THE BEAM INSTRUMENTATION AND DIAGNOSTIC CHALLENGES FOR LHC OPERATION AT HIGH ENERGY

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Abstract

This contribution will present the role of beam diagnostics in facing the challenges posed by running the LHC close to its design energy of 7TeV. Machine protection will be ever more critical, with the quench level of the magnets significantly reduced, so relying heavily on the beam loss system, abort gap monitor, interlocks on the beam position and fast beam current change system. Non-invasive profile monitoring also becomes more of a challenge, with standard synchrotron light imaging limited by diffraction and rest gas ionisation monitoring dominated by space charge effects. There is also a requirement to better understand beam instabilities, of which several were observed during Run I, leading to the need for synchronised bunch-by-bunch, turn-by-turn information from many distributed instrumentation systems. All of these challenges will be discussed along with the strategies adopted to overcome them.

INTRODUCTION

The first beam was injected into the LHC during tests in August 2008, with circulating beams established on the 10th September 2008. Nine days later disaster struck as a fault in one of the superconducting circuits led to the release of 600MJ of stored energy during a test of high current powering. It took over a year to recover from the damage caused by this event, with over 30 magnets needing to be repaired or replaced. After intensive investigations the source of this accident was concluded to be due to a faulty splice between the superconducting cables of neighbouring magnets. In addition it was found that for many magnets there was poor electrical and thermal conductivity between the superconducting cable and the copper stabiliser surrounding these joints. In the event of a magnet quench, when the superconductor becomes normal conducting due to overheating, these copper stabilisers take the full current until it can be safely extracted, a process which takes several minutes. Under such circumstances any poor contacts can lead to a thermal runaway, resulting in a similar accident to the one experienced in 2008. Due to these issues it was decided to initially run the LHC at half its design energy of 7TeV. This represents some 6kA in the main circuits, a current which was considered could be safely extracted even with such poor contacts still present in the machine.

The beam was back in the machine for commissioning on the 29th November 2009, with first physics collisions at 3.5TeV per beam occurring on 30th March 2010. This was the start of 3 years of nearly continuous LHC operation, culminating in the discovery of the Higgs boson on the 4th July 2012. During this time the stored beam intensity was gradually increased, with the energy also increased to 4TeV per beam in 2012. A total integrated luminosity of nearly 30fb^{-1} was accumulated over this period (Fig. 1), with the LHC ending the 2012 run reaching peak luminosities of 8×10^{34} cm^{-2}s^{-1}, close to its design value of 10^{34}.

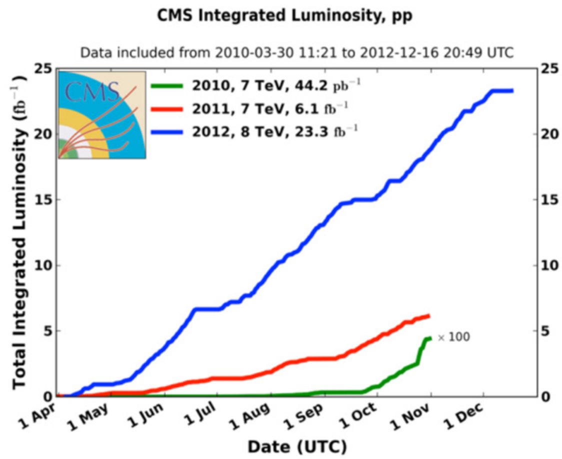

Figure 1: LHC performance during Run I.

In order for the LHC to work at, or close to, its nominal energy of 7TeV, major consolidation of all the superconducting circuits was necessary. Long Shutdown 1 (LS1) started on the 14th February 2013 with the aim of consolidating over 10,000 superconducting splices, reducing the effects of radiation to electronics and carrying out full maintenance on all equipment, including the majority of beam instrumentation systems.

At the time of writing, this consolidation work is complete and the LHC is in the process of being cooled to 1.9K before the start of hardware commissioning. The beam is currently expected back in March 2015, with the LHC foreseen to run at 6.5TeV for the remainder of that year.

The beam instrumentation and diagnostic systems of the LHC [1] worked remarkably well throughout Run I, and played an important part in the rapid commissioning and reliable operation of the machine. However many lessons have been learned and shortcomings identified, the majority of which have been addressed during the long shutdown. Run II of the LHC, at an energy close the design energy of 7TeV, will in addition bring its own challenges, and it is these that will be addressed in this contribution.

