LHC Machine and Experiment Interface Issues

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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.

I. INTRODUCTION

ATLAS and CMS are constructing general-purpose detectors in order to exploit the full discovery potential of the LHC machine. Their primary aim is to discover the Higgs boson, to explain the particle mass scale, and to search for other new particles such as those from Supersymmetry. They will be operational during the initial lower luminosity running as well as at the highest luminosity that will be available from the machine.

These experiments 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 both from the experiment itself and from the machine.

ALICE is a general-purpose heavy-ion experiment which is designed to study the physics of strongly-interacting matter and the quark-gluon plasma in Pb-Pb collisions. The ALICE physics programme also includes the study of proton-proton collisions at start-up, to commission and calibrate the experiment with beam, and proton-Pb and lighter ion collisions later. Proton-Pb running is required to benchmark the standard nuclear effects and to disentangle effects of the hot/dense medium.

Since the Time Projection Chamber (TPC) detector of ALICE can handle many thousands of simultaneous particles but only at relatively low event rates, the luminosity requested by ALICE is 10^{27} cm^{-2} s^{-1} for Pb-Pb and $<3 \times 10^{30}$ cm^{-2}s^{-1} for p-p running. The latter will be provided during normal high intensity proton running from halo-halo collisions with beam centres separated by $\geq 4\sigma$. With such a relatively low signal, ALICE will be sensitive to backgrounds during p-p running, in particular beam-gas at the collision point and the upstream straight section.

The LHCb experiment is designed to provide precision measurements of CP violation in B mesons, one of the major issues of the Standard Model. The experiment will exploit the large number of different B mesons produced at the LHC with an efficient trigger and particle identification. Due to its high trigger efficiency and the requirement of only one p-p collision per bunch crossing, LHCb requires only about 2% of the ultimate machine luminosity, i.e. $\sim 2 \times 10^{32}$ cm^{-2} s^{-1} at a β^* of 25 m. This will permit the exploitation of the experiment's physics potential from the very beginning of LHC operation.

Due to the relatively low luminosity, LHCb is sensitive to machine background (hadrons and muons) arising from the beam-halo and beam-gas collisions in the upstream residual gas. This is in addition to the dominant secondary particle background at the Interaction Point (IP) as for ATLAS and CMS.

Finally, TOTEM, to be installed at Point 5, will measure the elastic and inelastic scattering to deduce the total p-p cross section which is of interest both for studying the theory of strong interactions and for the accurate measurement of the LHC luminosity.

The following special conditions are required for the TOTEM runs:

- Small divergence beams (β^* of 1100 m).
- Detectors will be placed very close to the beams in Roman Pots in the warm straight sections of the machine.
- To avoid multiple scattering, dedicated runs with only 36 bunches will be needed and this together with the high β^* gives a luminosity of $\sim 10^{28}$cm^{-2} s^{-1}.
- No crossing angle with this special optics.

The lay-out of the LHC is shown in Figure 1. The experimental insertions hosting ATLAS, ALICE, CMS (and TOTEM) and LHCb are located at Points 1, 2, 5, and 8, respectively. Points 3, 4, 6, sand 7 are dedicated machine insertions and will house the cleaning sections, RF and beam dumps.

This paper presents some of the issues being discussed currently at the interface between the LHC machine and experiments. After reviewing the LHC operation parameters in Section II, the report analyses in Section III the requirements for the data exchange between the machine, experiments and technical services. Section IV presents the radiation field and beams losses in connection with the electronics and protection of equipment. The conclusions are given in Section V.

