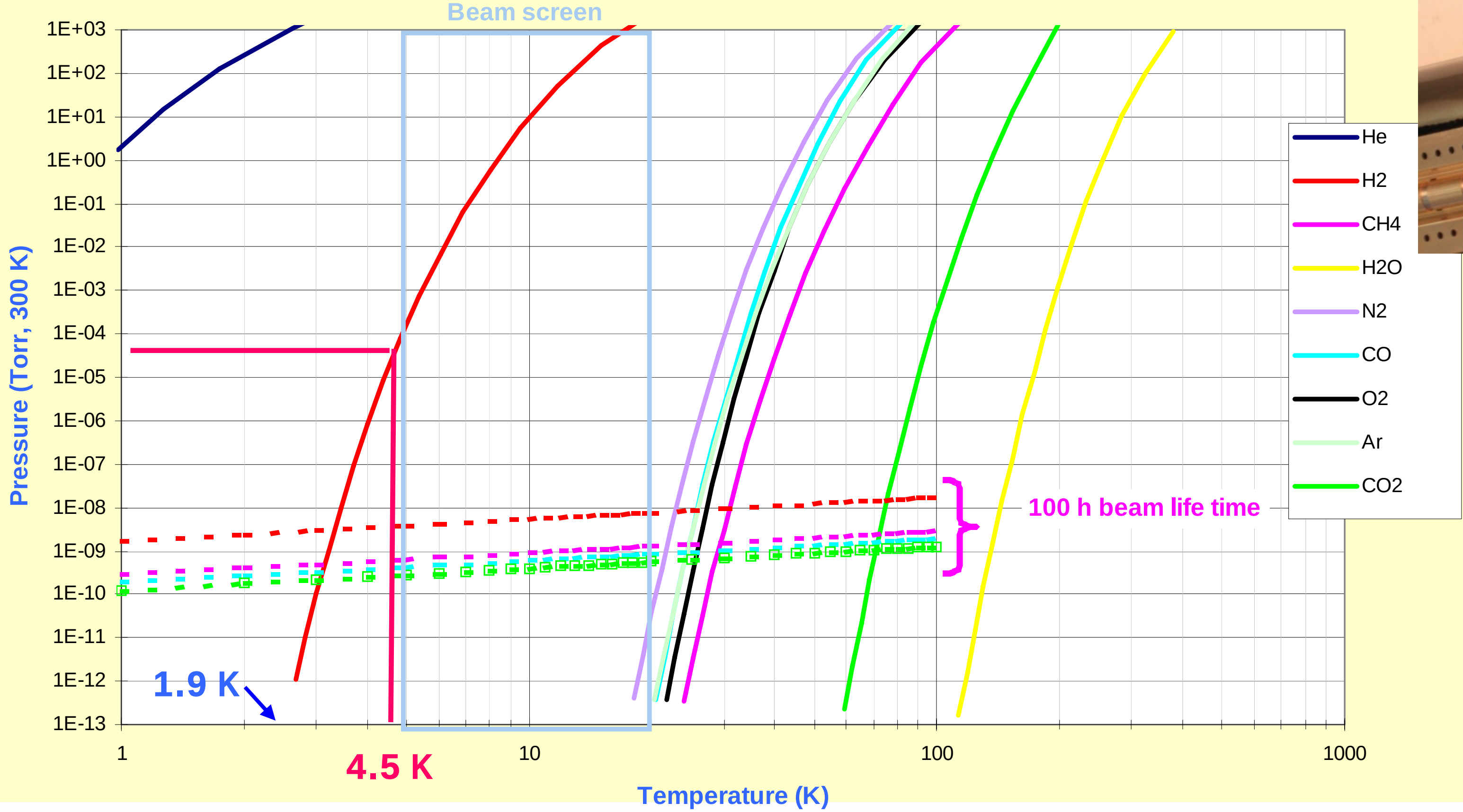


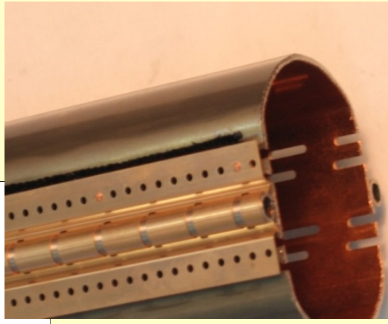
- Intercept most of the heat load
- Cryopumping ensures the beam lifetime
- Holes in the beam screen allow the transfer of desorbed molecules to the magnet cold bore surfaces where these can no longer be re-desorbed

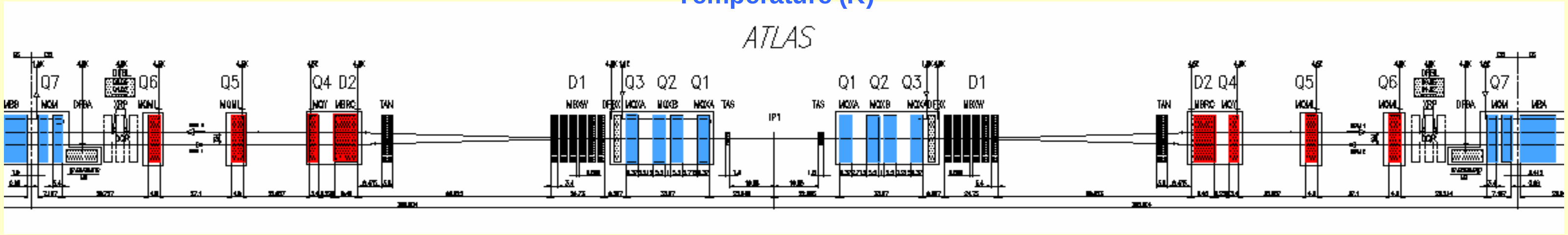
LHC beam vacuum

Cold beam vacuum at 4.5 K

Saturated vapour pressure from Honig and Hook (1960)







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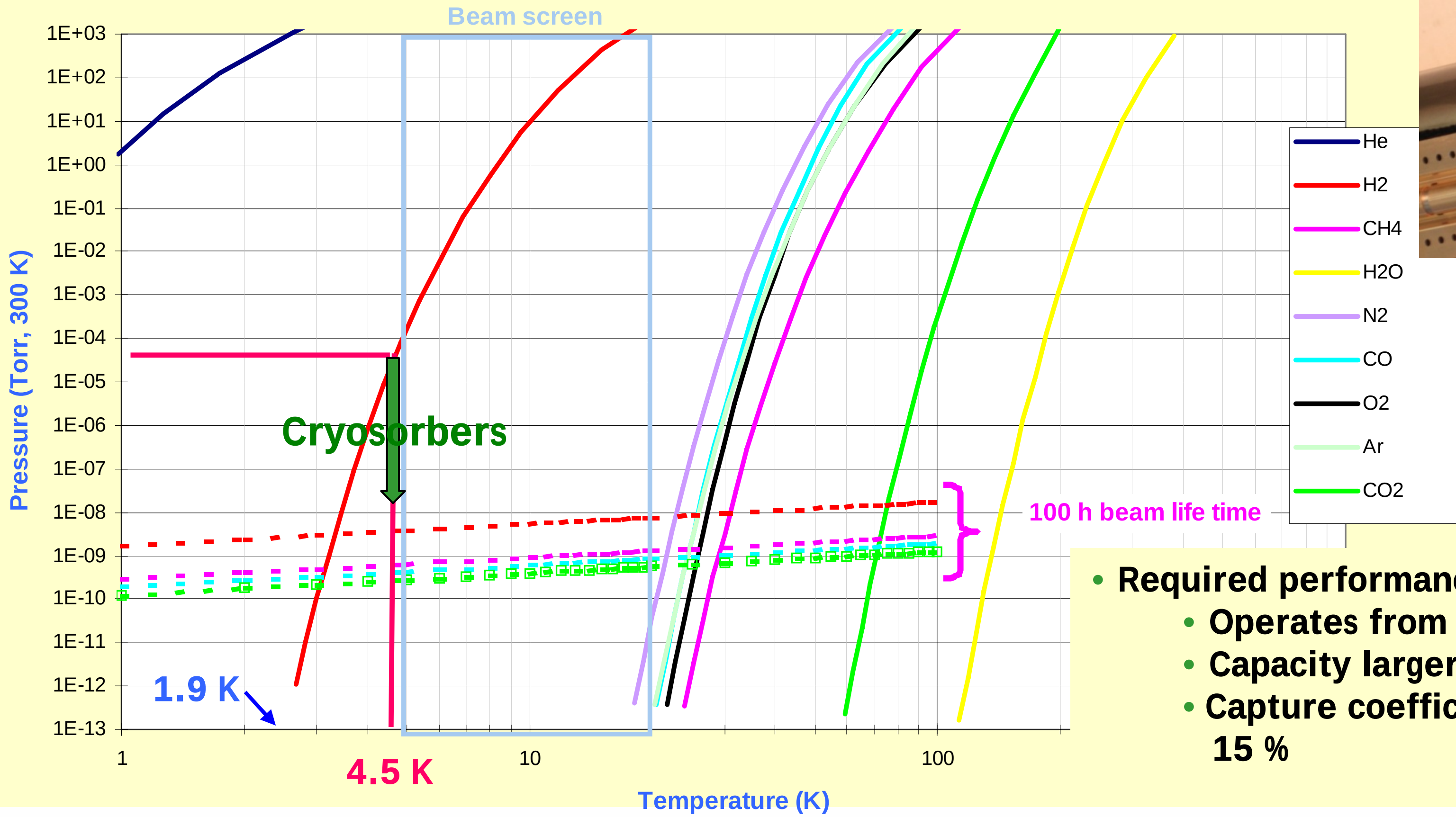
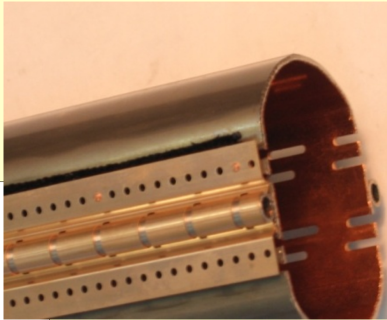
LHC beam vacuum

