

CYCLE WITH BEAM: ANALYSIS AND IMPROVEMENTS

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Abstract

The LHC 2016 proton beam cycles will be analysed, and proposals for improvements will be made based on the results. Some other suggestions are proposed for reducing the beam cycle time, for example modifying the combined ramp and squeeze, and their effects quantified. The objective is to present a synthesis of quantified potential improvements as a basis for further discussion.

INTRODUCTION

This paper looks only at the modes where beam is present. As such this excludes the determination of turnaround time, which is treated separately [1,2,3]. In 2016 a total of 178 fills reached Stable Beams.

Method

The analysis presented in this paper references only proton fills used for physics (containing Stable Beams mode). In 2016 this was almost exclusively with 25 ns fills. The determination of the moment when moving from one phase to the next is obtained by analysing when the beam mode is changed, according to the timestamps stored in the logging database. Beam modes are set by the LHC sequencer and thus this allows a good method reproducibility.

Further notes on the choice of beam modes are referenced in [4], explaining why some modes are not considered.

For each phase of the cycle the average time was calculated. In order to reduce the dependency on the tail of the distributions, which is mostly representative of problems and special fills rather than standard operation; the median value was also computed. By removing the tails, the median tends to remove the effect of the exceptional events to give a value which is representative of typical day-to-day operation.

THE 2016 LHC NOMINAL CYCLE

2016 v 2015

Several changes were introduced to the nominal cycle in 2016 compared to 2015. In particular the squeeze beam process, where the Beta* is changed to the physics value, was partly moved into the ramp, thus the ramp is now a 'Combined Ramp and Squeeze' (CRS). Previously the Beta* at IP1 and 5 was set to 10m until the start of the squeeze, however with the CRS the Beta* at the end of the ramp is 3m.

Although the CRS saved a significant fraction of the squeeze time, the Beta* in 2016 was chosen to be 40cm, whereas a value of 80cm was used in 2015. The luminosity

potential thus benefitted significantly, however the total squeeze beam process time to achieve the new Beta* target had to be increased to a similar length as used in 2015.

Finally during the Adjust beam mode, an additional beam process was necessary to implement an orbit bump close to the TOTEM roman pots, to meet the experiment request for adequate dispersion.

Table 1: Average time of beam modes in 2015 and 2016

Mode	Average 2015	Average 2016	Difference
Injection	72 min	65.6 min	-6.4 min
Prepare Ramp	10 min	4.9 min	-5.1 min
Ramp	20 min	20.5 min	+0.5 min
Flattop	5.9 min	5.6 min	-0.3 min
Squeeze	15.7 min	18.1 min	+2.4 min
Adjust	13.7 min	16.1 min	+2.4 min
Stable	5.7 hrs	10.0 hrs	+4.3 hrs
Total	137.3 min + 5.7 hours	129.0 min + 10 hours	-6.5 min +4.3 hours

Injection

The injection phase is the most intensive phase of the LHC cycle, with several manual actions performed and many factors that may have an impact on its length.

The injection phase is divided into two distinct phases: the setup of the machine with pilot beam intensity, and the setup and injection of the physics beam.

The pilot phase should be reproducible as the same actions are performed each time. Typically the correction of the orbit, RF phase, tune, chromaticity and coupling. However the total time is heavily influenced by machine availability, as demonstrated by the difference between the mean time of 23.5 min, and the median time of 14.6min.

The physics phase is prone to more variability, dependent on whether the transfer line trajectory requires correction (necessitating additional 12b trains, followed by dumping and starting to fill again), and also the number and length of trains being injected. The availability of beam from the injectors, and intensity of the circulating beam, also has a significant influence. By considering all fills reaching stable beams, a mean time of 39.2 min is achieved, and a median of 37.0 min. However this included many fills during the intensity ramp up which have fewer injections. By considering fills of more than 2000 bunches, the mean increases to 42.1min, for a median of 37.8min.

Two important situations present throughout most of 2016 influence the injection time: the status of the injection kicker vacuum (MKI8) [5], and the limitations of the SPS dump [6]. The Injection Kicker had a direct influence on the peak intensity permitted in B2, as injecting a proton current of more than $\sim 2.4 \times 10^{14}$ would cause a pressure rise to exceed the interlock level, preventing further injections.

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The SPS dump limitation limited the maximum length of the trains to 96 bunches (compared to the theoretical maximum of 288b), thus imposing an increase in the number of injections to reach a given total bunch count.

