Technological Challenges for the LHC Vacuum System

Ray VENESS
CERN Technology Department
Vacuum, Surfaces and Coatings Group
CERN
European Organization for Nuclear Research

2004: The 20 member states

15th April 2010
R.Veness: LHC Vacuum Challenges
The CERN accelerator complex

20 member states + observers (USA, Russian Federation, Japan,...)
Some 2500 staff members and 8000 visitors
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.
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.
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
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 $\leq 1\times10^{15}$ H$_2$ molecules m$^{-3}$ or a pressure at room temperature of $\sim 1\times10^{-8}$ 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.
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.

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.
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.
Saturated vapour pressures of common gases vs. temperature

You need to limit helium contamination into the system ‘by design’
• **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
    • \(~10^{17} \text{ photons s}^{-1} \text{m}^{-1}\) giving 0.2 \(\text{Wm}^{-1}\)

• **Gas desorption and recycling**
  – Synchrotron radiation photons desorb cryo-pumped gas
    • Desorption yield for \(\text{H}_2\) on copper at 10 K \(~5\times10^{-4}\) 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 gases vs. temperature

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

Honig & Hook (1960)
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
• **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
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
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.
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.
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.
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 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.
TiZrV NEG can provide a surface with sufficiently low $\delta_{\text{max}}$:

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.
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.
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, its 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.
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 $\rho$ the mass density.

Vacuum chambers also need a high modulus to resist bucking and minimize 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

Conical chambers, with angles originating at the interactions point

11m of beryllium chambers to optimise transparency

Highly optimised supports, with stretched cables
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.
‘Basic’ vacuum operations such as installing a chamber, or baking it out, become major logistical challenges.
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

15th April 2010
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 \(~100\mu S\). 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

Failure modes can lead to $\Delta T$ 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...
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.
The expanding helium generates forces which lift 30 T magnets off their supports, breaking additional lines.
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

<table>
<thead>
<tr>
<th>Beam Screen (BS)</th>
<th>BS with some contamination by super-isolation (MLI multi layer insulation)</th>
<th>BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.</th>
</tr>
</thead>
</table>

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

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.
• 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
• 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:
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.
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