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THE CHALLENGES FOR RUN II OF THE LHC

The three main challenges for Run II of the LHC are:

- ***Operating at higher energy.*** It is currently foreseen that the LHC will start running in 2015 at a top energy of 6.5TeV, with the possibility to increase in later years towards 7TeV depending on the quench behaviour at high field of the main dipole magnets. At this energy the quench thresholds will be significantly reduced compared to Run I, meaning that the machine will tolerate much less beam loss. As can be seen from Fig. 2, a single pilot bunch of 5×10^9 protons is close to the material damage threshold at 7TeV while a quench can be incurred if less than one millionth of a nominal beam is lost over a 10ms period.

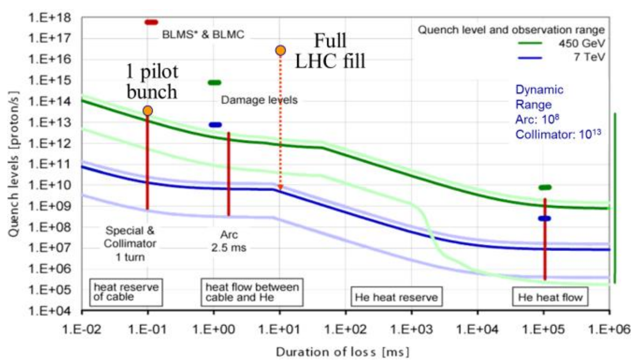

Figure 2: Estimated quench levels for the LHC at injection and top energy.

- ***Running with 25ns bunch spacing.*** During Run I the LHC was operating with a nominal bunch spacing of 50ns. Such a beam could be produced by the LHC injector chain with high brightness, and could be injected, accelerated and collided with little loss in the LHC. However, such a high intensity per bunch coupled with a low emittance, meant that the LHC experiments had to disentangle on average over 30 events per bunch crossing. In going to high energy and tighter focussing, this "pile-up" would become unacceptably large and hence operation at 25ns spacing is foreseen. This brings with it the problems related to enhanced electron cloud formation and beam induced RF heating due to the increase in total beam current.
- ***Coping with high brightness beams.*** While going to 25 bunch spacing is likely to reduce the brightness of the LHC bunches at injection (lower intensity and slightly larger emittance), the fact that they are accelerated to higher energy and hence reduced in size, will mean that at flat-top they will be significantly smaller than any beams produced during Run I. This will pose severe issues for the measurement of their emittances, required for the understanding and optimisation of the machine.

Each of these challenges will now be looked at in detail, with the role played by beam instrumentation and diagnostics in addressing them highlighted.

OPERATING AT HIGHER ENERGY

As stated previously, the main challenge of operating the LHC at higher energy is dealing with the reduced quench thresholds of the main dipole and quadrupole magnets. This poses two questions: how to deal with unidentified falling objects and how to ensure efficient collimation?

Dealing with Unidentified Falling Objects

Run I of the LHC was plagued by Unidentified Falling Objects (UFOs) creating beam losses that were large enough to trigger a beam abort by the BLM system[2]. In 2012, 20 beam dumps were identified to be associated with UFOs, with 14 of these occurring at 4TeV. In addition, some 17,000 candidate events were attributed to UFOs below the BLM threshold. The origin of these events is unclear, but as they appear at nearly all locations around the LHC they are believed to be the result of dust particles dropping into the vacuum chamber. The reduction of quench thresholds with energy will mean that at 6.5 – 7 TeV many more beam aborts can be expected. To buy some additional margin a relocation of the ionisation chambers of the beam loss monitoring system has been carried out during LS1 (Fig. 3).

Designed to protect the superconducting magnets from beam losses at maximum-beta locations, the original system had 3 ionisation chambers per beam and per quadrupole [3]. However, as UFOs can occur at any location, an event in one of the dipoles between two quadrupoles will result in a relatively small signal by the time the secondary shower reaches the beam loss monitor (BLM) sitting on the quadrupole. In order to avoid the dipole quenching, the BLM thresholds therefore have to be increased substantially, well above what is required to avoid quenches due to standard beam loss at the quadrupoles. After significant simulation work it was decided to move one of the BLMs per beam from the quadrupoles to the dipoles. This was found to leave sufficient redundancy to avoid quenches due to losses at the quadrupoles while gaining a factor 30 in sensitivity to UFO events occurring in the dipoles.

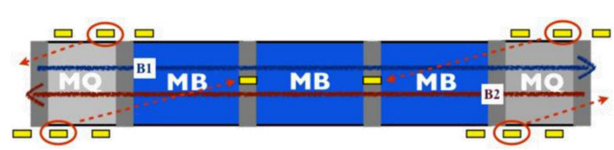

Figure 3: Relocation of beam loss system ionisation chambers (yellow) to optimise protection against UFOs. MQ - main quadrupole: MB - main bend (dipole).

While the beams will still be aborted should a large enough UFO even occur at 6.5-7TeV, the relocation of these BLMs will at least enable the thresholds to be set

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closer to what is required to avoid quenching in all magnets with losses generated by either a UFO event or via a standard loss scenario.

