INSTALLATION AND COMMISSIONING OF VACUUM SYSTEMS FOR THE LHC PARTICLE DETECTORS

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Abstract

The LHC collider has recently completed commissioning at CERN. At four points around the 27 km ring, the beams are put into collision in the centre of the experiments ALICE, ATLAS, CMS and LHCb which are installed in large underground caverns. The 'experimental vacuum systems' which transport the beams through these caverns and collision points are a primary interface between machine and experiment and were developed and installed as one project at CERN. Each system has a different geometry and materials as required by the experiment. However, they all have common requirements from the machine, and use many common technologies developed for the project. In this paper we give an overview of the four systems. We explain the technologies that were developed and applied for the installation, test, bakeout and subsequent closure of the experimental vacuum systems. We also discuss lessons learnt from the project.

INTRODUCTION

The four experimental vacuum systems are all 45.6 m long, spanning the LHC insertion triplets. These are fully-baked Ultra-High Vacuum (UHV) systems, but chambers, supports and vacuum equipment are mass and envelope optimised to minimise impact on physics. ATLAS and CMS, the two high-luminosity experiments, have vacuum systems symmetric about the interaction point (IP). ALICE and LHCb take data only in one forward direction, so their optimised chambers extend only in one direction.

ALICE, CMS and LHCb chose to use large conical chambers, with angles pointing at the IP to minimise 'background'-inducing interactions with beampipe materials. ATLAS chose to keep beampipe radii small to push detectors as close as possible to the beam axis.

INFRASTRUCTURE

Despite the radically different geometries of the vacuum systems in the 4 experiments, organisation as a single project allowed many synergies to be exploited. A number of special vacuum technologies were developed for all experiments [1]. The use of a common vacuum laboratory for assembly and test optimised resources and ensured that quality problems were quickly understood and resolved. Test benches were installed in the lab that allowed the complex support and detector opening scenarios to be simulated, along with qualification of vacuum performance and interfaces with experiments.

Transport and handling of the long, fragile, one-off vacuum chambers was a major issue. Two transport cases were designed for the 24 optimised chambers. In addition, a wide range of specific handling tooling was developed due to the difficult access in the experiments. This infrastructure will be re-used for the annual shutdowns.

INSTALLATION

ALICE

The beam pipes for the ALICE experiment can be divided in 3 groups:

Conical chambers in the forward 'absorber' shielding with diameters up to 450 mm are made of stainless steel. These are very difficult to access once installed so the bakeout system was designed to be robust with minimum thickness and heat load to the experiment;

The 4 m long central beryllium beam pipe had to be slid though ALICE central detectors and was mostly not accessible during the bakeout. A sliding oven in four sections and made of half-shells was made for installation and bakeout. This tool had to ensure a chamber temperature of 220 °C whilst the surrounding detector could not exceed 50 °C. Sprung supports held the rigid beryllium beam pipe inside the more flexible aluminium oven structure and ensured that the beam pipe was not overstressed during load transfers from installation to final configuration. Several iterations with prototypes were necessary to develop a tool that was safe for both detector and beampipe;

The third group of beam pipes were based on 'standard' LHC copper chambers, installed using procedures developed for the machine vacuum sectors.

ATLAS

The ATLAS experimental vacuum system consists of 6 cylindrical 'forward' chambers of increasing diameter symmetrically aligned around a central beryllium chamber 7.3 m in length. The beryllium chamber was integrated with the PIXEL detector on the surface some 6 months before installation and installed in the experiment as part of the detector package.

The main challenge with the remaining installation involved closing the 1000 Tonne end cap detectors, which slid over the beampipe with 3 mm clearance, but no access. This was achieved by a combination of close control of the end cap movement using air pads and video surveillance and displacement sensors installed on the chambers.

ATLAS is the only one of the 4 experimental systems with bakeout heaters, insulation and control permanently integrated along the whole sector. This required development of a highly reliable, lightweight, radiation resistant bakeout system.

More details of the design of the system can be found in [2].

