CHAPTER 19

INTERFACE WITH AND REQUIREMENTS FROM THE EXPERIMENTS

19.1 INTRODUCTION

In order to understand the requirements of the LHC experiments it is helpful to recall the physics which the LHC is expected to reveal and to note that protons are composite particles which means that the parton-parton centre of mass energy covers a wide range and therefore high energy hadron colliders access a much wider range of physics than for example electron-positron colliders. The extremely high design luminosity of the LHC (10^{34} cm^{-2}s^{-1}) results in some 10^{16} minimum bias events in a full year, but even with this enormous amount of raw data much of the new physics will be 'discovered' with a few hundred events. The LHC experimental challenge [1] is to find rare events at levels of 1 in 10^{13} or more.

The ATLAS and CMS collaborations are constructing general-purpose proton-proton detectors, which are designed to exploit the full discovery potential of the LHC [2,3]. Their detectors will be operational at the start-up of the LHC and will be able to investigate the physics accessible during the initial lower luminosity running as well as handling the highest luminosity that will be available later from the design machine.

The initial LHC physics programme also includes a general heavy-ion detector ALICE [4], designed to study the physics of strongly interacting matter in nucleus-nucleus collisions at the LHC. ALICE, as well as ATLAS and CMS, will be able to study the products from colliding beams of heavy nuclei such as lead. Collisions between these nuclei will produce 'little bangs' at an equivalent temperature around 100,000 times that at the centre of the Sun and a density up to 20 times that of normal matter. Under these extreme conditions, which mimic those in the period less than 1 s. after the 'Big-Bang', the constituent protons, neutrons and gluons are expected to 'melt' to form a Quark-Gluon Plasma (QGP).

The initial programme also includes the LHCb spectrometer [5] that is dedicated to the study of B-physics and TOTEM [6,7] with detectors designed to measure the total proton-proton cross-section at LHC energies as well as to study elastic scattering and diffractive physics.

These very large and complex experiments are already being installed at the four points around the circumference of the LHC, where the beams can be brought into collision, (IR1, IR2, IR5 and IR8) as shown in Fig. 19.1.

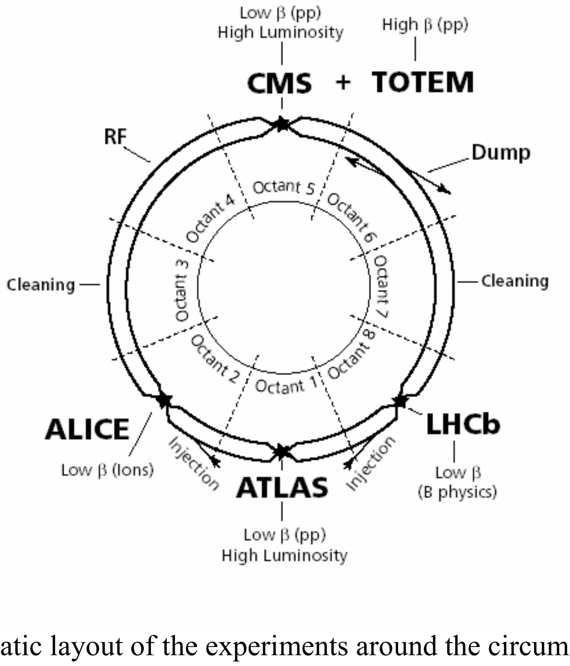


Figure 19.1: Schematic layout of the experiments around the circumference of the LHC.

19.2 REQUIREMENTS OF EXPERIMENTS

The experiments indicated in Fig. 19.1 each have particularities which allow them to focus on different aspects of LHC physics and as a result require different conditions to allow them to fully exploit the potential of the LHC.

19.2.1 The High Luminosity Experiments – ATLAS and CMS

The primary aim of the ATLAS and CMS experiments is to discover the Higgs boson and to search for other new particles predicted in theories beyond the Standard Model such as Supersymmetry. In the framework of the Standard Model, particles acquire mass through their interaction with the Higgs field. This implies the existence of a new particle – the Higgs boson H^0. In extensions to the Standard Model such as the Minimal Supersymmetric Standard Model (MSSM), there are 5 Higgs bosons – h^0, H^0, A^0 and $H^{\pm}$. ATLAS and CMS have been optimised to discover the Higgs boson(s) in the complete expected mass range. Supersymmetry also predicts that for every known particle there is a supersymmetric partner (sparticle) equal in charge but differing in spin. Production of sparticles will reveal itself through distinct kinematical signatures even at relatively low operating luminosities of the LHC machine.

The ATLAS detector is centred on a magnet configuration based on a 2 T inner superconducting solenoid around the inner tracking detector cavity and large superconducting air-core toroids outside the calorimetry. CMS employs a different approach to its detector layout, characterised by a single large 4 T superconducting solenoid magnet. The inner tracking detector and calorimeters are placed within the magnet bore. The iron of the return yoke houses the four layers of muon chambers, resulting in the overall CMS detector design being very compact.

Luminosity and Backgrounds

The design luminosity of 10^{34} cm^{-2} s^{-1} during one effective year of running (10^7 seconds) corresponds to an integrated luminosity of 100 fb^{-1}, which should yield of the order of 1000 Higgs events in each of the ATLAS and CMS experiments. ATLAS and CMS have to be able to identify these events among the total of 10^{16} minimum bias events. Between these two extremes there is a wealth of physics, some of which will be within reach of lower luminosities, but even W and Z production is only at the level of 1 event in 10^6. Therefore, ATLAS and CMS require high average luminosities and very reliable operation so that a sufficient number of rare events are recorded to establish a discovery. The high luminosities should be coupled with low backgrounds coming from both the high flux of secondary particles from the IP and stray particles from the LHC machine tunnel.

The schedule of the first year of LHC operation is not yet defined but an integrated luminosity of ~10 fb^{-1} would be a reasonable target. It is expected that this would yield around 100 Higgs events which would be sufficient to claim a Higgs discovery. Production of sparticles will reveal itself through distinct kinematical spectra even at the relatively low operating luminosities of the LHC machine expected in early 2007.

19.2.2 LHCb Requirements for B-physics

The LHC will be a very copious source of B mesons due to its high luminosity and the high $b\bar{b}$ cross section ($\sigma(b\bar{b}) \sim 500$ μb for $\sqrt{s} = 14$ TeV). The LHCb detector [5] has been designed to specifically exploit the large number of b-hadrons produced in order to make precision studies of CP asymmetries and rare decays in the B-meson systems. The experiment plans to operate with an average luminosity between 1×10^{32} cm^{-2} s^{-1} and 5×10^{32} cm^{-2}s^{-1}. The nominal luminosity of 2×10^{32} cm^{-2}s^{-1} corresponds to a production of 10^{12} $b\bar{b}$ events in one year of 10^7 s of data taking. Running at this luminosity has several advantages: the radiation damage will be reduced, the events will be dominated by single pp interactions that are relatively easy to analyse and the detector occupancy will remain low. In addition, this luminosity will allow the experiment to collect data for many years under constant conditions, since it can be obtained at a very early stage in the commissioning of the LHC and can be kept at its nominal value while the luminosities at the other interaction points are being progressively increased to their design values. This will be possible by tuning the low-β insertion with $1 \text{ m} < \beta^* < 50 \text{ m}$.

The LHCb detector is a single-arm spectrometer with a forward angular coverage from approximately 10 to 300 (250) mrad in the bending (non-bending) plane. The choice of the detector geometry is motivated by the fact that at high energies both the b-hadrons and the $\overline{\mathrm{b}}$-hadrons are predominantly produced in the same forward cone, a feature exploited in the flavour tag. The LHCb spectrometer is placed at IP8 in the existing hall that was hosting the DELPHI detector. A modification of the LHC optics, displacing the interaction point by 15 RF wavelengths (which corresponds to 3/2 bunch spacing or 11.25 m) from the centre in the direction of IP7, allows maximum use to be made of the existing cavern by freeing 19.7 m for the LHCb detector components, without the need for substantial civil engineering work. To maintain the symmetry of the beam optics around IP8, approximately 160 m of machine elements on both sides must be displaced. As a result it must be noted that this solution implies that only bunches separated by 25 ns and 75 ns will naturally produce collisions in the LHCb detector.

The LHCb spectrometer dipole [8] is a warm magnet with a high field integral of 4 Tm oriented vertically. The polarity of the field will be changed every run to reduce systematic errors in the CP-violation measurements that could result from a left-right asymmetry of the detector. The dipole magnet is expected to remain at its nominal field and polarity throughout an LHC physics run. It will give the circulating beams a horizontal angular kick, which must be compensated by adding three compensation magnets to the LHC lattice (Chap. 3.2.9). All magnets (spectrometer and compensators) will be ramped up together with the rest of the machine and in step with the beam energy. At injection the currents will be larger than zero.