Ensuring Efficient Collimation

The cleaning efficiency necessary to ensure that any beam loss in the cold arc is maintained well below the quench threshold is ensured by a comprehensive collimation system (Fig. 4) [3]. A series of primary, carbon-jawed collimators scatter the transverse and longitudinal beam halo, which is then absorbed by secondary carbon collimators with slightly larger opening. Tungsten-jawed tertiary collimators near the experiments and various protection devices complete the collimator hierarchy, cleaning-up the remainder of the secondary halo and protecting against equipment failure, such as the misfire of the dump kickers. During Run I the gap in the 1.2m long jaws of the primary collimators was only 2.2mm.

Ensuring the correct set-up of these ~100 moveable devices and ensuring that the beam remains centred during long periods of operation is the job of the beam loss and beam position system respectively.

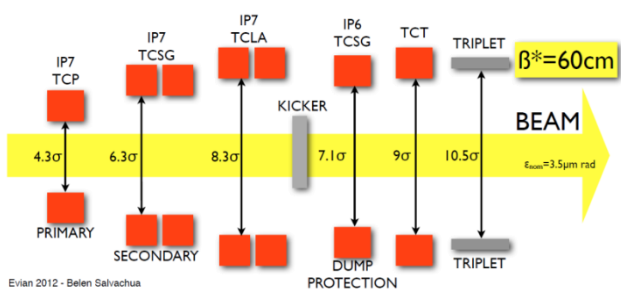

Figure 4: Collimation hierarchy in the LHC. Retraction in beam sigma for possible for operation at high energy.

Defining the Right Collimator Positions

Once a stable orbit has been defined, the setting up of the collimators is carried out using the LHC beam loss system [4], consisting of over 3000 ionisation chambers. With very low intensity beam in the machine, each collimator jaw is individually moved in until it touches the beam halo, inducing a loss spike which is detected in a neighbouring BLM. Initially this procedure took over a day to be performed for all collimators, but has since been reduced to less than one hour, thanks to the parallelisation of the task and an improved BLM data stream. Beam loss measurements are now published to the collimator control system at 12.5Hz, allowing the maximum 8Hz movement of the jaws.

Once centred, the collimation hierarchy is validated by so-called loss maps. This involves creating an artificial loss and monitoring the leakage of lost particles into the cold magnets using the complete BLM system. An example of such a loss map is shown in Fig. 5. It can be seen that the losses are all localised in the betatron and momentum cleaning collimation regions. The maximum leakage of lost particles into a cold magnet is less than 0.02%, within the design specifications.

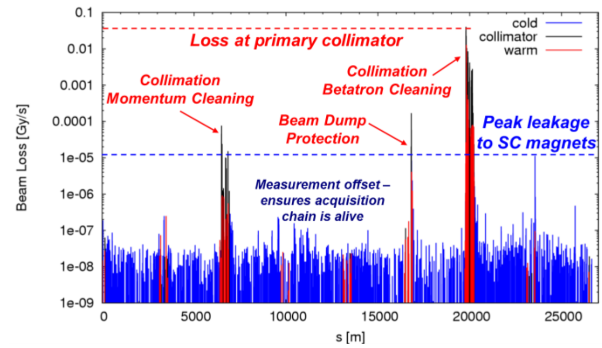

Figure 5: Example of an LHC loss map showing the measurements from all beam loss monitors around the LHC.

During LS1, all 16 tertiary collimators have been replaced by a design which includes embedded beam position monitors (Fig. 6) [5]. The settings of these collimators are linked to the amount of focussing possible in the experimental insertions. A better knowledge of the beam position at their location would enable safety margins to be reduced to allow tighter focussing, and hence higher luminosity.

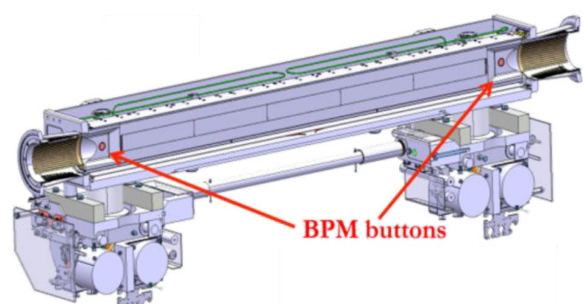

Figure 6: Design of the new LHC tertiary collimator with beam position monitors embedded within the jaw.

