EXPERIMENT-MACHINE INTERFACE ISSUES AND SIGNAL EXCHANGE

E. Tsesmelis, CERN, Geneva, Switzerland

Abstract

This paper provides an overview of issues arising at the interface between the LHC machine and the experiments. These issues will be required to guide the interaction between the collider and the experiments when operation of the LHC commences. In particular, an analysis of signals and parameters to be exchanged between the experiments and the accelerator will be presented. Emphasis will be 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.

The paper is based on discussions in working groups and committees, including the LHC Experiment-Accelerator Data Exchange Working Group (LEADE) [1], the LHC Experiment Machine Interface Committee (LEMIC) [2] and the LHC Technical Committee (LTC) [3].

LHC DATA EXCHANGE

Information to be communicated by the machine, experiments and the technical services has been discussed in the LHC Data Interchange Working Group (LDIWG) [4,5]. The 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. The communication link is based on the DIM Data Interchange Protocol providing a simple and robust publish/subscribe system which will support an on-change data exchange.

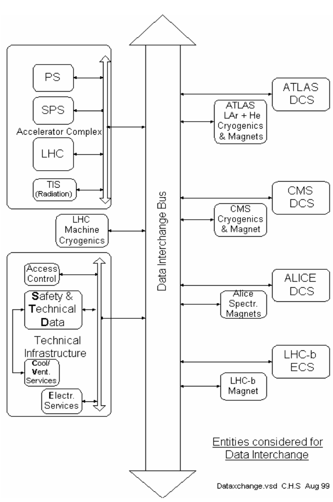

Figure 1: Entities considered for data exchange in LHC

Figure 1 shows the conceptual lay-out of the entities considered for data exchange while Table 1 provides examples of the information to be exchanged. The exchange is considered to be low frequency, at most about 250 kbps, and thus should not be limited by bandwidth, and should have a latency of < 1s.

Table 1: Example of information to be exchanged between the machine and experiments.

Entity	*Detail*
Spectrometer Magnets	Currents and polarity
Position of Moveable Detectors Components	LHCb Vertex Detector (VELO) TOTEM and potentially ATLAS Roman Pots
Background Measurements in detectors	Spatial and temporal distributions
Beam condition monitors	Standardized background monitors used as reference for machine tuning
Beam Characteristics	Vertex position (x,y,z) Luminous region
Absolute and Instantaneous Luminosity	Various sources for instantaneous (calorimeter currents, dedicated counters) TOTEM for absolute

Moreover, the LHC Logging System – TIMBER [6] – will provide a facility where information provided by the machine equipment groups will be stored in a database and become accessible for off-line analysis by users, including the experiments, in the form of either a graphical representation or file output.

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.

Table 2: Information to be sent from the experiments ATLAS and CMS to the machine.

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	Rates for individual bunches	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**

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, is required. This should be made available on TV monitors throughout CERN and also accessible via the WWW.

Table 3: Information to be sent from the machine to the experiments.

Producer	Measurement	Data Type	Production Volume (Bytes)	Production Speed	Production Rate (kB/s)	Expected Accuracy	Remarks
AB-BDI	Total beam intensity	Protons	8	1 sec	0.008	1%	
AB-BDI	Individual bunch intensities	Protons	28.512	1 min	0.475	5%	
AB-BDI	Average 2D beam size	mm	16	1 sec	0.016	15%	For transport to IP will require knowledge of beta function
AB-BDI	Average bunch length	ps	8	1 sec	0.008	1%	
AB-BDI	Total longitudinal distribution		285.120	1 min	4.752		Will be able to detect ghost bunches at the 0.1% level of nominal
AB-BDI	Average HOR & VER positions	um	32	1 sec	0.032	50um	From the BPMs located at QI either side of each IP
AB-BDI	Luminosity		28.512	10 sec	2.851	1% relative	This is a relative measurement between bunches
AB-BDI	Average Beam Loss		16	10 sec	0.002		Average of up to 50 selectable BLMs

Table 2 and Table 3 provide a minimum set of parameters to be exchanged. It is essential to retain flexibility in the data exchange mechanism as experience with experiment and machine operation develops. This may result in the number and choice of quantities exchanged to vary, thus altering the production rate and hence the data rate.

MEASUREMENT OF LHC PARAMETERS

Luminous Region

Calculations have been performed to estimate the luminous region around the Interaction Points (IPs) 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 ± 90 mm 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 ± 110 mm around the IP. 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. A similarly good match was determined for the barrel and end-cap Pixel detectors and the end-cap Tracker.

Fast reconstruction of tracks in ATLAS and CMS will provide a measurement of the longitudinal position of the collision to within ± 2 mm. Such measurements would require that the inner detectors, including the pixel detectors, are powered and operational and would only be possible once stable beams are established.

Transverse Centring of the Interaction Point

A well-centred collision point 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.

ATLAS and CMS plan to monitor the transverse position of the collision point by reconstructing tracks in the inner detectors. A measurement of this position to about 10 µm accuracy could be provided in 10 s.

