European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

Technological Challenges for the LHC Vacuum System

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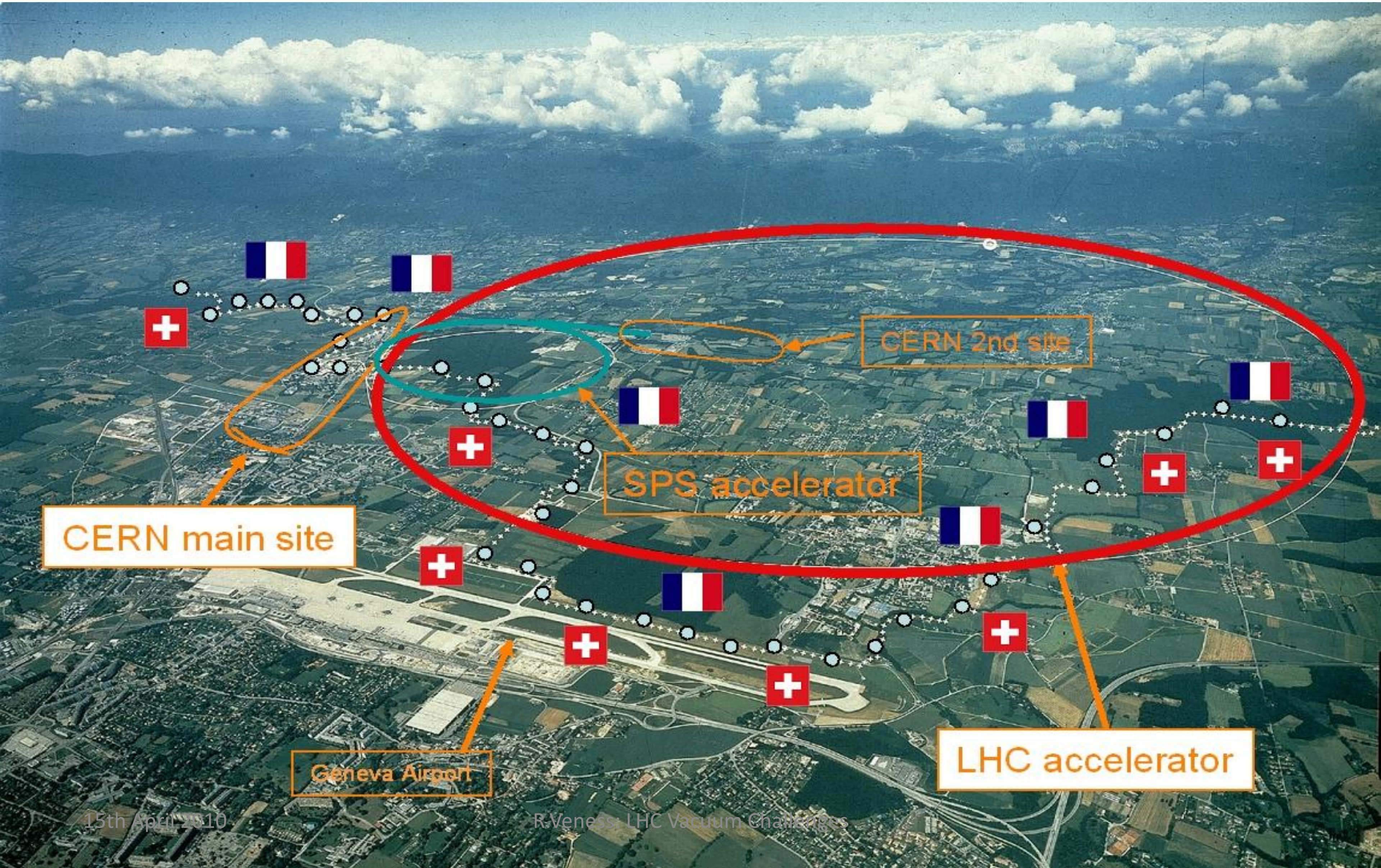
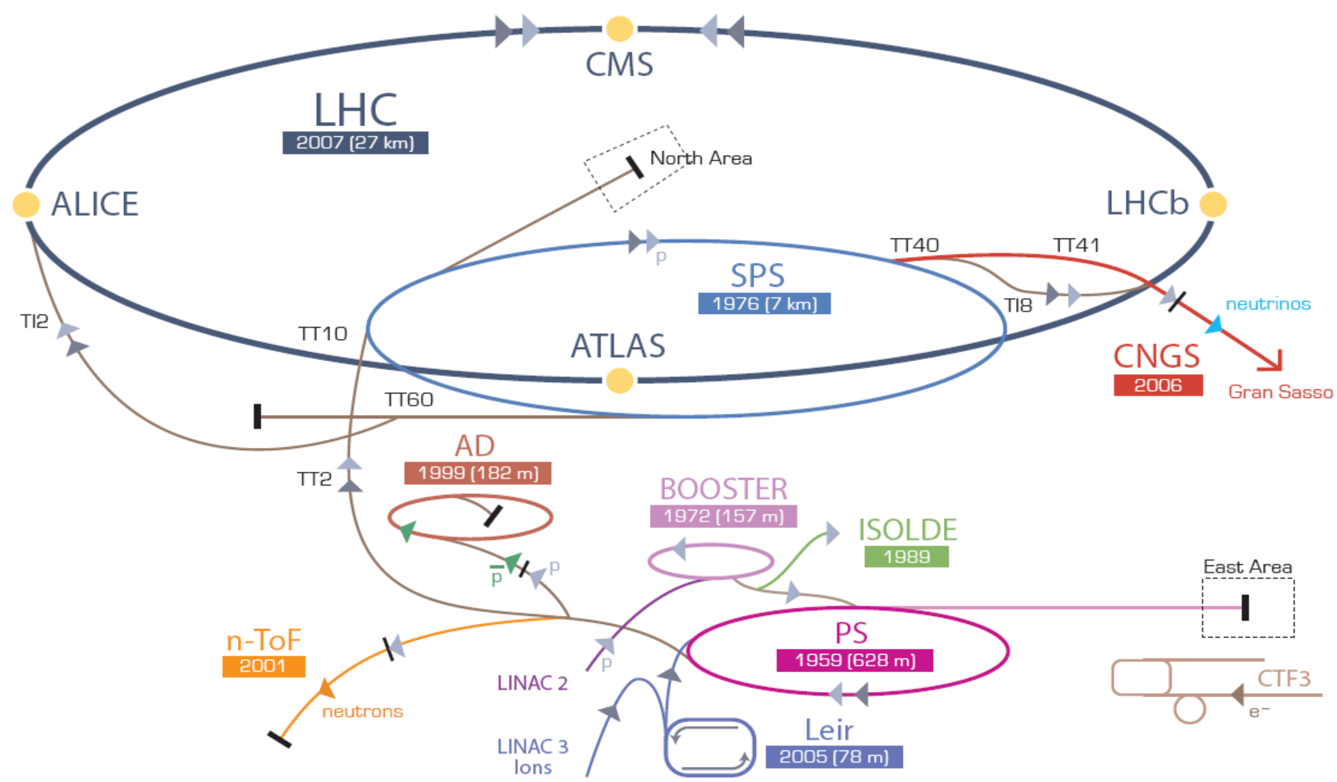


The CERN accelerator complex

20 member states + observers (USA, Russian Federation, Japan….)
Some 2500 staff members and 8000 visitors

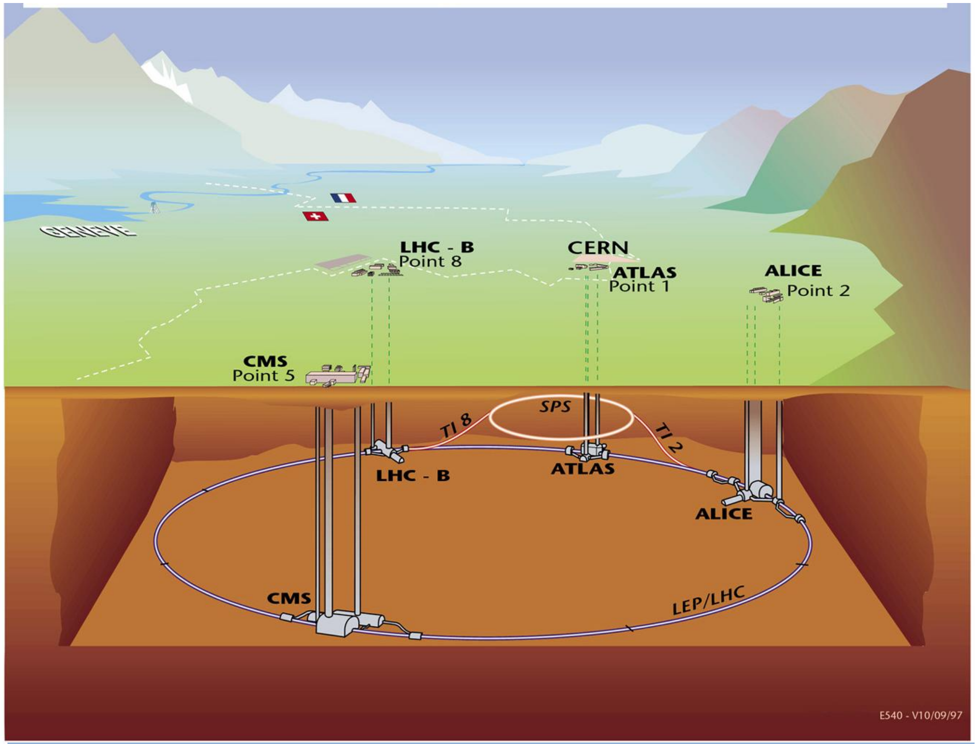


▸ p (proton) ▸ ion ▸ neutrons ▸ p̄ (antiproton) →+→ proton/antiproton conversion ▸ neutrinos ▸ electron

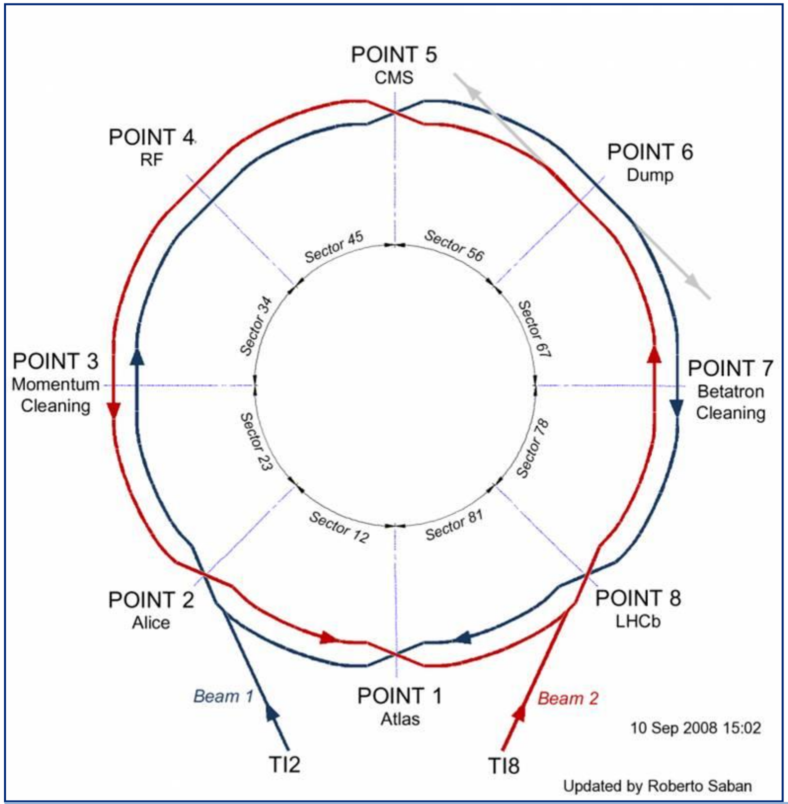
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

The Large Hadron Collider



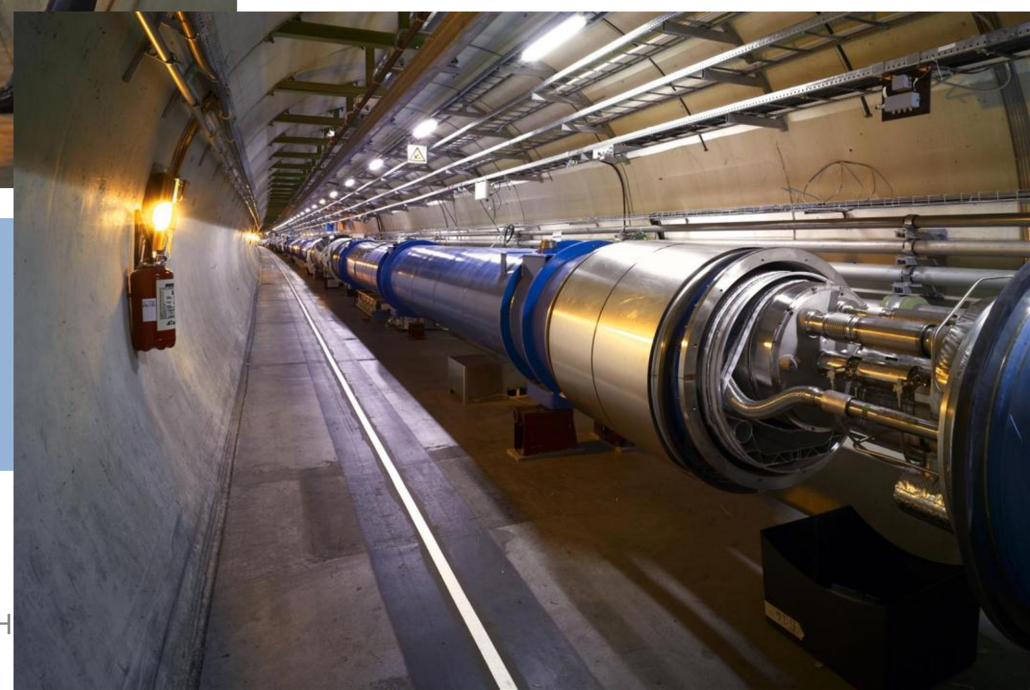
The LHC is installed in a 27km long tunnel, ~100m underground. It is designed to supply 7 TeV proton on 7 TeV proton collisions to 4 experiments, as well as heavy ion collisions



The machine is made-up of 8 arcs and 8 'long straight sections' . 2 counter-rotating beams are injected into the LHC from the SPS at 450 GeV. They are then accelerated in the LHC and put into collision