A prototype of such a collimator with embedded BPMs has been successfully tested in the CERN-SPS and showed that the time required to set-up the collimator to be centred within 10μm around the beam can be reduced to a mere 20 seconds [6]. The system uses two pairs of button pick-ups, one at the upstream and one at the downstream end of the collimator, slightly retracted from the face of the jaw. The signals are processed using compensated diode peak detector electronics, specially designed to give excellent resolution, < 100nm, for centred beams [7]. This electronics for accurate, high resolution orbit measurements has been so successful that it will now also be extended to work in parallel to the existing bunch-by-bunch orbit and trajectory system in critical locations.

Maintaining the Right Collimator Positions

Once the right collimator positions have been defined, the role of maintaining the beam in their centres is the job

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of the LHC beam position system [8]. This is comprised of 1054 beam position monitors, the majority of which (912) are 24mm button electrode BPMs located in all arc quadrupole cryostats. The remaining BPMs are enlarged (34mm or 40mm) button electrode BPMs mainly for the stand alone quadrupoles, or stripline electrode BPMs used either for their directivity in the common beam pipe regions or for their higher signal level in the large diameter vacuum chambers around the dump lines.

The beam position acquisition electronics is split into two parts, an auto-triggered, analogue, position to time normaliser which sits in the tunnel and an integrator/digitiser/processor VME module located on the surface. Each BPM measures in both horizontal and vertical planes, making a total of 2156 channels.

The data from all these channels is fed at 25Hz to a central orbit feedback system which, using a regularised SVD approach and a closed loop bandwidth of 0.1Hz, can maintain orbit stabilities of typically better than 70µm globally and 20µm in the arcs. The measured fill-to-fill reproducibility when going into collision at the ATLAS interaction point throughout 2012 is shown in Fig. 7. Whilst a slow drift of 80µm is seen to build-up over the year, the reproducibility from one fill to the next is excellent with the difference only 7µm rms.

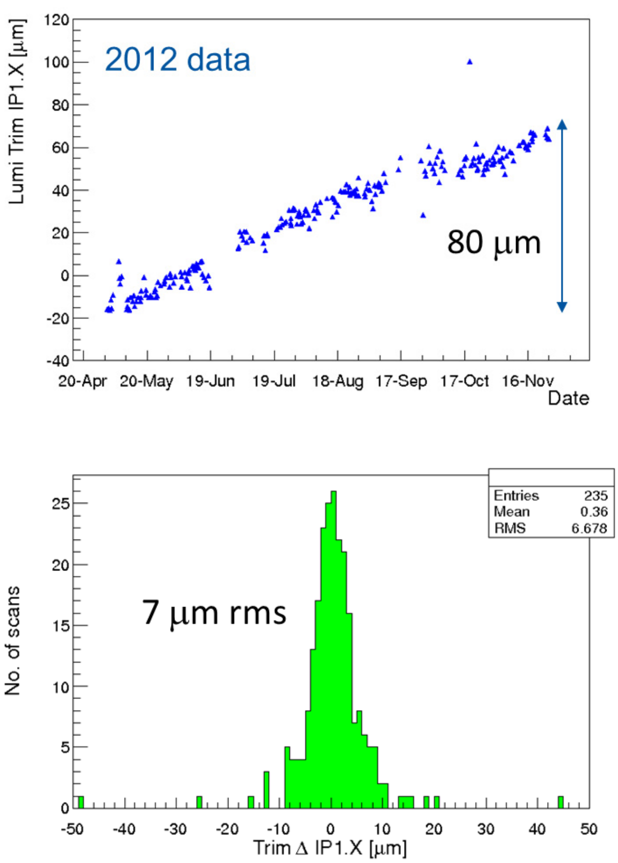

Figure 7: Orbit reproducibility going into collision at the ATLAS experiment as measured in 2012.

The main performance limitation of the orbit feedback is linked to an observed systematic position dependence on temperature that initially caused errors of greater than 300µm on the orbit measurements. This was reduced to the order of 100µm during Run I by regular calibration and applying temperature corrections to the data. To eliminate this problem for Run II, temperature controlled racks have been added to house the BPM surface electronics. These maintain a stable temperature to within ±0.2°C which should keep any orbit drifts below 10µm.

RUNNING WITH 25NS BUNCH SPACING

The main challenge of running with 25ns spaced bunches in the LHC will be dealing with the electron cloud that this generates [9]. This cloud of electrons is created due to secondary emission from the beam pipe wall, initially via ion bombardment or synchrotron radiation. As these electrons drift into the chamber they are accelerated by a passing bunch, hitting the opposite wall and creating more secondary electrons. This process is repeated with the following bunches, creating and avalanche of electrons, which eventually forms an electron cloud. Apart from creating a dynamic pressure rise and an additional heat-load for the cryogenic circuits, it also has an impact on beam quality, with the induced instabilities leading to particle loss and emittance growth.