The LHCb detector can reconstruct a B-decay vertex with very good resolution and provide excellent particle identification for charged particles. Excellent vertex resolution is essential for studying the rapidly oscillating B-mesons and in particular their CP asymmetries. This implies that the extrapolation distance between the first measured point on a track and the primary vertex needs to be reduced to the minimum possible. This is achieved by placing the LHCb Vertex Locator [9] as close as possible to the beam. In practice, this is limited by the aperture required by the LHC machine. During physics running conditions, the minimum distance between the beam and the Vertex Locator is expected to be ~ 5 mm and will be limited by the beam size and safety considerations. During injection, the aperture required by the LHC machine increases and the Vertex Locator needs to be retracted by 3 cm (Sec. 19.3.2).

19.2.3 Heavy-ion Interactions for ALICE, ATLAS and CMS

The ALICE collaboration has designed a dedicated heavy-ion detector to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies [4]. It will study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected. The existence of such a phase and its properties are a key issue in QCD for the understanding of confinement and of chiral-symmetry restoration.

The ALICE central detector is embedded in a large magnet (the magnet of the LEP L3 experiment) with a weak solenoidal field that will be on during the whole LHC cycle. The ALICE forward muon arm [10], designed to measure the complete spectrum of heavy quark vector mesons via their muonic decay in pp and heavy-ion collisions, is placed outside the L3 magnet. It will consist of a large dipole magnet with a 3 Tm field integral in the horizontal direction that will give the circulating beams a vertical angular kick, that, as in the LHCb case, must be compensated by adding three compensation magnets to the LHC lattice (Chap. 3.2.5). The polarity of the dipole magnet will be changed on a regular basis in order to check systematic effects that could affect the event reconstruction. All magnets (spectrometer and compensators) will be ramped up together with the rest of the machine and in step with the beam energy. At injection the currents will be larger than zero.

The ALICE detector has two sets of zero-degree calorimeters (ZDC) located symmetrically on both sides of IR2 far downstream in the machine tunnel. The ZDCs will provide fast information about the centrality of the collisions and they will be used as a luminosity monitor measuring the rate of mutual electromagnetic dissociation in the neutron channel [11]. The ZDCs will be placed at 116 m from the IP in the IR2 long straight section, between the dipole magnets D1 and D2, where the common beam vacuum pipe in the experimental insertion and inner triplet region is separated into two beam vacuum pipes before entering the D2 magnet. When LHC is operating with heavy ions, the D1 magnet will deflect all lighter ions produced in the interaction region (fragments) and separate them from the ion beam. Neutral particles will follow the bisector of the two ion beams. The best positions of the ZDCs are therefore as close as possible to the entrance of the D2 magnet, where the neutral detector module can be installed in between the two beam vacuum pipes and the positive detector modules can be installed close to the outside of the beam vacuum pipes. Therefore the beam pipe design in that region has to accommodate the ZDCs and minimise the material in front of them (Sec. 19.3.2).

Moreover, both ATLAS and CMS have shown an interest in heavy-ion physics. Their heavy-ion physics programme can be fulfilled with their baseline detector layout. However, the addition of ZDCs is presently under study in both ATLAS and CMS. The LHC is able to produce heavy-ion collisions in the three interaction regions at the same time. However, the two additional interaction regions will imply a reduction of the beam lifetime [12, 13].

A list of the ALICE luminosity and beam requirements can be found in the following and in reference [13].

Lead-Ion interactions

Collisions of Pb-Pb ions will provide the highest energy density and the first physics pilot run will already provide a wealth of information on global event properties and large cross section observables, particularly in the ALICE detector. For the study of interactions with low cross sections some further 1-2 years of Pb-Pb runs at the highest possible luminosity should provide sufficient statistics. For this physics it is expected that both ATLAS and CMS will also participate.

The luminosity for Pb-Pb collisions has limitations coming from both the detectors and the accelerator. For the ALICE detector, two different limits are coming from the main tracking device, the Time Projection Chamber (TPC) and the Forward Muon Spectrometer. The TPC limits the maximum useful luminosity to 10^{27} $cm^{-2}s^{-1}$ because of event pile-up during the 90 μs drift time. However, it is conceivable that it can be operated at higher luminosities, in particular if the multiplicity turns out to be in the lower part of the expected range. The luminosity limitation of the muon spectrometer comes from the maximum acceptable illumination of the trigger chambers, the Resistive Plate Chambers (RPCs) of 50-100 Hz cm^{-2}. This limit corresponds to a maximum usable luminosity of 2-4 × 10^{28} cm^{-2} s^{-1}. A more stringent limitation on the luminosity is coming from the machine. In the case of electromagnetic dissociation with subsequent electron-capture, the single-charge-changed ion will be lost from the circulating beam in the dispersion suppressors of the machine. In order not to exceed the quench limit of the magnets the luminosity for Pb-Pb will have to be limited to about 1×10^{27} cm^{-2} s^{-1}.

The predicted cross-sections for these electromagnetic interactions and the additional experiments participating in the heavy-ion programme are expected to seriously affect the luminosity lifetime, limiting it to only three hours [13] in the case of three experiments. It is then highly desirable to find new methods to maximise the integrated luminosity without exceeding the quench limit in the magnets. The method proposed in the reference [14] called β-squeeze, will not only maximise the integrated luminosity, but will also produce a constant luminosity during the runs that will make it easier to handle the space-charge effects in the ALICE TPC.

Additional Pb-Pb runs at lower energy would allow ALICE to measure an energy excitation function and to connect to results from RHIC. Finally, some rare processes limited by statistics in the early runs could require additional high-energy Pb-Pb running.

Lighter ions and hybrid interactions

Like the SPS and RHIC programmes, a comprehensive heavy-ion programme will be possible at the LHC, not only colliding the largest available nuclei at the highest possible energy, but also by carrying out a systematic study of lighter ions and hybrid collisions.. Such a programme will take several years and will include colliding beams of different ion species as well as ions against protons. The separated RF systems of the two LHC beams make hybrid collisions possible although an upgraded RF control system will be needed.

For a later phase, a number of ion running options will be possible, the relative importance of which will depend on the initial results. For a direct comparison of the Pb-Pb and pp data, a dedicated pp run at the Pb-Pb nucleon-nucleon centre of mass energy, $\sqrt{s_{NN}} = 5.5\mathrm{TeV}$, is also probably advisable.

As for the Pb-Pb collisions, the useable luminosities with lighter ions and hybrid collisions have limitations coming from the LHC injectors and ion sources as well as quench limits in the LHC itself and also in detectors such as the ALICE TPC or the trigger chambers of the muon spectrometer. A list of the maximum acceptable luminosities for the different kinds of collisions can be found in reference [13].

19.2.4 Proton Running for ALICE

The pp collisions are an integral part of the heavy-ion physics programme both because of their intrinsic interest and because they are needed to obtain reference data. Moreover, pp runs will provide low multiplicity, thus simpler, data to commission and calibrate the components of the ALICE detector. Hence, they are needed during the whole period of ALICE operation, both initially as well as in later years for shorter periods prior to every heavy ion run.

The pp runs for ALICE will be in parallel with those for the other experiments, but at much reduced luminosities in IR2 in order to keep the pile-up in the TPC and Silicon Drift Detectors at acceptable levels. The luminosity during the pp runs has to be limited to ~ 3 × 10^{30} $cm^{-2}s^{-1}$, corresponding to an interaction rate of ~ 200 kHz. At this rate, ALICE records on average, 20 overlapping events, i.e. 95 % of the data volume corresponds to unusable partial events. This has obvious negative consequences both in terms of data storage and offline computing requirements as well as reducing the physics performance of the central barrel detectors because of increased occupancy. The optimal detector operation and physics performance with the TPC, i.e. no pile-up, is at ~ 10^{29} $cm^{-2}s^{-1}$. ALICE will therefore request pp collisions in IR2 with both the maximum acceptable rate (3 × 10^{30} $cm^{-2}s^{-1}$) in order to maximise integrated luminosity for rare processes as well as with lower luminosity (10^{29} $cm^{-2}s^{-1}$) to collect statistics for large cross section observables and global event properties at optimum DAQ bandwidth and detector performance.

Depending on the beam intensity and emittance, the luminosity reduction can be obtained either with displaced beams or with larger β^* values which, however, are limited by the available aperture in the inner triplet. For nominal beam conditions both methods need to be used. With a β^* of around 10 m, a parallel beam separation of 5 σ is required with otherwise nominal beam parameters. However, during the LHC running-in phase, beam intensities and luminosities are lower than their nominal ones and the reduction in luminosity may be reached by simply increasing the β^* values. If feasible, this is highly desirable since the most stable running conditions are expected without beam displacements.