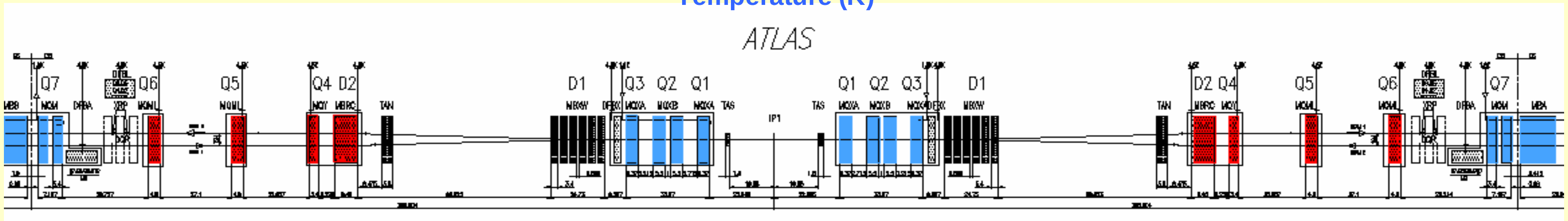
Cold beam vacuum at 4.5 K

Saturated vapour pressure from Honig and Hook (1960)



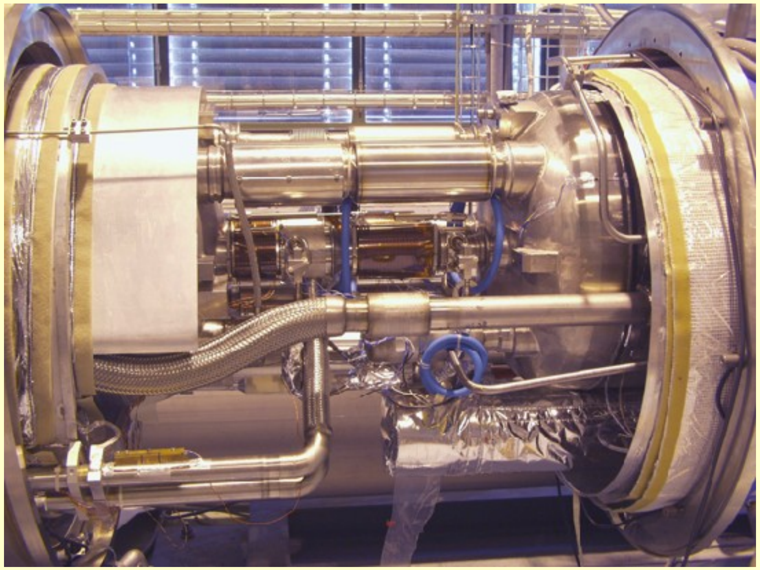


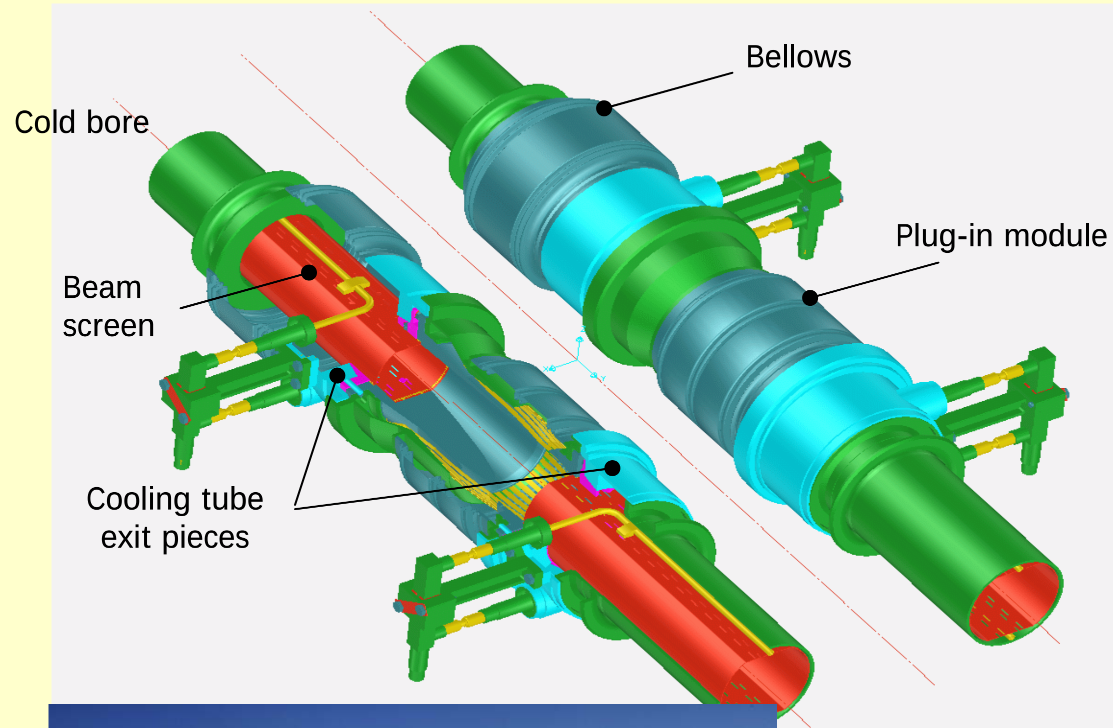
- **Required performances (200 cm²/m):**
  - **Operates from 5 to 20 K**
  - **Capacity larger than 10^{18} H_2/cm^2**
  - **Capture coefficient larger than 15 %**

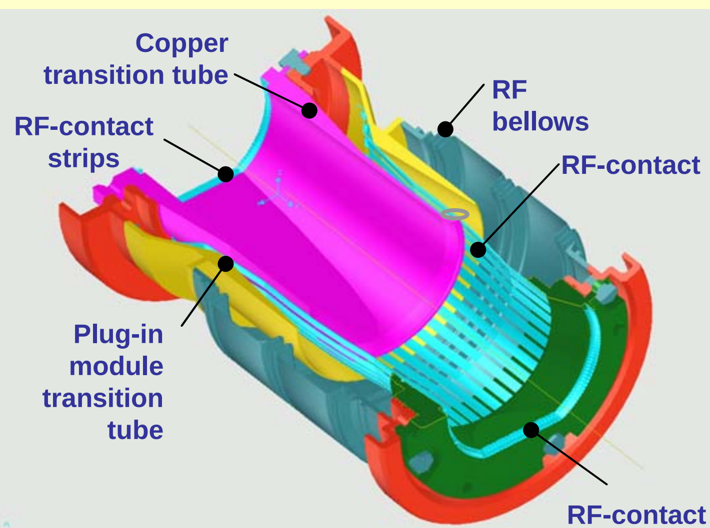


LHC beam vacuum

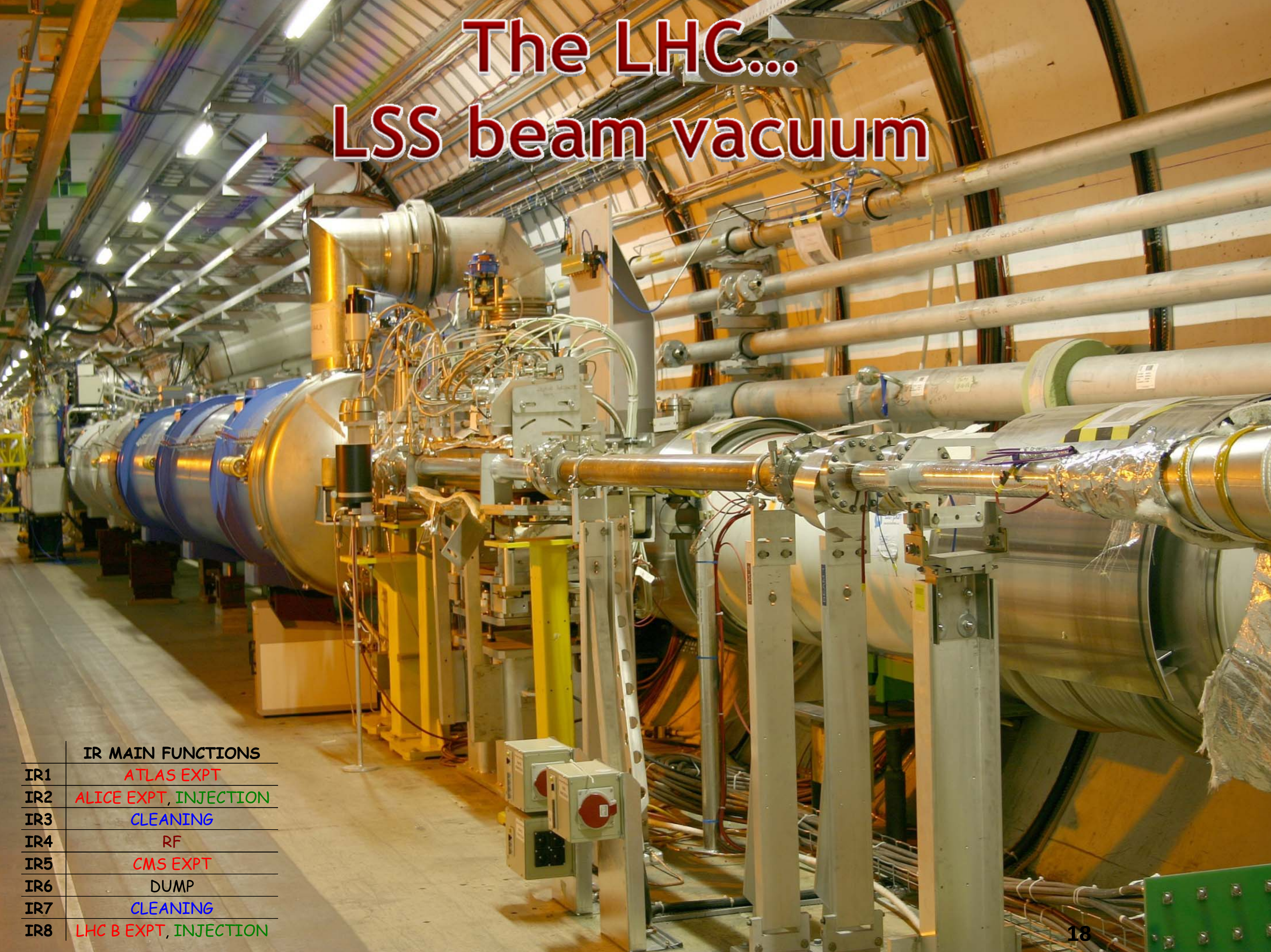
Interconnecting the beam lines







The LHC…
LSS beam vacuum



	IR MAIN FUNCTIONS
IR1	ATLAS EXPT
IR2	ALICE EXPT, INJECTION
IR3	CLEANING
IR4	RF
IR5	CMS EXPT
IR6	DUMP
IR7	CLEANING
IR8	LHC B EXPT, INJECTION