For a given bunch spacing, the threshold at which this cloud can develop is given by the secondary electron yield of the wall material. This can be lowered by scrubbing the surface with a dense electron cloud, which is why many machines introduce scrubbing runs with high intensity beams at low energy. Moving from 50ns spacing to 25ns spacing significantly lowers the secondary electron yield threshold at which a significant electron cloud forms. It can therefore be expected that during Run II it will be even more important to be capable of observe instabilities, measure beam loss and monitor emittance growth.

Bunch by Bunch Diagnostics

Understanding the effects of the electron cloud and other instabilities can only be effectively done using bunch-by-bunch measurements. In the LHC nearly all instrumentation systems have therefore been designed to deliver such data, with many improvements carried out during LS1.

Two new types of fast beam current transformer have been installed to improve the bunch by bunch resolution of the existing system and remove the dependency on beam position and bunch length observed during Run 1 [10]: an integrating current transformer developed in collaboration with Bergoz Instrumentation [11] and a wall current monitor developed at CERN. Both are aimed at providing a bandwidth of up to ~100MHz, less than 0.1%/mm position dependence and 0.1% bunch length dependence.

The synchrotron light monitor is also capable of providing bunch by bunch diagnostics and has already been used extensively to study the effect of electron cloud on emittance blow-up. In this mode a Proxitronic Nanocam, HF4 S 25N NIR intensified via a multichannel

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plate between the photocathode and the camera sensor, is used in gated mode to scan through the individual bunches. The present acquisition chain (analogue camera ⇒ frame grabber ⇒ software) is limited to about 16 frames/s, which implies that it takes some 3 minutes to scan though all bunches. A plan to upgrade this to the maximum camera rate of 50 frames/s is foreseen in the near future.

Fig. 8 shows an example of bunch by bunch emittance measurements during the scrubbing run used to condition the machine against electron cloud effects at the start of 2011. Instabilities leading to increased emittance are clearly visible on one beam towards the end of the injected batches. These measurements were invaluable in quantifying the improvements made during the course of this conditioning. It has also been used to detect non-uniformity in the emittance of the beam coming from the LHC injectors, leading to an optimisation campaign which resulted in much better emittance uniformity.

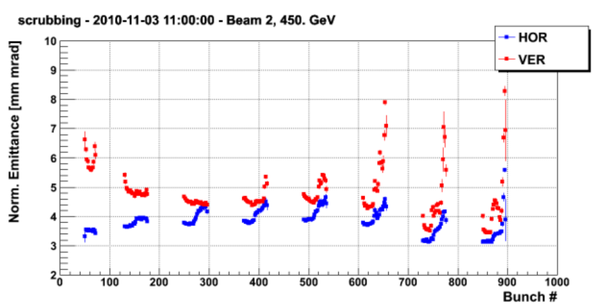

Figure 8: Bunch by bunch emittance showing the blow-up of some bunches due to electron cloud instabilities.

Intra-Bunch Diagnostics

Another important diagnostic to understand the origin of instabilities is intra-bunch measurement. During Run I various instabilities, leading to beam loss and emittance growth, were observed during the beta squeeze (while focussing the beam in the experiments) and whilst going into collision. Disentangling the many possible causes of these instabilities requires a detailed knowledge of their effect on the beam. Although general oscillation data showing that an instability had occurred was available during Run I, it was not possible to distinguish between coupled bunch and intra-bunch motion. The reason for this was twofold. Firstly there was no reliable trigger to freeze the acquisition buffers of the systems that were measuring bunch-by-bunch when the instability occurred. Secondly, the resolution of these systems was often insufficient to observe the instability before the beams were aborted.

To address these two points a new Multiband Instability Monitor (MIM) is being developed [12]. This system exploits the fact that the frequency spectrum of an unstable bunch will be modified depending on how it is oscillating. By measuring this frequency spectrum the modes of the oscillation can therefore be inferred.

The MIM under construction will measure the amplitude of the intra-bunch motion in 16 different frequency bands separated by 400MHz, from 0.4-6GHz. A stripline pick-up is used to provide the input signals, which then transit a 16 channel filter bank, before being converted to baseband by 16 parallel direct diode detection channels. This should give the system sufficient sensitivity to detect sub-micron oscillations, allowing it to both trigger other systems and give valuable information on the type of instability being observed.

COPING WITH HIGH BRIGHTNESS BEAMS

Beam Induced RF Heating

During Run I beam induced RF heating was observed on many pieces of equipment [13]. This effect comes about due to the intense LHC beams generating RF wakes in these structures, which are then amplified by the following bunches. If the cooling is insufficient, or the RF power absorbed too great this can have serious consequences. It has led to the failure of RF fingers, damage to the injection protection system and the overheating of injection kickers and forward physics experiments. In addition is resulted in the failure of the extraction mirror support for the synchrotron light monitor and a blistering of the mirror coating.