However, there will be a need for re-alignment of the experiments to the machine. The cavern floors are expected to move over time due to the settling of the concrete and due to the hydrology of the geology. 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.

Experiment Measurements on the Collision Quality

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 of cluster rates 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.

LHC Timing Signals and Distribution to the Experiments

The Timing, Trigger and Control (TTC) [7] architecture provides for the distribution of synchronous timing, Level-1 trigger broadcast, and individually-addressed control signals to electronics controllers with the appropriate phase relative to the LHC bunch structure, taking account the different delays due to particle time-of-flight and signal propagation.

In addition, timing signals will be available through the LHC Beam Synchronous Timing System (BST) [8]. The BST's primary use will be to synchronise the LHC beam instrumentation but GPS timing signals as well as LHC data will be available to be added to the experiments' event records and detector control systems.

The LHC RF group will provide three clocks to the experiments: a stable reference clock at 40.08 MHz delivered from the Faraday Cage at Point 4, which will serve as a 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.

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.

While the machine is in colliding mode, the RF group guarantees a clean, stable and non-interrupted 40.08 MHz signal within the range of the experiment QPLLs. However, during access, after a beam dump, during periods of shutdown or repair, the RF-supplied bunch frequency can be (almost) anything and could even be missing. The experiments, therefore, need to implement a switch at the TTC input to select either the RF-supplied signal or a local reference.

The LHC Beam Position System

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 at Points 1, 2, 5 and 8. The BPTXs will be located about 175 m from the IP and will be used exclusively by the experiments. Button electrodes have been chosen for 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 interaction regions, thus determining whether the 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.

Determination of Collision Rates

The LHC Collision Rate Monitor - *Luminometer* – will provide a means to monitor the machine operation parameters and conditions [9]. Its anticipated applications include the initial beam finding and beam overlap maximization, equalization of the collision rates amongst the experiments, monitoring of the crossing angle, and the bunch-by-bunch measurement of the collision rate. The *Luminometers* will be installed in a slot inside the TAN absorbers and two technologies – fast ionization chambers and polycrystalline Cadmium Telluride detectors – have been studied.

ATLAS has proposed to install a dedicated detector – Luminosity measurement using Cerenkov Integrating Detector (LUCID) - for the monitoring the collision rate at Interaction Region 1 (IR1) [10]. The proposed detector consists of 200 gas-filled (C_4F_{10}) Cerenkov tubes per end to be installed in front of the TAS absorbers. The detector has a fast response to provide bunch-by-bunch information on the collisions.

RADIATION AND BEAM LOSSES

Introduction

The LHC machine and experiments will operate in an unprecedented hostile radiation environment. Secondaries, primarily from the high-luminosity pp-interactions for ATLAS and CMS and also from beam losses in the machine for ALICE and LHCb, will be responsible for the high radiation background which could damage the detector elements, including their electronics.

Radiation Monitoring

The need to monitor the radiation field has been acknowledged. The radiation monitoring system for the experiments and experimental areas is based on the following components [11]:

- A Beam Condition Monitor (BCM) situated around the beampipe within the pixel detector volume will provide online monitoring of the beam conditions with the possibility of requesting a beam abort, injection inhibit and detector power ramp-down. Studies of polycrystalline diamond (PCVDD) have ascertained the applicability of such technology to the BCM. The response of PCVDD to beam has been shown to be linear over ten orders of magnitude and has been proven to meet the stringent radiation-hardness conditions required for the LHC.

- A combination of the BCM with active and passive dosimeters will provide a mapping of the radiation field during the initial LHC operation phase in order to check the simulation results and identify possible leaks in the radiation shielding. Examples of active dosimeters include RadFETs, Optically Stimulated Luminescence devices (OSLs) and forward-biased p-i-n diodes, while Thermoluminescence Dosimeters (TLDs), Radio-Photo Luminescent (RPL) monitors and Polymer-Alanine foils will be used as passive devices.

- The combination of such active and passive dosimeters together with the ionization chambers of RAMSES [12] will provide a mapping of the integrated radiation exposure to be used for post-mortem analysis in case of equipment failure, for studies of activation levels to plan the accesses and to implement corrective measures like improvements to the radiation shielding.

Beam Losses

Several mechanisms have been identified as leading potentially to beam losses [13]. 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 IPs. 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 BCM 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. The accident duration at the LHC is estimated to be 260 ns, during which up to 10^{12} protons can be lost at Point 5 (CMS). The dose per unsynchronised LHC beam abort is shown in Figure 2. The experiment beam abort system will not be able to handle the fast speed of such an accident but it has been used as a worst-case scenario for benchmarking the BCM.

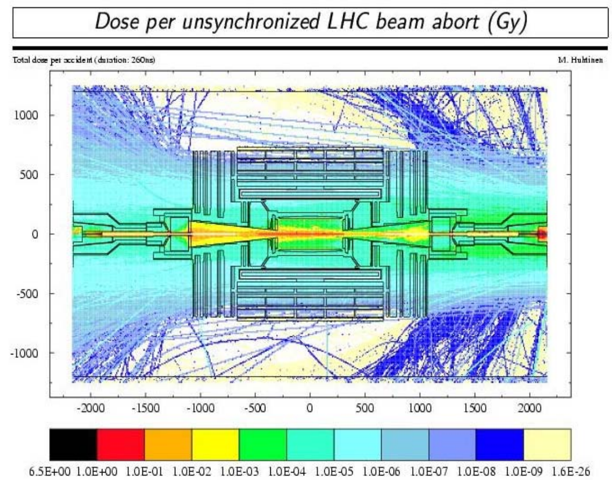

Figure 2: Dose at Point 5 per unsynchronised beam abort [14].