LHC beam vacuum
LSS beam vacuum

- 6 km of RT beam vacuum except standalone cryo-magnets
- For each sector (twin or combined beams)
  - 2 weeks for bake-out preparation
  - 1 week for bake-out and NEG coating activation
- Bake-out of beam vacuum
  - 230°C for NEG coated chambers
  - 320°C for vacuum instrumentation
- Extensive use of NEG coatings
  - ⇨ Baked-out allows the activation of NEG coatings
- Pressure lower than 10^{-10} Pa after activation
  - ⇨ Pressure reading limited by outgassing of the gauge port

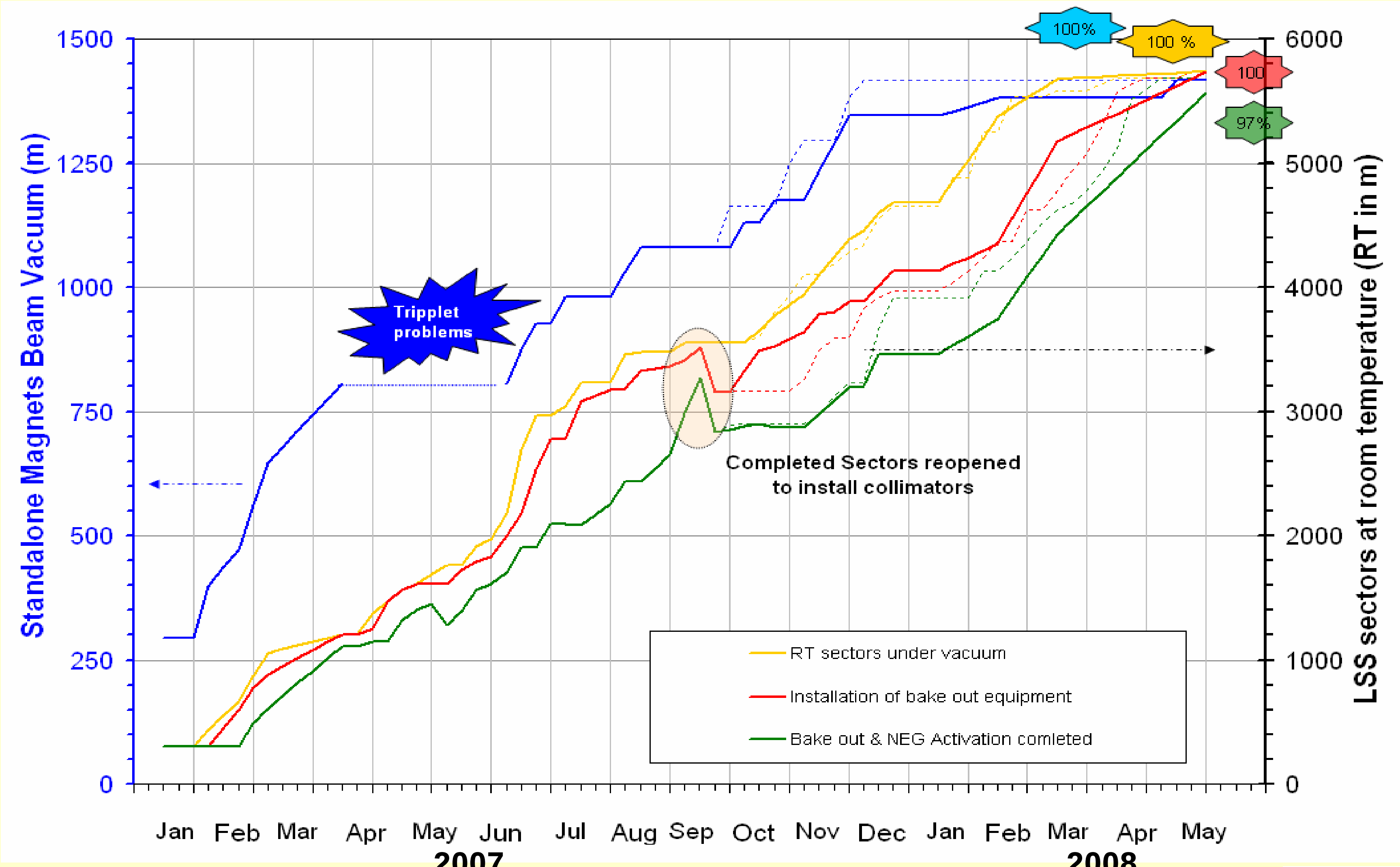
LSS beam vacuum
Completed LSS vacuum sectors

- Ion pumps to avoid ion instability by pumping noble gasses and CH_4 and to ensure the safety interlocks
- Sector valves to prevent saturation of the NEG coating when warming up the cryo-magnets

LHC beam vacuum
LSS beam vacuum

- The LSS in a few numbers
  - Overall length: ~6000 m
  - Beam components (collimators, instrumentation, RF…): >330
  - Vacuum sectorisation modules (twin+combined): 191
  - Bellows modules w/wo instrum. (gauges, pumps): 1780
  - NEG coated drift space vacuum chambers: ~2000
  - Pumps & Instrumentation:
    - 780 ion pumps
    - 1084 Pirani and cold cathode Penning gauges and 170 Bayard-Alpert gauges
- Installation rate:
  - 305 meters installed in January'07
  - Installation completed in May'08
  - ☞ ~100 meters per week !
    - Installation of supports and chambers
    - Alignment & Interconnection with bellows modules
    - Pump down & leak detection
    - Installation & testing of bake-out
    - Bake-out & NEG coating activation
  - ☞ 8 sectors re-opened for consolidation

LSS beam vacuum
LSS installation overview

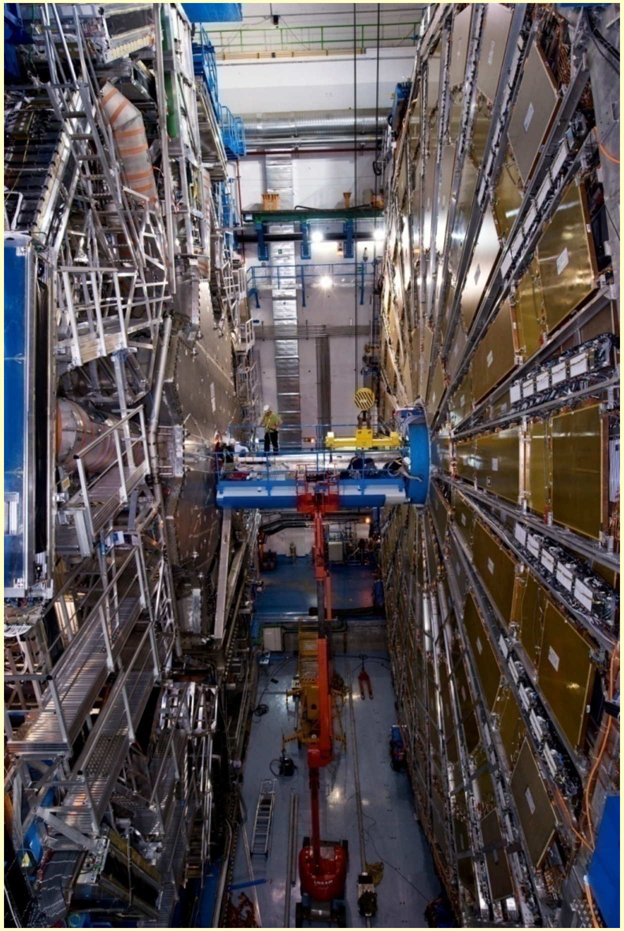


The LHC...
Detectors beam vacuum

LHC beam vacuum
Detectors beam vacuum

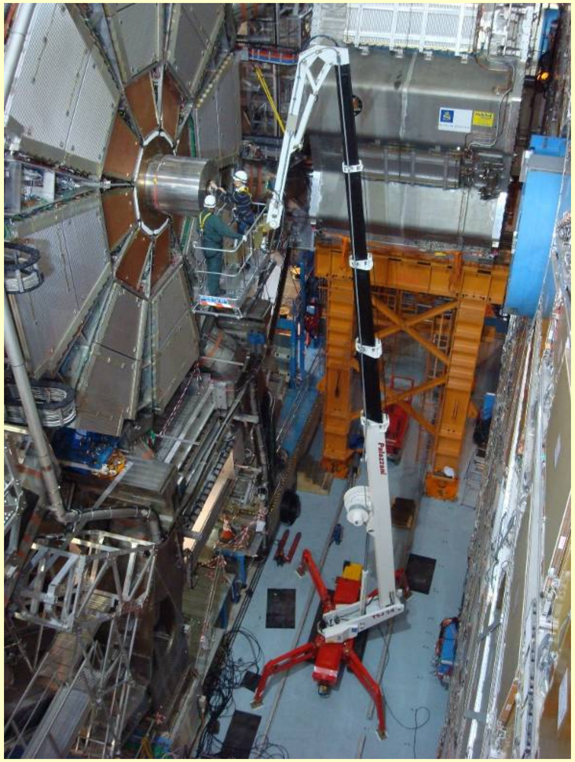
- **Integration: Vacuum installation follows detector closure**
  - "Bad surprises" are not acceptable
  - Temporary supporting and protections are required at each stage of the installation
- **Reliability**
  - Leak detection and bake-out testing is compulsory at each step of the installation since vacuum pipes get encapsulated in the detector
- **Availability**
  - Detector installation imposes the "speed" and sequence of the installation
- **Performances**
  - Vacuum ($<10^{15}$ $H_2.m^{-3}$), HOM, impedance and alignment requirements must be fulfilled
- **Engineering**
  - Beryllium and aluminum material used since "transparent" to the particles which shall escape from the collision point of the detectors
  - Bake-out innovative solutions to fit with the limited space available between vacuum pipes and the detector