19.2.5 Dedicated Operation for TOTEM

TOTEM is an experiment dedicated to the measurement of total cross section, elastic scattering and diffractive processes at the LHC [6, 7]. The total cross section will be measured using the luminosity independent method that is based on the simultaneous detection of elastic scattering at low momentum transfer and of inelastic interactions. This method also provides an absolute calibration of the machine luminosity. The measurement of the total cross section is the first objective of the TOTEM collaboration at the earliest stage of operation of the LHC. The experimental apparatus consists of forward inelastic detectors placed in the experimental insertion of IR5 and of three sets of telescopes, called Roman Pots, placed symmetrically on both sides of the IR far downstream in the machine tunnel. The inelastic detectors will measure the overall rate of inelastic reactions while the Roman Pots will detect protons scattered at very small angles in elastic or quasi-elastic reactions.

The Roman Pots are special devices mounted on the vacuum chamber of the accelerator. In its retracted position the Roman Pot leaves the full aperture of the vacuum chamber free for the beam as required at injection. Once the final energy is attained and the circulating beams are stable, the Roman Pot is moved toward the machine axis by compressing the bellows until the inner edge of the detectors are at a distance of the order of one millimetre, or 10 σ from the beam. Particles scattered at very small angles at the IP can therefore be detected. The detectors inside the pots will be silicon detectors which may be operated at cryogenic temperatures. The three sets of telescopes will be placed in IR5 at each side of IP5 in the warm sections between TAN-D2, Q4-Q5 and Q5-Q6. The beam pipe design in this region will easily accommodate the three sets of Roman Pots (Sec. 19.3.2).

Since the cross sections involved are large, the measurements can be performed at the relatively low luminosity of 10^{28} $cm^{-2}s^{-1}$. This is achievable both by reducing the nominal LHC number of bunches to 43 (Chap. 20.6) and the nominal number of protons per bunch to ~ 0.4 × 10^{11}. These two reductions have the very desirable features of allowing a zero crossing angle beam operation and of decreasing the risk both for the Roman Pots and the LHC in case of beam accident.

The measurement of the total cross section can be performed only with special optics at high β^* which allows the detection of particles emitted at very small angles. In fact with optics at high β^* the beam divergence at the IP becomes very small while the beam size is relatively large. As already mentioned the corresponding loss of luminosity is not a problem because of the large cross sections involved in the measurements. The best configuration for the elastic scattering corresponds to the optics with parallel-to-point focusing from the IP to the Roman Pot location. In this case the displacement of the particle at the detector placed in the Roman Pot is proportional to the scattering angle θ and does not depend on the actual transverse position of the collision point. This has the advantage that measuring the particle position at the Roman Pots allows the scattering angle to be reconstructed in a way that is unambiguous and straightforward. A special optics with β*= 1540 m has been designed for the dedicated TOTEM runs (Chap. 4.6). This optics has the advantage that the parallel-to-point focusing is achieved in both the vertical and horizontal plane at the same location.

The study of elastic scattering at large momentum transfer (above $|t| \approx 1\mathrm{GeV}^2$) where the cross section is rather small cannot be achieved with β*= 1540 m because of the large reduction in the counting rate due to low luminosity and for acceptance reasons. For this study the optics at β*=18 m, which is used when injecting beam into the LHC, is well suited. Given the small cross section, no reduction in the nominal number of bunches is foreseen for this measurement implying that a non-zero crossing angle will be required to avoid unwanted collisions in the part where the two beams share a common beam pipe.

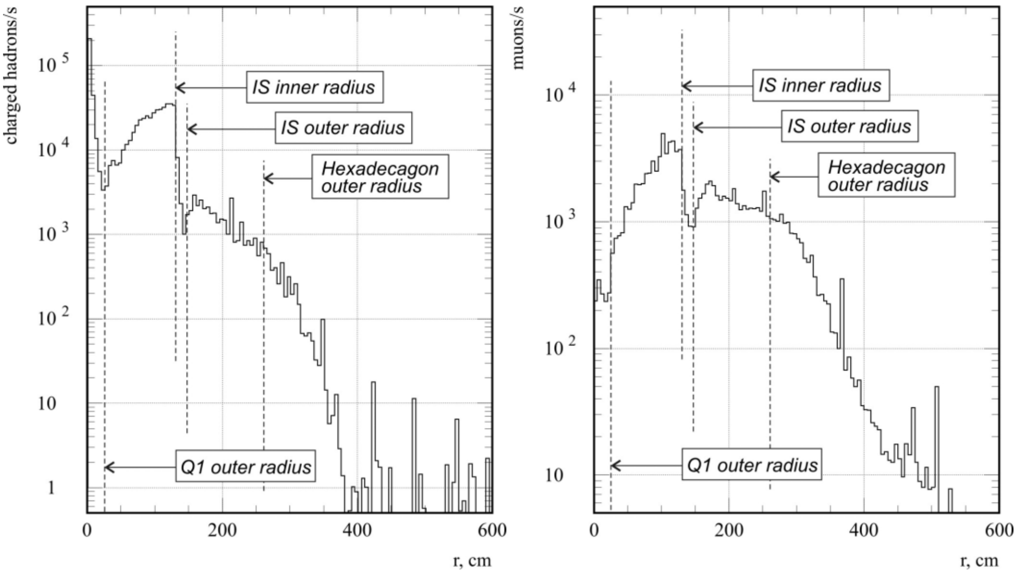
The detection of the particles emitted at very small angles will require moving the Roman Pots as close as possible to the beam. The reduction and the control of the beam halo is therefore of crucial importance, as well as, the reduction of beam-gas interactions. In addition the minimum distance of approach is proportional to the size of the beam at the position of the Roman Pots themselves. Operation with a transverse emittance reduced by approximately a factor of three with respect to the nominal one will then have the two desirable consequences of reducing both the beam size and the beam angular spread. The beam stability at the Roman Pot location has to be of the order of a few microns.

19.2.6 Machine Induced Backgrounds

Stray particle background

Each beam in a hadron collider is accompanied by stray particles outside the beam pipe, which are likely to cause background in detectors in the experimental areas. Simulations for the LHC have been made in order to estimate the importance of this effect and supply to the experiments the particle flux and characteristics, such as energy distribution and type of particles, which they can expect to enter their experimental cavern [15, 16]. All likely sources of stray particles have been included in these simulations, notably, beam-gas interactions at all points around the circumference of the machine, particles originating from the beam cleaning insertions (collimator inefficiency) and secondary particles from one collision point, which if they are transported by the machine structure could in principle create background in an adjacent experiment. The particles in question come mainly from secondary and higher order scattering as for example from the beam pipe in the inner triplet quadrupoles where the exceptionally high β function means that the aperture is limited to about 10 beam sigma and any halo particles outside that will interact in the vacuum chamber wall and produce showers of lower momentum particles. Similarly points of high dispersion will catch off-momentum particles from whatever source and the beam pipes in such regions can become a secondary source of background particles accompanying the beam. It is important to note that the high energy component of these background particles retain a close time correlation with the bunch structure.

It turns out that for reasonable estimates of the residual gas pressure in the LHC, even in the presence of nominal intensity beams, the main source of the machine background described above is scattering of beam particles by residual gas molecules in the proximity of the experiment, the dispersion suppressor and long straight section. The latest residual pressure estimates [17, 18] suggest that the highest residual pressures will exist in cold sections where there is synchrotron radiation and thus these regions such as the D2/Q4 cryostat will be a primary source of background. This is particularly true for ATLAS and CMS as these high luminosity experiments require a very heavy forward shielding around the TAS absorbers and Q1 quadrupoles to avoid backscattering of forward particles from their own collision region. This heavy forward shielding will very effectively close the machine tunnel as seen by the detectors of the experiment and greatly reduce the importance of all stray particles except muons. Sources such as the residual gas in the D2 vacuum chamber 150 m upstream of this shielding are the main sources of these muons. Fig. 19.2 [16] shows the flux of particles entering the ATLAS cavern as a function of radial distance from the beam. All particles inside a radius of 130 cm are inside the planned forward shielding of ATLAS and many of the hadrons in this region will be absorbed.

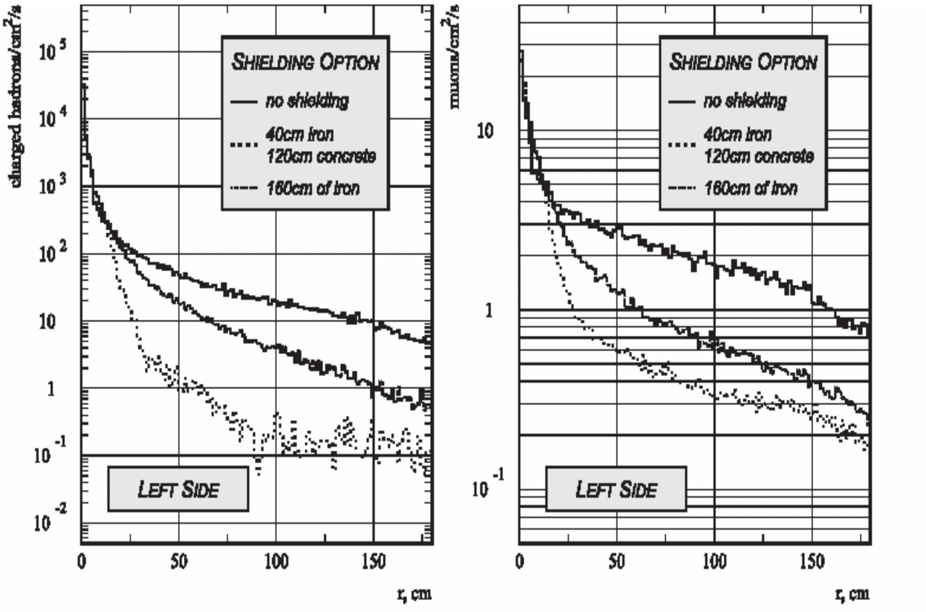


a) b)

Figure 19.2: Distributions of stray particles cm^{-2} s^{-1} entering UX15, the ATLAS experimental cavern, as a function of radial distance r (cm) from the beam, for a) charged hadrons and b) muons. The radial dimensions of the Q1 quadrupoles and various parts of the forward shielding are indicated by the dotted lines.

