INTERFACING WITH THE LHC ACCELERATOR
DURING PHYSICS OPERATION

T. Wijnands

Abstract

A number of critical LHC machine experiments interface issues are highlighted. Particular emphasis is given to particle losses and their impact on the LHC performance. It will be shown how the risk of radiation induced failures to equipment can be reduced via shielding, radiation tolerant equipment designs and on-line radiation monitoring. Recent data on beam induced backgrounds and radiation at the Tevatron and in CDF (Fermilab) is given as an example.
Interfacing with the LHC accelerator during physics operation

T. Wijnands
CERN, 1211 Geneva 23, Switzerland
Thijs.Wijnands@cern.ch

Abstract

A number of critical LHC machine experiments interface issues are highlighted. Particular emphasis is given to particle losses and their impact on the LHC performance. It will be shown how the risk of radiation induced failures to equipment can be reduced via shielding, radiation tolerant equipment designs and on-line radiation monitoring. Recent data on beam induced backgrounds and radiation at the Tevatron and in CDF (Fermilab) is given as an example.

I. INTRODUCTION

When the LHC is operated according to the design specifications [1], protons will be lost from the beam in various ways during a fill for physics. Present estimates [2] indicate that for a nominal fill with $6 \times 10^{14}$ protons, approximately $2 \times 10^{14}$ protons will be lost during the fill and approximately $4 \times 10^{14}$ will eventually end up on the beam dump at the end of a physics run. The spatial and temporal distribution of these proton losses during the fill is important because it has a large influence on the LHC performance. In fact, it will be a major challenge to distribute proton losses in time and around the ring in such a way that the luminosity is maximised, the backgrounds are minimised and the design tolerances of the equipment in the tunnel, the underground areas and in the experimental caverns is not reached.

For a fixed machine design, proton losses and detector backgrounds can be modified by varying the position of the collimator jaws, reducing the beam intensity or the $\beta^*$. These issues are presented in detail in another paper presented at this conference [3]. This paper will focus mainly on the balancing of proton losses in time and space with respect to the equipment tolerances.

For nearly all equipment very close to the beams, design constraints are derived from estimates of the maximum power density caused by lost protons. Examples are the designs for the collimator jaws [4], the Front Quadruple absorbers (TAS) [5] and the D1 separation dipoles [6] which all use special materials to avoid melting and/or evaporation.

Further away from the beam, the deposition of radiation induced heat per unit volume is much lower and equipment design constraints are usually defined in terms of the hadron flux, the 1 MeV equivalent neutron flux and the total dose. Electronic components and systems are known to be very sensitive to the radiation and radiation tolerant components and designs are used in the tunnel, the underground areas and the experimental areas [7].

A similar approach was adapted for measuring proton losses. Close to the beam, Beam Loss Monitors [8] and the Beam Conditions Monitor [9] will provide spatial and temporal information on where the protons are lost. These monitors have a fast response time (100 $\mu$s or less) and are connected to the beam dump.

Further away from the beam, radiation monitors located at the position of the equipment will register the variation of the radiation levels due to lost protons. The response time of these radiation monitors is larger (1 ms or more) and excessively high levels will generate an alarm.

II. PROTON LOSSES

A. Spatial distribution

In high intensity beams, space-charge effects and injection errors lead to the formation of an inner beam core surrounded by a beam halo. Under normal operating conditions, the cleaning sections in IR3 and IR7 are designed to provide efficient cleaning of the halo and these areas will therefore inevitably become very radioactive.

The LHC is designed in such a way that the primary collimator jaws represent the smallest aperture available to the beams. Particles in the beam halo will therefore always hit the primary collimator jaws first (figure 1).

Figure 1 : The LHC aperture ($\sigma$ represents the beam size).

The secondary and tertiary collimators represent wider aperture limitations followed by the protection devices (the TCDQs, injection protection) and finally, the mechanical aperture of the beam pipe (diameter 56 mm).

In the high luminosity insertions, pp collisions will make the main contribution to the losses and the consequent radiation levels. Only inelastic scattering give rise to particles with at sufficient high angles to remain inside the experimental caverns. The elastic and diffractive collision products will flow down the beam pipe into the tunnel and may be lost in the long straight section or on the collimator jaws in IR or IR7.