LHC beam vacuum
Detectors beam vacuum-ATLAS

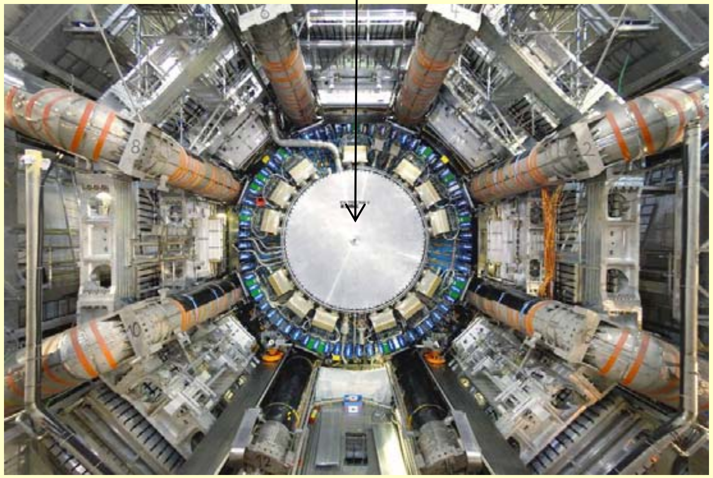


VA vacuum beam pipe installed before closure of the endcap

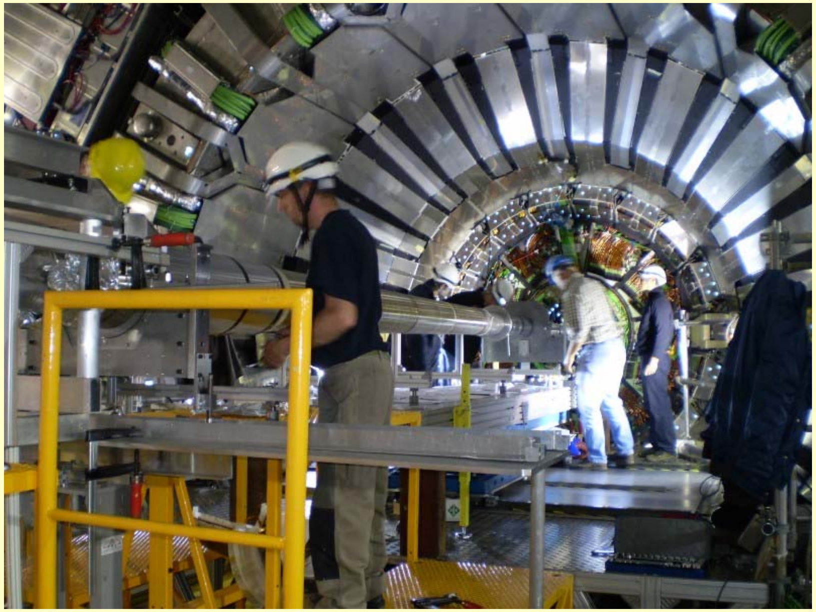
Vacuum technician installing part of the beampipe support system



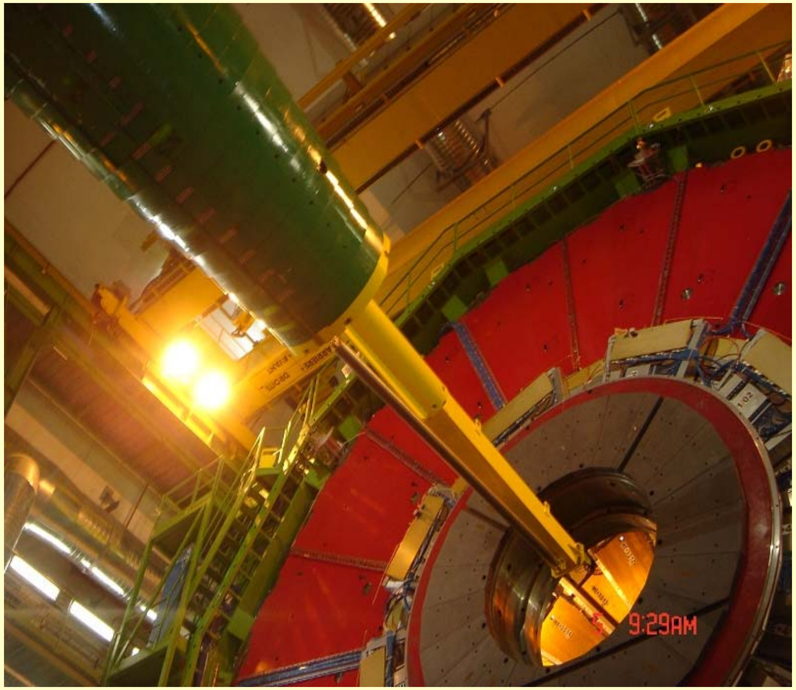
Vacuum beam pipe ID 50 mm



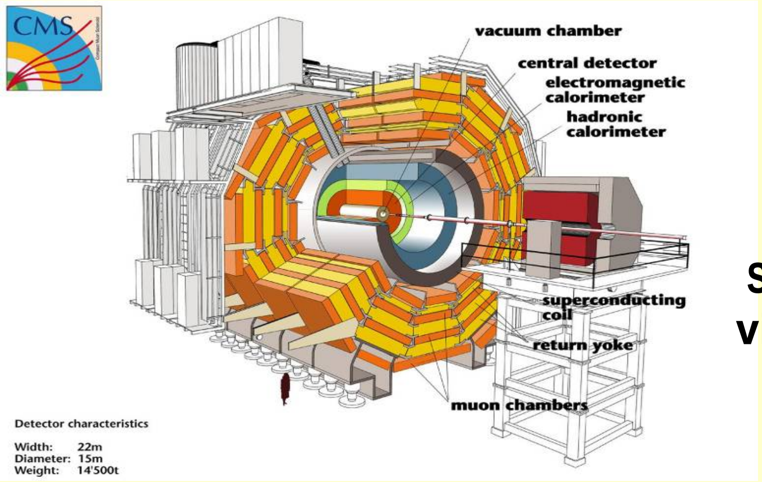
LHC beam vacuum
Detectors beam vacuum-CMS



CMS endcap pipe installation

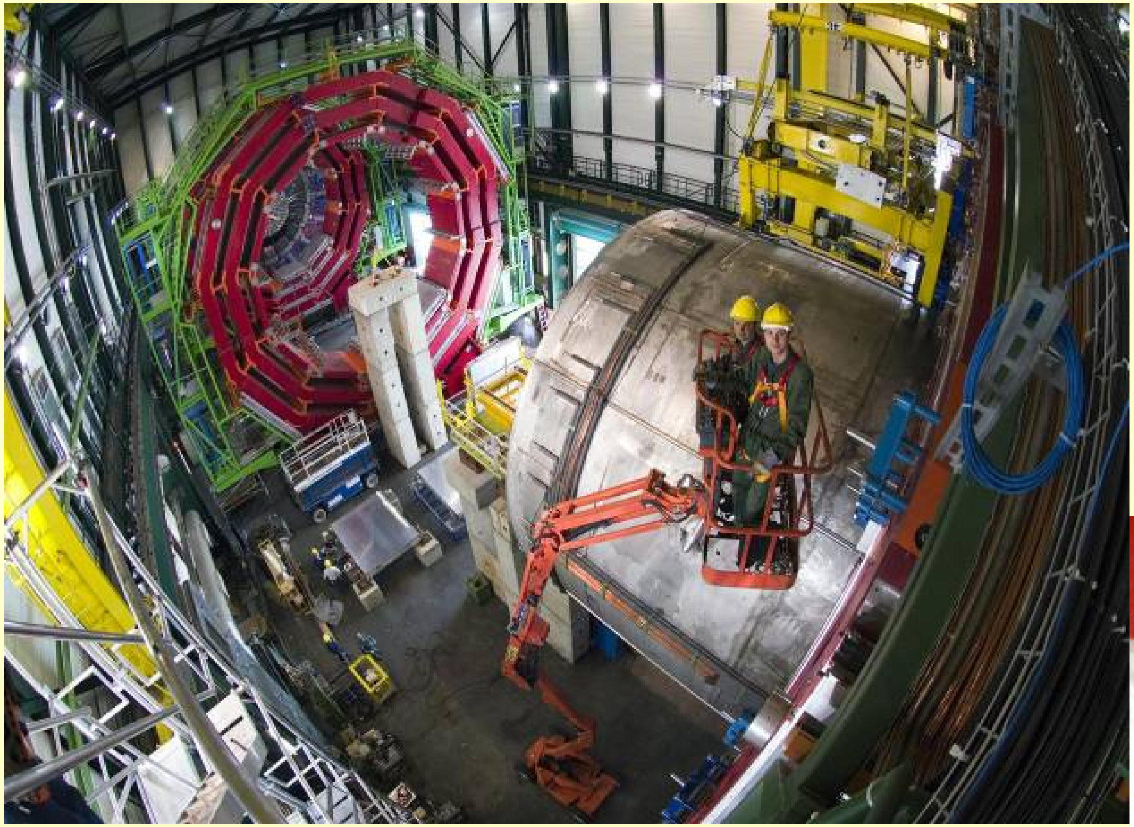


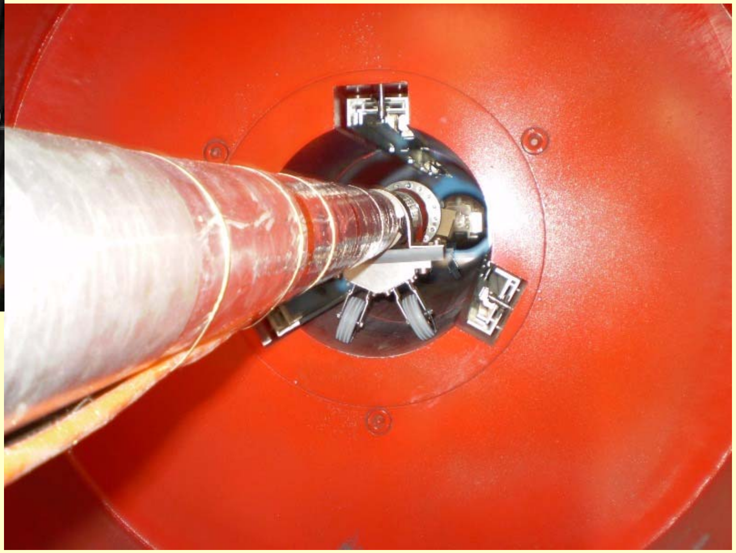
Vacuum pipe installed close to the TAS absorber