Tunnel shielding plugs

The low luminosity experiments, ALICE and LHCb do not need TAS absorbers to protect the inner triplet quadrupoles from secondaries and therefore have no need for heavy forward shielding. Both these experiments will have to rely on shielding plugs in the machine tunnel just before the entrance to their experimental cavern. It is impractical to install more than about two metres of iron and these walls will be far from complete. In most cases they have to be built around the inner triplet cryostat and may also have a cryoline passing through them. In practice, the latter is not of any great importance, nor are the services around the tunnel wall, because the important leakage all occurs close to the beam. ATLAS and CMS also benefit from the small aperture of the TAS absorber 34 mm diameter and as a result the background in ALICE and LHCb where there is no such aperture restriction is substantially larger. At Point 2 and Point 8 in addition to the muon background seen in ATLAS and CMS there is a considerable flux of hadrons entering the experimental caverns depending upon the effectiveness of this shielding wall. The levels are around 10^6 hadrons per second and 10^5 muons per second in the absence of shielding. A preliminary study of shielding walls suggests that the hadrons can be reduced by a factor of between three and ten [19]. Example distributions of particles entering UX85 and the effect of different shielding configurations from reference [19] are shown in Fig. 19.3.



a) b)

Figure 19.3: Example distributions of stray particles entering UX 85, a) charged particles b) muons, as a function of the radial distance r (cm) from the beam with different configurations of iron and concrete shielding in the upstream tunnels.

Background from the TAS absorber

As mentioned above the high luminosity interaction regions of the LHC have a TAS absorber at approximately 19 m from the IP. This 1.8m long block of copper has the smallest beam aperture consistent with the beam size at injection in order to intercept as many secondary particles from the IP as possible. All of these particles would otherwise enter the cold mass of the inner triplet and energy deposition directly into the SC coils or total power into the cold mass would cause the superconducting quadrupoles to quench. At design luminosity some 200 W is deposited in each TAS absorber and almost all of this energy would otherwise reach the inner triplet. The particles that strike the TAS are mostly absorbed, but a few are back scattered and the TAS becomes a major source of background in the muon chambers of ATLAS and CMS [20]. By surrounding the TAS with an equivalent of up to two metres of iron, all but low energy neutrons can be absorbed. The neutron doses have been evaluated for different shielding configurations and the final layouts chosen are a compromise between performance, practicality and cost. The two metres of iron equivalent is needed around the TAS to reduce the background in the large area ATLAS muon chambers to acceptable levels [21]. A somewhat lighter shielding is required by CMS to protect their muon chambers installed in the iron return yoke of their solenoid magnet [22]. Both ATLAS and CMS expect to have to incorporate neutron absorbing layers such as polyethylene or Boron-loaded concrete in the final shielding needed with luminosities above 10^{34} $cm^{-2}s^{-1}$.

Below a luminosity of 10^{33} $cm^{-2}s^{-1}$, TAS absorbers are unnecessary and none need to be installed for either ALICE or LHCb. Both these experiments will have a very much lower background from backscattered particles, as described above, not only because of the lower interaction rate (luminosity), but also because the Q1 quadrupoles are further from the detectors of the experiments and have a larger beam aperture than the TAS absorbers.

19.2.7 Requirements of the LHC Experiments in the First Year of LHC Operation

Physics Impact of Lower Energy Operation at Start-up

For safer and more reliable operation at start-up, the LHC machine may run at lower than the nominal 14 TeV energy by about 10%. It is anticipated that this will not last for more than a few months [23].

Running at lower energy has repercussions on the physics discovery potential. The cross-section times the branching ratio of the Higgs boson is low and the discovery is essentially rate limited. Therefore, in this initial period, the discovery of the Higgs boson will most probably be out of reach. However, the

Supersymmetry processes have strong cross-sections and the discovery of 'sparticles' is not rate limited. Some discoveries can still be made with a few weeks of running at luminosities of 10^{33} cm^{-2} s^{-1}. Hence, a lower rate due to lower cross-sections at lower centre-of-mass energies does not much affect the Supersymmetry discovery potential at start-up.

Therefore, the requirement from ATLAS and CMS to start at the design energy is not a strong one, i.e. start-up can take place at a lower energy. Clearly, running at the design 14 TeV energy must start as soon as possible and in order not to have to combine data from too many different energies, the experiments wish to move to the design energy in one step.

It should be noted that the potential for b-physics can be exploited in ATLAS, CMS and LHCb even at the lower centre-of-mass energies. The effect of lower energies for LHCb is expected to be negligible. In the case of TOTEM, data taking at energies lower than the nominal one is welcome, as it will allow the measurement of elastic scattering at lower momentum transfer.

Impact of Event Pile-up

The number of pile-up events per crossing depends on β^* and the product of the number of protons in each interacting bunch. Understanding the performance of the LHC detectors is easier when there are few or no overlapping events since the track density is low thus making track and energy reconstruction much easier. Furthermore, the quality of calibration, alignment and synchronisation can be checked more easily. Consequently, ATLAS and CMS would like to operate in conditions with no more than ~2 overlapping events during the initial physics data taking until the performance of the detectors is properly understood [23].

As mentioned above, the LHCb experiment expects to have their nominal luminosity of 2×10^{32} cm^{-2} s^{-1} available at a very early stage with a minimum β^* of 1 m. As their B-trigger does not allow any pile-up they will ask for β^* to be increased to maintain this low luminosity and their only concern will be that if commissioning with a 75 ns bunch spacing is not replaced rapidly by 25 ns running they will lose integrated luminosity.

Activities in the LHC Experiments during the commissioning of the LHC

As a reminder, the nominal LHC running conditions for the two high luminosity experiments ATLAS and CMS are: 1.15×10^{11} protons / bunch, a β^*=0.55 m, a bunch crossing interval of 25 ns and a luminosity of 10^{34} cm^{-2}s^{-1} This leads to about 20 overlapping events per crossing.

Activities in ATLAS and CMS will follow developments in the LHC machine leading up to the first physics run according to the possible timeline given in reference [23]. Following the completion of the installation and equipment commissioning, the accelerator will be set up for safe operation. The setting-up will start with one low intensity bunch, increasing to multiple bunches and raising the bunch intensity to close to the nominal.

It should be noted that the superconducting magnets of ATLAS and CMS as well as the solenoid magnet of ALICE will be on throughout all normal operation of the LHC, while the warm dipole spectrometer magnets of ALICE and LHCb, which need special compensation for closed orbit correction, will be ramped proportionally to the main LHC dipole field. This will have to be taken into account at an early stage in the commissioning of the machine.

The experiments will carry-out studies of synchronisation, vacuum quality, beam-gas interactions and their rejection, profile of beam-gas interactions and muon halo triggers and finally catalogue detector problems. Collisions of one bunch on one bunch will then follow rising to collisions with 43 on 43 bunches with bunch intensities rising close to the nominal bunch intensity, all done with zero beam crossing angle. Beam squeezing will then commence to get to low β^*. It should be noted that crossings involving bunches with nominal intensities and nominal β^* lead to 20 pile-up events/crossing, which is considered too high by ATLAS and CMS for these initial phases. The experiments will start recording first pp collisions and will continue the synchronisation studies and the cataloguing of detector problems. Subsequently, a beam crossing angle will be introduced and the running configurations that have been explored could include:

(i) 75 ns bunch-spacing, β^*=1.0 m., 0.9×10^{11} protons/bunch, 936 bunches at a luminosity of a few 10^{32} cm^{-2}s^{-1},

(ii) 25 ns bunch-spacing, β^*=0.55 m., 0.4 × 10^{11} protons/bunch, 2808 bunches at a luminosity of a few 10^{32} cm^{-2} s^{-1}.

The latter running configuration would correspond to the scrubbing runs at 25 ns bunch-spacing required to address the issue of the electron cloud.

