EFFECT OF COLLISION PATTERN IN THE LHC ON THE BEAM STABILITY: REQUIREMENTS FROM EXPERIMENTS AND OPERATIONAL CONSIDERATIONS

G. Papotti, G. Arduini, R. Giachino, W. Herr, E. Métral, T. Pieloni, CERN, Geneva, Switzerland
S.M. White, BNL, Upton, New York, USA; X. Buffat, N. Mounet, EPFL, Lausanne, Switzerland

Abstract

Coherent instabilities of bunches in the LHC bunch train can be observed when the tune spread from beam-beam interactions becomes insufficient to ensure Landau damping. In particular these effects are seen on bunches with a reduced number of beam-beam interactions due to their collision pattern. Furthermore, such a reduction of the necessary stability can occur during the processes when the beams are prepared for collisions or during the optimization procedure. We discuss observations and possible countermeasures, in particular alternatives to the existing beam manipulation processes where such a situation can occur.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN, Geneva, is a 27 km long circular accelerator and collider [1]. It features 8 straight sections: 4 Interaction Points (IPs) are reserved for accelerator equipment and 4 house particle physics experiments. IP1 and 5 contain ATLAS and CMS, the high luminosity experiments, while IP2 and 8 accommodate ALICE and LHCb, together with beam injection (beam 1 through IP2, clockwise; beam 2 through IP8, counter-clockwise).

The luminosity requirements of the four experiments are very different [2]. While the two high luminosity experiments require to push the high intensity proton physics performance, Alice and LHCb have luminosity limitations. The different luminosity requirements impact the choice of beam parameters, the construction of the filling schemes and other operational choices (e.g. β^* at the IP, the need for luminosity levelling techniques, etc.). The operational settings in 2012 are recalled in more detail next.

Recurrent observations of beam instabilities (i.e. loss of Landau damping [3]) drove changes in the way the LHC was operated in 2012. This paper concentrates on the changes put in place to overcome the observed instabilities, e.g. changes in the physics filling pattern and in the way the beams are brought into collisions. Alternative ideas, not yet exploited in operation, are also proposed.

EXPERIMENTS REQUIREMENTS

The Alice and LHCb experiments run with strong pile-up limitations in high intensity proton operation: Alice at $\mu \approx 0.02$ and LHCb at $\mu \approx 2.5$ (the pile-up μ is the number of inelastic interactions per bunch crossing). The limitations come from various factors that range from detector damage to event size limitations, to data taking optimization [2]. A less aggressive $\beta^* = 3$ m was used in IP2 and 8 with respect to $\beta^* = 0.6$ m used in IP1 and 5 in 2012, in addition to techniques of luminosity control and levelling.

Concerning LHCb, luminosity levelling on the maximum possible number of bunch pairs was the only way to achieve the integrated luminosity targets in the available time (i.e. at least 1 fb^{-1} per year). The luminosity was operationally levelled by transversely offsetting the beams at the IP since 2011 [4], so that the experiment could run at a constant instantaneous luminosity of $4 \cdot 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$.

Given that the pile-up limitation in Alice is even stronger, the experiment ran for most of 2012 based on collisions of the "main" bunches with so-called "satellite" bunches ("main-satellite" collisions). Satellites bunches have a much lower charge (about a factor 1000 lower than the main bunches), contained in buckets at 25 ns from the main ones (which are at a 50 ns spacing). Levelling by transverse offset was also used when necessary.

The use of satellite bunches is possible only thanks to the 50 ns spaced "main" bunches, and will not be applicable in the case of use of the nominal 25 ns spaced bunches. In case of use of 25 ns beams, collisions in Alice will have to rely on "main-main" collisions with a large transverse offset (e.g. $\approx 4-5\sigma$ was used in 2011), higher β^*, etc.

2012 FILLING SCHEMES

Many constraints have to be taken into account in the creation of a filling scheme, but here we recall only a few, namely the experiments location and the possible bunch spacings. ATLAS, Alice, CMS are located at the IP symmetry point, LHCb is 11.25 m away from it. ATLAS and CMS are diametrically opposed, so the same bunch pairs collide in the two experiments. Bunch spacings that can be created in the LHC injector chain are: 25 ns, 50 ns, 75 ns, 150 ns, or >250 ns. Higher bunch frequencies cannot be handled by the experimental readout.

Due to the experiments location, a four-fold symmetry in the filling pattern allows achieving the highest number of colliding pairs. Changes to bunch spacing, emittance or intensity are possible during filling, but often cumbersome due to the way beams are prepared and tuned at the injectors. These changes are preferably avoided and the injected bunches have similar characteristics across filling, so that colliding pairs at the different IPs are also similar.

The filling scheme used in the first part of 2012 was designed to maximize the number of colliding pairs for IP1/5

ISBN 978-3-95450-122-9

Table 1: Number of main-main collisions per IP for two physics filling schemes used in 2012. The schemes are based on 50 ns spaced bunches. ALICE ran on main-satellite collisions, thus with 0 main-main collisions.