Schematic view of the CMS detector

LHC beam vacuum
Detectors beam vacuum-CMS





LHC beam vacuum
Installation & Logistics

- **Resource management**
  - Resources must be ready but the installation speed is fixed by the available slots i.e. previous installation step must be completed
  - Parallelism has to be started to cope with delays
  - Co-activities with the hardware commissioning need to be solved
- **Material management & handling**
  - Components need to be:
    - Tested at the surface
    - Transported into the tunnel right on time (limited underground storage)
      - At the right place
      - With the appropriate orientation
  - Logistic efforts per week (installation speed: 100 m/wk)
    - ~ 25 vacuum pipes (~7m in length)
    - 60 supports
    - 10 pallets (bellows modules, tooling, bake-out material)
    - Bake-out regulators (x3), pumping stations (x3), leak detector & RGA
- **Independent handling of the non-conformities**

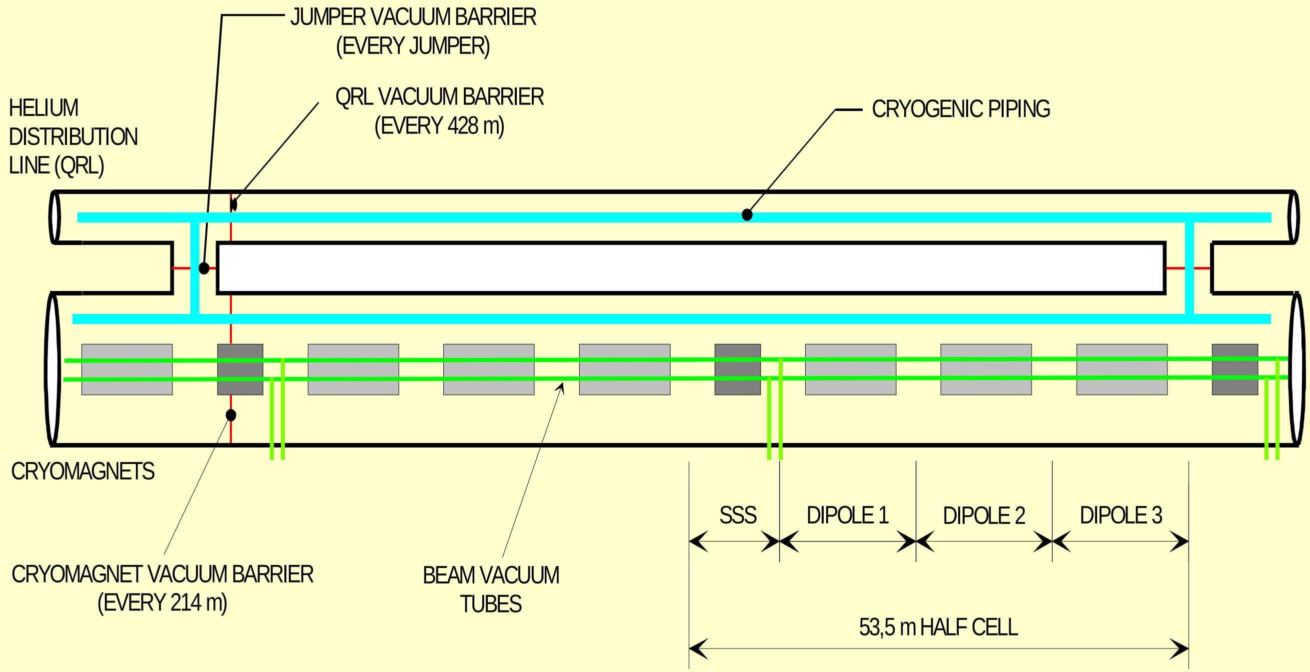
The LHC…
Insulation vacuum

LHC insulation vacuum

- The insulation vacuum is a high vacuum
  - Between the inner cold cryogenic lines and the outer envelope
  - Between the cryomagnet and its cryostat
  - ⇨ Both are wrapped with super insulation layers
- Before the cool down, this vacuum is pumped out with mobile and fixed turbo molecular pumping stations down to a pressure in the 10^{-1} Pa
- The cool down will bring a huge additional pumping of the water which is the dominant gas in this pressure range. Then:
  - The mobile pumping units are removed
  - The fixed pumping station remain in place in order to pump the gasses during the warming up or the small helium leaks

LHC insulation vacuum
Vacuum system layout in the Arcs

SCHEMATIC OF LHC ARC BEAM & INSULATION VACUUM.



VACUUM SECTOR CHARACTERISTICS	CRYOMAGNETS	QRL	BEAM VACUUM
VOLUME (m^3)	80	85	24
LENGTH (m)	214	428	2796
MLI AREA (m^2/m cryostat)	200	140	---
NUMBER OF VACUUM SECTORS (/arc)	14	7	1 + 1

What needs to be leak tested ?

- Welds between insulation vacuum & beam vacuum
- Welds between helium lines & insulation vacuum
- Elastomer joints between air & insulation vacuum

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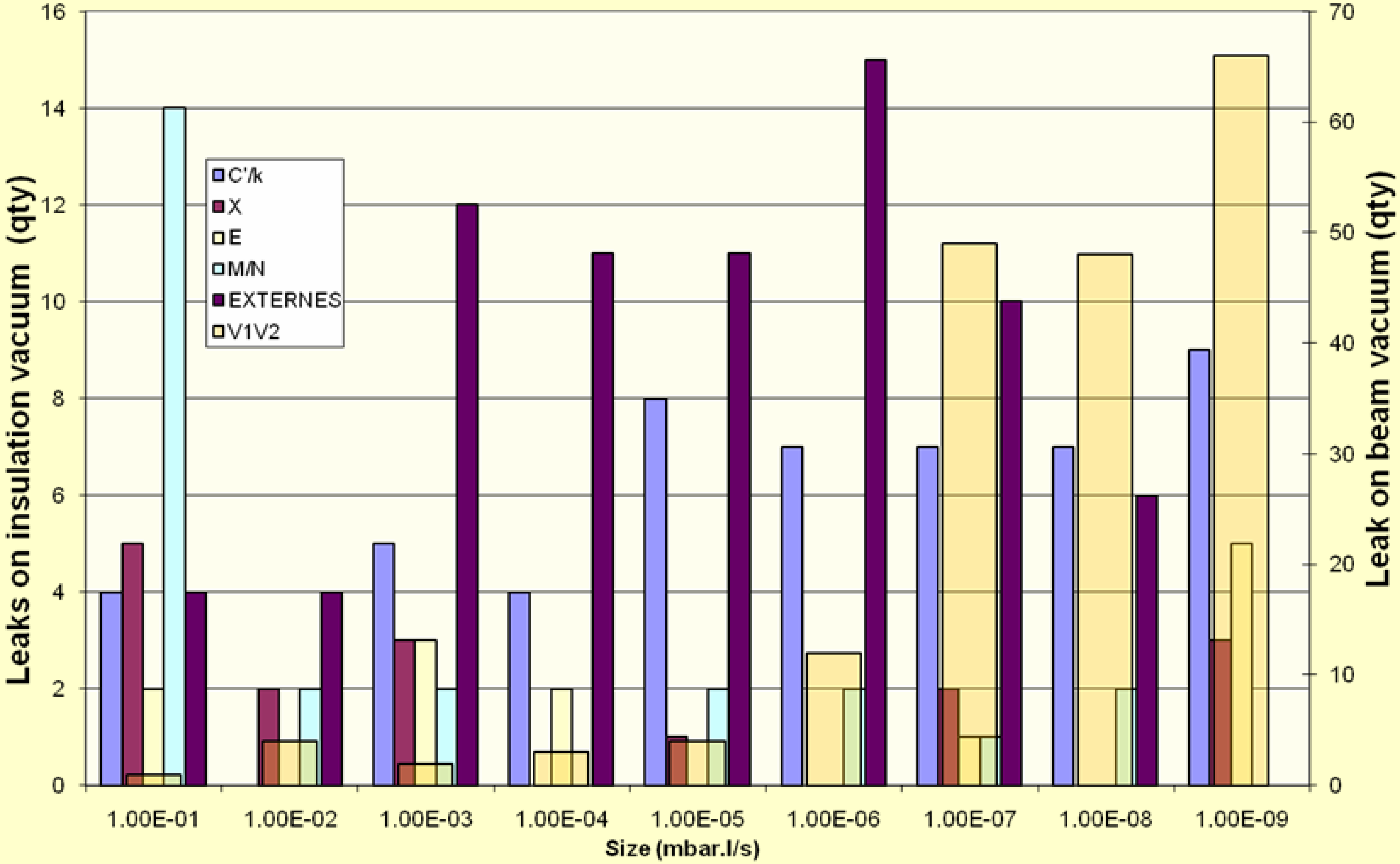
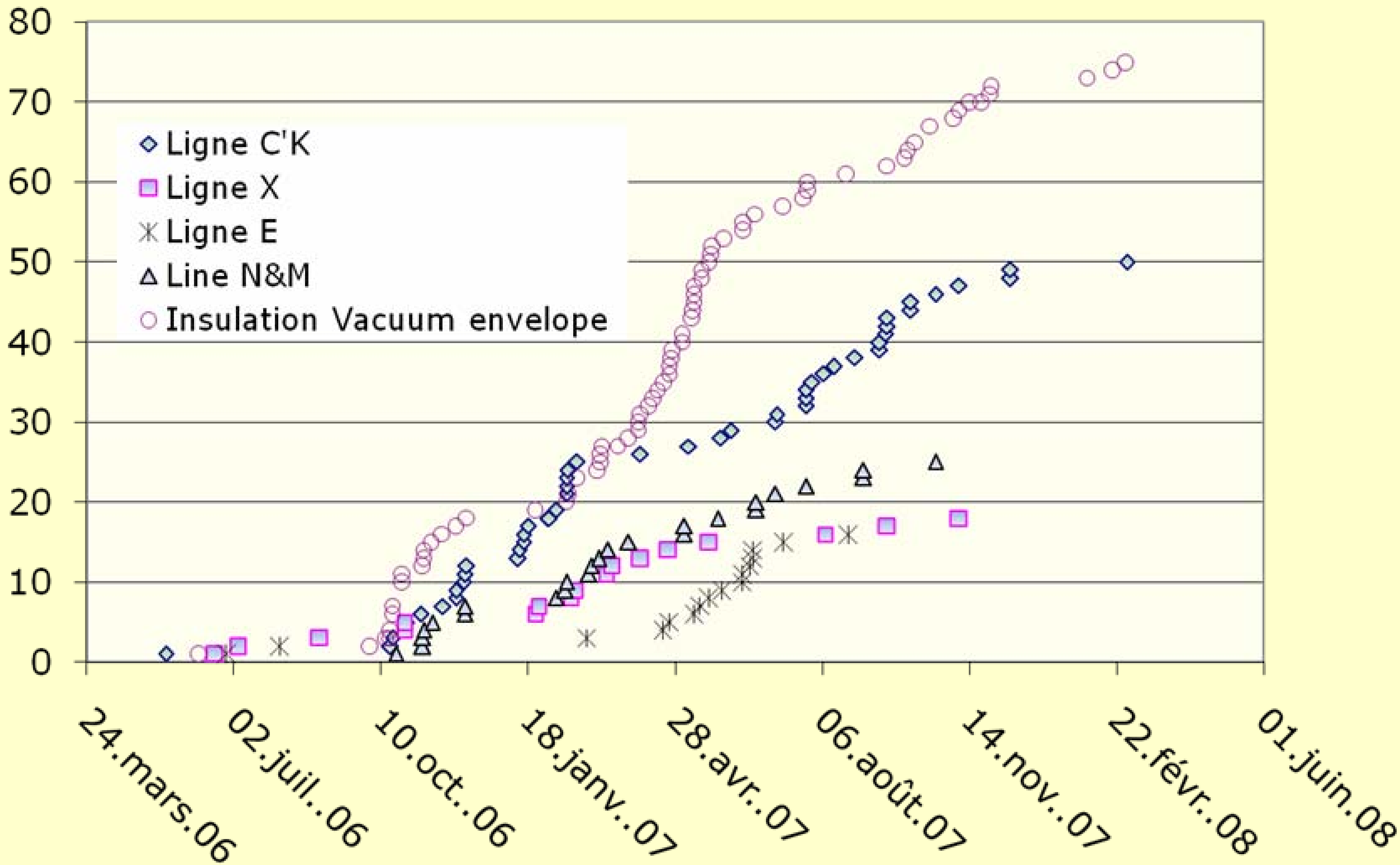
LHC insulation vacuum
Distribution of leaks by sizes