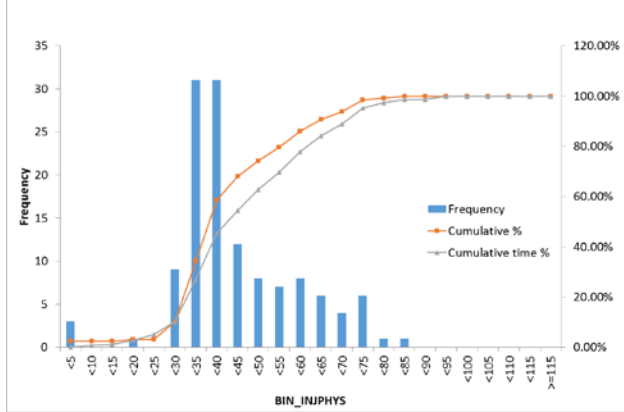


Figure 1: Histogram of time in injection physics beam mode (where more than 2000b are injected)

Considering injection of both the pilot and physics beams of more than 2000b, the average time in 2016 was 65.6min, with a median of 52.4 min.

Further details are discussed in [7].

Prepare Ramp

This beam mode is declared when the injection process is completed and some operations, such as change of feedback reference, settings incorporation and loading are done to prepare for the energy ramp. This phase is well reproducible and the distribution is quite narrow with an average of 4.9 min and a median of 4.2 min. In seven cases the beam mode lasted more than 10 minutes, and all can be attributed to problem solving, with no particular pattern identifiable.

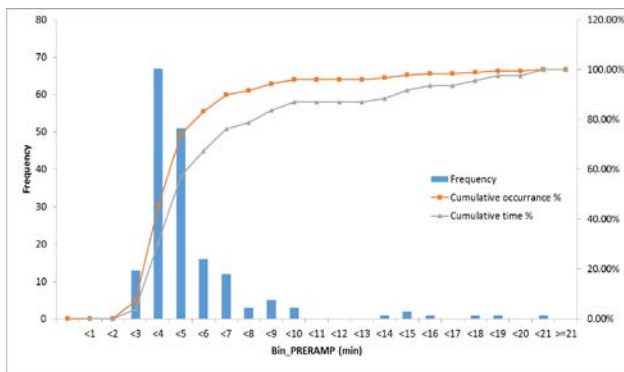


Figure 2: Histogram of time in prepare ramp beam mode

Ramp

The beam mode Ramp is declared right before the timing event is launched and terminates once arrived at flattop. For this reason the time distribution is extremely sharp and the average (20.5 min) and the median (20.4 min) are very close to each other and to the settings length (1210 sec).

Flattop

Once the energy ramp is completed the Flattop beam mode is declared for performing some actions (feedback reference change, settings incorporation and loading) to prepare for the squeeze; the tune change into collision tunes is also performed. The distribution has an average of 5.6 min with a median of 4.2 min. In six cases the beam mode lasted more than 15 min, all attributed to planned studies and measurements.

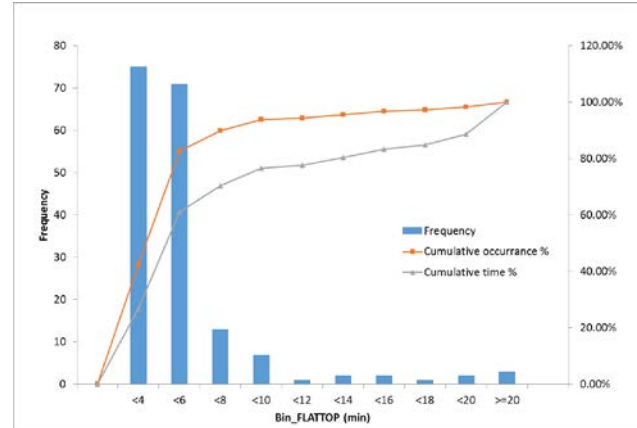


Figure 3: Histogram of time in the flattop beam mode

Squeeze

The distribution of Squeeze reflects the settings length, as this beam mode is set just for their execution. The average is 18.1 min while the median is 18.0 min.

Adjust

The Adjust beam mode is the phase when the beams are brought into collisions. This phase consists of two parts as the high and low luminosity regions are treated separately. Once the collisions are established, the luminosity is optimized and the orbit feedback with reduced gain is switched on. The following beam mode (Stable Beams) is declared sometime during the last manual actions (so ending this beam mode), with an average time of 16.1 min and a median of 14.1 min. The increased time compared to 2015 reflects the addition of a beam process to insert a bump to the right of CMS, increasing the dispersion for the TOTEM Roman Pot experiment.