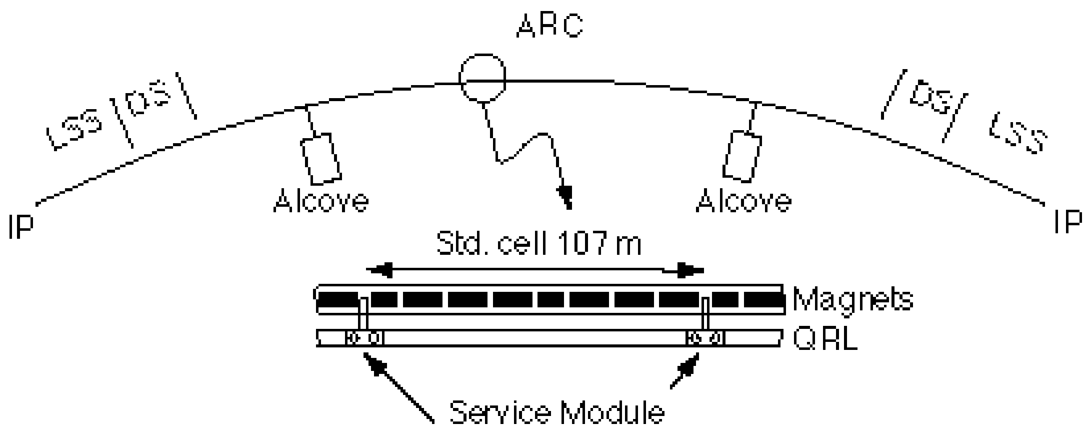
Superconducting magnets in the LHC

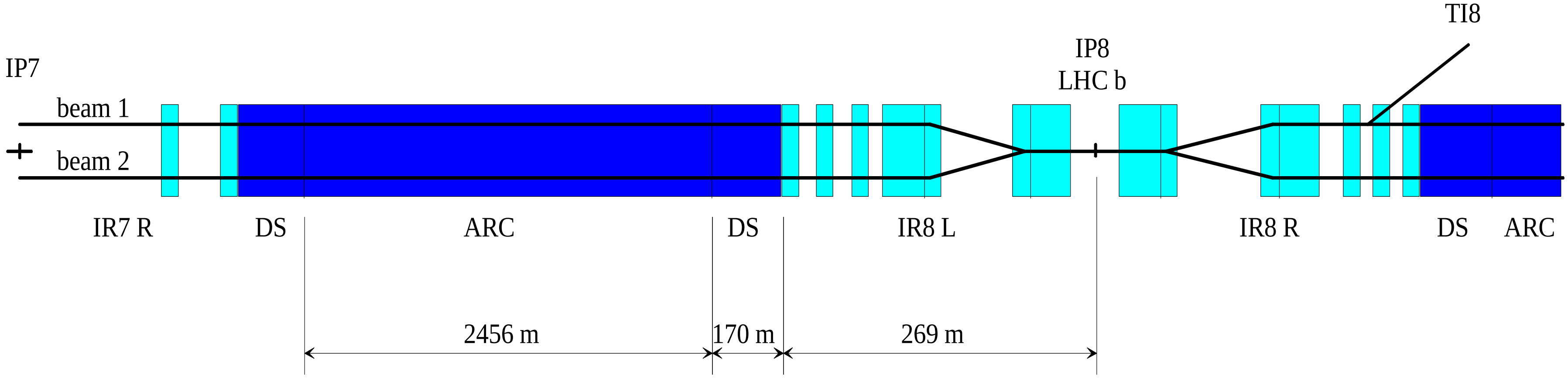
There are 1232 main dipoles (14.3 m length each) for beam bending and 398 main quadrupoles for beam focussing, plus more than 6000 correctors to preserve beam quality in space (emittance) and energy (chromaticity)



Main dipoles use superconducting Rutherford cables (Cu-clad Nb-Ti) circulating 11’000 A and giving a nominal field of 8.33 Tesla operating in superfluid helium at 1.9K

LHC Sector - Vacuum

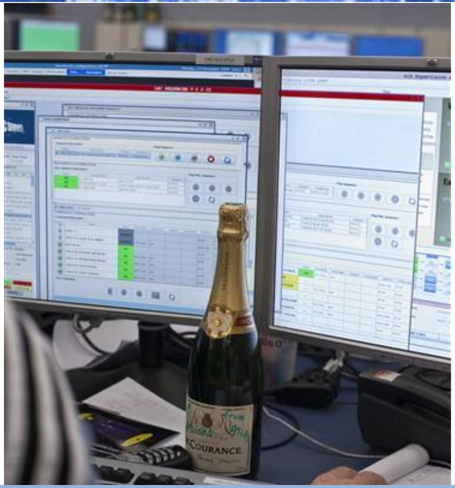




Contents

- Why do we need Ultra-High Vacuum in the LHC?
- The cryogenic vacuum system
  - Beam screen concept and technology
  - Installing and commissioning the cold sectors
- The room temperature vacuum system
  - NEG coating technology
  - Beam vacuum for the LHC experiments
  - LHC beam dump window
- Getting the LHC started
  - ‘the sector 3-4 incident’
  - Consolidation after the incident
- Summary

Why does the LHC need a beam vacuum?



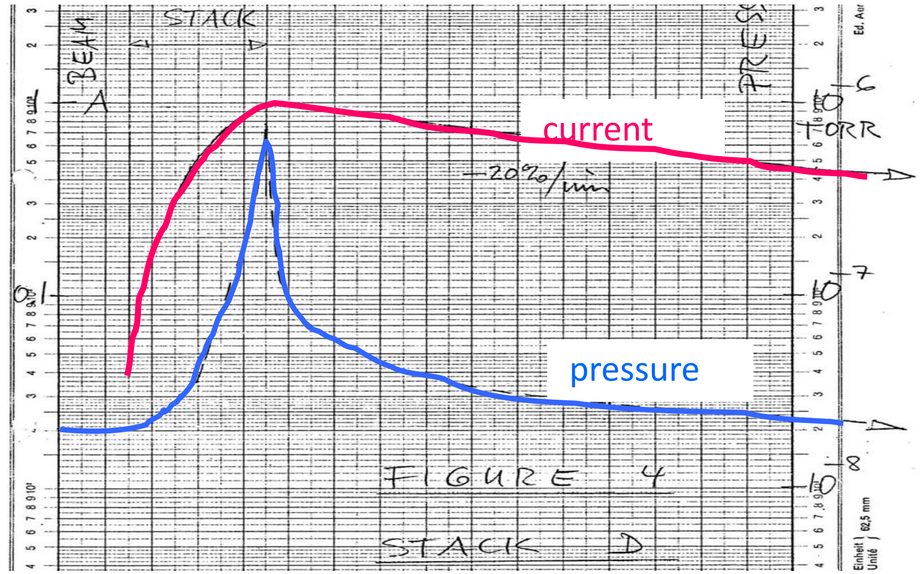
High-energy protons colliding with residual gas particles can be lost by nuclear scattering. This limits beam lifetime and causes heat load on cryogenics.
LHC defined a 100h beam lifetime limit, giving a gas density of ≤ 1×10^{15} H_2 molecules m^{-3} or a pressure at room temperature of ~1×10^{-8} mbar.

Interactions near to the experimental collisions also cause background 'noise' for the detectors

The circulating charged beams induce 'image currents 'in the vacuum chamber walls. These cause resistive heat loads and can impact on beam stability.
This means that the chamber (also called beampipe) needs a low electrical resistivity

Why does the LHC need a beam vacuum?

Synchrotron radiation photons produced by the circulating beams impact the vacuum chambers causing a direct heat load, desorb gas from surfaces and cause the emission of photo-electrons. Electrons can be accelerated by the charged proton beam and cause secondary electrons to be emitted when they impact the walls.

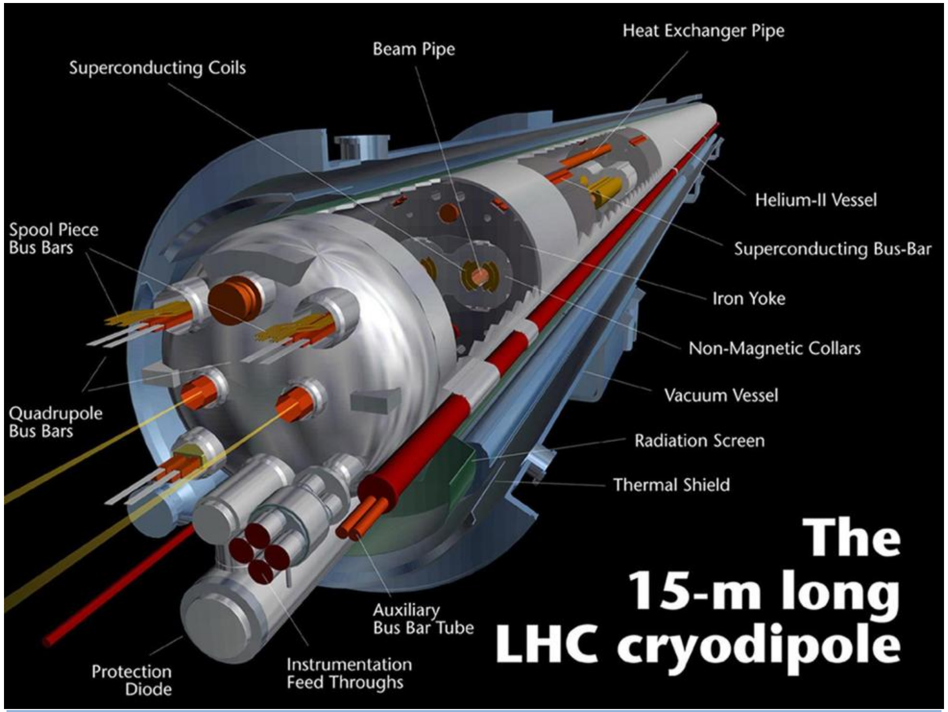


First documented pressure bump in the ISR

E. Fischer/O. Gröbner/E. Jones 18/11/1970

Ion induced desorption:
Residual gas can be ionised by the beam. These ions are then accelerated towards the wall, where they impact and can release gas from the surface.
Electron and ion desorption are described by their respective desorption yields, which are functions of the chamber wall material and treatment

LHC Cold Vacuum Challenges

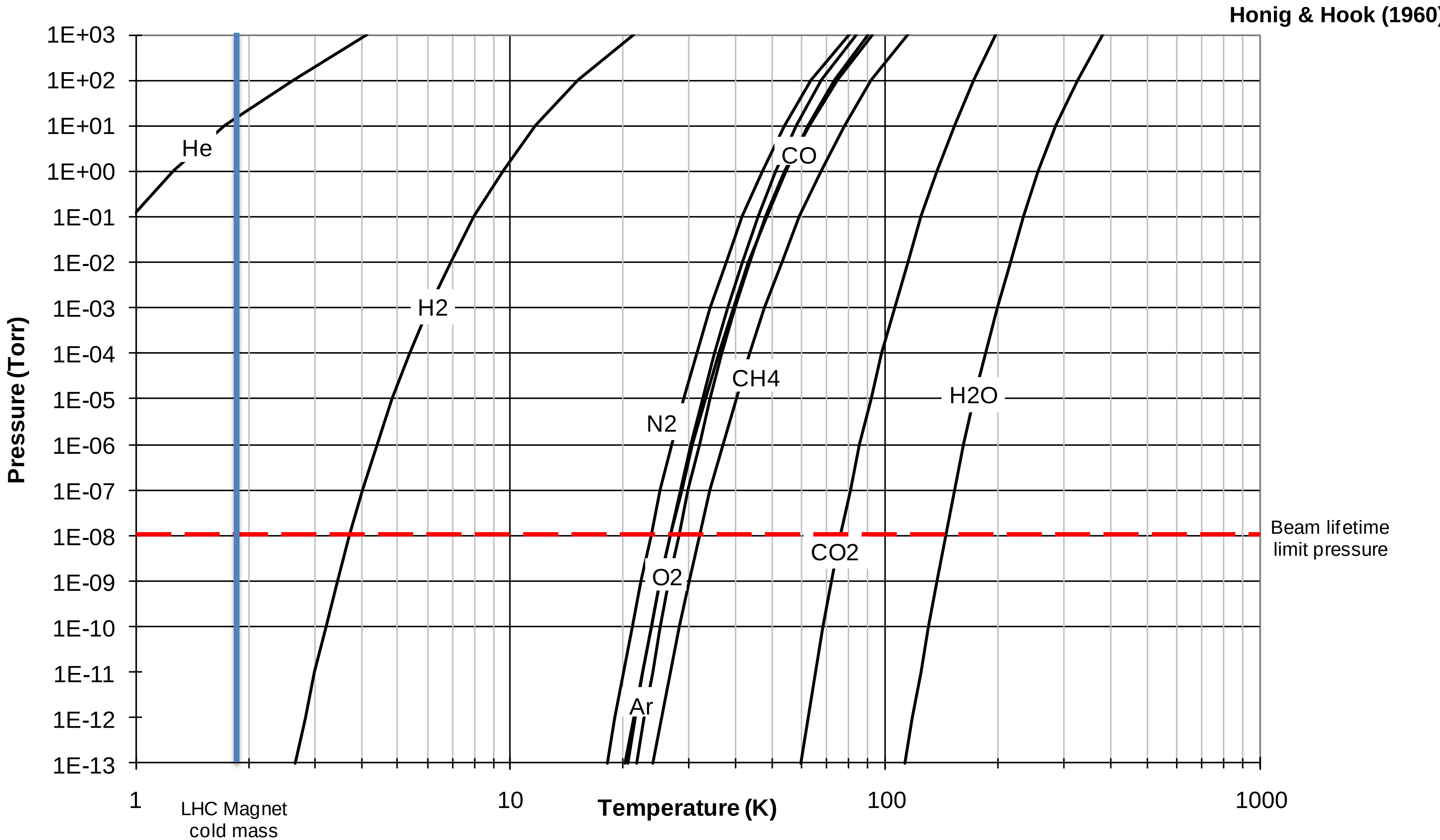


The LHC 8 cold arcs consists of a continuous chain of cryo-dipoles and SSS (FODO quadrupoles and a corrector package) at 1.9K. From the vacuum point of view, this means one continuous 'sector' some 2.8km long

Between each magnet is a cold 'interconnect' with flexible bellows to allow for thermal contraction (42mm for a dipole!) and alignment offsets.
Surrounding the magnets and interconnects is an insulation vacuum to minimise heat inlet

Cryogenic vacuum should be free…

Saturated vapour pressures of common gasses vs. temperature



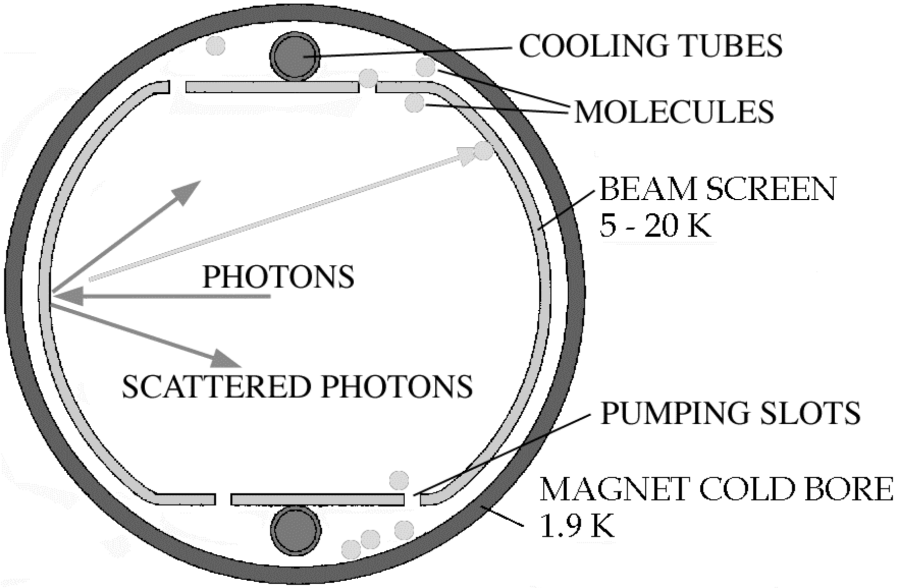
You need to limit helium contamination into the system 'by design'