The experiments ATLAS and CMS will continue studies of synchronisation, setting-up for physics running and recording first physics events. A three-month shutdown period may then be needed to allow the experiments to install sub-detectors that are ready, but were not installed before start-up, e.g. pixel detectors, and solve problems encountered during the initial running period.

The LHC accelerator and experiments would then be ready for the first physics data run. Starting with an accelerator configuration with a 75 ns bunch-spacing, 936 bunches and a luminosity of 10^{32} cm^{-2}, the experiments will continue verifying their detector synchronisation. The bunch intensities will be increased until pile-up leads to greater than 2 pile-up events / crossing and then move to 25 ns bunch spacing, i.e. to 2808 bunches.

Two options have been identified for accumulating subsequently a large data set:

1. If operation with the 25 ns bunch-spacing is satisfactory, the luminosity should be raised to around 10^{33} cm^{-2} s^{-1} and accumulation of physics data should continue.
2. However, if problems are observed with the 25 ns bunch-spacing operation or if the experiments desire higher integrated luminosities (i.e. they have understood detector operation with >> 2 overlapping events / crossing), running at 75 ns bunch-spacing with > 2 pile-up events / crossing can be considered.

The high luminosity experiments, ATLAS and CMS, prefer to carry-out the bulk of the initial physics data-taking at 10^{33} cm^{-2}s^{-1} and 25 ns bunch spacing.

A potential physics run could last for about seven months integrating a luminosity of up to 10 fb^{-1} per experiment in ATLAS and CMS. At the end of a long physics run, or a long winter shutdown period, a Pb-Pb ion run of approximately two weeks is requested by ALICE, at a lower than nominal luminosity, to yield a few days of good data taking. Any such run will also be used by ATLAS and CMS to obtain a first taste of heavy-ion data.

As mentioned above, the LHCb experiment is expects to be able to reach optimum running conditions of one interaction per bunch crossing rather early in the commissioning of the LHC. With a 75 ns bunch separation this occurs at a luminosity below 10^{32} cm^{-2}s^{-1} and the main concern of LHCb will be to gain a factor of three in integrated luminosity by moving as rapidly as possible to a bunch spacing of 25 ns.

The TOTEM running scenario during the first year of the LHC expects data taking with single beams for calibration and background study purposes. Several one day runs with β^* = 1540 m and β^* = 18 m are needed for the total cross section and the elastic scattering at large momentum transfer measurements. In addition, TOTEM plans to take data with β^* = 0.55 m together with CMS to study diffractive events for $L < 10^{33}$ cm^{-2} s^{-1}.

The physics programme of the LHC, even in its first year, is expected to be extremely fruitful and it will be a considerable challenge to assign priorities and make the best possible use of this early running.

19.2.8 The Collision Region

Calculations have been performed to estimate the collision region around the interaction points taking into account the nominal LHC parameters and also the longitudinal spread of a bunch during a coast. It is estimated that 95% of the luminosity is found within a distance of ± 9 cm around the IP. Studies of the ATLAS Inner Detector reconstruction show that in order to preserve the assumed performance of the experiment, at most 5% of the integrated luminosity may be outside the distance ± 11 cm around the IP. As for CMS, global inefficiencies of 0.2% and 3% were estimated for the Inner and Outer Tracker Barrel detectors, indicating a good coverage of the luminous region by the Tracker. Similarly a good match was determined for the barrel and end-cap Pixel detectors and the end-cap Tracker.

Similar values for the collision region are estimated for ion-ion collisions.

Transverse Centring of the Interaction Point

A collision point well-centred in their detectors is required by the experiments. The maximum transverse variation during a coast is expected to be < 20% of the nominal beam width of $\sigma_{x,y}$ = 16 μm, while the maximum transverse variation of the beam collision point between coasts is likely to be < 1 mm. Despite this the LHCb collaboration has designed their VELO detector to accommodate maximum transverse shifts of up to ± 5 mm, so as to include alignment errors.

However, there will also be a need for re-alignment of the experiments to the machine. The new cavern floors are expected to move over time due to the settling of the concrete and due to the hydrology of the geology. Estimations for the ATLAS cavern suggest up to 5.5 mm settling of the floor over the 6 months following installation due to the weight of the ATLAS detector, followed by a 1 mm per year lift of the floor due to the hydrostatic pressure.

Some adjustment of the ATLAS detector is possible, but may need to be extended. CMS includes an adjustment mechanism based on jacks and grease pads that allows lateral and vertical adjustments of ± 50 mm during machine shutdown periods. Alternatively, given the survey link between the machine tunnel and experimental areas, the interaction regions can be aligned to the experiments to within about ± 1 mm.

Satellite Bunches

While transferring the beam from one machine to another (PS -> SPS and SPS -> LHC), two phenomena are to be considered:

(a) the uncaptured beam which is lost at the beginning of acceleration and
(b) the beam captured in unwanted locations giving rise to satellite bunches.

At IP1, IP2, IP5 and at IP8, collisions between satellites may occur every 2.5 ns at the same vertex as nominal bunches and in the worst case may occur 9 times more frequently than normal collisions. At IP8, there is an additional possibility of collisions between satellites and normal bunches at the beginning and end of each 72-bunch train. For TOTEM running, since there is no beam crossing angle, there is the possibility of additional collisions between satellite and normal bunches every 37.5 cm on either side of the IP.

A high-sensitivity longitudinal profile monitor should detect satellites at the 0.001% level within minutes in the LHC. However, satellite bunches in the SPS are likely to create satellites in the LHC but measurements in the SPS are difficult and limited only to the percent level. Detection of satellites in the SPS may be used to prevent injection into the LHC, but this would require new instrumentation that is currently not foreseen. The experiments, however, expressed their satisfaction that a satellite frequency at the percent level is acceptable and thus an upgrade to the SPS instrumentation is not needed.

19.3 INTERFACES WITH THE EXPERIMENTS

19.3.1 Data Exchange

Data exchange, both at the hardware and software levels, has the aim of communicating information on the state of the machine, experiments and technical services as a whole and on their various sub-systems, as well as providing a means to understand the causes of error by acting as a recording and diagnostic tool. These communication links will be required to guide the interaction between the collider and experiments when operation of the LHC commences. Emphasis is placed on observables that can provide a measure of the LHC machine operating conditions for the experiments and that can be used by the experiments to give feedback to the machine operation as well as to protect their detectors against damage from spurious operating conditions of the machine. This section discusses the subset of exchanged information most relevant to the data exchange.

Fig. 19.4 shows the conceptual lay-out of the entities considered for data exchange. The exchange is considered to be low frequency, ~1 kbps and therefore should not be limited by bandwidth and have a latency of < 1s. The commercial protocol to be implemented is currently being defined.

The LHC data from the machine and experiments will have an absolute UTC time stamp, which will be derived from several GPS modules. These modules will be located centrally in the PS Complex, with auxiliary modules at each of the other accelerators and at each pit of the LHC from where a fibre will be connected to the experiments.

It should be noted that in addition to the above information, a concise summary of the machine operation status, as has been the case for the PS, SPS and LEP, will be made available on TV monitors throughout CERN and also accessible via the WWW.

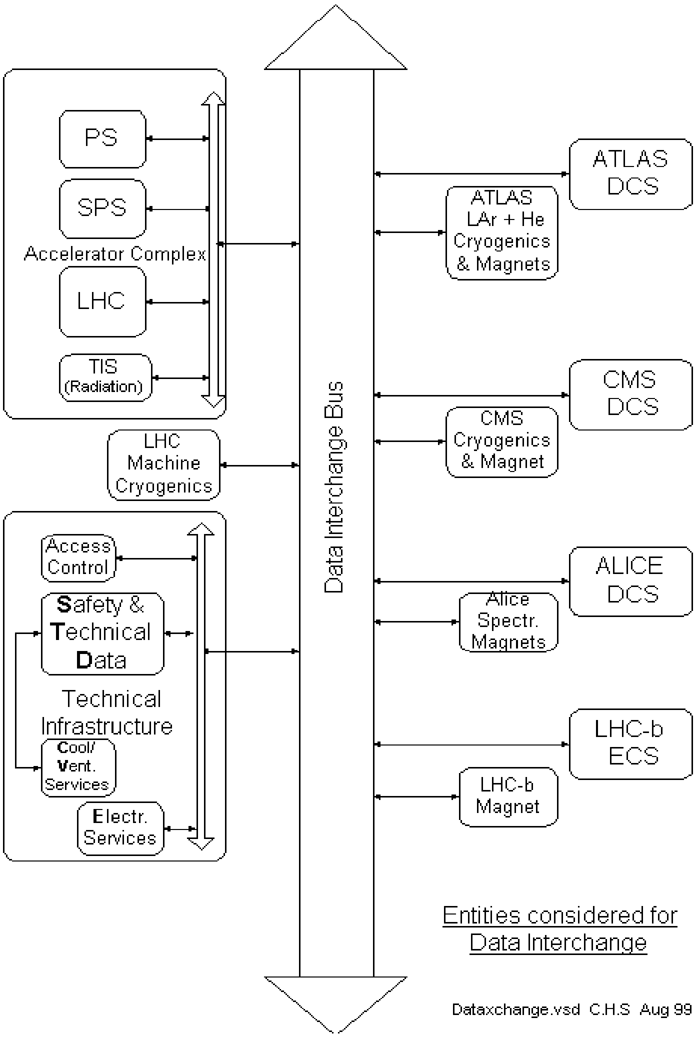


Figure 19.4: Schematic of the exchange of data between the experiments and the LHC

Experiment Measurements of the Collision Parameters

The experiments, ATLAS and CMS, have studied what information might be provided to the LHC machine relating to beam conditions. Each experiment aims to provide at least one estimate of the luminosity, at least one rate measurement sensitive to beam–beam collisions and at least one rate measurement per beam sensitive to beam-related background. Under stable running conditions, each experiment should also be able to provide three-dimensional information on the position and size of the luminous region; this could possibly be supplemented by the average angle of the beams in the horizontal and vertical planes.