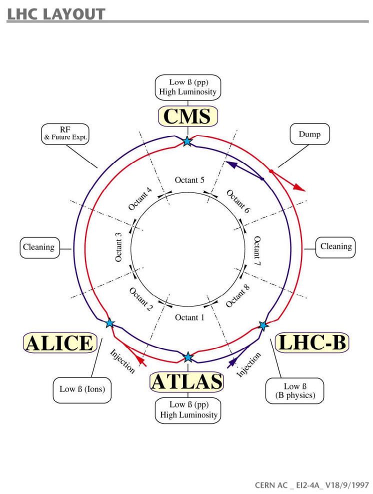

Figure 1: Lay-out of the LHC

The paper is based on discussions in working groups and committees, including the Ad-hoc LHC Machine-Experiment Parameter and Signal Exchange Working Group [1], the LHC Experiment Machine Interface Committee (LEMIC) [2] and the LHC Commissioning Committee (LCC) [3].

II. LHC MACHINE OPERATION

A. Machine Parameters

The construction of the LHC is well-underway, as is the installation of the first equipment and services. The LHC ring is scheduled to be complete in Q4 of 2006. Following a period of cool-down at the end of 2006, the machine's systems will be commissioned in Q1 of 2007.

Table 1: LHC Machine Parameters for Proton Operation

Parameter	Units	Nominal	Ultimate
Number of Bunches		2808	2808
Bunch Spacing	ns	25	25
Protons per Bunch	10^{11}	1.1	1.7
Average Beam Current	A	0.56	0.86
Norm. Trans. Emittance	μm	3.75	3.75
Longitudinal Emittance	eV.s	2.5	2.5
Peak RF Voltage	MV	16	16
RF Frequency	MHz	400	400
r.m.s. Bunch Length	cm	7.7	7.7
r.m.s Energy Spread	10^{-4}	1.1	1.1
IBS Emittance Growth	hr	115	76
Beta at IP1-IP5	m	0.5	0.5
Full Crossing Angle	μrad	300	300
Luminosity Reduction due to Crossing Angle		0.81	0.81
Luminosity at IP1-IP5	10^{34} cm^{-2} s^{-1}	1.0	2.3

The parameters for machine operation for proton running are given in Table 1, while those pertaining particularly to the Pb-ion operation are presented in Table 2.

Table 2: LHC Machine Parameters for Pb-ion Operation

Parameter	Unit	Nominal
Energy per Charge	TeV	7
Ions per Bunch	10^7	7.0
Number of Bunches		592
Bunch Spacing	ns	100
Full Crossing Angle	μrad	570
Luminosity at IP2	10^{27} cm^{-2} s^{-1}	1.0

The LHC will be filled with protons according to the scheme shown in Figure 2. Of the 3564 buckets making up one LHC ring, 2808 will contain protons. These buckets will be filled using 3- and 4-batch cycles from the PS Complex interleaved in the form 334 334 334 333, where each batch from the PS will consist of 72 bunches spaced by 25 ns (or initially by 75 ns). The gaps in the LHC bunch train are due to the LHC injection kicker rise-time (0.94 μs) and the LHC dump kicker rise-time (3 μs).

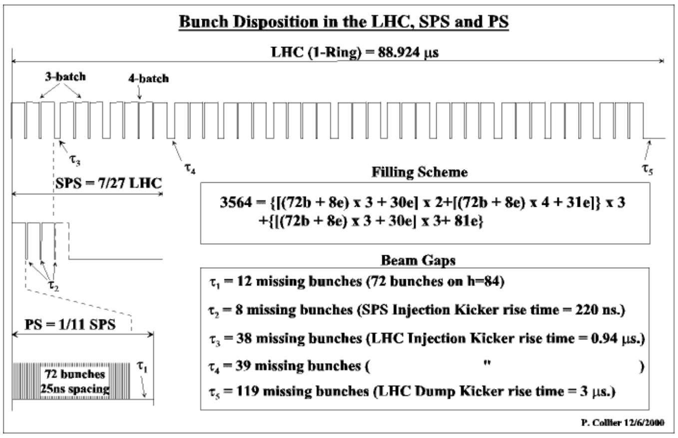

Figure2: Proton Bunch Disposition in the LHC, SPS and PS

The bunch disposition for Pb-ion operation will follow the scheme below where `b' stands for filled bunch and `e' stands for empty and where the nominal basic spacing is 100 ns:

3x[2x{13x[4b+1.25e])+7.75e}+(12x[4b+1.25e]+7.75e]+

1x[2x{(13x[4b+1.25e])+7.75e}+(8x[4b+1.25e])]+28.75e

B. Luminosity

The nominal luminosity of 10^{34} cm^{-2} s^{-1} for a total of 200 days corresponds to an integrated luminosity of 70 fb^{-1}, yielding of the order of 1000 Higgs events. The nominal luminosity will be reached only after a series of steps starting in April 2007. According to current ideas, a pilot run, consisting of a single beam and single bunch of about 5×10^9 protons, will be set up first. This will be followed by the introduction of the second beam with similar characteristics as the first to give collisions. Subsequently, the accelerator will be commissioned with a lower than nominal beam power in order to reduce the risk of quench and damage to the machine, derived from running with a 75 ns bunch spacing, corresponding to 940 bunches, and about one-quarter of the nominal bunch current. Under these conditions, the peak luminosity during this commissioning phase can not exceed 2×10^{32} cm^{-2} s^{-1}. Running with these machine commissioning conditions for the equivalent of 200 days could yield an integrated luminosity of ~ 2 fb^{-1}. After optimisation of the machine, the aim is to reach an instantaneous luminosity of 2×10^{33} cm^{-2} s^{-1} which could yield about 10 fb^{-1} of integrated luminosity for a 200-day equivalent run. It should be noted that due to LHC machine staging, which includes the partial installation of the dump dilution kickers, running at 75 ns bunch spacing in order to reduce the electron cloud effect and delaying installation of the 200 MHz RF capture system, a peak luminosity of 10^{34} cm^{-2} s^{-1} is ruled out for the initial physics run.

Assuming the current estimates on intra-beam scattering, beam-rest gas scattering and beam-beam interactions, a luminosity lifetime of about 14 hrs. is expected for proton operation, following which the beams will be dumped. The corresponding time for Pb-ion operation is ~8 hrs, and is limited by nuclear effects and naturally scales with the number of running experiments. The minimum turn-around time is estimated to be 1 hr., but could well be much longer, e.g. between 5 and 10 hrs., depending on the number of attempts needed to bring the machine back into collision mode. During this turnaround time it may be possible to have access into the machine tunnel and experimental areas.

C. Luminous Region

Calculations have been performed to estimate the luminous region around the 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 ± 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. A similarly good match was determined for the barrel and end-cap Pixel detectors and the end-cap Tracker.

D. 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.

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. Estimations for the ATLAS cavern show that a 2 mm settling of the floor from the time the concrete is poured to the time ATLAS gets possession of their experimental cavern and a 5.5 mm settling of the floor over the first 6 months thereafter due to the weight of the ATLAS experiment. Moreover, a 1 mm / year lift of the floor due to the hydrostatic pressure is estimated.

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 which allow 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.

III. LHC DATA EXCHANGE

A. ENTITIES TO BE EXCHANGED

Information to be communicated by the machine, experiments and the technical services was discussed in the LHC Data Interchange Working Group (LDIWG). 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.

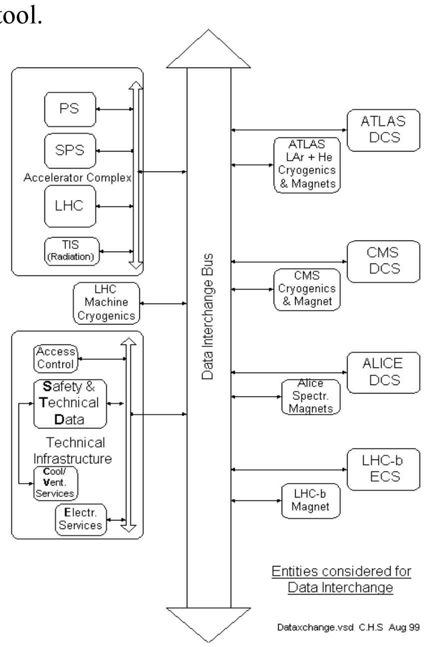

Figure 3: Entities considered for data exchange at the LHC

Figure 3 shows the conceptual lay-out of the entities considered for data exchange. The exchange is considered to be low frequency, at most about 100 kbps, and thus should not be limited by bandwidth, and should 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 may 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, is required. This should be made available on TV monitors throughout CERN and also accessible via the WWW.