Cryogenic vacuum issues

- Cryogenic heat loads
  - Removing 1 W of heat at 2K requires ~1kW of power at 300K
  - Image currents induced in the beam pipe by the beam current depend on the resistivity of the wall material
  - Synchrotron radiation photons and subsequent photoelectrons
    - ~10^{17} photons $s^{-1}m^{-1}$ giving 0.2 Wm^{-1}
- Gas desorption and recycling
  - Synchrotron radiation photons desorb cryo-pumped gas
    - Desorption yield for H_2 on copper at 10 K ~ 5×10^{-4} mol photon^{-1}
  - Photons have a high reflectivity at grazing incidence, so could impact many times on the beam pipe surface

LHC Beam Screen Concept

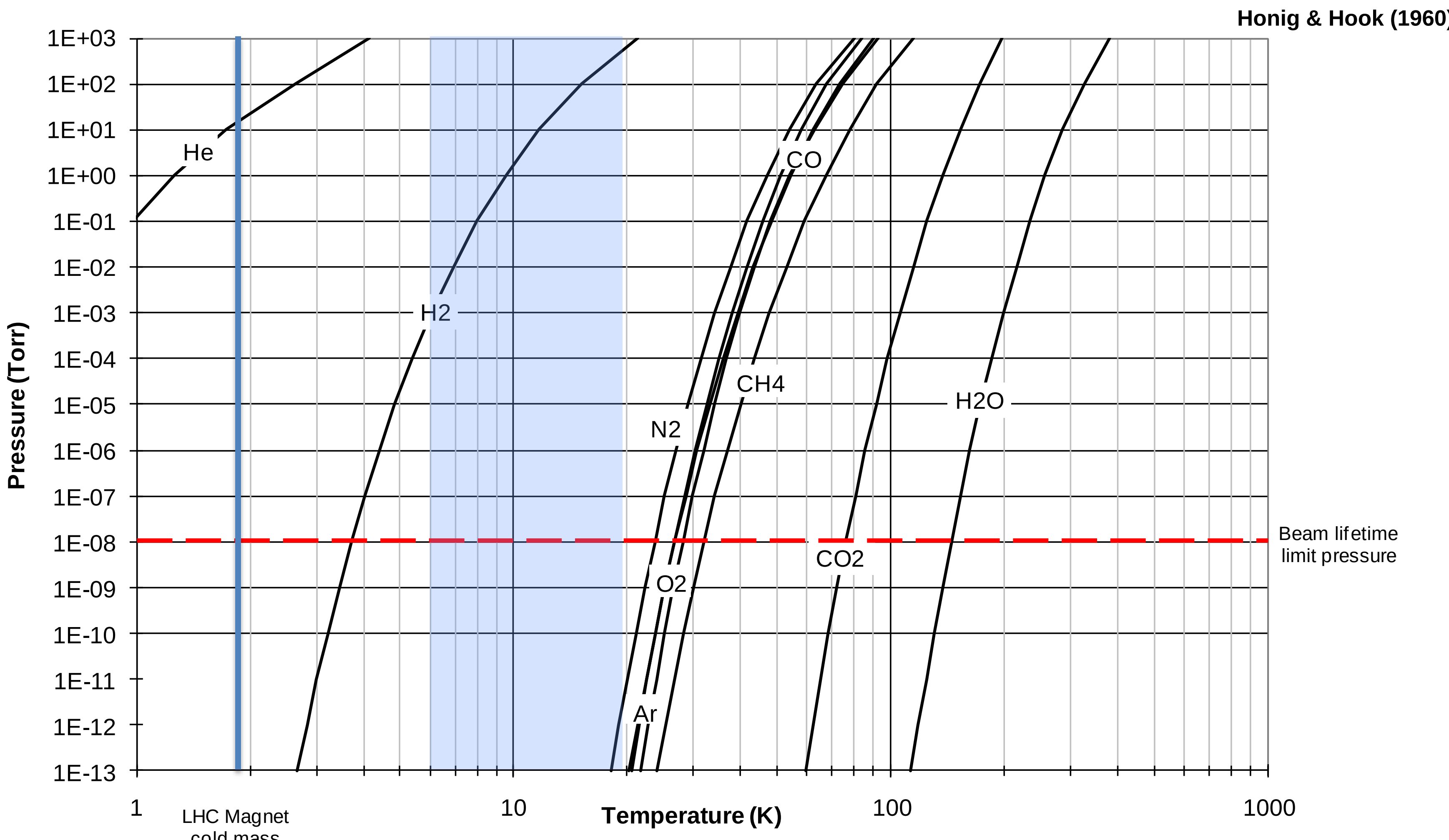
- Concept
  - Add beam 'screen' inside vacuum chamber to intercept synchrotron radiation
  - Copper lining on the inside of the screen minimise image current losses
- Cooling
  - Maintain screen at a higher temperature 5-20 K
  - Power needed to remove heat from liquid helium at 5 K is less than half that for superfluid at 2K



- Pumping
  - Add pumping slots to allow desorbed and recycled gas to migrate through and be pumped by the 2 K cold bore
  - Cryopumped gas on cold bore is screened from desorption by SR

The LHC cryo-pumping solution

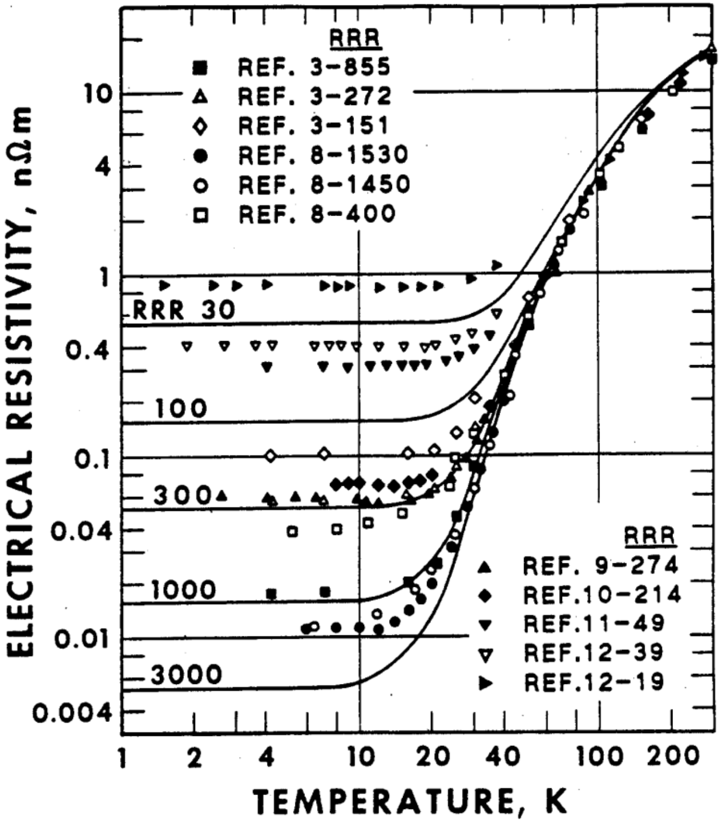
Saturated vapour pressures of common gasses vs. temperature

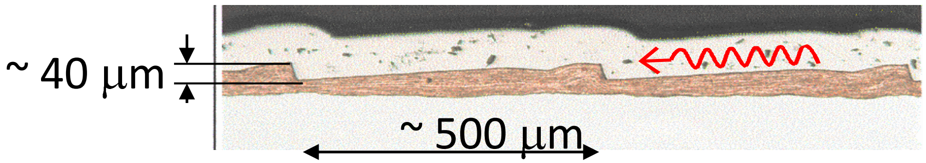


Hydrogen migrates from the 5-20 K beam screen to the 2 K cold bore

Copper beam screen layer

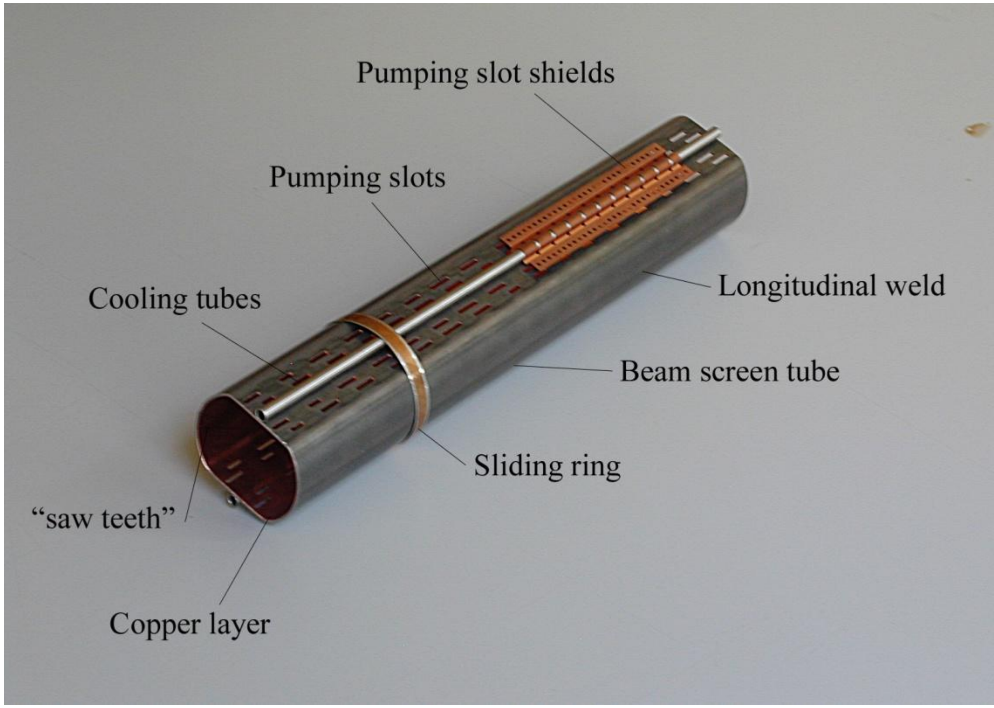
- Residual Resistivity Ratio (RRR)
  - ratio of the resistivity at 273K to that at 4K
  - Strong RRR effect in copper allows a thin, low resistivity coating, but sensitive to lattice imperfections such as impurities and mechanical work
  - Beam screen uses a 50µm co-laminated coating
- Saw teeth
  - Photon reflectivity cut by adding a saw tooth pattern strip to the inner surface of the beam screen





Stainless steel beam screen

- Beam screen form
  - ‘race track’ shape to maximise beam aperture whilst leaving room for the liquid helium cooling tubes
  - Pumping slots randomly distributed to prevent beam instabilities



- Stainless steel with copper liner
  - High conductivity copper with gives low beam impedance and minimises image current heating, but eddy currents during quench give large electro-mechanical forces, so you need a high-strength steel support
  - Stainless steels at very low temperatures have high strength, but show a number of undesirable effects, such as martensitic transformations and increased magnetic permeability
  - A special stainless steel grade (P506), high in manganese was developed with very low (>1.005) relative magnetic permeability

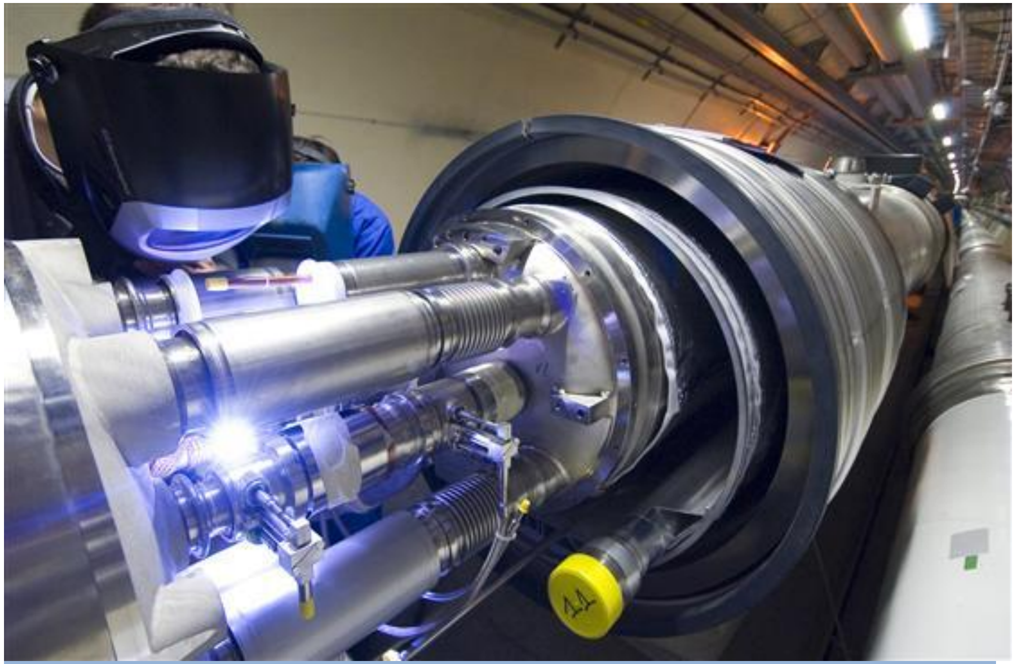
UHV Engineering on a large scale

	# assemblies installed	# variants of assemblies	Total assembled components
Beam Screens	3464	66	3464
Cold interconnects	3440	23	89440
Cold-warm transitions	212	13	2756
Cold BPMs	830	6	4150

- European industry manufacture
  - Beam screens and beam position monitors (BPMs) were manufactured by European contractors following standard ‘lowest compliant bidder’ tendering process
- Russian institute manufacture
  - All cold interconnects and many other components were manufactured, assembled and tested in a Russian HEP institute, via a collaboration agreement with the Russian Federation
  - CERN made all detailed designs and supplied all materials

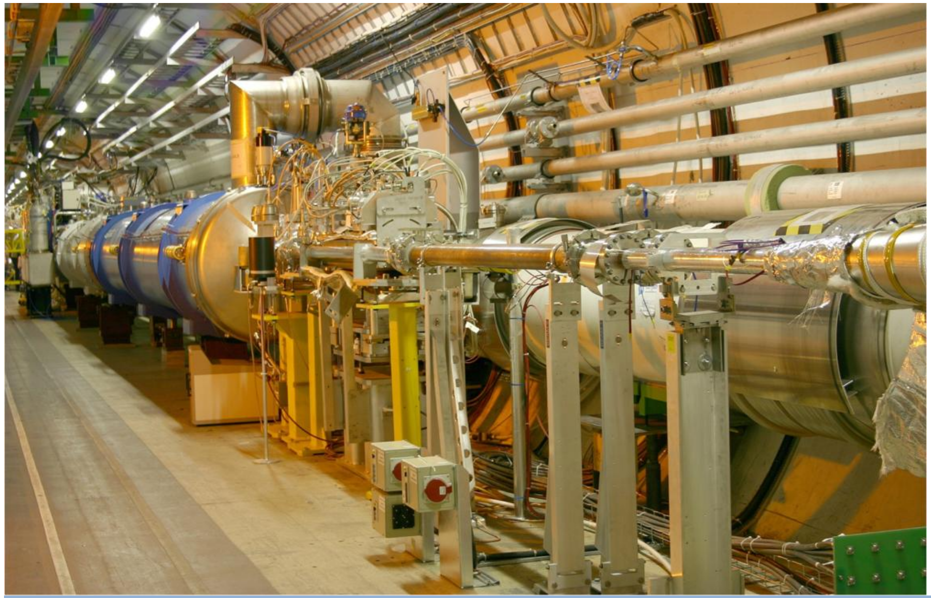
Installation and Commissioning

Cryogenic beam vacuum assembled on the surfaces – some 100’000 components with 65’000 welds