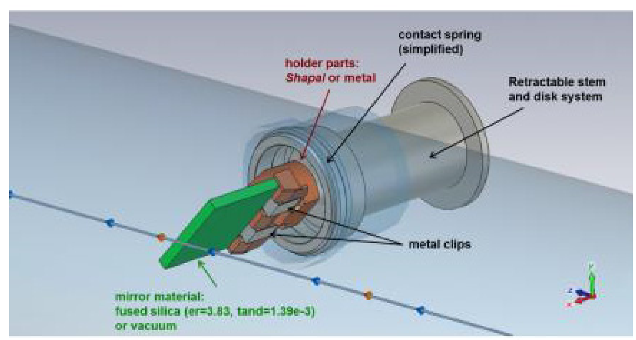

Figure 9: Original synchrotron light extraction mirror support. The metal holder, which was surrounded by ferrites, acted as an antenna, absorbing RF power from the beam and heating the complete structure.

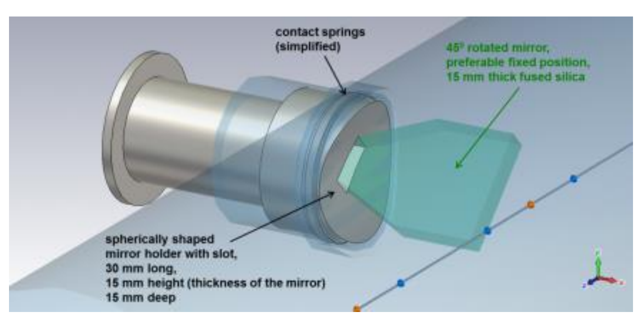

Figure 10: New synchrotron light extraction mirror support. A long mirror is held in place by a spherically shaped holder which maintains the continuity of the beam pipe.

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An intensive electromagnetic simulation campaign [14] showed that with the existing design (Fig. 9) the ferrites used to detune the cavity and absorb the RF power could be heated well above their Curie temperature. The assumption is that this then led to an overheating of the mirror and support. The best alternative found is shown in Fig.10. This still allows the mirror to be placed a few centimetres from the beam and uses the same extraction tank. The design significantly reduces the RF coupling to the beam, and should allow the structure to dissipate any heat generated via conduction and radiation. Such holders have now been produced (Fig. 11) and installed on both beam lines.

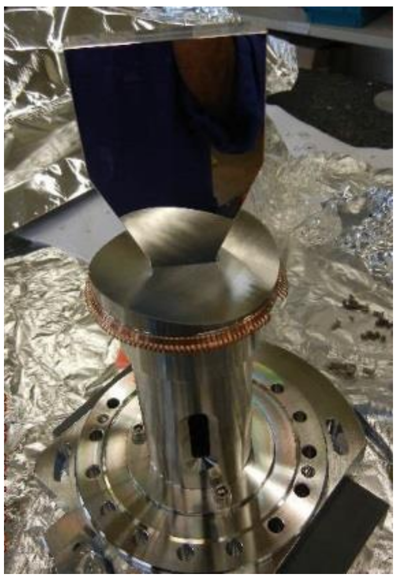

Figure 11: New synchrotron light extraction mirror and support.

Measuring Small Beam Sizes

During Run I, the LHC was equipped with 4 beam size measurement devices: optical transition radiation screens for the setting-up of injection and extraction; wire-scanners for absolute measurement and the calibration of the other devices; synchrotron light monitors; rest gas ionisation monitors. Each of the three devices used with circulating beam presented limitations, and will be further pushed to measure the even smaller beam sizes expected at 6.5-7TeV.

Wire-Scanners

The operation limits for the LHC wire-scanners during Run II are defined by the process of wire sublimation (Fig. 12) [15]. At the injection energy of 450GeV the limit sits at a total intensity of around 2.7×10^{13} protons. This was sufficient during Run I to measure the first full injected SPS batch of 144 bunches with 50ns spacing. However, it will not be sufficient to measure a full injected SPS batch of 288 bunches with 25ns spacing. In addition the limit at 6.5TeV has been calculated to be at 2.7×10^{12} protons, which is a mere 20 bunches. Dedicated runs will therefore be required to use the wire-scanners to cross calibrate the other devices.

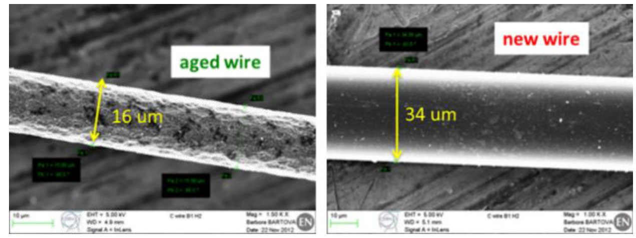

Figure 12: The effect of sublimation on the carbon wire of the LHC wire-scanners.