CMS

CMS consists of a central beryllium pipe with 10 conical and cylindrical chambers symmetrically arranged on both sides.

As with ALICE, the bakeout of the central pipe required an insertable furnace. A common development of the furnace elements was made for the two experiments, but with a different structure and interface.

One of the main challenges with CMS installation was the schedule. The vacuum system was the last part of CMS to be installed, and many construction problems had made CMS the last of the 4 experiments to be completed. Three steps were made to address this: Pre-assembly of chambers, bakeout equipment and control minimised the work in the tunnel; Intensive qualification of chambers, procedures and tooling in the vacuum lab were made to ensure maximum reliability; Finally, long hours in the final phases of installation and leak testing at night allowed 2.5 weeks gain on the 10 week installation window. CMS was commissioned 1 week before LHC start-up.

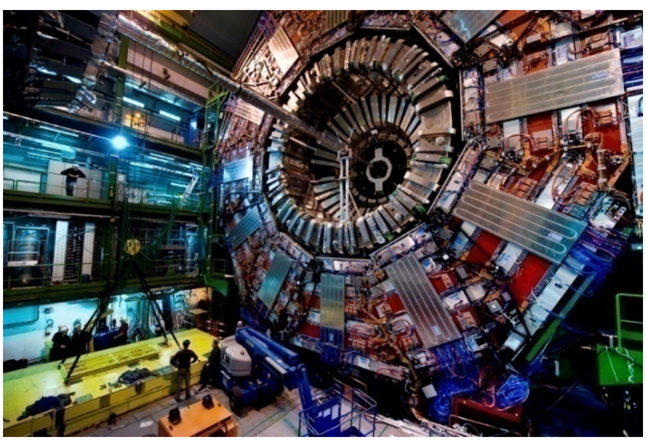

Figure 1: Beampipe during bakeout in CMS.

LHCb

LHCb differs from the other experiments in that a ‘Vertex Locator’ (VELO) detector is inserted inside a vacuum tank around the IP, separated from the beam vacuum by a thin aluminium foil. This detector and its vacuum control system were produced by the NIKHEF institute [3].

In addition, very low background requirements in the LHCb experiment justified the selection of beryllium as the material for 13 m out of the 20 m of long conical vacuum chambers. The fragility, toxicity and high manufacturing cost of beryllium imposed severe constraints from the design to the installation in the cavern. Dedicated tooling was produced to handle and protect each of the three Be sections. Inside the dipole magnet, the beampipes are suspended on stainless steel cables up to 3 m long. In order to minimise the work around the fragile beampipes, these cables were pre-tensioned on support rings that were pre-aligned using theodolites to about 0.1 mm accuracy. Force transducers were used during alignment to ensure a precise cable tension. Once in place, the beampipes were connected with aluminium expansion joints and leak tested. A removable protection is assembled around the beampipe before working on surrounding detectors.

The 4th section was made of stainless steel and installed inside the calorimeter and muon systems. Chamber supports are a major source of background and reliability of the aluminium bellows requires improvement. Both are being considered for future upgrades.

COMMISSIONING

Bakeout Equipment

The bake-out control system consists of PID Regulation, complex temperature cycles, interlocks, error management, remote control, alert and diagnostic tools.

There are several hundred heaters per LHC experimental area. In order to save space and material, the number of sensors, cables and connectors has been reduced; as a result several heaters are regulated on the same channel (e.g. ATLAS with 136 regulated channels for more than 400 heaters).

The main risk with this kind of regulation is failure of the heater at the location of the sensor. Several control tools have been developed to address this risk, for example: Management of set vs. measured temperature (i.e., if the measured temperature drops, the program stops the corresponding channel and sends an alert message); limitation of the maximum power based on laboratory tests; duplicate sensors in critical areas such as beryllium chambers; independent thermal interlocks from sensors in the detectors.