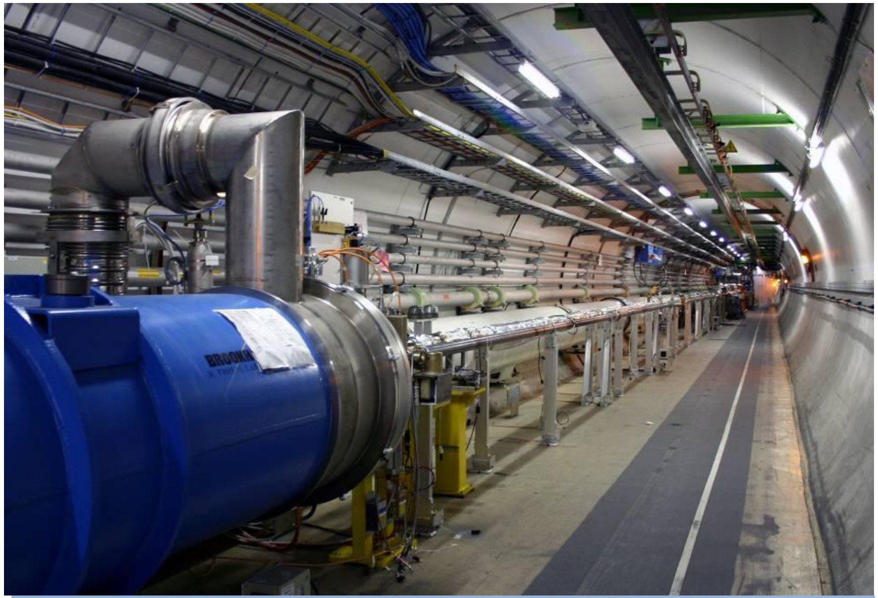


Cryogenic beam vacuum was fully-welded in the tunnel to maximise the long-term reliability – some 7’500 welds on the beam vacuum

Room Temperature Vacuum



There are some 6 km of room temperature vacuum chambers in the LHC. They link the drift spaces between cryomagnets and house room temperature equipment such as collimators and beam instrumentation



They have the same requirements in terms of beam lifetime and stability as the cold sectors, but do not benefit from cryopumping. A new technology: *sputtered non-evaporable getter,* was developed for the LHC

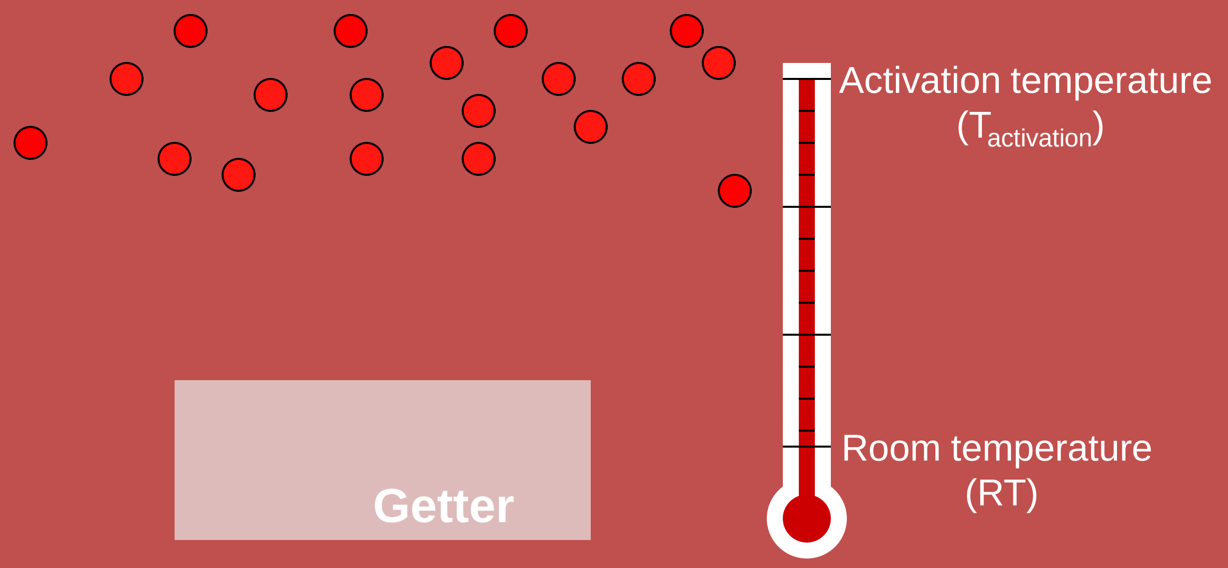
Non-Evaporable Getters

What is a Non Evaporable Getter (NEG)?

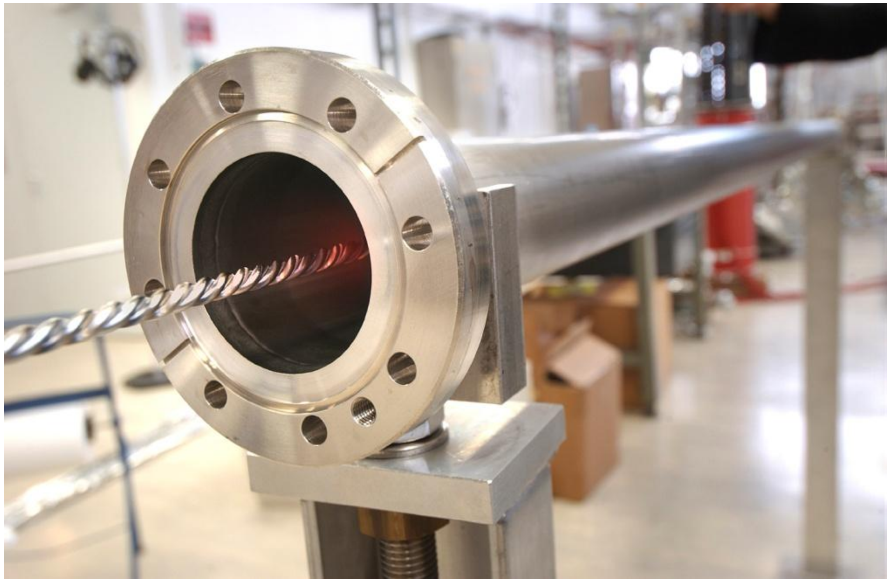
A *Getter* material presents a reactive surface to most gas species, adsorbing (*gettering*) impinging molecules.

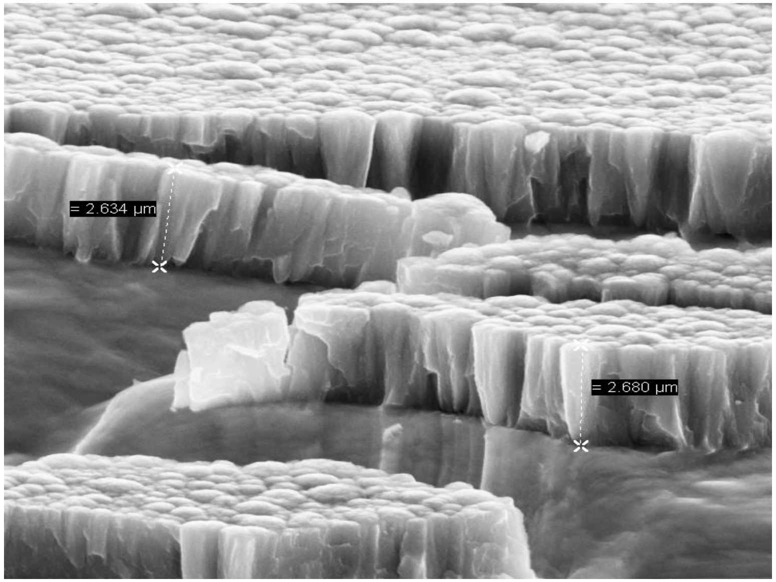
Once saturated, the *gettering* activity ceases and no more gas is pumped.

A *Non Evaporable Getter (NEG)* can be regenerated by heating to its activation temperature during a certain time.



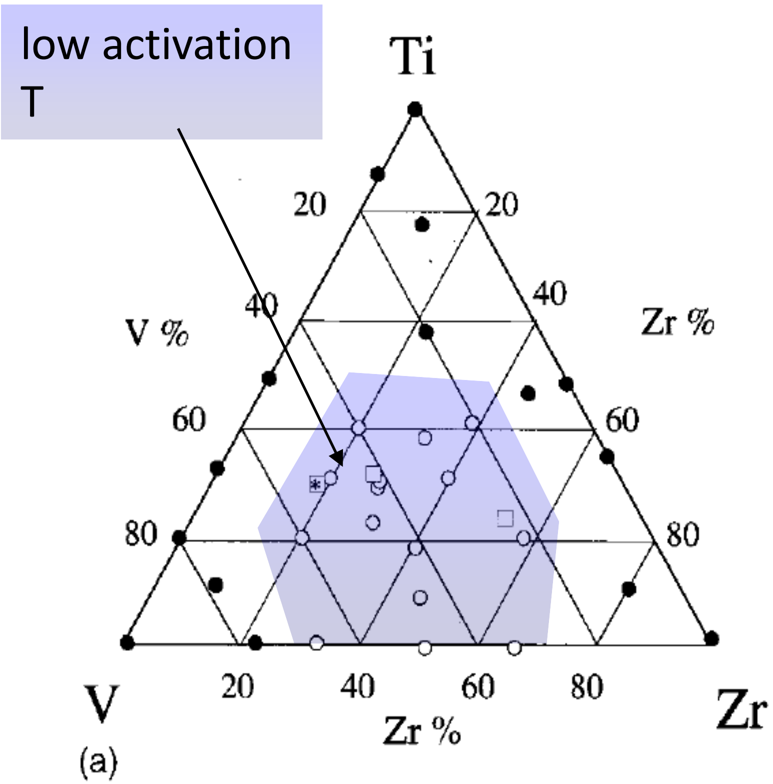
NEG coating process

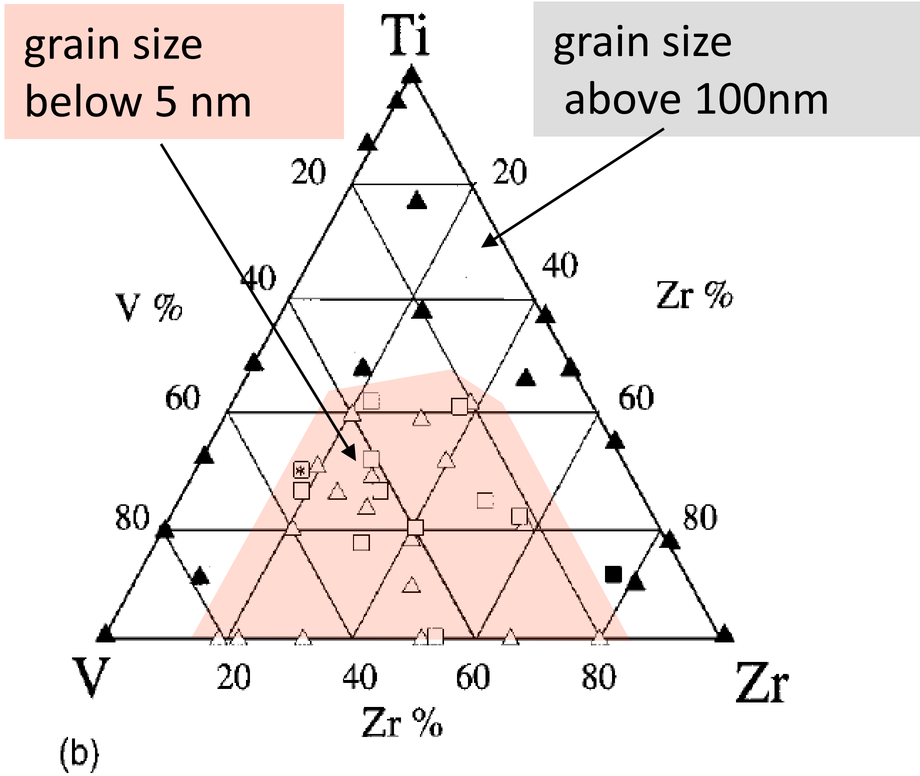




Optimised DC-magnetron process with target made of inter twisted wires of titanium, zirconium and vanadium allows the whole inside surface of vacuum chambers to be coated. This turns the chamber – usually the source of outgassing – into a pump

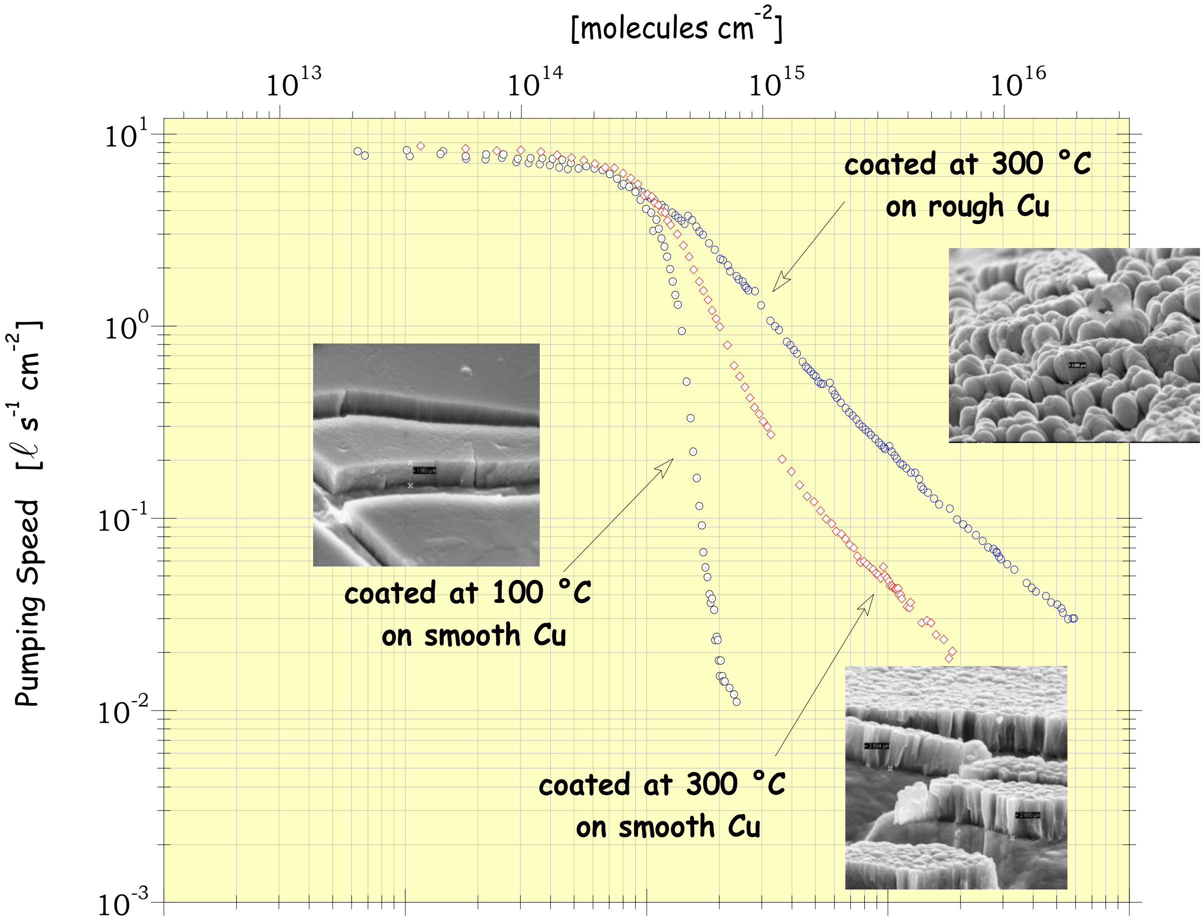
NEG activation temperature





There is a strong correlation between structure and activation T: diffusion at lower T is favoured in coatings with very small grains. Activation temperature was reduced from 450-700°C down to 200°C. This allowed sputtered NEG coatings to be used on standard (high-temperature grade) engineering materials such as OFS copper and 2219 aluminium