Synchrotron Light Monitor

With a new extraction mirror in place it is hoped that the imaging accuracy of the synchrotron light monitor will be much improved for Run II. In addition, wave-front distortion measurements using the Shack-Hartman mask method will be used to measure and correct for any remaining distortions. However, at 6.5-7 TeV the imaging will be dominated by diffraction. The optical system has therefore been redesigned to use ultra-violet (UV) compatible optics and a CCD camera with a UV sensitive photocathode, rather than the visible optics and camera used in Run I. Even so, when imaging in a narrow band at 250nm, the contribution from diffraction is estimated to be ~250µm compared to a beam size of only 180µm. A good understanding of the diffraction effects and all other distortions will therefore be necessary to extract an accurate absolute beam size from these images.

Due to the extent to which imaging is expected to be dominated by diffraction at 6.5-7TeV a new optical line has been added to perform interferometry, though a collaboration with KEK (Japan), SLAC (US) and CELLS-ALBA (Spain) [16]. This non-diffraction limited technique is widely used in electron machines with very small beam sizes and relies on the fact that the visibility of the interference pattern is dependent on the beam size. The results of simulations showing the expected interference patterns in the LHC at injection and top energy are shown in Fig. 13, with the dependence of the visibility on beam size presented in Fig. 14.

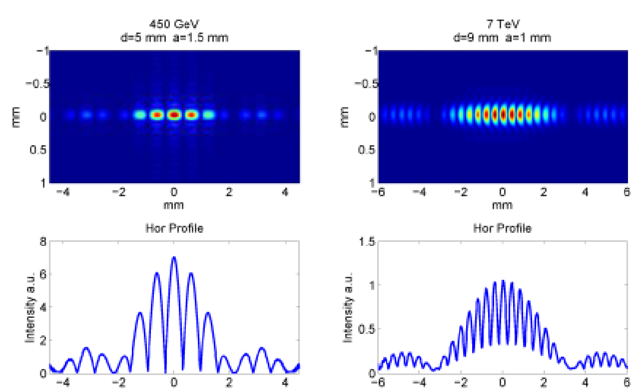

Figure 13: Simulation results showing the expected interference patterns from synchrotron radiation at injection and top energy.

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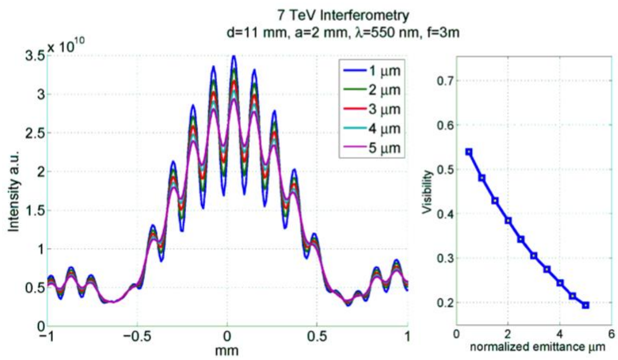

Figure 14: Simulation results showing the expected variation of visibility with beam size.

It is hoped that with the modifications to the extraction mirror and the standard imaging system, plus the addition of interferometry, the synchrotron light monitor will continue to give accurate beam size measurements during Run II.

Ionisation Profile Monitor

The LHC ionisation profile monitor (IPM) is based on electron collection using a 0.2 T guide magnet, a multi-channel plate for amplification and an optical readout from a phosphor screen with a radiation-hard camera [17]. While this monitor has worked well with Pb^{54+} ion beams, it was seen to suffer from severe image distortion during the proton energy ramp. This was suspected to be due to space-charge effects from the high brightness proton beams, something that was confirmed by simulations using the PyECLOUD code [18]. The distorted profile (Fig. 15) cannot currently be deconvoluted to extract the original profile, and the only real solution to this problem seems to be to increase the magnetic guide field to around 1T. This is not currently foreseen, and thus the IPM will only be used to measure Pb^{54+} ion beams during Run II. This was in any case its primary purpose as Pb^{54+} ion beams emit very little synchrotron light at the LHC injection energy of 450GeV.

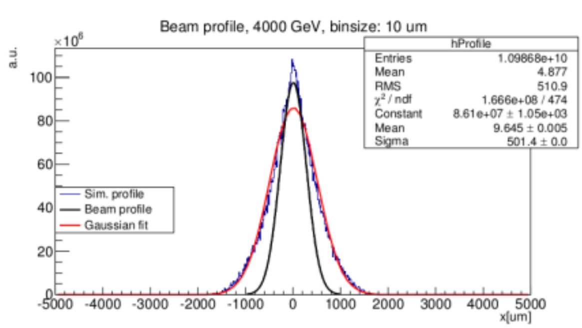

Figure 15: Profile as measured by the IPM at 4TeV showing the large distortion due to space charge.