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 machine behaviour by the BCM. The BCM will operate independently from the other experiment sub-detectors and would give a response time of the order of two beam orbits.

Alongside many of the machine sub-systems, an input from the experiments to the machine Beam Interlock Controller is foreseen 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.

MACHINE-INDUCED BACKGROUND

The experiments request that the collision luminosities be coupled with low backgrounds both from the experiments themselves and from the machine. The machine-induced background is proportional to the beam current while particle fluxes from proton-proton collisions scale with the luminosity. The machine-induced background consists of the secondary particle flux produced by proton losses upstream and downstream of the IPs, i.e. in the arc cells, dispersion suppressors and straight sections. The secondary flux results from the inelastic and elastic collisions of beam particles with the residual gas nuclei, the inefficiency of the cleaning system and from proton-proton collisions at a high-luminosity IP giving energetic protons transported to and lost in an adjacent interaction region.

Due to the relatively low luminosity, both ALICE and LHCb are particularly sensitive to machine-induced background and shielding walls are being integrated into the tunnel lay-out. However, at IR2 (ALICE) and IR8 (LHCb), there is only a minimal space available for the installation of shielding between the detector and the beampipe.

Calculations for IR8 show that the integrated absolute rate of machine-induced background is 4×10^5 particles/s and is dominated by the beam-gas collisions [15,16]. The cleaning inefficiency and contribution of collisions at IP1 are found to be negligible. Although the LHC machine lay-out is symmetric, differences between the IR3 and IR7 cleaning insertions and between the β* values for ALICE and LHCb, result in separate calculations being required for IR2.

The more substantial forward radiation shielding at IR1 (ATLAS) and IR5 (CMS) will result in the radiation levels in the experimental caverns being low (1 Gy/year) and both ATLAS and CMS will be rather insensitive to the machine-induced background. The rates for muons, which are the only particles that will penetrate the shielding from the machine side, are estimated to be below 10 $\mu\ cm^{-2}\ s^{-1}$ [17,18,19].

Event rates from beam-halo muons and beam-gas collisions expected in ATLAS and CMS during an LHC single-beam period are found to useful for commissioning the experiments [20]. Beam halo muons can be used for calibration and alignment studies of the end-cap detectors while beam-gas collisions directly inside the inner detector cavity can provide data for the alignment of the tracker since such beam-gas events resemble pp collisions.

CONCLUSIONS

An overview of some issues relevant to the interface of the LHC machine and experiments has been presented. In an effort to ensure the highest quality data to be recorded by the experiments and the correct operation of the machine, these issues need to be understood and planned from now and should incorporate experience from previously and presently running facilities. Good communication between the LHC experiments and the machine is essential for the effective exploitation of the physics at the LHC.

The LHC experiments, in close collaboration with the LHC Machine, are developing tools and mechanisms to exchange information and to monitor the LHC beams and collisions.

REFERENCES

[1] http://cern.ch/lhc-data-exchange

[2] http://lhc.web.cern.ch/lhc/lemic/lemic.htm

[3] http://lhc.web.cern.ch/lhc/lcc/lcc.htm

[4] http://ab-div-co.web.cern.ch/ab-div-co-is/Controls/WG/LDIWG/Welcome.html

[5] http://itco.web.cern.ch/itco/cgi-bin/OverSiteList?conffile=../MeetingLists/LDIWG/meetings_CONFIG.pl&go=report

[6] http://lhc-logging.web.cern.ch/lhc-logging/

[7] http://ttc.web.cern.ch/TTC/intro.html

[8] *http://sl-div-bi.web.cern.ch/sl-div-bi/Conf&work/LHC-BI review/Slides/Savioz.Beam_Synchonous_Timing.ppt*

[9] EDMS Document Number 347396

[10] CERN/LHCC/2004-010, LHCC I-014

[11]http://lhcp.web.cern.ch/lhcp/TCC/PLANNING/TCC/RadmonWorkshop/radmon_radwg_worshop.htm

[12] http://proj-ramses.web.cern.ch/proj-ramses/

[13] O. Brüning, `Mechanisms for Beam Losses and their Time Constants', Session VIII: LHC Commissioning and Operation: Machine Protection, Chamonix XI 2001

[14] M. Huhtinen, private communication

[15] LHC Project Note 258 (2001)

[16] LHC Project Report 500 (2001)

[17] LHC Project Note 324 (2003)

[18] LHC Project Report 722 (2004)

[19] A.I. Drozhdin *et al.*, NIM A381 (1996) 531

[20] ATLAS Internal Report ATL-GEN-2004-001