The experiments have demonstrated their ability to assess the quality of the collisions based on measuring observables in their detectors. Several trigger rates will be measured continuously by the experiments. For example, the measurement rate of various kinds of clusters and muon candidates above threshold can be integrated over all bunches and can also be measured on a bunch-by-bunch basis. Information from the muon detectors can be used to study the muon halo and the neutron background. Moreover, information from the forward rates and the vertex counting per event in the inner detectors would provide a measurement of the relative luminosity. Finally, a measure of the occupancies in the hadron calorimeter sectors may lead to an estimation of the background imbalance. Transmission of the summary information can be performed at least every minute.

A fast reconstruction of the collision point can also be provided by ATLAS and CMS. A 10 µm transverse position accuracy and a 2 mm longitudinal position and luminous region accuracy can be measured within about 600 s. Such measurements require that the inner detectors, including the pixel detectors, are powered and operational and would only be possible once stable beams are established.

The following table summarises the present ideas. However, it is essential to retain flexibility in the data-exchange system (e.g. in the number and choice of quantities to be exchanged, the production interval and hence the data rate). Note that the numbers given in Tab. 19.1 are for a minimum set of information and that the information ultimately produced might have a larger volume. It is assumed that 4-byte words are used for all quantities.

Table 19.1: Data exchange from experiments to accelerator.

Producer	**Measurement**	**Units**	**Production Volume (Bytes)**	**Production Interval (sec)**	**Data Rate (Bytes/sec)**
ATLAS/CMS	Total luminosity	$cm^{-2}s^{-1}$	4	1	4
ATLAS/CMS	Average rates	Hz	12	1	12
ATLAS/CMS	Luminosity per bunch	$cm^{-2}s^{-1}$	14256	60	238
ATLAS/CMS	Individual bunch rates	Hz	42768	60	713
ATLAS/CMS	Position and size of luminous region (average over all bunches)	cm	24	600	0.04
ATLAS/CMS	Total per experiment				966

Concerning the rates (both average and bunch-by-bunch), the numbers in Tab. 19.1 assume one rate sensitive to beam-beam collisions and one rate per beam sensitive to beam-induced background. Additional rates, e.g. from calorimetric and muon detectors that are sensitive to the radial and phi distributions of beam-related backgrounds, will be developed in collaboration with the machine groups. ATLAS and CMS will endeavour to be flexible in the production and choice of rates to be transmitted as experience with machine operation accumulates.

Data exchange from the accelerator to the experiments

Tab. 19.2 provides an example of data to be distributed from the LHC machine to the experiments, based on measurements taken with the beam instrumentation of the machine.

It is the responsibility of the experiments to measure their own absolute luminosity. Standardised, simple, fast and robust machine luminometers are provided to set up the machine for physics, optimise its performance and make comparisons from run to run. The event rate of these luminometers may be calibrated by comparing with the luminosity from the experiments and by the Van der Meer method, cross-checks will also be possible by calculations using the best available beam parameters. From experience, cross-checks with data from LHC detectors are equally valuable to understand possible differences in the luminosities of LHC IP's. The beam parameters necessary to calculate the luminosity will be transmitted to the experiments (optics parameters, bunch-by-bunch beam emittances and currents).

LHC Timing Signals and Distribution to the Experiments

The LHC RF group is considering three clocks: a stable reference clock at 40.08 MHz delivered from the Faraday Cage at Point 4, which will serve as the reference clock of the LHC machine and which can be used by the experiments to clock their electronics and two clocks which will drive the RF for the two beams. The latter will be locked to the reference clock but will vary since they will be adjusted to follow the bunches in the machine.

Table 19.2: Example data to be distributed by the LHC to experiments

Measurement	**units**	**Production Volume (Bytes)**	**Transmission rate**	**Expected Accuracy**	**Remarks**
Total beam intensity	proton	8	~1 sec	1%	
Individual bunch intensities	proton	28,512	~1 min	5%	
Rms beam sizes	mm	16	~1 sec	15%	For transport to IP will require knowledge of β-function
Rms bunch sizes	mm	44,928	~1 min	15%	
Average bunch length	ps	8	~1 sec	1%	
Total longitudinal distribution	proton/bucket	285,120	~1 min		Will be able to detect ghost bunches at the 0.1% level of nominal
Average HOR & VER positions	µm	32	~1 sec	50µm	From the BPMs at Q1 either side of each IP
Luminosity b-by-b		28,512	~100 sec	1% relative	
Beam Loss	proton/s	80	~1 sec	Few % relative	Average over up to 50 selectable BLMs

The experiments rely on collisions being as close as possible to the nominal IP at the centre of their detectors. The jitter of the reference clock is approximated to be ~10 ps at the origin, while the RF clocks will be less accurate and whose phase could differ from that of the reference clock by up to 300 ps. As the jitter affects the average time of collisions in the experiments with respect to the reference clock and the average collision point itself, the latter jitter implies a significant displacement from the nominal IP, since, for example, the CMS calorimeter digitisation requires a timing signal with <50 ps jitter.

The Experiment Beam Position Monitors (BPTX)

A total of 1166 Beam Position Monitors (BPMs) are needed for the LHC and its transfer lines. This includes one experiment BPM (BPTX) timing pick-up per incoming beam in IR 1, 2, 5 and 8. The BPTXs will be located about 150 m from the IP in front of the D2 magnets and will be used exclusively by the experiments. Button electrodes will be used as the pick-up technology.

Two applications of the BPTX timing signals have been identified by the experiments. They may be used to monitor the phase of the clock of the two beams locally at the IRs, thus determining whether the Timing and Trigger Control (TTC) system is synchronised with the actual arrival of the bunch. Moreover, the monitors can be used to identify the location of the gaps in the LHC bunch train, which is considered to be particularly useful during the setting up stage of the experiments.

Beam Abort Signals

Several mechanisms have been identified as leading potentially to beam losses. For example, a magnet quench, a trip of power converters or the RF system, or an unsynchronised beam dump may lead to damage to both machine and experiment elements.

One of the fastest beam loss mechanisms is due to a power converter trip in the D1 warm magnets around the IRs. The time constant, i.e. the time interval from the equipment failure to when the beam loss will occur, is about 5 turns. A fast beam abort signal from the experiments could act on this time scale.

In addition, an accident with the beam dump at the Tevatron has highlighted the danger of an unsynchronised beam dump. In such a scenario, the dump kicker does not hit the dump gap, either because of a loss of timing or control or, as in the case at the Tevatron, a problem with the RF de-bunched the beam, thus eliminating the dump gap. Beam dump malfunctions affect mainly CMS, as it is adjacent to the dump insertion IR6. The accident duration is estimated to be 260 ns, during which up to 10^{12} protons can be lost in IR5 (CMS). The experiment beam abort system will not be able to handle the fast speed of such an accident scenario. The installation of an absorber in IR6 will protect the machine (and CMS).

A dedicated machine protection system is being developed for the machine and the experiments are also studying methods to send an abort signal to the machine on observation of spurious behaviour in their monitors. Diamond and silicon detectors are being evaluated as dedicated detectors in the experimental areas to be used in the beam abort mechanism. They will operate independently from the other experiment sub-detectors and would give a response time of the order of two beam orbits.

It has been agreed that alongside several machine sub-systems, an input from the experiments to the machine Beam Interlock Controller is included in the design of the machine protection system. This would allow a signal from the experiments to give the BEAM PERMIT and a BEAM ABORT if the PERMIT is absent.

19.3.2 Experimental vacuum systems

Introduction

The experimental vacuum system is the part of the LHC main ring that passes through the four experimental interaction points. This is perhaps the most sensitive sector of the LHC vacuum system as it must conform to two markedly different sets of requirements. It must conform to the standard LHC vacuum system specification for dynamic beam vacuum and impedance (Chap. 12). However, it must also cause the minimum of interference with the detection performance of the experiments, which in general means that the material introduced into the path of the secondary particles from the IP must be minimised.