Pumping Characteristics for CO

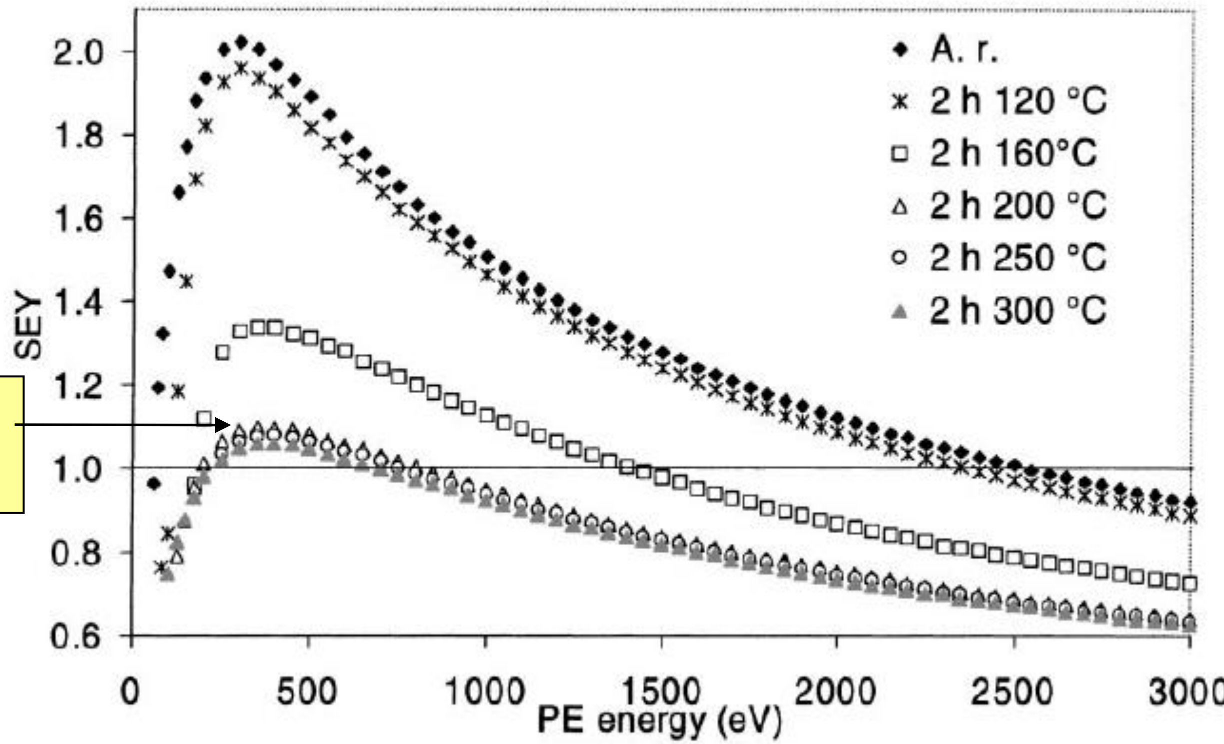


Pumping speeds and pump capacity were optimised by adjusting surface roughness. The pumping speed for chemically active gases is extremely high. However, the pump capacity between re-activations is still in the order of a few mono-layers of gas, so the technology requires ultra-high vacuum design to eliminate leaks and minimise contamination from non-NEG coated surfaces

Seconday Electron Yield

TiZrV NEG can provide a surface with sufficiently low δmax :

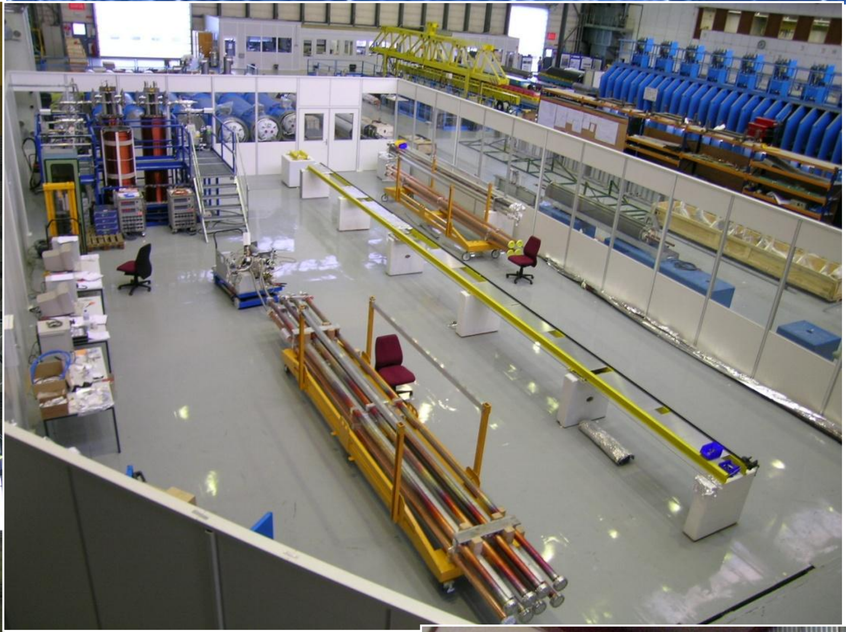
activation at 200C, 2h



Henrist et al. Appl.Surf.Sci, 2001

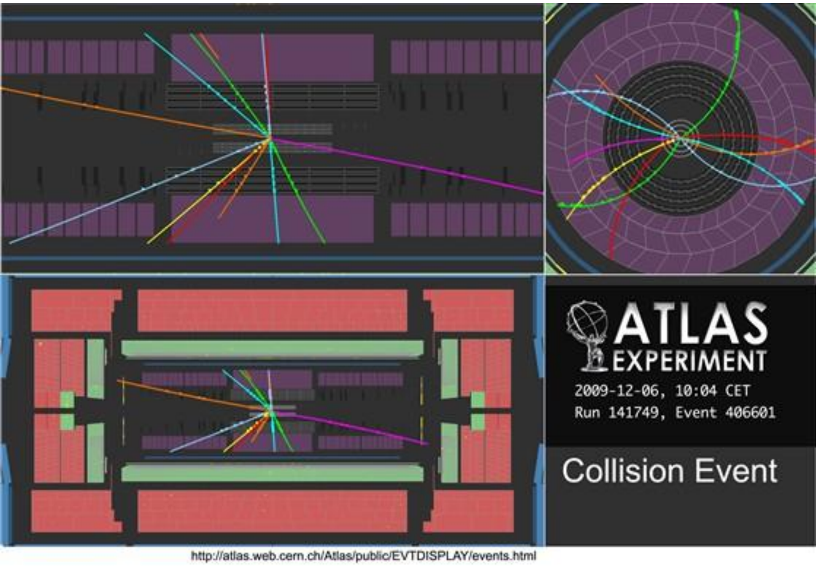
A sputtered NEG coating, activated at 200°C for 2 hours also has a low secondary electron yield. Tests made in the SPS ring at CERN have shown that this successfully suppresses electron cloud effects with LHC-type beams

NEG coating ‘factory’

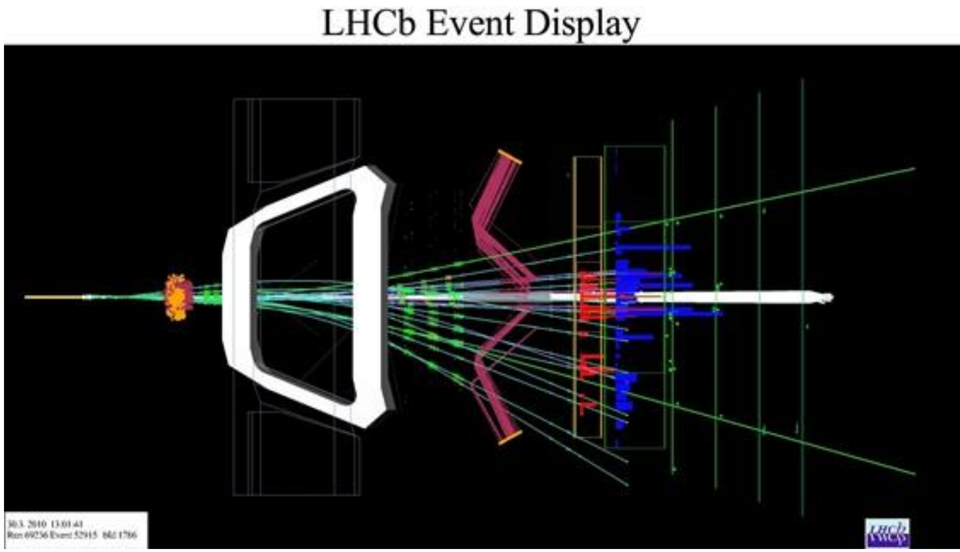


LHC construction required a NEG coating ‘factory’ to be built at CERN, based around an 8m long solenoid. As well as over 600 standard chambers, many special objects for LHC experiments and room-temperature magnets were coated

Vacuum in the Experiments



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html



Experimental detectors are sensitive to nuclear scattering between beam and residual gas.
But also to interactions with the beam-beam collision products and the beampipe.
So not only the pressure, but the chamber, it's supports and all other equipment are important

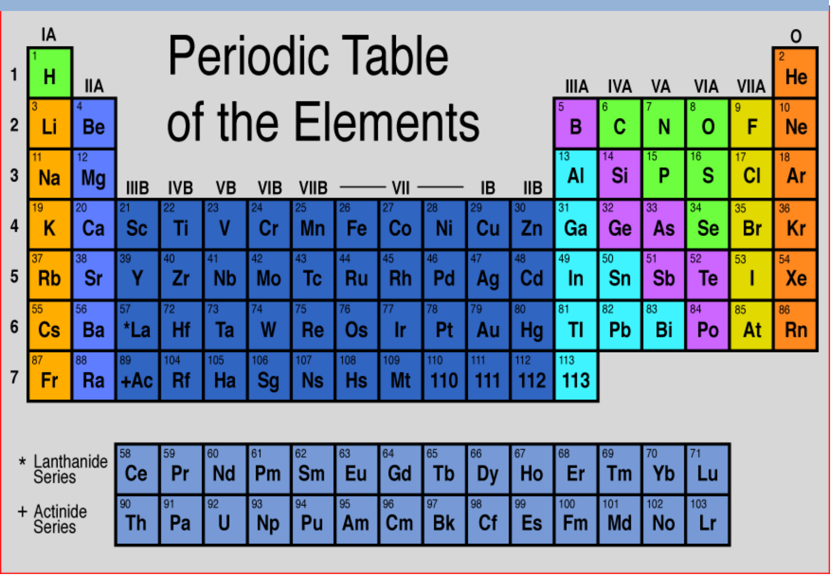
There are generally two solutions to this problem:
Make the vacuum chambers, along with supports, and all other equipment as transparent as possible.
Design the shape of the chambers so that interactions between particles and chambers take place outside of 'acceptance' of detectors

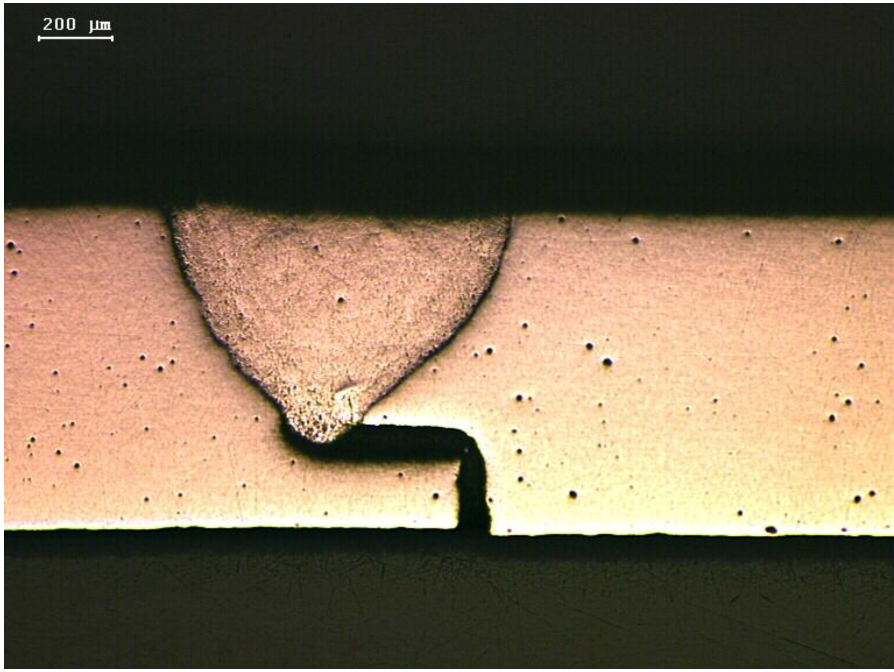
Transparent Chambers

Radiation length X_0 characterizes the amount of matter traversed by a particle and can be approximated by

$$X_0 = \frac{7.16A}{\rho Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

Where Z is the atomic number, A the atomic mass and ρ the mass density

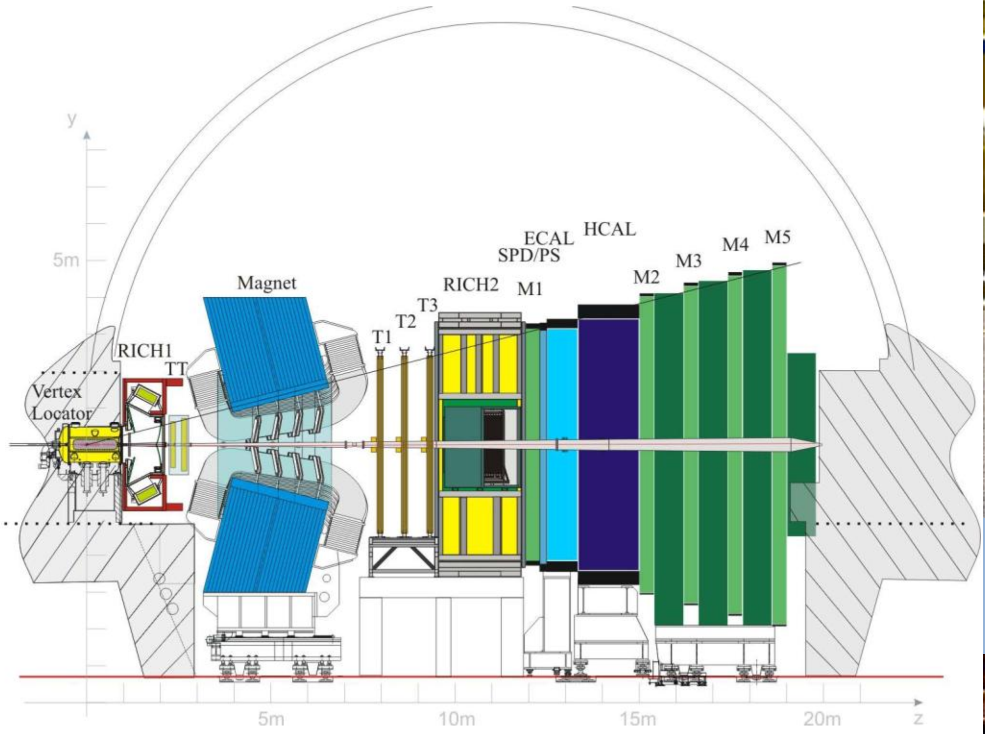




Vacuum chambers also need a high modulus to resist bucking and minimise supports: Beryllium is the material of choice.