LHC insulation vacuum
Leaks as a function of time

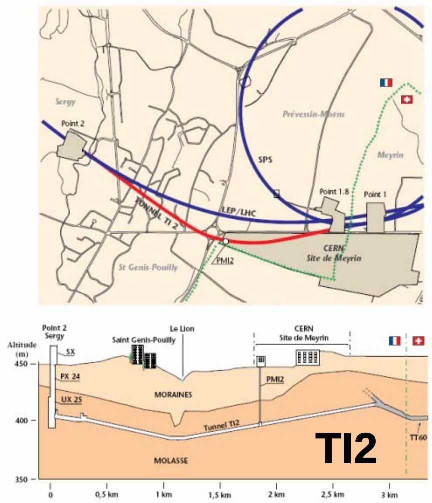


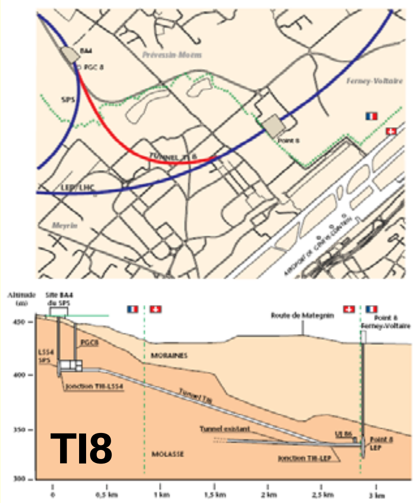
LHC insulation vacuum
Operational aspects

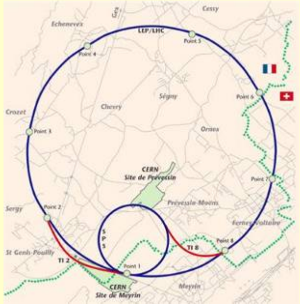
- Three types of vacuum problems are expected:
  - Helium leaks inside the insulation vacuum
    - ⇨ Not cryopumped ⇨ vacuum relies on the fixed turbo molecular pumping stations
    - ⇨ P>10 Pa will lead to an interlock to the cryogenic system.
  - Leaks between the air (tunnel) and the insulation vacuum
    - ⇨ Same as for previous case
    - ⇨ Ice blocks can also occur inside the insulation vacuum increasing the heat losses
  - Leak between the insulation and beam vacuum – can occur only in the magnets
    - ⇨ Helium will leak into the beam vacuum
      - Small leaks will only cause troubles for leak detections
      - Big leaks will result in an increase of the beam-gas scattering leading to a magnet quench

The LHC...
SPS to LHC injection transfer lines

LHC beam transfer lines
Injection lines







TI8: Mainly bending magnets and a constant slope

TI2: Change of slopes and straight sections… Downstream part had to wait until the completion of the magnet transportation

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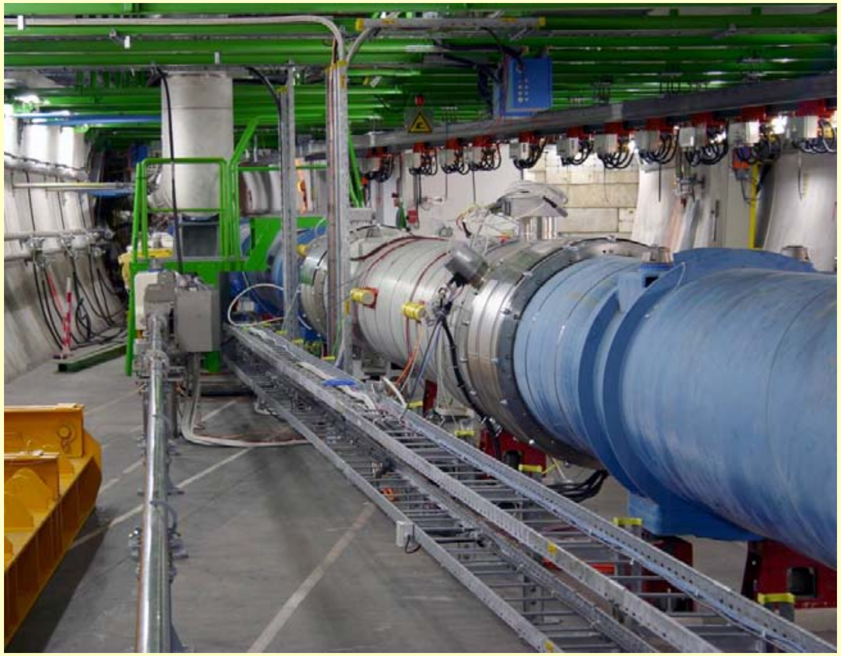
LHC beam transfer lines
Injection lines



The main challenges :

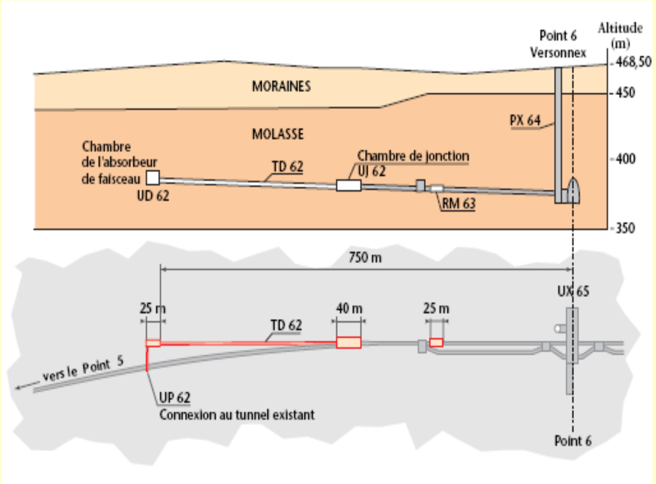
- Russian contribution to the LHC Project ⇨ magnets and vacuum system manufactured and installed by BINP Novosibirsk
- Space restrictions when the transfer lines arrives in the main LHC tunnel
- Survey of the vacuum chambers was an issue due to the vertical and horizontal bending

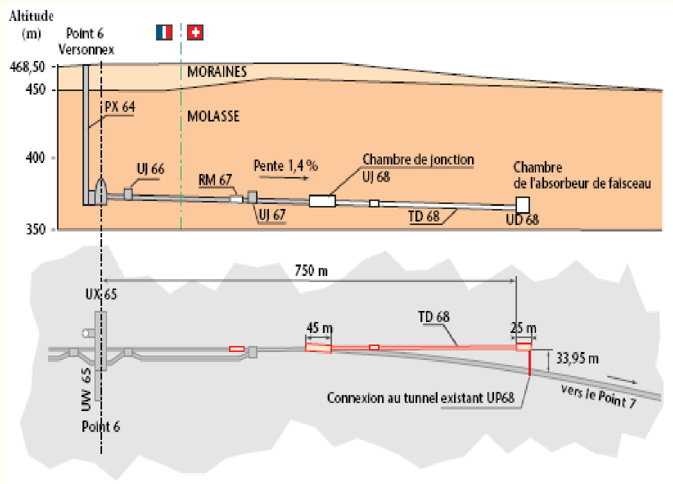
The transfer lines in a few key numbers:

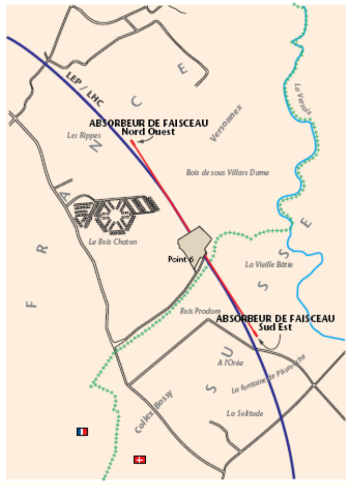
- 2 x 2.7 km in length, chamber OD from 212 mm (SPS) to 63 mm (LHC)
- Bellows & pumping ports 1315
- Chambers (incl. magnets) 1240
- Supports ~1200
- Beam Positioning Monitors 120
- Ion pumps & gauges 150