Scheme	IP1/5	IP2	IP8
1	1331	0	1320
2	1377	0	1274

and 8, resulting in the number of colliding pairs indicated in the first line of Table 1 (scheme 1).

Problems with this filling scheme were observed already in mid-May 2012, when fills were terminated prematurely due to instabilities causing abundant losses (see for example Fig. 1). The instabilities affected only selected bunches, which had the peculiarity of colliding only in IP8 (levelled by separation). The lack of Landau damping with respect to the other bunches that collide in IP1/5 was identified to be the reason for the development of the instability [3].

The easiest cure to the instability was then to change the filling scheme so to have head-on collisions in IP1/5 for all bunches, and thus gain the head-on beam-beam tune spread that would provide the necessary damping. Note that head-on collisions in one IP only would have been sufficient, but this is not possible due to the IP1/5 location symmetry. The different experiments can be provided a different number of colliding pairs by shifting the injection buckets appropriately: scheme 2 in Table 1 was obtained by shifting 3 injections with respect to scheme 1 and was used for physics until the end of the year, apart from small variations, presenting no issues as the ones previously described. The scheme variations concerned the initial short train used for transfer line stability verification. This train consisted of 12 bunches in the beginning of the year, and 6 bunches later on. These trains were used to provide non colliding bunches in IP1/5 left for systematic background studies for ATLAS and CMS (e.g. 3 bunches in Scheme 2). Note that, in case of 25 ns or 75 ns beams, the filling scheme can be

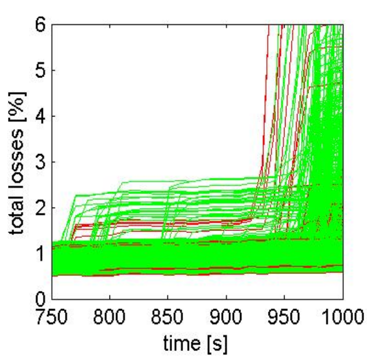

Figure 1: Percent losses per bunch for beam 2 in fill 2731 (time since the start of squeeze): some bunches go unstable and lose intensity non negligibly. Red curves for bunches colliding in IP1/5, green for bunches colliding in IP1/5/8.

arranged so be symmetric and have maximum number of collisions in IP8.

2012 OPERATIONAL CYCLE

The 2012 operational cycle for nominal proton physics operation was divided in the following phases: preparation of the machine for injection ("ramp down" of the magnets from top energy, or "precycle" after power off, to ensure magnetic reproducibility); injection of beam in the two rings; energy ramp (from 450 GeV to 4 TeV); betatron squeeze from $\beta^* = 10$ m to $\beta^* = 0.6$ m (for IP1 and IP5, or to 3 m for IP2 and IP8); "adjust" phase (when the beams are made collide, by collapsing the separation bumps); then beams are left in collisions for physics production for several hours. The crossing and separation planes in IP8 were tilted for collisions with respect to the standard horizontal and vertical scheme [5]. This allowed avoiding tertiary collimator re-setup that would have otherwise been required at each LHCb spectrometer polarity flip (which can be as frequent as about every ten days of physics production).

In the first part of 2012, the preparation of the "LHCb tilting" procedure was done after the separation bumps collapse and in the same function (for simplicity, i.e. it could have been easily removed if needed).

Instabilities starting at the end of squeeze were observed throughout 2012, with both octupole polarities. They caused beam losses, emittance blow-up and loss of fills; their origin is not fully understood [6]. In a few occasions early on in the run, it was tried to bring the beams into collisions as quickly as possible so to take advantage of the beam-beam tune spread. This was ineffective as the beams were yet not fully head-on during the LHCb tilting, but rather separated by a fraction of a sigma, as the smaller fine tuning was missing (luminosity scan knobs). In order to advance the Landau damping from head-on beam-beam tune spread, the adjust function was split into two in the middle of the run so to perform LHCb tilting only after having setup collisions in IP1/5 and 2 (see Fig. 2). This change was made coincide with the recovery that regularly follows the programmed stops for planned maintenance, so to profit of an already planned period of intensity ramp-up.

The price to be paid was a short delay in making the beams available for physics as two functions were played instead of one (from 220 s, to 65+220 s, plus the time to perform luminosity scans and load the second function on the power converters). It also has to be pointed out that the instability was not cured, and emittance blow up on selected bunches was still observed after the change [7], but further fill dumps were avoided. Moreover, the losses during the process became much more reproducible [8].