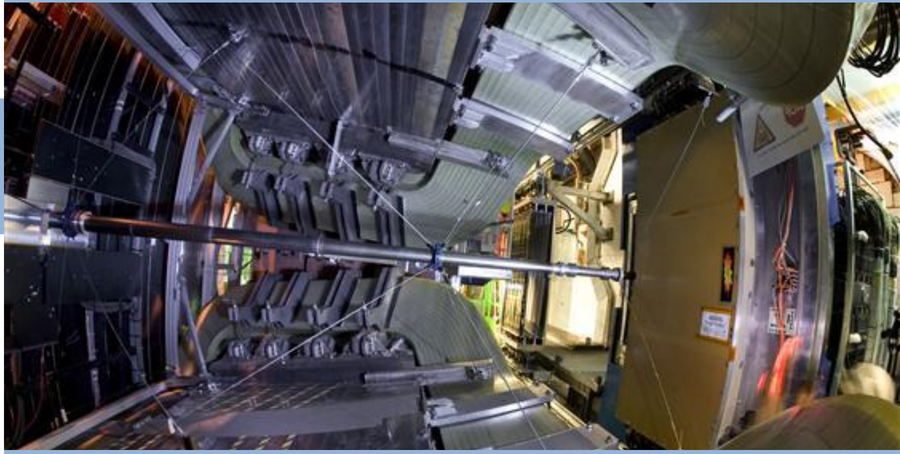
Beryllium technology developed for the LHC includes chambers machined from block, EB welding and vacuum brazing

Example of LHCb Vacuum System



11m of beryllium chambers to optimise transparency

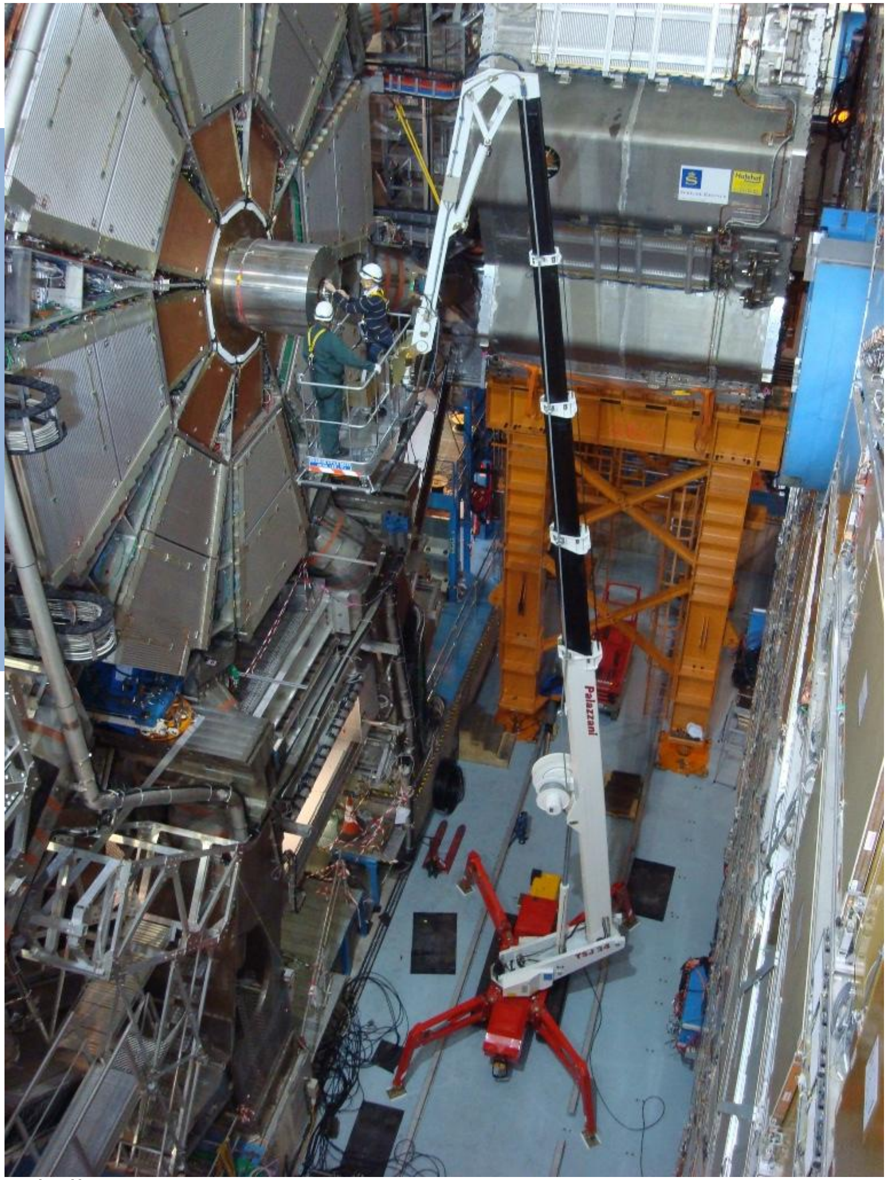
Conical chambers, with angles originating at the interactions point



Highly optimised supports, with stretched cables

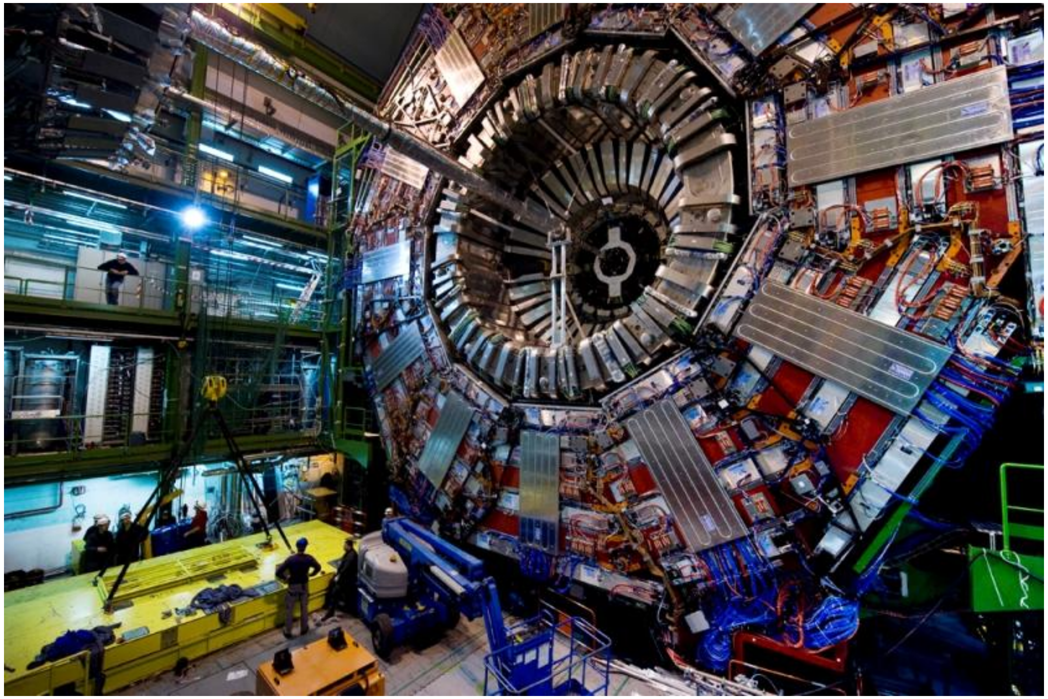
Access and Environment in the Experiments

The LHC experiments are huge (ATLAS measures 22m diameter by 40m long).
High civil engineering costs means that the experimental caverns are ‘just’ large enough for all the equipment.
By definition, the beampipe passes though the middle – ie, 11 m from the ground in ATLAS
This means that access to the beam pipes is always a challenge

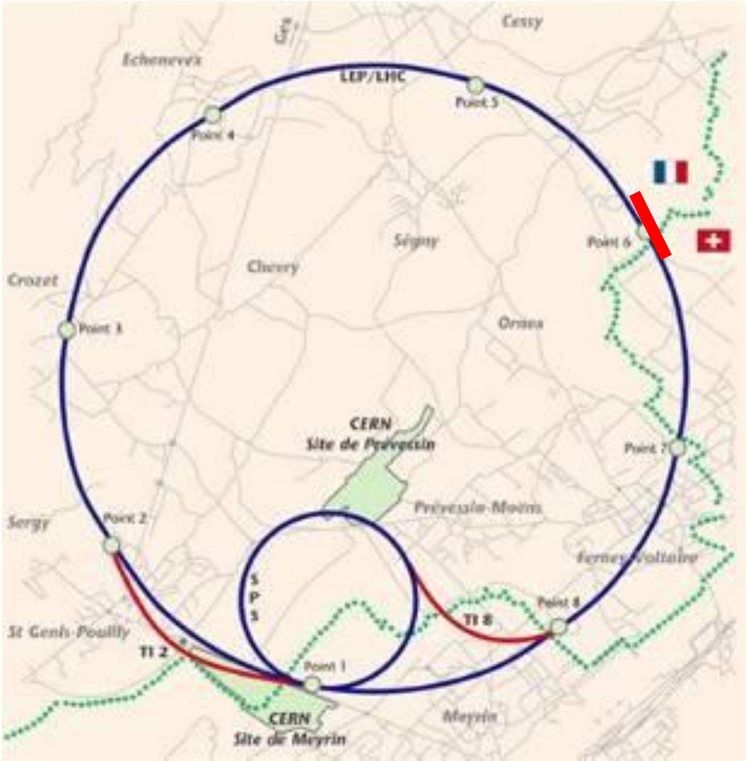


Access and Environment in the Experiments

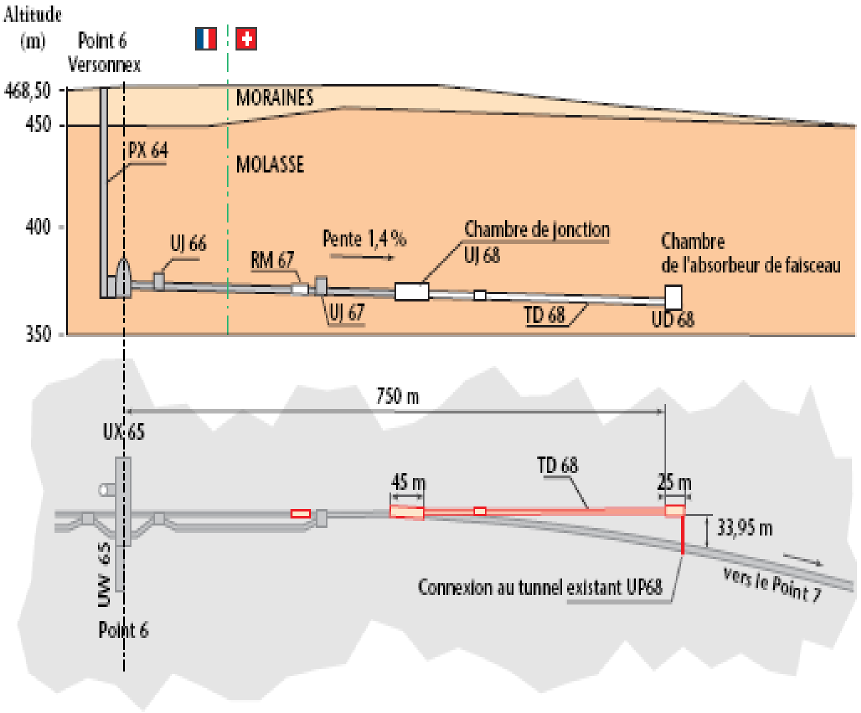
‘Basic’ vacuum operations such as installing a chamber, or baking it out, become major logistical challenges



LHC beam dump lines

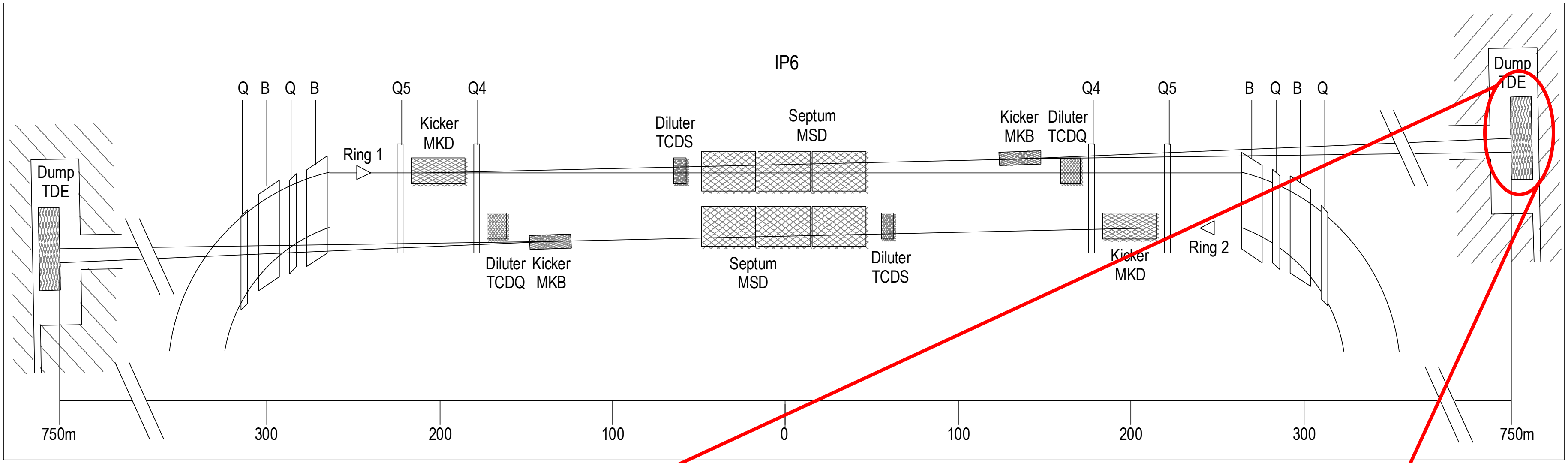


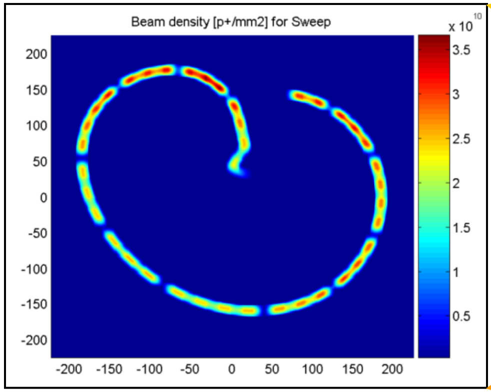
One of the ‘special’ straight sections of the LHC, the beam dump system safely removes the spent beams at the end of a fill.

