MACHINE PROTECTION FOR THE EXPERIMENTS OF THE LHC

R.B. Appleby*, D. Macina, CERN, Geneva, Switzerland

Abstract

The LHC stored beam contains 362 MJ of energy at the top beam energy of 7 TeV/c, presenting a significant risk to the components of the machine and the detectors. In response to this threat, a sophisticated system of machine protection has been developed to minimize the danger, and detect potentially dangerous situations. In this paper, the protection of the experiments in the LHC from the machine is considered, focusing on pilot beam strikes on the experiments during injection and on the dynamics of hardware failure with a circulating beam, with detailed time-domain calculations performed for LHC ring power converter failures and magnet quenches. The prospects for further integration of the machine protection and experimental protection systems are considered, along with the risk to near-beam detectors from closed local bumps.

INTRODUCTION

The Large Hadron Collider at CERN will operate in proton-proton or ion-ion collision mode, with two beams housed in a 27 km tunnel. The machine is composed of 8 sectors, with 8 arcs and 8 long straight sections, and there are currently 6 approved experiments spread over 4 interaction regions. The stored proton beam at the top energy of 7 TeV/c and at nominal intensity contains 362 MJ of energy, which is a considerable increase over existing machines and presents considerable risk to the elements of the machine. This beam also presents considerable risk to the experiments, particular when the experiments present detector regions close to the beam (near-beam experiments). For example, the forward region of the CMS experiment contains the TOTEM [1] experiment, comprising of a set of roman pots sitting as close as 10 σ from the 7 TeV/c proton beam, which is almost as close as some elements of the collimation system. The effective protection of these near-beam experiments requires integration into the primary machine protection system [2] and ensuring they are as fully protected as possible from beam strikes.

In this paper, the protection of all the LHC experiments from the machine is considered and the degree of protection evaluated during injection of setup bunches and during normal operation with stored circulating beams. It is very challenging to completely and reliably protect the experiments throughout the life of the LHC and sometimes very rare events occur, e.g. [3]. However the current systems of machine protection provide a high level of protection for the experiments for the nominal machine layout.

INJECTION

The risks to the experiments when injecting arise from the incorrect fields of magnet in the arcs or long straight sections. These ultra-fast failure scenarios, at a time scale of less than 1 turn, can arise from incorrectly set magnets on injection, a communication error or from faulty hardware. The subsequent first turn distorted orbit may strike part of the machine or detector regions, causing partial loss or a direct strike of an injected bunch. The potential impact of this class of accident is reduced by the use of a low population of injected protons - the pilot, safe or setup bunch - where the injected number of protons is limited to 3-4 $\times 10^{10}$. This limit is set to minimise the damage caused by beam strike, whilst still allowing operation of the machine elements. Further protection to injected beam loss is provided by the beam interlock system, which only permits injection when the LHC ring is ready for beam, and the magnet current interlocks, which are done in software and controlled by the Software Interlock System (SIS).

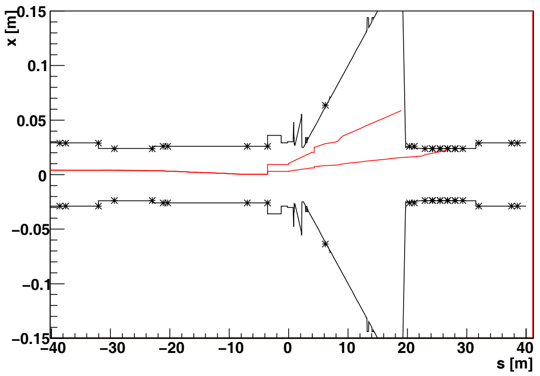

Figure 1: The range of compensation dipole corrector (MBXWH) settings which are dangerous for the LHCb beam pipe and interaction region magnets for beam 1 and excess current in the magnet. On this plot s=0 corresponds to the interaction point and the centre of the experimental cavern.

The first-turn beam strikes for the experiments have been studied for LHCb and ALICE in [4] and for ATLAS in [5]. Figure 1 illustrates these calculations, and shows the envelope of injected beams which could strike either the machine or parts of LHCb for incorrect injection settings of the LHCb compensation dipole corrector MBXWH. Specifically, this figure shows the possible beam strikes for beam 1, where the current in the magnet is increased from nominal to the design maximum. An analogous calculation for ALICE is shown in the left plot of fig-

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[*] robert.appleby@cern.ch

ure 2 for the case of a first-turn field error in the separation dipole D1, which can cause injection trajectory changes due to the high field strength. The impact on the beam strike scenarios with injection jitter (1.5σ in both planes) can be seen in the right plot of figure 2, where a Monte Carlo calculation of the beam size and envelope shows potential beam strike on LHCb for errors in the final triplet corrector MCBXH.