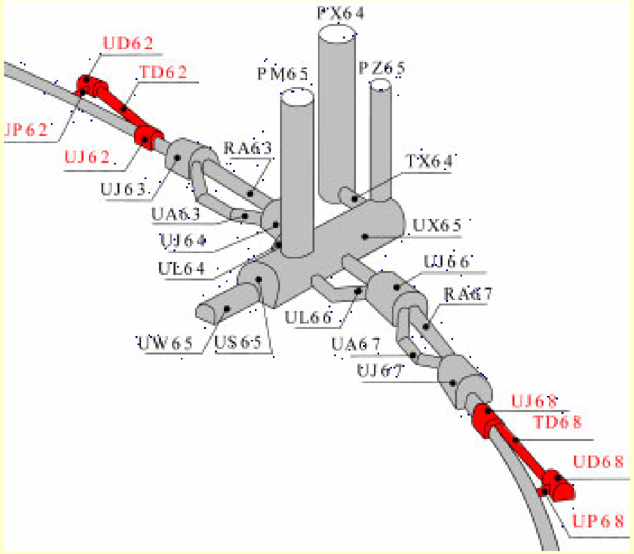
The LHC…
Beam dump transfer lines

LHC beam transfer lines
Dump lines









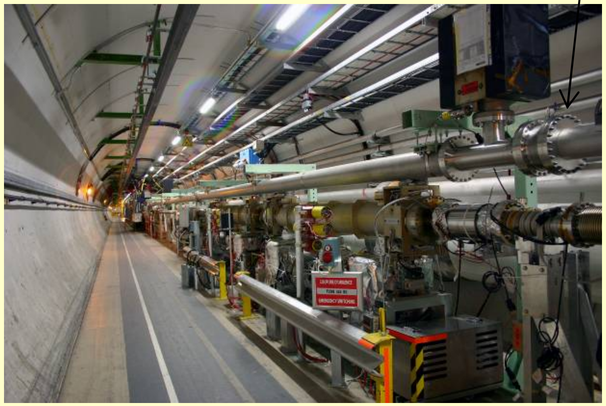
<u>The transfer lines in a few words:</u>

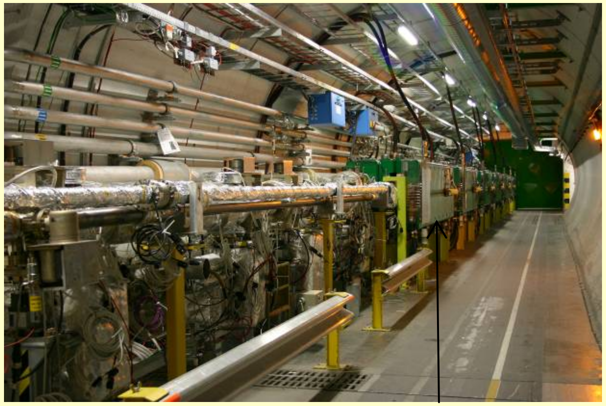
- The beam energy i.e. 362 MJ/beam @ 7 TeV is enough to melt 500 kg of copper, is equivalent to the energy of a 400 tons TGV @ 150 km/h !
- To avoid the instantaneous melting of the dump absorbers, the beams have to be diluted.
- A spiral path is obtained by a combined vertical and horizontal deflection resulting in beam pipes of increasing diameters up to 600 mm upstream of the beam dump bloc !