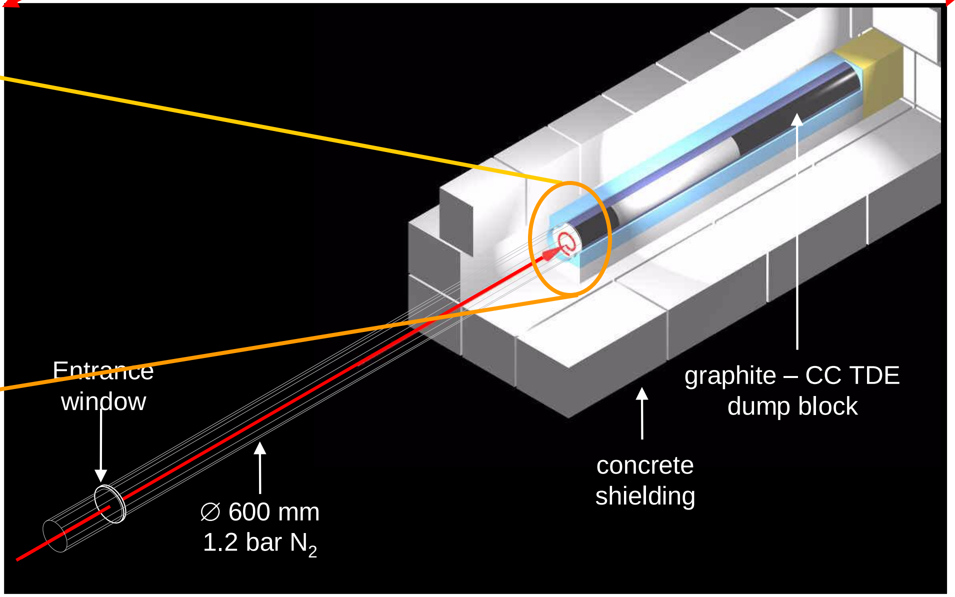


The beam is ejected from the LHC into a 600 m long tunnel before being absorbed in a large carbon block

Overview of beam dump system







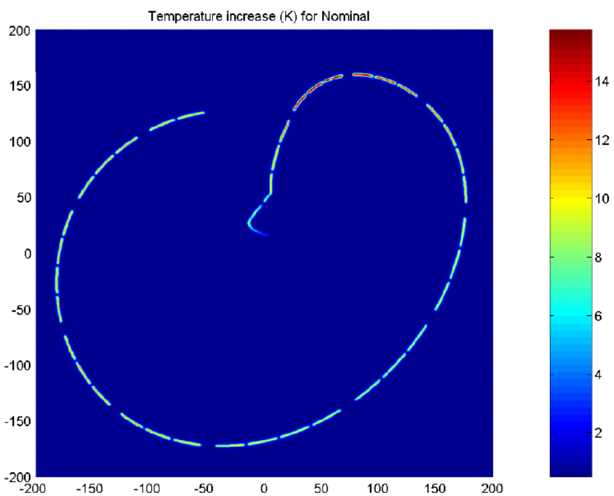
Courtesy of B.Goddard

Window installed in dump line

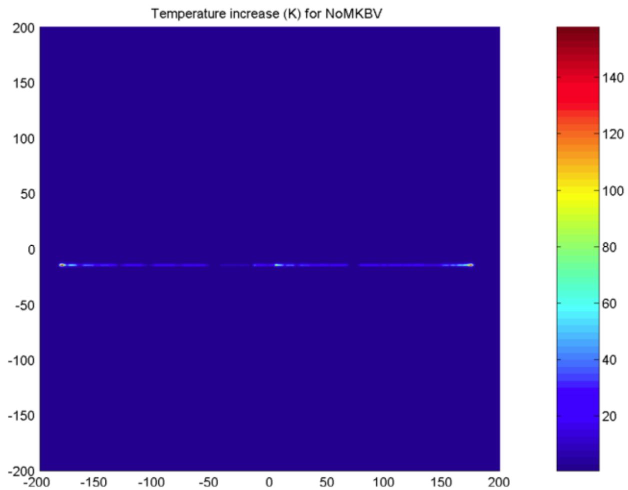
Beam dump entrance window has a 600mm aperture with a structure of carbon-carbon composite to resist pressure loading. Leak-tightness is ensured by a 0.2mm thick foil

382 MJ passes through the window in ~100µS. Due to the high radiation length of carbon, only 600 J is calculated to be absorbed by the window. In addition, a very low coefficient of thermal expansion in the fibre direction mean that mechanical thermal stresses are very small

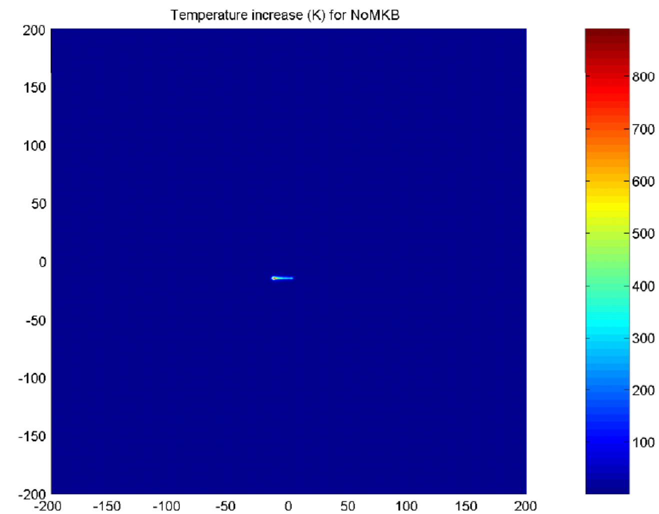
Issues with the beam dump window



Nominal dump

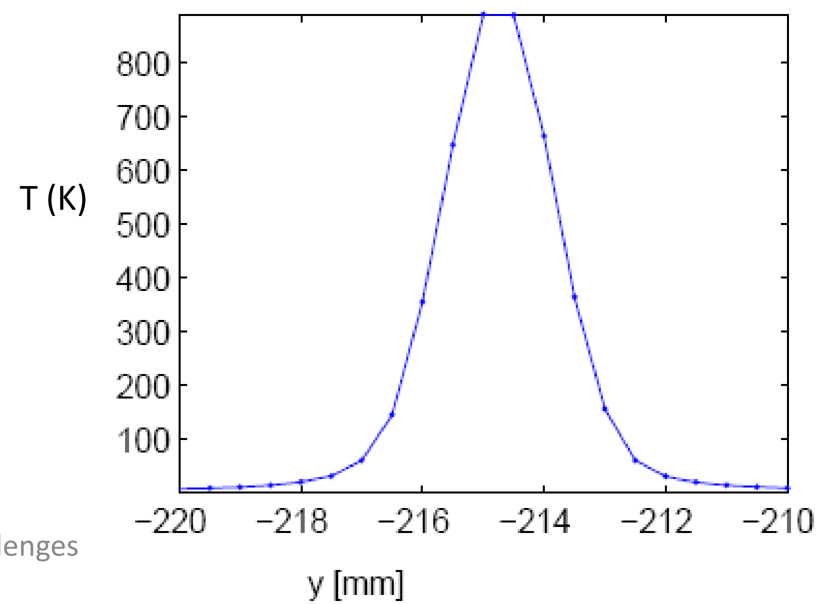


Vertical kicker failure



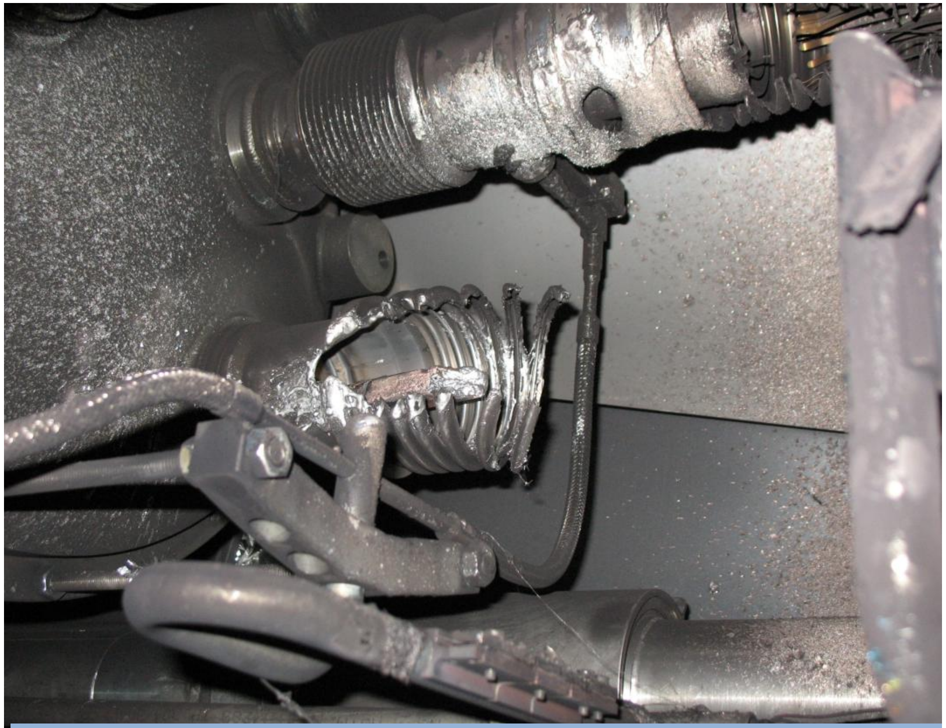
Total kicker failure

Failure modes can lead to ΔT up to 500°C/mm across the surface of the composite. This means ~10°C between individual fibres.
Both materials data and engineering models (which are already limited for these 'new' materials) are of questionable reliability under these conditions
A new test facility (HiRadMat) is being built to collect data for this kind of issue

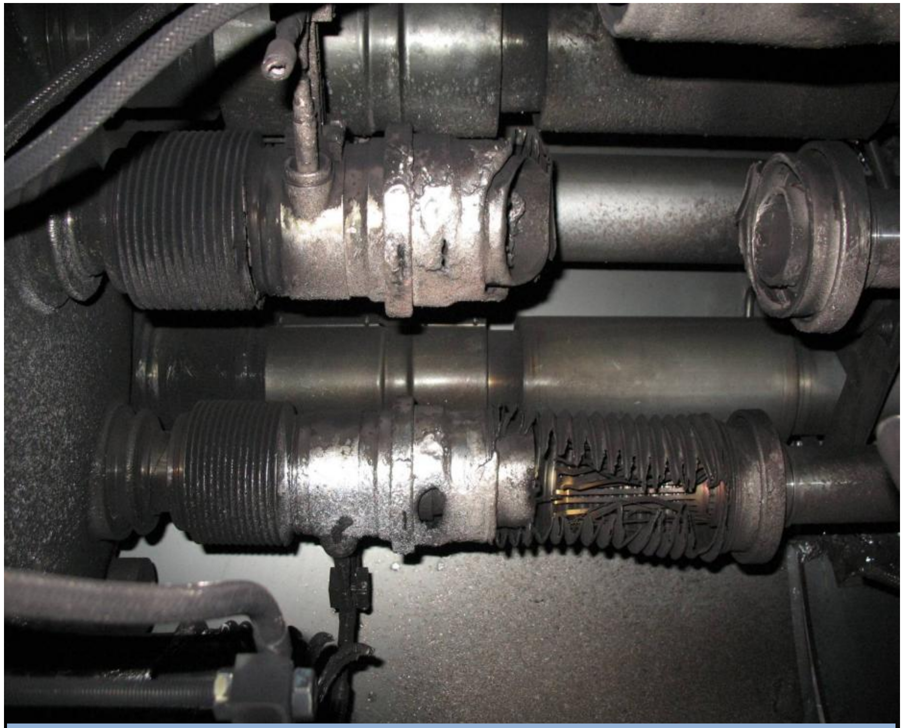


On the 10th Sept. '08, everything was working…

…for 9 whole days!

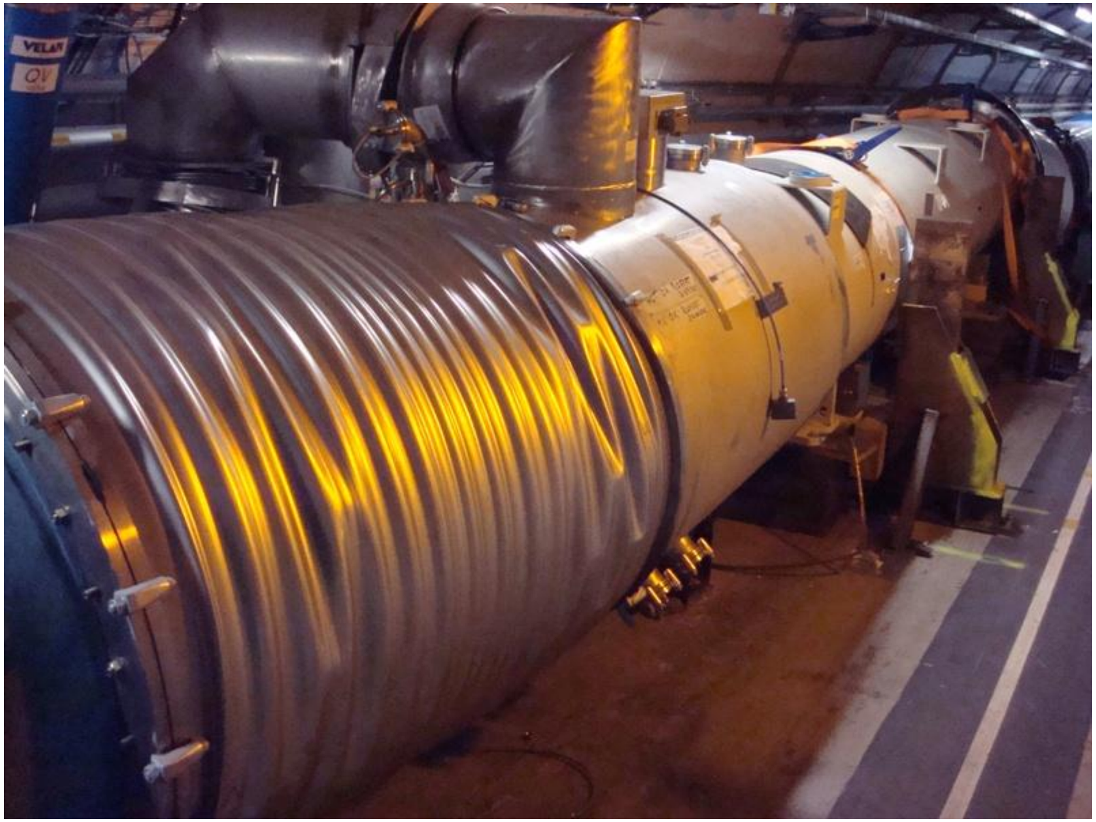


A faulty bus-bar in a magnet interconnect failed, leading to an electric arc which dissipated some 275 MJ