Beam Gas Vertex Detector

The beam gas vertex (BGV) detector [19] is a new instrument being prototyped on one of the LHC beams after LS1, under the auspices of the High Luminosity LHC upgrade project. A collaboration between CERN, EPFL Lausanne (Switzerland), and RWTH Aachen (Germany) has been formed to design, develop, install and commission a demonstrator BGV system for the LHC by the end of 2015. This non-invasive beam gas interaction detector is based on developments for the LHCb experiment [20], where the vertex detector was successfully used with gas injection during Run I to measure 3D beam profiles during collisions for absolute luminosity determination [21].

Unlike for LHCb, where the detector is placed very close to the beam and can therefore only be used during stable beams in collision, the aim with the BGV detector was to design a robust instrument that could be used for beam size measurements for machine operation at all times in the LHC cycle. Its final specifications are to provide a relative bunch width measurement with 5% accuracy within 1 minute and an absolute average beam width measurement to an accuracy of 2% within the same time. For the demonstrator it was considered essential to maintain the functionality of real-time bunch-by-bunch profile measurements with a resolution of about 5 %, but within an increased 5 minute measurement interval, while the absolute accuracy requirement was relaxed to 10 %.

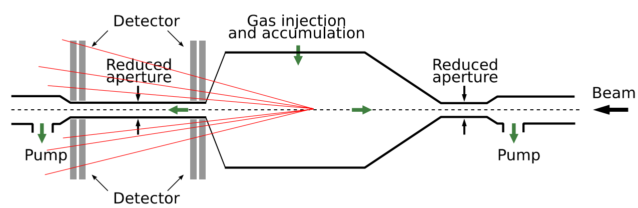

Figure 16: Principle of the beam gas vertex detector for transverse beam profile measurement.

The principle of the device is shown in Fig. 16. The LHC proton beam interacts with an injected gas volume to produce secondary particles. These are peaked in the forward direction and are tracked using a set of tracking detectors. By tracing back from the detected tracks the original vertex can be located, provided that the quantity of intervening matter is small enough to limit the amount of multiple-scattering.

The main subsystems are: a neon gas target at a pressure of 6×10^{-8} mbar, a thin aluminium exit window, tracking detector based on scintillating fibre modules read out by silicon photomultipliers, hardware and software triggers, and a readout and data acquisition system based on that used for LHCb. As the tracking detector is external to the vacuum chamber, no movable parts are needed. The final design is shown in Fig. 17.

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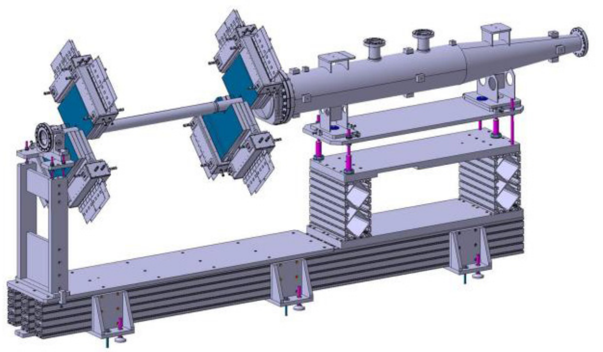

Figure 17: The demonstrator Beam Gas Vertex detector installed in the LHC during LS1.

SUMMARY

During the first long LHC shutdown nearly all beam instrumentation devices have been consolidated or upgraded with a few new additions installed, to cope with the challenges of the next 3 years of running at close to top energy.

After being dismounted for the repair work on the superconducting magnets, the BLMs have been re-installed in a configuration that should help cope with the threat of quenches due to unidentified falling objects. All the quench thresholds have also been updated with simulations and results and from tests performed at the end of the last run.

The BPM system sees the addition of temperature controlled racks for added measurement stability, embedded BPMs in collimators and the test of a new, high resolution diode orbit system for improved resolution at critical locations.

The synchrotron light monitor has a new extraction mirror that will hopefully eliminate the effects of beam induced RF heating suffered during Run I. It also sees the addition of a new interferometry line and the use of UV optics.

Instability monitoring will be provided by the new multi-band detector, while a new technique for non-invasive beam profile measurements will be tested with the beam gas vertex detector.

Other improvements include: a revamped schottky system for on-line chromaticity and bunch-by-bunch tune measurements, new fast beam current transformers for better bunch-by-bunch performance, and improved correction algorithms for the single photon counting longitudinal density monitor.

With the original LHC beam instrumentation already having shown its worth during Run I it is hoped that these upgrades and new additions will help meet the challenges of Run II.

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