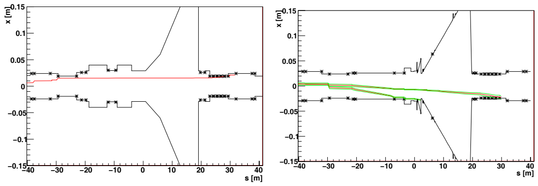

Figure 2: The left plot shows a possible MBX.4L2 (D1) dipole settings which is dangerous for the ALICE beam pipe and interaction region magnets, where s=0 corresponds to the interaction point and the centre of the experimental cavern. The right plot shows the range of the corrector on Q1, MCBXH, settings, which are dangerous for the LHCb beam pipe and interaction region magnets for beam 1 and excess current in the magnet. The effects of injection jitter and 3σ beam envelope scraping have been included. In this plot, the beam centroid is shown in red and the beam envelope is shown in green.

The protection from first turn beam strikes on the experiments arises from only permitting injection into an empty machine, only injecting a reduced proton bunch (pilot or setup bunch) and from the software interlocks. These magnet current interlocks will provide protection from magnet mis-settings provided they are set sufficiently tightly to prevent the beam strike scenarios illustrated by figures 1 and 2. For the IR region corrector dipoles, the software current interlocks are initially set to an equivalent kick angle of 100 μ rad, which is shown in [4] to be sufficiently tight to avoid beam accidents. Similarly, the separation dipole interlocks are initially set to 3% of nominal current, which again is sufficient to protect against injected beam accidents [4]. The results and level of protection for ATLAS and CMS are similar, with some differences due to the TAS.

A further source of injection turn orbit distortion can arise from misalignment of the final triplet, where a kick of 100 μrad can be caused by a misalignment of the order of 1 mm. The arguments for magnet errors apply to this distortion and the experiments should be protected from a kick of this magnitude.

CIRCULATING BEAM

There are a large number of failures that can impact a stored beam, with a variety of time constants. The most critical failures are those which happen on the shortest time constants and strongest magnets, for example the failure of a normal conducting separation dipole in a region of large β-function, the quench of a string of arc dipole magnets, or the failure of power converter during injection and the subsequent setting of the output voltage to the maximum value [6, 7]. The resulting magnet field change will cause an orbit distortion around the LHC ring for the case of a dipole failure (including in the aperture restrictions of near-beam experiments and in collimators), a β-beat and tune shift for the case of a quadrupole failure and higher order beam dynamical effects for the case of higher order element failure, and particles will begin to touch the aperture as soon as several turns after the start of the failure. The time constant and the distribution of the loss depends on the class of the failure and the location in the ring. The protection against these losses takes the form of passive absorbers installed at key locations, together with active monitoring through beam loss monitors located close to aperture restrictions and monitoring devices such as magnet current monitors. These monitoring devices are capable of issuing a beam dump request though the beam interlock system, which can dump the beam within several hundred microseconds.

To demonstrate the protection of the near-beam experiments from hardware failures, figure 3 shows the time-dependent proton distribution for a 450 GeV beam with collision optics at the TOTEM roman pots located 220 m from the interaction point of CMS, when at $t = 0$ the power converter RD1.LR1 powering the LSS1 separation dipoles D1 fails. This failure causes an exponential change in the separation dipole fields and a subsequent deviation of the closed orbit around the LHC ring. The calculations shows the orbit deviation at TOTEM occurs very rapidly and beam loss begins within a few turns. The location of the beam loss around the ring is shown in figure 4, where the peaks correspond to losses on primary and secondary collimators in LSS7. This loss would be detected on adjacent beam loss monitors, triggering a beam dump, or the fast current change in the separation dipoles would be detected by a current monitor, again triggering a beam dump. Therefore figures 3 and 4 show that the TOTEM pots are in the shadow of the collimations system and are protected against the failure of the power converter RD1.LR1 provided the collimators are correctly aligned. In [6], studies have been done for all the near-beam experiments for 450 GeV and 7 TeV collision optics stored beams, where it was showed that the experiments are always in the shadow of the collimation system for the failure scenarios considered.