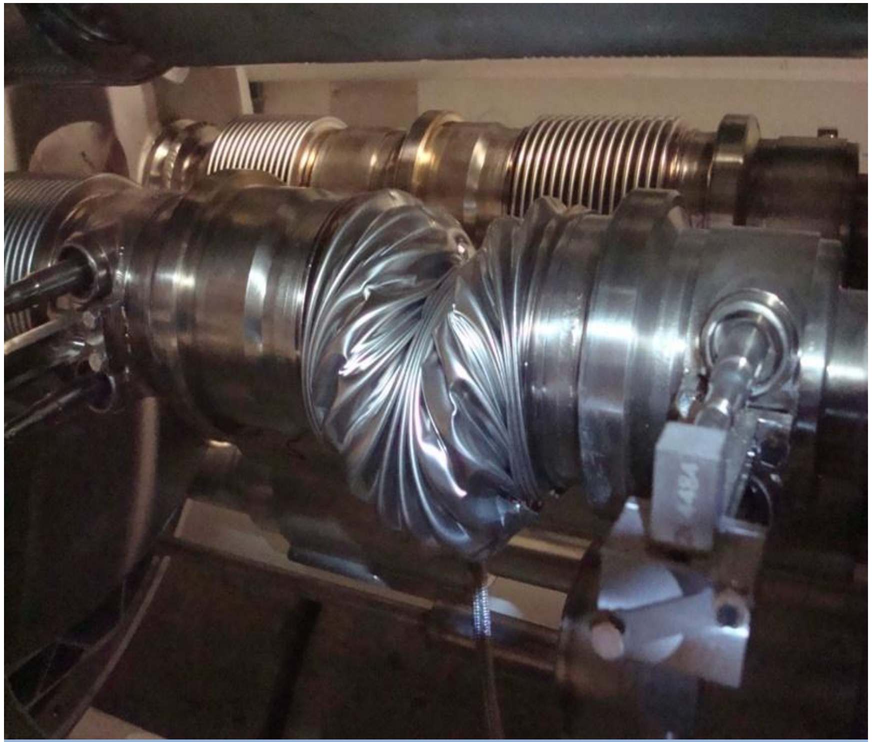
This burnt through beam vacuum and cryogenic lines, rapidly releasing ~2 tons of liquid helium into the vacuum enclosure

Collateral damage: magnet displacements



The expanding helium generates forces which lift 30 T magnets off their supports, breaking additional lines

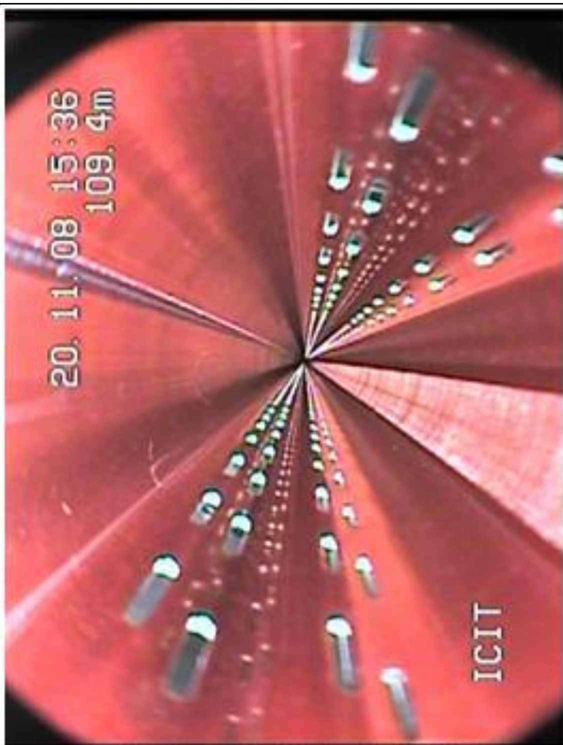
Impact on the beam vacuum

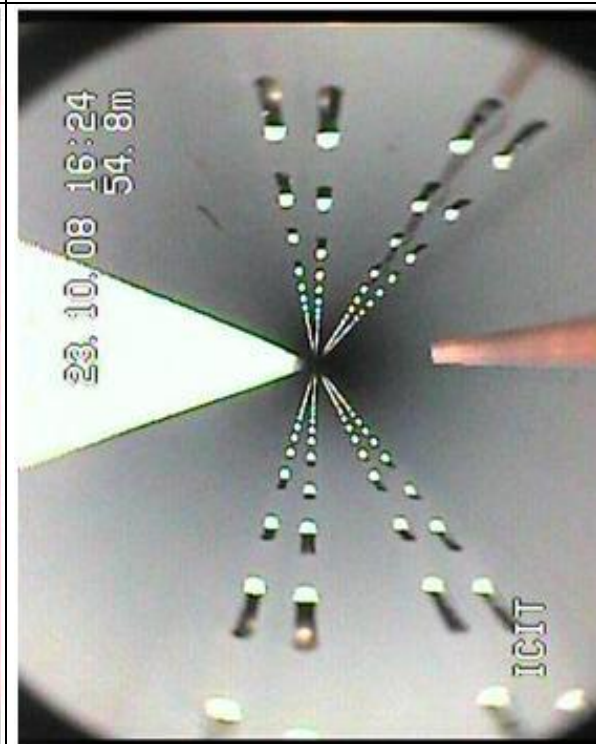


The pressurised helium enters the beam vacuum, buckling bellows designed for external pressure which are then crushed as the magnets warm-up to room temperature

Impact on the beam vacuum system

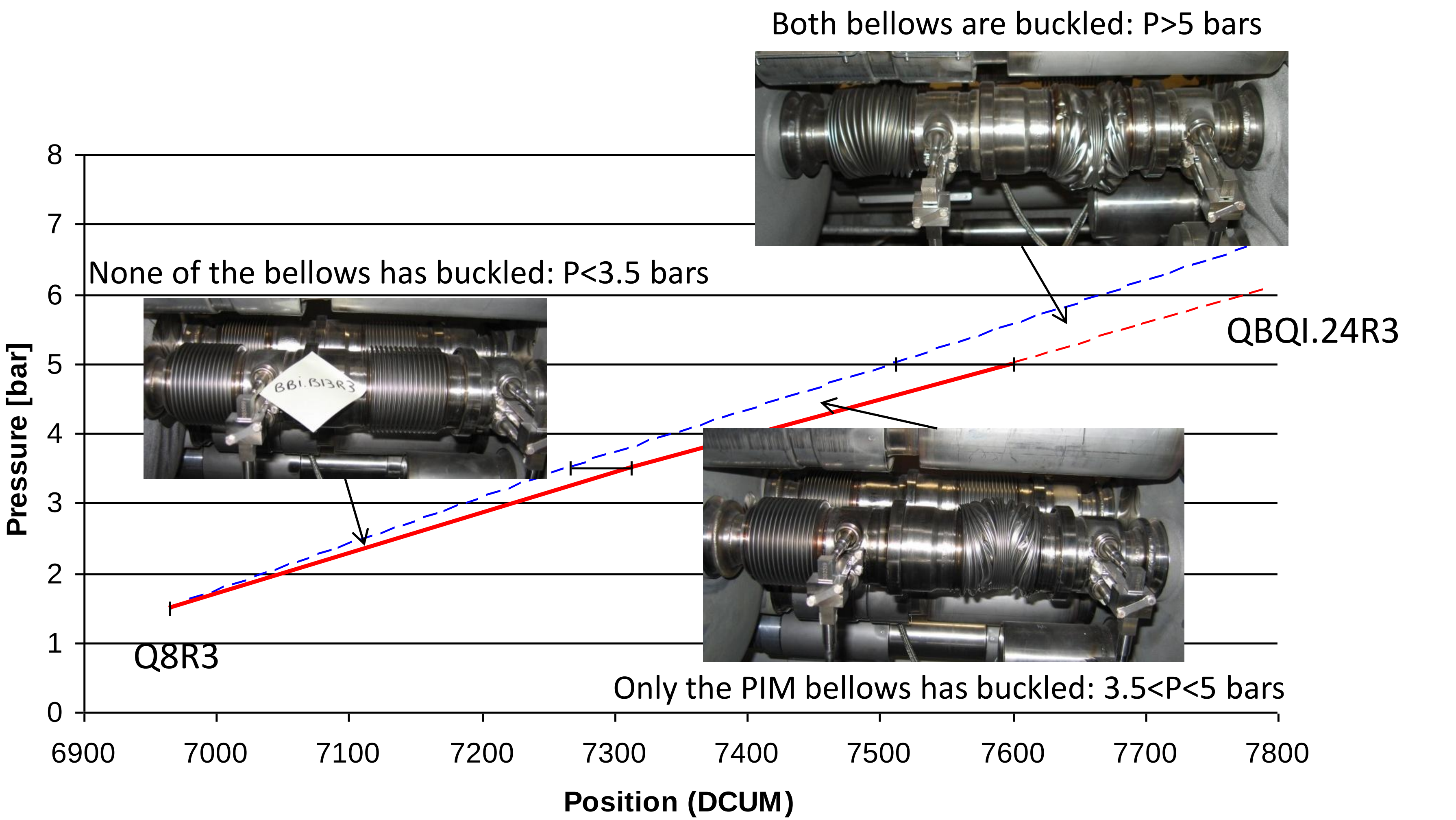
Beam Screen (BS) : The red color is characteristic of a clean copper surface	BS with some contamination by super-isolation (MLI multi layer insulation)	BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.





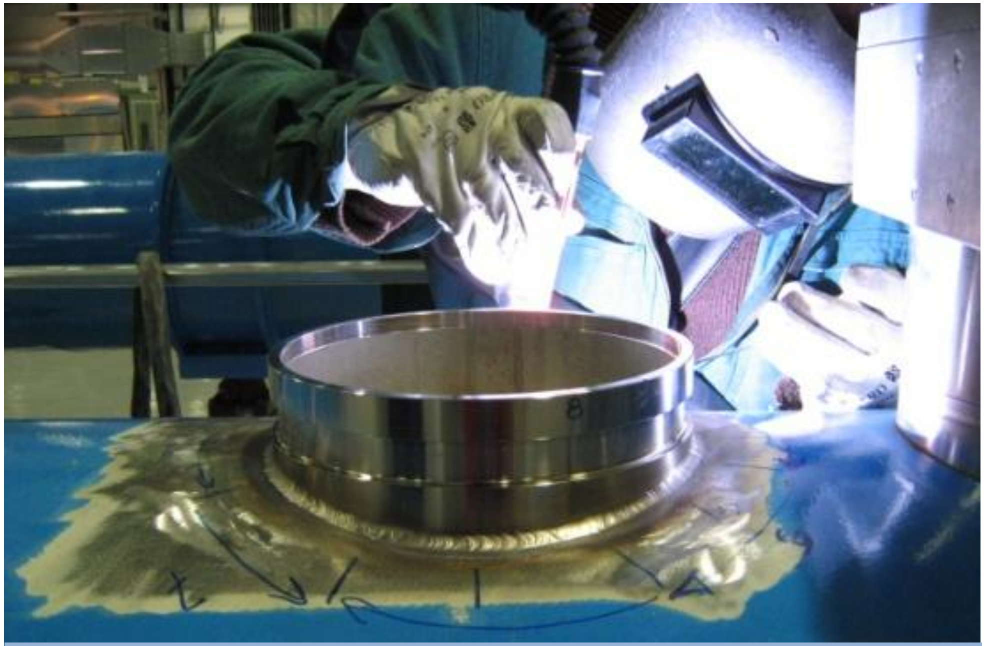
The pressure wave pulls debris – principally metallic soot and fragments of cryogenic ‘super-insulation’ and distributes it over the whole 2.5 km of continuous cryostat

Analysis of the Pressure Wave



The fact that the interconnection bellows had been thoroughly designed and tested allowed us to have a good estimate of the maximum pressures along the beam line

Consolidation after the incident



A number of actions were taken to reduce the probability and impact of any future similar incident

The same group of people on November 2009, a little older and perhaps wiser

Several more actions are planned for the coming years – in particular for the vacuum system, the design and addition of ‘fast shutter valves’ that would limit the spread of pressure waves and debris

Closing Remarks

- The physics requirements for the LHC has pushed forward vacuum technology in many areas, and these will be applied to future machines such as ILC and CLIC
  - New vacuum technologies such as sputtered NEG and optimised equipment for experiments
  - New materials such as P506, carbon-carbon composites and new beryllium technology
  - UHV engineering, but on an industrial scale never before seen
- Although the LHC beam vacuum is built and initial experience has been good, we are now exploring new territory…
  - Interactions between particles and surfaces at high energy
  - Performance of transparent, radiation resistant materials

Closing Remarks II

- Development work on the vacuum system is far from finished
  - We have a 10-year upgrade programme for all 4 experimental vacuum systems, implementing new materials and techniques to optimise the physics performance of the detectors
  - Planned performance upgrades to the LHC and it's injector chain will require significant re-design and new technologies such as amorphous carbon coatings
  - LHC has moved from a phase of construction and commissioning to one of operation, but also R&D. This requires new skills and new collaborations

Acknowledgements

- I would like to thank the following colleagues at CERN for their help and materials:
  - V.Baglin, F.Bordry, P.Cruikshank, C.Garion, B.Goddard, J.M. Jimenez, L.Rossi, M.Taborelli,
- Several of the better photos are from:
  - M.Brice/CERN Photo

- General background material can be found at:

  - O.Grobner, “Overview of the LHC vacuum system” Vacuum 60 (2001) 25-34
  - P.Chiggiato and P. Costa Pinto, “Ti-Zr-V non-evaporable getter films: from development to large scale production for the Large Hadron Collider”, Thin Solid Films 515 (2006) 382-388
  - M.Bajko et al. “Report of the Task Force on the Incident of 19th September 2008 at the LHC”, CERN-LHC-PROJECT-Report-1168

Additional Material

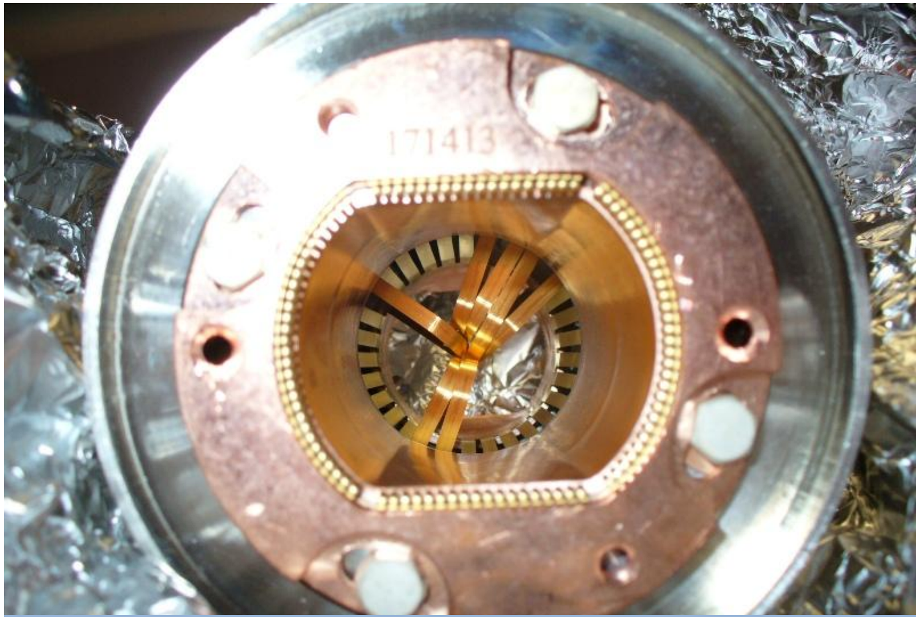
Environment

In ATLAS, the most delicate ‘PIXEL’ detector was built around the beampipe in a clean room

In both ATLAS and CMS, the high flux of particles coming from the collisions require shielding around the beampipe, and will mean remote handling of some components

We had our share of problems…

A critical assembly called a ‘plug-in module’ which ensures electrical continuity between adjacent cryo-magnets: 3’600 in the LHC



We found ~40 damaged after a thermal cycles of the machine with fingers blocking the beam aperture: A combination of manufacturing faults and magnet positioning