LHC beam transfer lines

Dump lines

Ejected beam



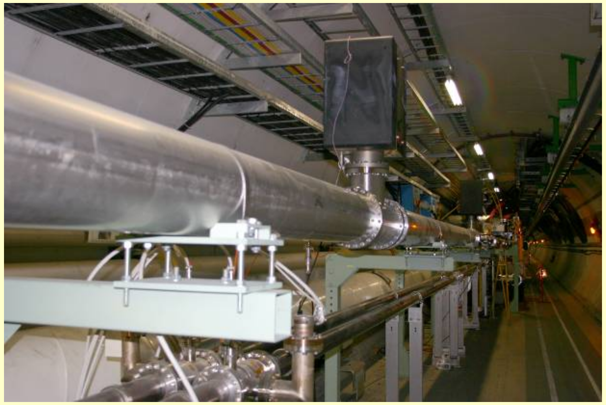


Ejected beam installed above the two circulating beams

Sector valve on dump line

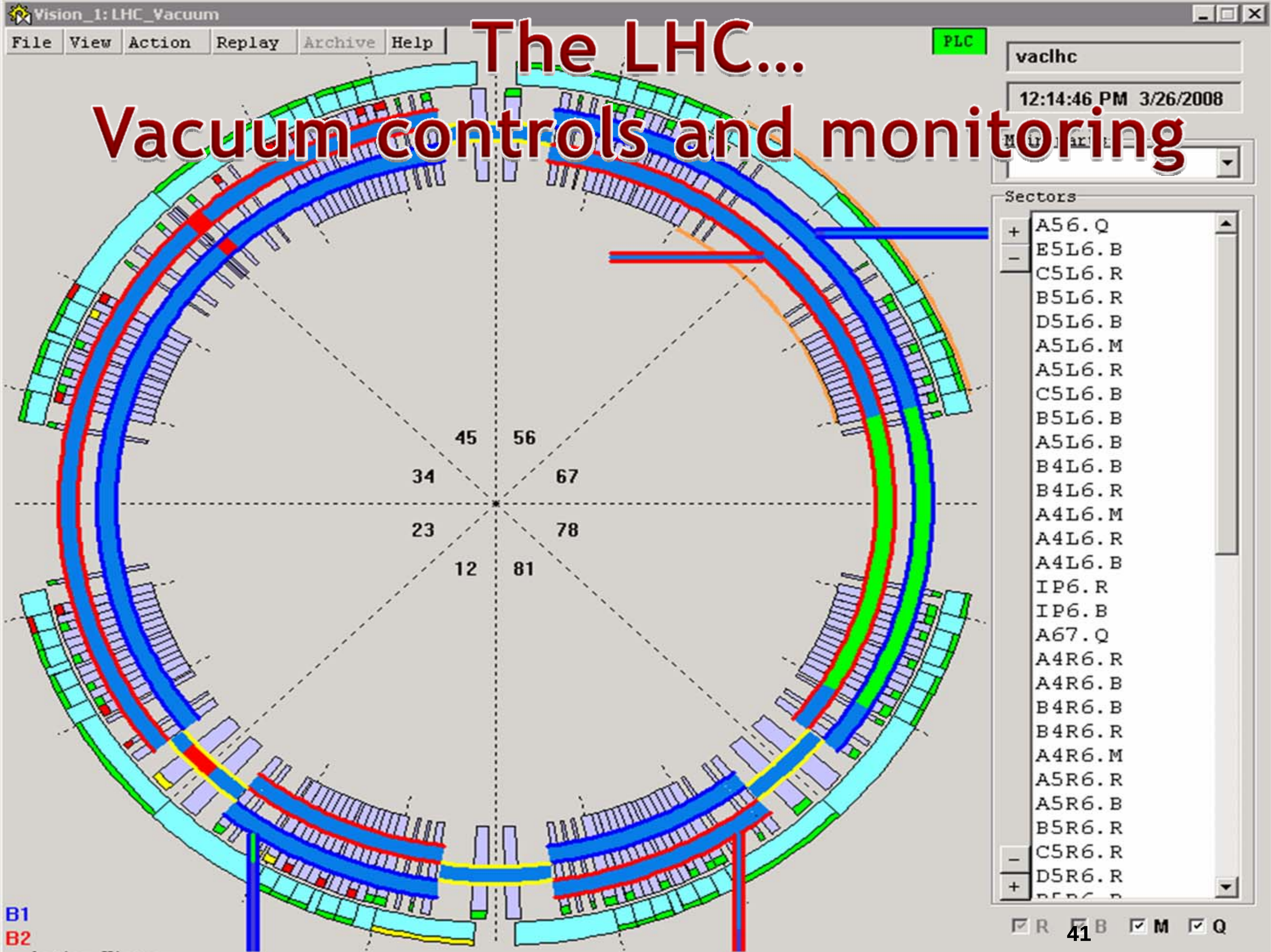
Ejection Septum magnets

50x 400 l/s ion pumps



600 mm beam pipes – last 100 m before the dump absorber

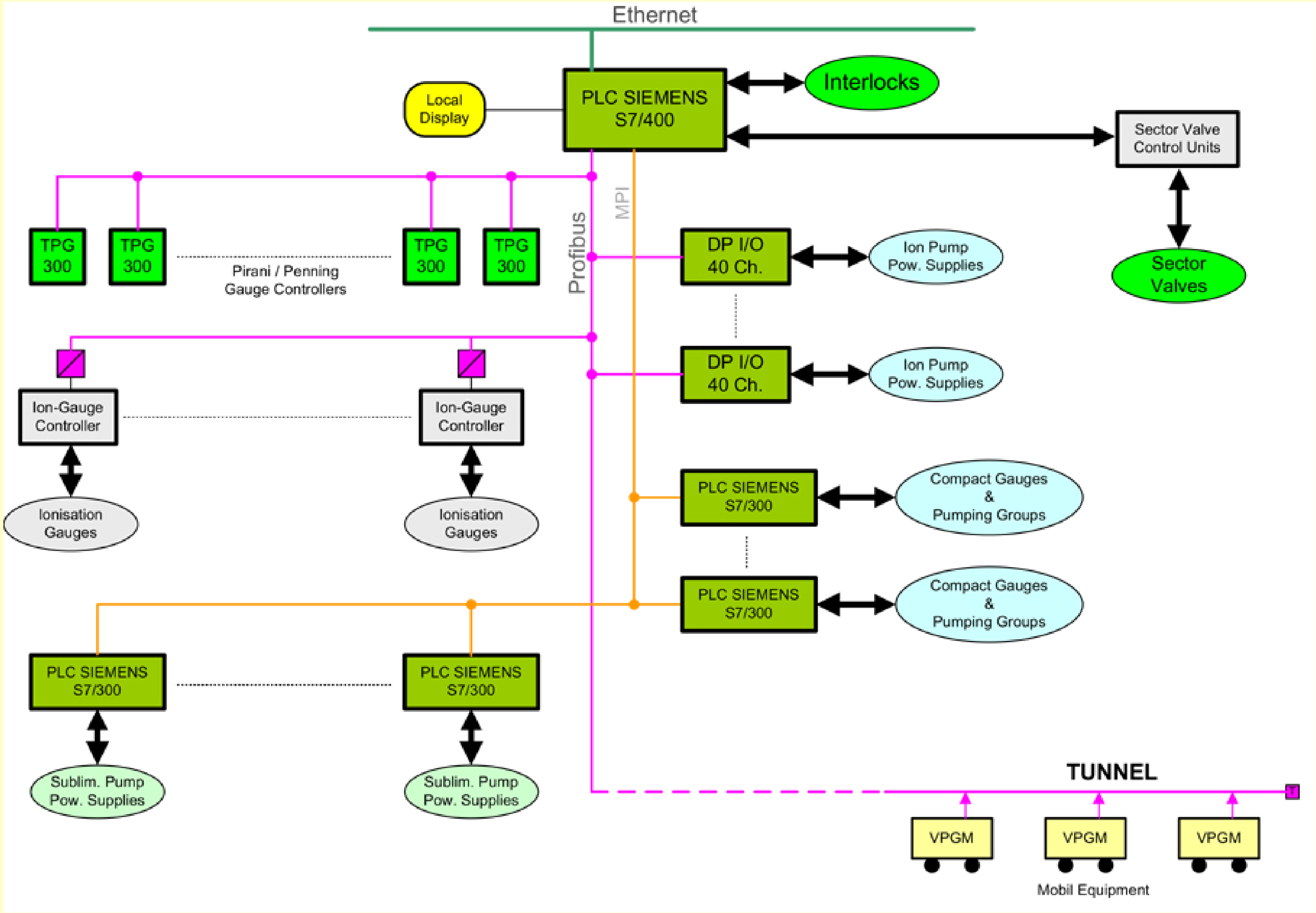
The LHC…
Vacuum controls and monitoring



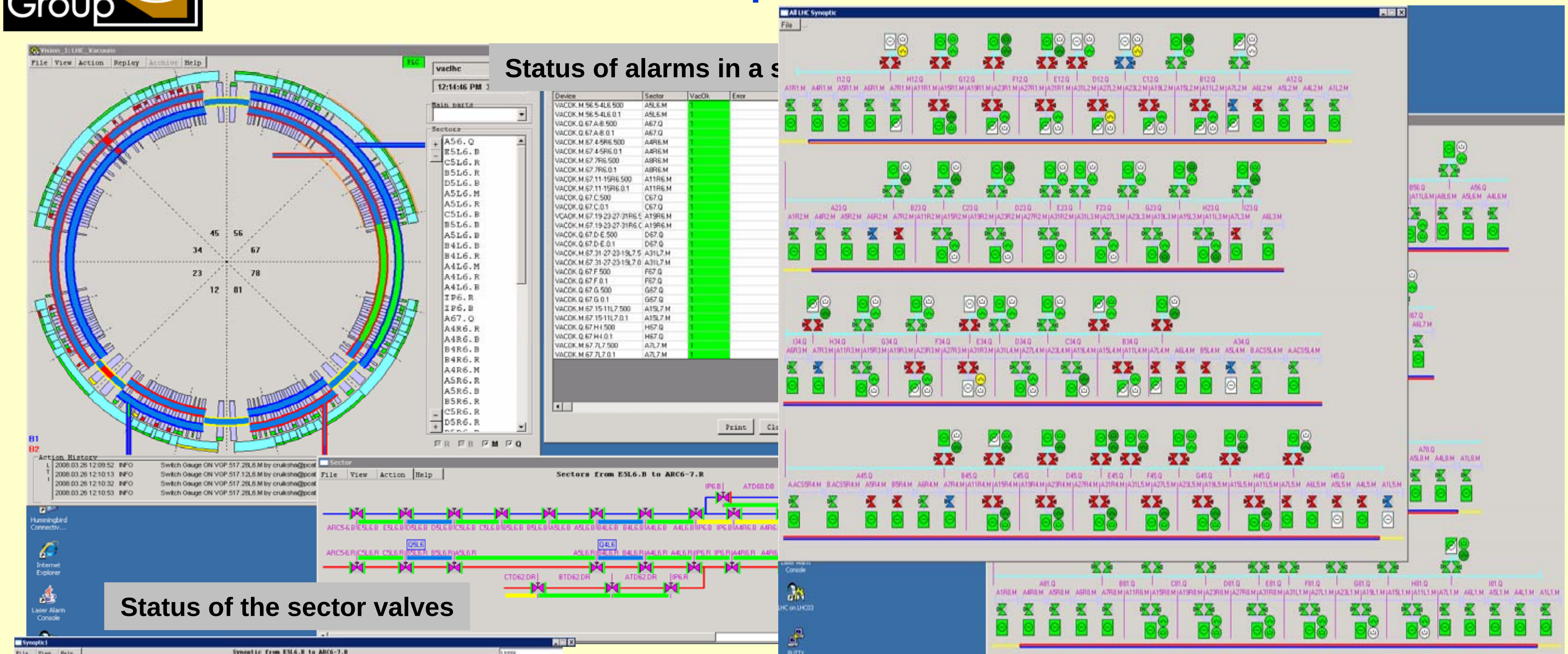
Controls & Monitoring
The "distributed" controls approach

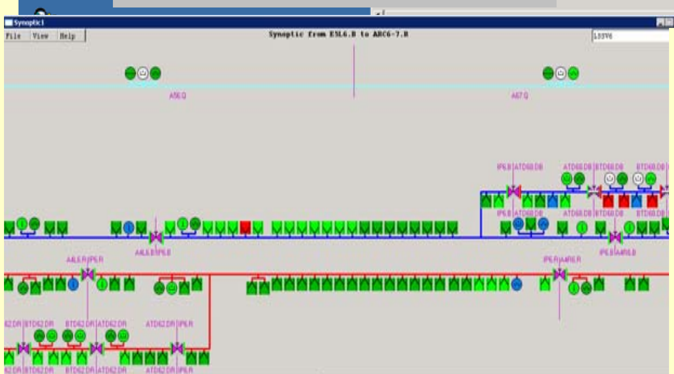
- Increasing accelerator size and emergence of mobile equipment
  - Lengths of vacuum sectors, distances from access point
  - ⇨ "Local control" has no longer any meaning
- Have the control means close to the process
  - e.g. embarked microcontrollers on mobile pump stations and on mobile bake out regulation controllers
- Connect equipment using a fieldbus
  - To reduce cabling cost
- Allow for portable control devices
  - A portable PC in LHC, connected via WiFi
- Use operational models
  - Make supervision, logging and alarms software independent from equipment manufacturer

Controls & Monitoring
The “distributed” controls approach



Controls & Monitoring
Vacuum Supervision Interface





Upgrade campaign of the control and monitoring interfaces launched in 2002 for all CERN accelerators

- PLC based interfaces, same concept for all accelerators
- Vacuum pumps, valves, instrumentation and alarms can be accessed remotely and controlled if required
- Actions and status are stored in order to allow post-mortem analysis

Closing Remarks

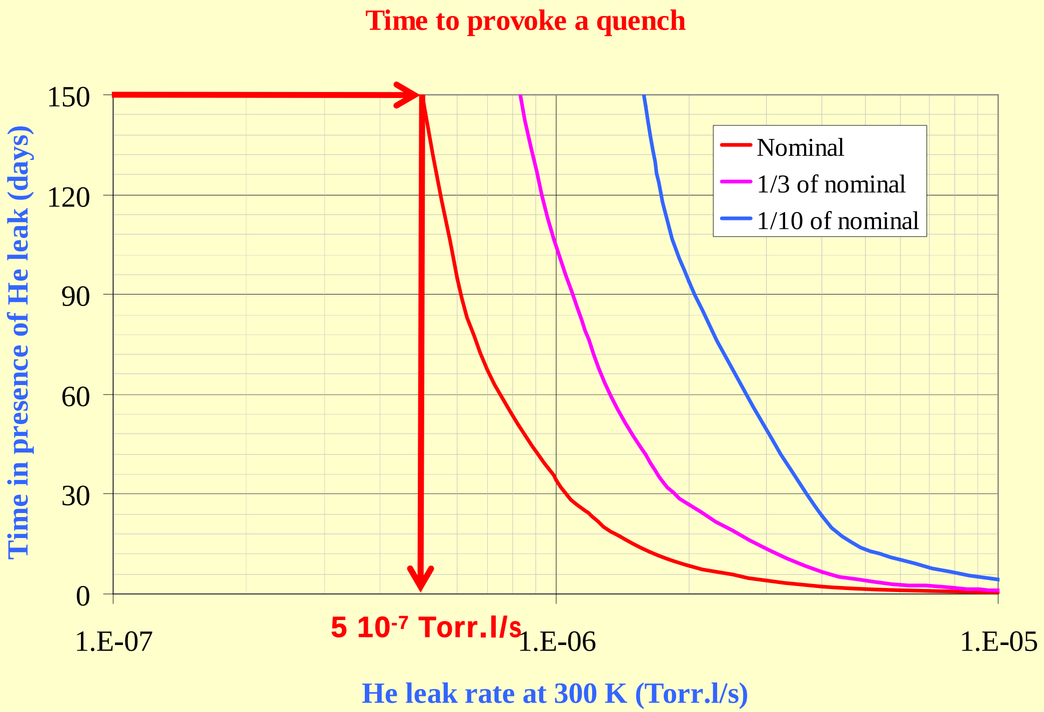
- The operation of the LHC will challenging
  - In the insulation vacuum, by:
    - Helium leaks
  - In the beam vacuum, by:
    - The expected dynamic effects at high intensities
    - The staging of the collimators
    - The pressure rise induced by the collimator halos
    - The helium leaks

Closing remarks

He Leak Rate with Risk of Quench

- 1 year of operation ~ 150 days

Helium leak rate above 5 10^{-7} Torr.l/s shall be detected to avoid the risk of a quench !



- **Lower leak rate :**
  Require a pumping of the beam tube on the yearly basis (cold bore >~4K)
- **Larger leak rate will provoke a magnet quench within :**
  30 to 100 days beam operation for He leak rate of 10^{-6} Torr.l/s
  A day of beam operation for He leak rate of 10^{-5} Torr.l/s

Acknowledgments

The work presented here is the result of several years of work and studies of many colleagues working with and in the field of vacuum science at CERN and in the world through collaborations. It will be a challenge in itself to name all the people involved.

After many years of studies, conceptions, designs, procurements, installations and commissioning, the imminent start of the LHC in the coming months is the result of their effort.