In the regular ARCs, protons will scatter on residual gas molecules and may be lost locally. The amount of loss is directly proportional to the density of the residual gas, a quantity which is difficult to control during a physics fill.
In physics, the collimator jaws are practically the only operational tool available to redistribute the proton losses around the ring. Optimising the collimator settings is a complicated task as there are many collimators per beam (108 jaws in total) and because there are many beam loss monitors to survey (~3500 in total). In addition, there is the risk of quenching of the superconducting magnets and inflicting radiation damage to equipment. The manoeuvring between the quench limit of the magnets on the one hand and radiation damage to equipment on the other by adjusting the collimator setting will reveal an operational constraint of the LHC.

B. High luminosity regions

At design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ and a total cross section of 110 mbarn, the pp collisions in IP1 and IP5 generate 1190 W of power which is carried away by the collision products. Only the collision products from inelastic pp interactions that leave the IP at sufficient large angles will remain in the experimental caverns. Most of these particles will end up in the TAS absorber depositing approximately 270 W in the front absorber. The remainder of the power is deposited in the inner triplets (200 W), the D1-TAN area (210 Watt) and further downstream in the dispersion suppressor region (see table I).

<table>
<thead>
<tr>
<th>Collision</th>
<th>Destination</th>
<th>Deposited Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inelastic</td>
<td>TAS, triplet,D1,TAN</td>
<td>680 W</td>
</tr>
<tr>
<td>Single diffractive</td>
<td>Dispersion</td>
<td>220 W</td>
</tr>
<tr>
<td></td>
<td>Suppressors in IR</td>
<td></td>
</tr>
<tr>
<td>Single diffractive</td>
<td>IR7 cleaning</td>
<td>60 W</td>
</tr>
<tr>
<td>Elastic</td>
<td>IR3 cleaning</td>
<td>230 W</td>
</tr>
</tbody>
</table>

1. Beam induced power deposition in IR1 & IR5

The power induced in the superconducting parts of the low-$\beta$ quadruples have been a reason for concern because they may be sufficient to cause quenches. One obvious way to improve the situation would be to enhance the absorption of collision product by the TAS absorber but this has the disadvantage of increasing the amount of backscattered neutrons and thus the detector backgrounds. Therefore, a more complete simulation was carried out to optimise the designs of the TAS absorber, the absorbers for the low beta quadrupoles and the TAN absorber. In addition, additional collimators were placed in front quadrupole Q5 to avoid it from quenching.

Further downstream, simulations indicated rather high radiation levels in the RR tunnel enlargements [10]. This was equally a reason for concern because a large amount of electronic equipment will be installed here. The main source of the radiation was particle losses in the D1-Tan area and the collimator TCL.5 in front of Q5 quadrupole magnet. A staged shielding was adapted to reduce the radiation levels in the RRs around IR1 and IR5 by a factor 10 to acceptable low levels.

Simulation results, quench limits and radiation tolerances all have large uncertainties and only operation with beam can make clear where these operational limits are situated exactly. The manoeuvring between the quench limit, the radiation tolerance of equipment in the RRs to maximise luminosity while keeping the backgrounds to a minimum will reveal another operational constraint for the LHC.

III. DIAGNOSTICS

C. Protection Devices

During Physics operations, the Beam Loss Monitors (BLMs) and the Beam Conditions Monitors (BCMs) will protect respectively the superconducting magnets from quenching and the inner detectors from radiation damage.

The Beam loss Monitors will generate a beam dump trigger when the losses exceed previously defined thresholds. The superconducting main magnets can quench at very low loss levels (the equivalent of approximately 1000 protons at 7 TeV) so that this equally reduces the risk of inflicting radiation damage to electronic equipment. The BLMs located in the cleaning sections and those close to critical aperture limitations have a time resolution of 1 turn while the BLMs along other parts of the rings have a time resolution of 2.5 ms.

Figure 2: BCM sensors based on PCV diamond

The Beam Conditions Monitors are designed to protect sub-detectors from adverse beam conditions and to request a beam abort if necessary. Presently, the 4 BCMs foreseen to be installed in the CMS detector will provide a mapping of the radiation fields inside the detector with a turn-by-turn time resolution.

D. Radiation Monitors

The RADMON radiation monitors are designed to monitor radiation levels at the location of equipment in the tunnel, the underground areas, on the walls of the experimental caverns and inside the detectors.