This second requirement has led to the development of a number of specific technologies for the experimental vacuum systems, in particular for the choice of materials and geometries for the vacuum chambers, the optimisation of the mass and size of both vacuum chambers and vacuum equipment.

The designs for the experimental vacuum systems have been the subject of a number of reviews. These have concluded in interface specifications agreed, or under agreement with the experiments [24, 25, 26, 27]. However, in some limited areas the final designs are still under discussion.

The ‘very forward’ regions between 18 and 22 m from the IP, where the vacuum systems inside the experiments interface with the standard machine long straight sections, also have a number of particular requirements. In the high luminosity experiments, ATLAS and CMS, this region sees a very high radiation flux from the interactions. The TAS absorber [28] and vacuum equipment installed here will become radioactive, requiring special equipment and precautions. In all experimental insertions the space here is very limited and agreement between machine and experiments is necessary before equipment can be installed [29].

Experimental Vacuum Technology

Although the layout of the experiments and hence the vacuum systems are quite different from each other, a number of common technologies have been developed and applied as required by the experiments.

The vacuum chamber directly around the IP of all experiments except LHCb is made from Beryllium, chosen for a combination of excellent transparency to particles, good mechanical properties and compatibility with ultra-high vacuum (UHV). New beryllium technology has been developed for the LHC in order to improve the leak tightness and minimise the external envelopes of the chambers. Beryllium chamber sections are now machined from solid rod and assembled by welding. Beryllium sections are either welded to aluminium or vacuum brazed to stainless steel. The central parts of ALICE, ATLAS and CMS use similar designs for this beryllium section. The inner diameter of 58 mm was the minimum acceptable for aperture and allows silicon vertex detectors to be as close as possible to the collision region.

The other beam vacuum chambers in the experimental areas are either constructed from stainless steel (with a copper coating to minimise machine impedance) or AA 2219 aluminium. This alloy has been approved at CERN for use in these areas as it maintains mechanical strength at the temperatures required for activation of the NEG (Non Evaporable Getter) coatings, whilst being considerably more transparent to particles than stainless steel.

In order to minimise the background due to the beam pipe in the forward regions, the ALICE, CMS and LHCb experiments have chosen to use conical beam pipe sections with a conical angle originating at the IP. These cones are terminated by thin ‘windows’, through which the particles pass at a quasi-acute angle.

UHV flanges have been specially designed to minimise the mass of material and external dimensions [30]. They have only 35% of the mass of a standard UHV flange and are used in different diameters in all four experiments.

Due to the estimated contact dose of 45 mSv in front of the TAS [31], a special remotely actuated flange system has been designed and will be used in the two high luminosity insertions.

The vacuum pumping inside the experiments is based on sputtered Non-Evaporable Getter (NEG) pumps, recently developed at CERN [32]. These have the advantage of adding very little mass whilst providing a high local pumping speed. These NEG pumps require periodic re-activation by heating the chamber to 250°C. It is expected to re-activate the NEG once per year during the winter shutdown.

Two special systems have been developed to enable this re-activation in the experimental chambers. In certain areas, access to the chamber will be difficult and the re-activation system will be permanently left in place. Heating systems based on stainless steel conductors laminated in Kapton sheets have been developed and approved for the high temperatures and radiation levels. Insulation will be either silica aerogel or high performance ceramic fibre (Microtherm). The central parts of CMS and ALICE will be re-activated by specially developed removable bake-out furnaces that will be installed on rails and then removed after re-activation.

The ALICE Beam Vacuum

The ALICE experiment being installed in IR2 is asymmetric about the IP. The vacuum chamber shown schematically in Fig. 19.5, can be divided functionally into three different sections: the central part (CP) which needs high transparency to secondary particles; the RB26 side which is a stainless steel cone embedded in a heavy muon absorber and the RB24 side which is upstream of the CP and has no physics requirements from the experiment.

The CP will have a 4 m long beryllium chamber connected to stainless steel extensions and bellows. The removable heating system will be installed each time a NEG re-activation is needed and will require a shutdown of several weeks. The RB26 side will be copper-plated stainless steel sections with increasing thicknesses from 1 to 3 mm. It consists of three beam pipes connected by commercial UHV flanges. These three chambers are supported inside the muon absorber. Each chamber has an axial fixed point inside the absorber bore, sliding supports and bellows. The sliding supports will be made of stainless steel and designed to minimise the heat load into the absorber during NEG re-activation. Due to the difficult access to the beam pipe, a permanent Kapton / Microtherm heating system will be installed. This has been optimised for this application due to the limits on radial space and heat input to the absorber block.

The RB24 section will be installed with standard warm LSS components.

In addition to the experimental area, ALICE has detectors in the LSS of the LHC. The ‘Zero Degree Calorimeter’ or ZDC is installed ~116 m from IP2, in front of the D2 magnet. This is the recombination region where the single beam pipe that passes through the IP becomes two parallel pipes for the standard LHC twin aperture. ALICE takes advantage of this recombination to install a neutral particle detector in between the twin apertures and a proton detector to the side of the apertures, using the D1 magnet as a spectrometer magnet [11].

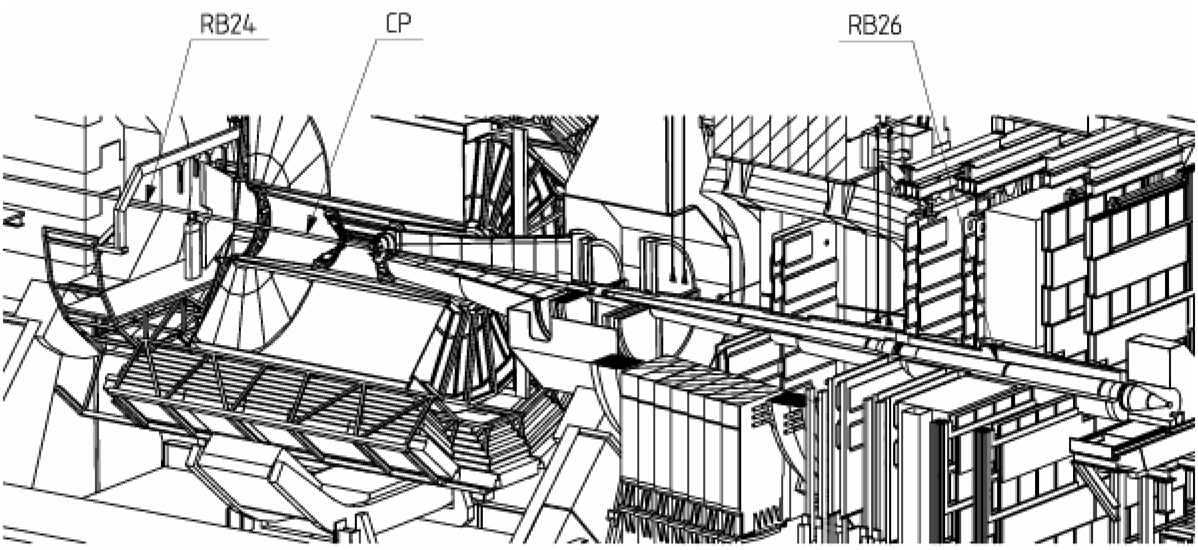


Figure 19.5: The ALICE Beam Vacuum System

The ATLAS Beam Vacuum

The beam vacuum system in ATLAS is functionally symmetric about the IP. It has a 7.3 m long central chamber inside the inner detector, 7 m of which is beryllium with extensions and minimised flanges in AA 2219 aluminium. This chamber is equipped with a permanent Kapton foil / Aerogel NEG activation system. At either end is a specially developed low-mass ionisation pump with 20 l/s nominal pumping speed [33]. This is required due to the small diameter of the ATLAS chambers which gives a poor pumping speed for the gasses not removed by the NEG. The vacuum chamber then passes through the 92 mm bore argon end-cap calorimeter. This restricts the diameter of the beam pipe up to 10 m from the IP. From this point the chamber increases to 80 mm ID and then 120 mm in two steps. At ~19 m from the IP, the diameter drops to 34 mm through the remotely operated flange and into the TAS.

All of the chambers with the exception of the inner detector chamber are made from copper-coated stainless steel. However, studies are under way to replace some sections with AA 2219 aluminium.