During this first bakeout, it was not possible to monitor the real power supply but only the percentage of the maximum power (by monitoring the power relay command). In order to have a more reliable system this percentage monitoring will be replaced by an ammeter, allowing calculation of the instantaneous power and hence give faster response to an unexpected event.

Due to the required high transparency to particles and the need of detectors to be as close as possible to the beam, the bake-out equipment was designed to be removable almost everywhere. In some cases, where it was impossible to displace detectors or to access the beam pipes, permanent bake-out equipment was installed. In particular in ATLAS, for which highly transparent bakeout equipment was designed [2], and on the ALICE absorber chambers. General design parameters of bakeout equipment were set to reach up to 350°C, with an insulation specified to 80°C in free air convection. The equipment is a ‘jacket’, a heating tape with insulation or an oven, depending on the different shape of the chambers and their accessibility.

Commissioning

The LHC experimental vacuum chambers are almost entirely coated with TiZrV Non-Evaporable Getter (NEG) [4]. Upon activation by bakeout of the sector, a very low residual gas pressure is achieved, fulfilling requirements on beam lifetime and beam-gas background in the experiments.

Bake-out is required - as everywhere else in the LHC room temperature sectors – not only to activate the NEG, but to lower the outgassing rate of non-coated sections. In order to optimise NEG performance and prolong the NEG lifetime, the bake-out cycle comprises two phases: bake-out of non-NEG surfaces (140°<T<350°C for ~ 24h) and NEG activation (T>180°C for 24h). The maximum temperature per element and ramp rates were limited by mechanical integrity of chambers and risk of damage to seals by differential thermal expansion. In most cases 50°C/h was applied, while for the massive copper absorber blocks (TAS) in ATLAS and CMS, the rate was limited to 30°C/h. The VELO vacuum vessel in LHCb was a special case since the bake-out could not be optimised for UHV performance: the maximum bake-out temperature was limited by the detector to 150°C (at 30°C/h) for stainless steel and aluminium components, with few m^2 surface area.

Full bake-out cycles were performed between 2007 and 2008 on the four experiments. The ultimate pressures reached in the sectors between the TAS blocks in ATLAS and CMS, in the ALICE chamber and in the conical section of the LHCb chamber were in the order of 2.10^{-11} mbar with ion pumps on. The gas composition was dominated by hydrogen with some methane (not pumped by the NEG) and hardly any other gas species. In the TAS regions the pressure was about one order of magnitude higher. In the case of the LHCb VELO, the ultimate pressure after several days bake-out was limited to 10^{-9} mbar, and dominated by water.

Injection of Ultra-Pure Gas

The experimental chambers and supports are mass-optimised to maximise transparency to particles and hence fragile, particularly when under vacuum. They must therefore be vented to atmospheric pressure after bakeout to allow removal of jackets and closure of the detector.

In order to avoid losing the effect of the bakeout, the venting is made with ultra-pure neon (with a few ppb impurity content). This preserves the NEG characteristics, since it is not pumped by NEG, whilst not interfering with leak detection. A system called the ‘Gas Injection System’ [5] was designed for the 4 experiments to inject purified neon into the chambers and pump it out without contamination. This UHV system, which is radiation hard and permanently installed into the experimental caverns, includes a SAES filter able to purify gas at high pressure and is able to fill the sector to slightly above atmospheric pressure in about 2 hours. In the LHCb experiment, the injection speed is limited by the maximum pressure difference across the VELO RF foil, and the total fill time goes up to between 8 and 12 h. The gas injection system performance was validated on a mock-up system 20 m long, with NEG coating and equipment such as gauges and ion pumps as used in the room temperature sectors of the LHC accelerators.

CONCLUSIONS

The commissioning of the experimental vacuum systems was completed in September 2008 – The successful end of the 14-year project. Qualification of components and testing of assemblies on the surface meant few major problems were encountered during installation. Organisation as a common project led to significant cost savings, flexibility with staffing and good feedback on quality from one installation to another.

A number of upgrades are planned to improve the physics performance, minimise activation at LHC design luminosity and reduce the risk of damage during future shutdowns.

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