ALTERNATIVE SCHEMES

A minimum of stability is reached when the beam separation is at $\approx 1 - 2\sigma$ (more on this is reported in [9]), and this has two types of consequences on operation. Firstly,

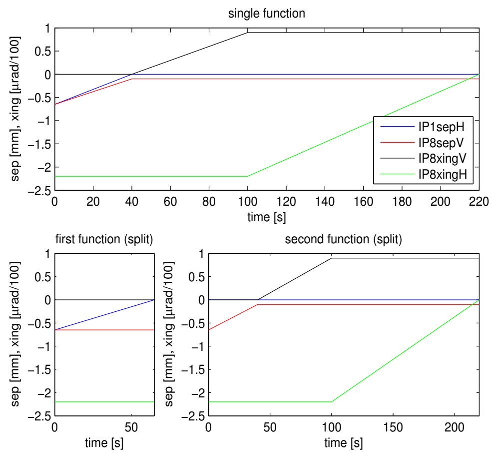

Figure 2: Functions describing the collapsing of separation bumps and changes of crossing angles in adjust. Top: initial function used in 2012; bottom: split functions.

during the process of collapsing the separation bumps in the adjust phase, the crossing of the critical region is unavoidable as the speed for the bump change is finite, but a few solutions can be devised. On one side, the collapsing should be made as fast as possible (the speed of the magnetic field change is limited by the Power Converters that power the magnets used for the bump). In 2012, the bumps used the MCBX families (common to the two beams), but alternative bump schemes that do not include them would allow a faster speed while providing sufficient strength. Another option is to collide one IP (or one plane) at a time, so to go through the minimum of stability for only one IP (or plane) at a time. The time required scales linearly with the number of IPs done sequentially, e.g. indicatively twice the time is required for working on one IP at a time with respect to two IPs at once.

During 2012 machine studies, it was also tried to bring the beams into collisions during the squeeze, and continue the squeeze with colliding beams [10]. This allows to take advantage of the abundant tune spread from head-on beam-beam before stability can become critical. Colliding during the squeeze (and β^* levelling) is considered for operation already after the Long Shutdown of 2013-2014 (LS1).

A similar configuration in which the stability reaches a minimum happens also while levelling with a transverse offset. In order to maintain the desired luminosity at IP8, the offset was adjusted during a physics fill in small steps so to modulate the overlap between the two beams to obtain the desired rates [11]. This can result in a non-negligible amount of time spent in the region with critical stability. No real limitations to levelling with transverse offset were found, though, as long as the offset bunch pair had enough tune spread by head-on collisions elsewhere (i.e. in IP1/5). Consequently, luminosity levelling by transverse offset is still an option for IP2 or 8 after LS1, provided that the bunches collide head-on in IP1/5. This can be easily achieved by the use of symmetric filling schemes.

CONCLUSIONS

Instabilities often affected the LHC beams in 2012, for the first time in LHC operation. Proton physics operation was steered continuously to try and cure these instabilities. Two successful examples are presented in this paper: a change of filling scheme to overcome the loss of Landau damping for bunches that lacked tune spread, and the anticipation of the setup of collisions in the other IPs with respect to LHCb tilting so to profit earlier on from head-on tune spread. Other possibilities for future operation are also sketched.

ACKNOWLEDGEMENTS

The authors thank the operation shift crews for the abundant observations of instabilities. Many colleagues in the accelerator physics group are also acknowledged for the abundant discussions on the instabilities and their sources.

REFERENCES

[1] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, "LHC Design Report", CERN-2004-003-V-1.

[2] R. Jacobsson, "Needs and requirements from the LHC physics experiments", Proceedings of the ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders (BB2013), Geneva, 18-22 March 2013.

[3] W. Herr et al.,"Observations of instabilities in the LHC due to missing head-on beam-beam interactions", TUPFI032, these proceedings.

[4] G. Papotti et al., "Experience with Offset Collisions in the LHC", Proceedings of the 2nd International Particle Accelerator Conference (IPAC11), San Sebastian, Spain, 4-9 Sep 2011, TUPZ025.

[5] R. Alemany-Fernandez et al., "Study and Operational Implementation of a Tilted Crossing Angle in LHCb", TUPFI011, these proceedings.

[6] T. Pieloni et al., "Observations of two-beam instabilities during the 2012 LHC physics run", TUPFI034, these proceedings.

[7] M. Hostettler et al., "Luminosity lifetime at the LHC in 2012 proton physics operation", TUPFI029, these proceedings.

[8] G. Papotti et al., "Beam losses through the LHC operational cycle in 2012", TUPFI028, these proceedings.

[9] X. Buffat et al., "Head-on and Long range Beam-beam Interactions in the LHC: Effective Tune Spread and Beam Stability due to Landau Damping", TUPFI035, these proceedings.

[10] X. Buffat et al., "Colliding during the squeeze and β^* levelling in the LHC", TUPFI033, these proceedings.

[11] F. Follin and D. Jacquet, "Implementation and experience with luminosity levelling with offset beam", Proceedings of the ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders (BB2013), Geneva, 18-22 March 2013.

ISBN 978-3-95450-122-9