The CMS Beam Vacuum

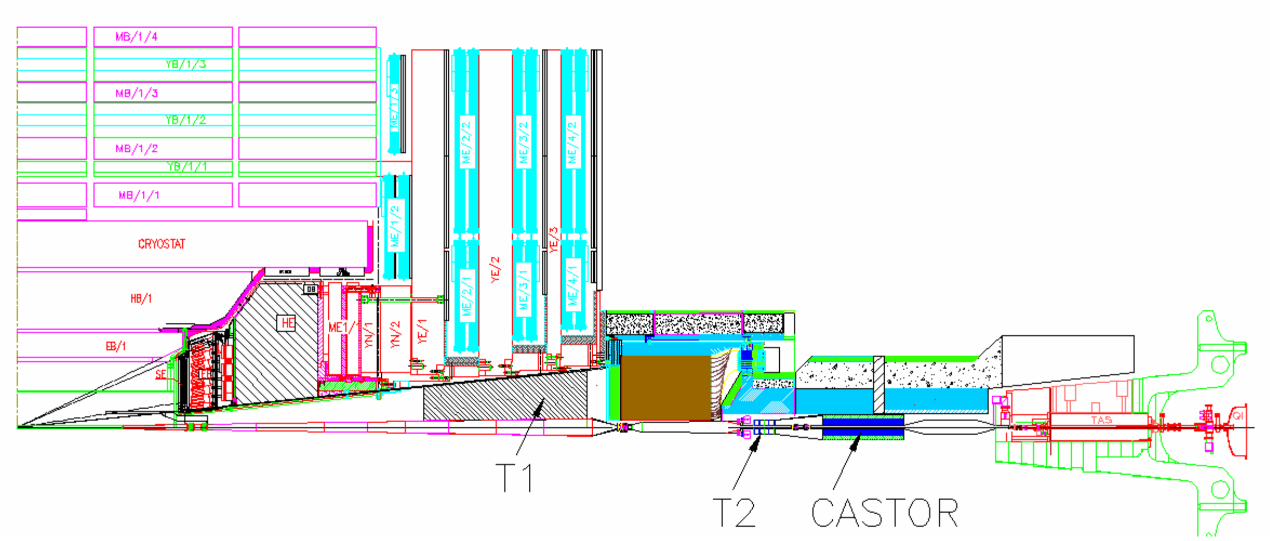


Figure 19.6: Half-section through the CMS beam vacuum system also showing the detectors of both CMS and TOTEM.

The beam vacuum system in the CMS detector is functionally symmetric around IP5. As shown in Fig 19.6 it has a ~6.2 m long central chamber of which 3.8 m is beryllium. Either side of this beryllium tube is a transition to a copper-plated stainless steel cone of ~15 mrad opening angle. This cone continues to the second chamber which passes through the CMS end cap, up to 10.6 m from the IP. There is then a 'window' with a 15° angle as the chamber diameter reduces to pass through the HF calorimeter. In the 'forward' region between 13 and 18 m the chamber will pass through the TOTEM T2 telescope and CASTOR detector before the remotely activated flange assembly in front of TAS. This forward region design is still under discussion with the experiment.

The central chamber is heated for NEG re-activation by a removable system, running on the rails used for PIXEL detector installation. The PIXEL detector must be removed to re-activate the NEG.

The LHCb Beam Vacuum

The IP at Point 8 is offset from the centre of the cavern and the LHCb experiment will be installed on one side only with the vacuum chamber layout illustrated in Fig. 19.7. The silicon Vertex Locator (VELO) detector is installed around the IP inside a 'vertex tank', separated from the beam vacuum by a thin aluminium membrane. The detectors and membrane can be moved close to the IP for data taking [9].

The VELO vertex tank is terminated by a thin aluminium window covering 390 mrad opening angle. From this starts a double conical vacuum chamber with 25 mrad and then 10 mrad opening angles. LHCb will have around 12 m of beryllium or beryllium-aluminium (Al-Be) alloy with increasing thickness from 1 to 2.4 mm. Beryllium is more transparent than the alloy, the final cost/benefit choice between these materials will be made by the experiment. Tests of the Al-Be material have been performed to determine its mechanical behaviour at bake-out temperatures, its creep performance and weldability by electron beam. An aluminium bellows universal joint with 0.4 mm wall thickness has been developed for LHCb and will be used to decouple the beryllium chambers.

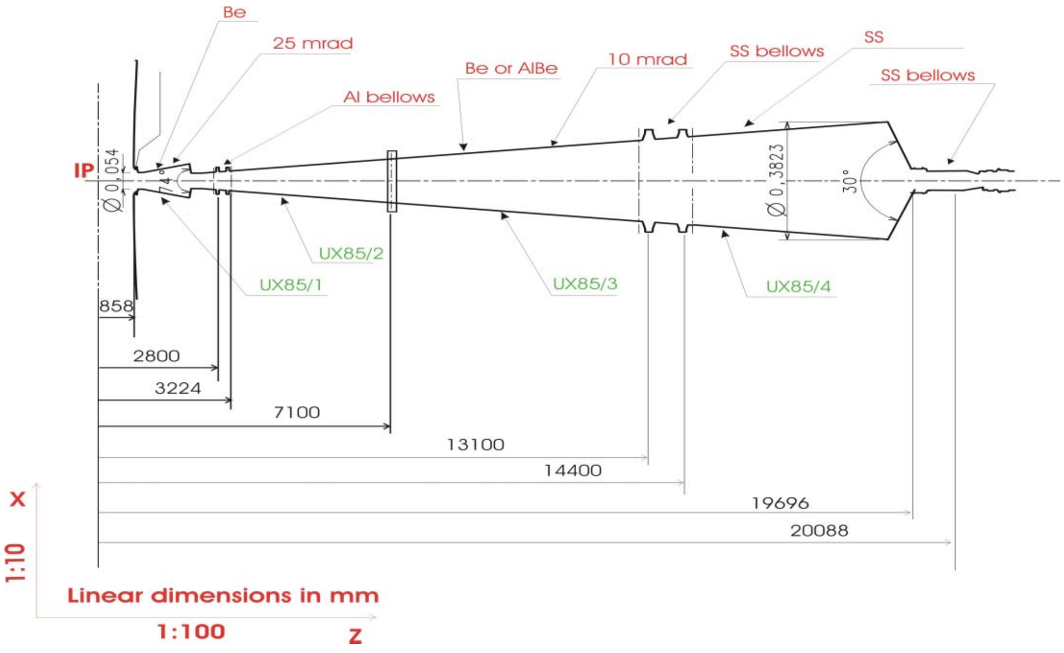


Figure 19.7: Schematic view of the LHCb beam-pipe

A stainless steel cone will be installed inside the muon detectors where the beam pipe transparency is of lower importance. The easier access to the beam pipe compared with the other LHC experiments allows removable bakeout systems for most of its length. Only the stainless steel section UX85/4 will have a permanent system installed. Upstream of the experiment, the beam pipe will consist of standard warm LSS components.

The TOTEM Beam Vacuum

Part of the TOTEM experiment is situated inside the CMS experimental area at IP5 and part in the LSS of IR5. The T1 and T2 telescopes, inside the CMS area are mounted close to the vacuum chamber as shown in Fig. 19.6. A chamber compatible with both CMS and TOTEM has been agreed.

The other part of the experiment consists of pairs of 'Roman Pot' detectors installed at ~150 m, ~180 m and ~215 m from the IP as shown in Fig. 19.8. These Roman Pots allow detectors to be moved close to the accelerated beam whilst remaining outside the beam vacuum. The detectors will be in a secondary vacuum completely separated from the primary beam vacuum by a thin window. For safety and reliability it has been decided to ensure that this thin window can resist a pressure of 1 atmosphere from either side.

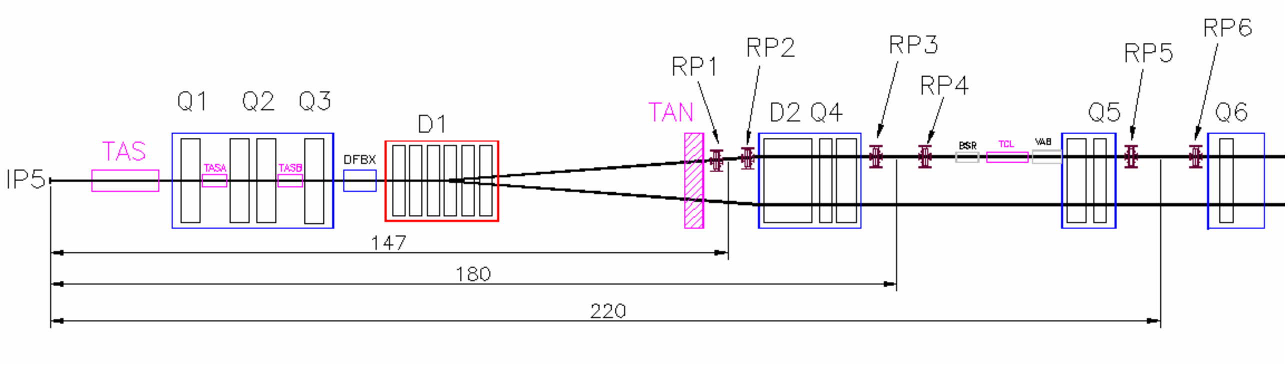


Figure 19.8: The layout around IP5 showing the position of the "Roman Pots" (RP1-6) for the detectors of the TOTEM experiment.

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