The available aperture for the beam in the region of a near-beam experiment can be reduced by the formation of a closed local bump, which can be created the correctors available for global orbit correction, crossing angle and separation bump creation. The bumps can be made by an operator or, albeit unlikely, as a result of an orbit correction algorithm. The 10σ beam distance for TOTEM corresponds to 1 mm for the horizontal pot in the 220 m station, which is the most vulnerable to local bumps. The left-hand plot of figure 5 shows a 3-magnet horizontal closed bump

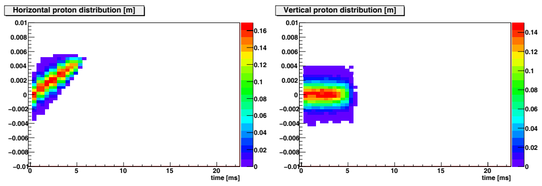

Figure 3: The horizontal and vertical proton distribution at the TOTEM roman pots as a function of time, for a circuit error in RD1.LR1. The calculation was made for a 450 GeV stored beam with nominal collision optics.

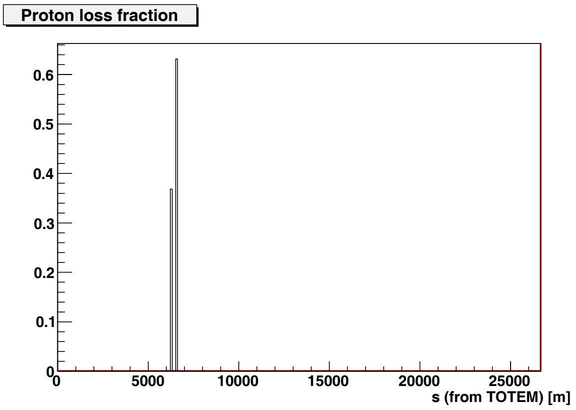

Figure 4: The proton loss map around the ring for a circuit error in RD1.LR1. The calculation was made for a 450 GeV stored beam with collision optics. The major loss spike corresponds to loss on a primary collimator.

across the 220 m TOTEM station, which is opened 199 m from the IP and closed after the TOTEM station. This bump, with correctors strengths consistent with the orbit correction creates a horizontal orbit distortion of +1 mm at the 220 m TOTEM station, sending the beam into the horizontal pot on the outside edge of the beam pipe. The right-hand plot in figure 5 shows the possible vertical bumps at 220 m, which cannot impact the vertical detectors if the vertical correctors are kept within their limits (this excludes the allowance of global orbit correction, which provides a further safety margin). The correctors used to apply the local bumps across TOTEM are slow, and change at 0.5 A/s and so a bump of 1mm at TOTEM will be applied over a long timescale of many seconds. However, it should be noted that there are many ways to create closed bumps across the experiment and the subsequent reduction of aperture in this region is potentially very dangerous to the near-beam detectors.

Finally, the possibility exists of an circulating beam asynchronous beam dump, where an abnormal orbit propagates around the LHC ring. This can potentially cause a large orbit distortion around the near-beam experiments and potential beam loss. For further details and a full discussion see [8].

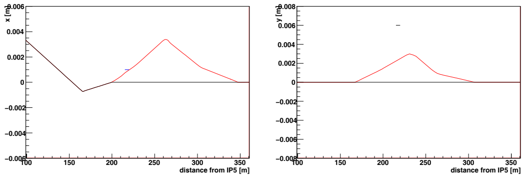

Figure 5: The formation of horizontal and vertical local closed bumps across the TOTEM 220 m station. The available correctors can make a dangerous horizontal bump, but not a vertical bump. The black line shows the ideal orbit, the red line shows the bumped orbit and the blue line denotes the physical boundary of the TOTEM pot.

CONCLUSION

In this paper the protection from the LHC machine of the experiments is reviewed. From ultra-fast injection turn beam strikes the experiments are protected from by only permitting reduced population proton bunches to be injected into an empty machine, coupled with the use of software interlocks on the magnet currents. This provides sufficient protection for all experiments provided the software interlocks are maintained. Longer-timescale scenarios can be found for a stored circulating beam, when a magnet fails or quenches, or a power converter fails. The protection against these kinds of scenarios comes from well-aligned passive protection systems, ensuring the experiments are in the shadow of the collimators, and the use of active monitoring devices connected to the beam interlock system. These systems should provide sufficient protection for the experiments. Finally, local bumps across experiments can reduce the available aperture significantly, and their formation needs to be carefully monitored using the beam loss monitor and magnet current interlock systems.

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