B. *EXPERIMENT MEASUREMENTS ON 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 the rates of clusters of various kinds 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 10 s. Such measurements would require that the inner detectors, including the pixel detectors, are powered and operational and would only possible once stable beams are established.

C. *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 be 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.

D. *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 150 m from the IP in front of the D2 magnets and will be used exclusively by the experiments. The choice of pick-up technology will be made in collaboration with the experiments and candidate technologies include stripline couplers, button electrodes or wall current monitors.

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 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.

The choice of technology and location of the front-end electronics will determine the requirements for the cables. Although the cables for the BPTXs will be procured and installed by the LHC machine, they will be under the financial and logistical responsibility of the experiments. The experiments have expressed interest to pull cables to their galleries in the underground areas and from there to the underground counting rooms.

The front-end electronics will be under the responsibility of the experiments. The electronics should be a common development between all the experiments and the machine. To this end and to clarify all outstanding issues concerning the BPTXs, a technical liaison group is being set up between the experiments and the machine.

IV. RADIATION AND BEAM LOSSES

A. *RADIATION FIELD AND SHIELDING*

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 do damage to the detector elements, including to their electronics. Doses up to 1 Gy for 10 years of LHC operation at the ultimate luminosity are estimated for the experimental cavern of CMS at a distance away from the beam line, rising to 10^6 Gy along the beam line inside the experiment [4]. Such reported doses could do damage to even the electronics on the balconies in the experimental areas.

Radiation levels can be controlled to these levels because of the significant radiation shielding inside the experimental areas, thus making the experiments insensitive to the machine-induced background such as upstream beam losses. Muons make up most of the remnant radiation penetrating the shielding from the machine side, and their rate is estimated to be below 10 muons $cm^{-2}\ s^{-1}$ [5].

B. BEAM LOSSES

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 [7] 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 experiments could act on this time scale.

In addition, a recent 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 at Point 6. The accident duration is estimated to be 260 ns, during which up to 10^{12} protons can be lost at Point 5 (CMS) and the dose per unsynchronised LHC beam abort is shown in Figure 4. The experiment beam abort system will not be able to handle the fast speed of such an accident scenario. The installation of an absorber at Point 6 has been proposed to protect the machine (and CMS).

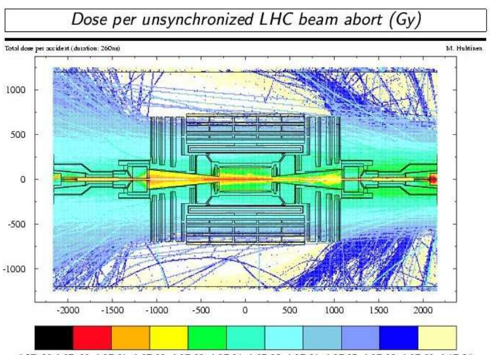

Figure 4: Dose at Point 5 per unsynchronised beam abort [4]

A dedicated machine protection system is being developed for the machine, and the experiments have also recently begun 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 is re-assuring to see that 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.

V. 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.

With five approved experiments, there will undoubtedly be compromises to be made and priorities to be fixed. Moreover, after initial operation, there may be requests for special running conditions, such as lower energies for comparison with Tevatron data and lighter ion species and various energies for the ion programme. Totally new experiments can not be excluded and already a sixth experiment MOEDAL is preparing its experimental design.

VI. REFERENCES

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