In the accelerator tunnel and on the cavern walls, there is no strict space limitation and the RADMON devices at these locations can provide on-line digitised measurements of the dose, dose rate and hadron flux at a maximum 100 Hz.
type of RADMON devices are packed in aluminium shielding of 13 x 5 x 9 cm (figure 3).

Figure 3: RADMON radiation monitor for use in the tunnel, the underground areas and on the cavern walls.

The RADMON for the inner detectors are more compact and aim at measuring the integrated damage to the inner detectors from the long term exposure to radiation. Measurements of the integrated dose and the hadron fluence are made several meters away, outside the detector at a frequency of approximately once per day.

Figure 4: RADMON radiation monitor for use in the Inner detectors of ATLAS.

E. Post mortem analysis

The measurements of beam loses and associated variations of the radiation levels are distributed in space to provide a rather complete picture of the evolution of the proton losses in time and space in the high luminosity insertions at the time a beam dump request was triggered. The RADMON monitors will use a fast rotating buffering system where data will be stored locally at the gateway level. A post mortem server will make available the data from the BLMs, the BCMs and the RADMON radiation monitors. To the Detector Control Rooms and the CERN Control Centre (CCC).

A complete understanding of the spatial and temporal distribution of the losses in the high luminosity IRs throughout a physics fill will provide useful feedback to operations and will expose potential limitations in the design that could eventually limit the LHC performance.

F. Experience from CDF

The Collider Detector at Fermilab (CDF) is an experiment at the Tevatron where proton and anti-proton beams at 1 TeV collide head on. In a typical store, the proton beam has an intensity of 5-9 $10^{12}$ protons and the anti-proton beam 0.1 – 1.5 $10^{12}$ antiprotons producing a luminosity of $L = 1-5 \times 10^{30}$ cm$^{-2}$ s$^{-1}$.

Figure 5 : Top view of the CDF experiment. The proton beam is incident from the left. The arrows indicate the location of the 4 CERN radiation monitors.

During initial operation and after a major detector upgrade, a number of radiation induced failures appeared [11]. They varied from the failure of low voltage power supplies to the increased background and even silicon radiation damage in the detector itself. A detailed study revealed that both losses in the inner triplets and from the gaps in the detector shielding could contribute significantly to the increased radiation levels in the collision hall.

Figure 6 : Location of the Radiation Monitors at CDF

To confirm this hypothesis, 4 CERN radiation monitors with online readouts were installed inside the detector and on the cavern walls were the sensitive electronic equipment is
located (Figure 6). By interfacing the system with the accelerator controls network (ACNET) the variations of the radiation levels can also be related to machine operations.

![Figure 7: Hadron fluence in the CDF collision hal over a 90 days operational period. The location of the RADMON monitors is given in figure 6.](image)

During a 90 days operation period, a total of $2 \times 10^8$ hadrons per cm$^2$ with an energy $E > 20$ MeV were detected in the inner part of the detector. Close to the wall of the collision wall, the hadron flux is approximately 4 times lower. The accumulated dose in silicon over the same period appeared to be rather low (7 rad for the inner detector and 4 rad at the cavern walls). This suggests that the main radiation damage effect for the electronics is probably Single Events and not Total Dose.

**IV. CONCLUSIONS**

The LHC is a complex machine with tight operational margins, high stored energy in the beams and a lot of sensitive material and equipment in the tunnel and experimental caverns. During a physics fill, it will be an operational challenge to distribute the beam losses in time and space around the rings in such a way that quenching of the superconducting magnets is avoided, that radiation damage to equipment is limited, that backgrounds are kept to a minimum and the luminosity maximised.

Diagnostics such as BLMs, BCMs and the RADMON radiation monitors have sufficient temporal and spatial resolution to relate variations in the proton losses and the associated radiation levels to machine operations and to provide a complete post mortem analysis in case the machine protection devices trigger the beam dump.

Experience from CDF and Fermilab suggest that Single Events caused by high energy hadrons will probably be the main damage effect during initial operation of the LHC and that cumulative damage from Total Dose will only appear at a later point in time.

**V. REFERENCES**

[6] ATLAS radhard web page
[8] LHC-BLM-ES-0001.00 rev 2.0, DMS 328146