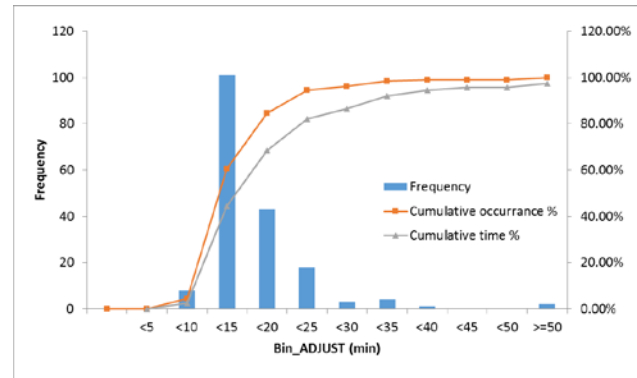


Figure 4: Histogram of time in the adjust beam mode (with 15 end of fill machine studies removed)

The computed values are found after removing 15 End of Fill Machine Development periods, where the beam mode was put back to Adjust following a physics run to allow some specific measurements to be made.

A total of seven instances of the beam mode lasted more than 30 min. No particular pattern can be identified as to the source of the delays. The longest times are attributed to resolving a BPM issue and also to finding collisions in CMS (due to triplet movement).

Stable Beams

The time in Stable Beams is found to be 10.0 hours on average, with a median of 8.2 hours.

The termination of a period in stable beams is either by a deliberate operator action (programmed dump) or by an unforeseen event inducing a beam dump (typically resulting in an early termination of the fill).

The reason for a programmed dump in the early weeks is due to the desired machine protection objective being achieved and thus the desire to move to higher intensities. As intensities stabilised in the machine, the reason for a programmed dump is to obtain optimum luminosity production. Taking into consideration the average turnaround times, for standard emittance beams the optimum time for luminosity production was ~24 hours. This time reduced to ~18 hours when the beam production mode moved to Bunch Compression Merging and Splitting (BCMS) beams in July.

The average and mean figures include all data, independent of the reason for terminating the stable beam mode. A significant improvement on 2015 can be seen, principally due to the primary objective of luminosity production in 2016, whereas in 2015 the objective was to explore the machine operating envelope.

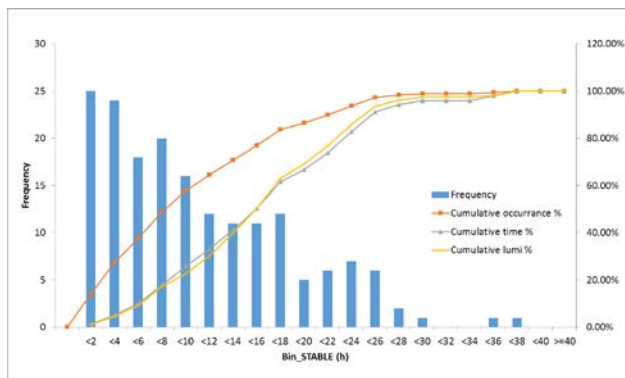


Figure 5: Histogram of time of all fills in stable beams

OUTLOOK FOR 2017

Following the positive experience of CRS in 2016, the scope to further reduce the Beta* during the ramp is being considered. First estimates indicate that ~300s can be saved in the squeeze if a 1m Beta* is chosen as target for the end of the ramp [8]. Further timesavings of ~100s are also possible should the investigations into a faster ramp prove to be successful [8]. Additional time gains are still possible should the ATS optics be adopted, with possible ~500s time savings available based on early studies.

Another aspect to be explored further is the collision of all IPs simultaneously. Currently the high luminosity IPs are brought into collision before the levelled IPs to allow additional degrees of freedom, however this could be optimised. Should the orbit bump be again required for the TOTEM experiment, it may be of interest to also include this beam process as an additional step in the squeeze, and not as a separate task.

Incremental time gains are also possible by focusing on the many small steps to bring the beams from injection to collision. As an example, some sequencer tasks could be made more in parallel, such as loading settings to different equipment groups (perhaps requiring some additional development).

CONCLUSION

When comparing performance in 2016 with 2015, on average the total time required to inject, accelerate and collide the LHC beams has been reduced by 6.5minutes. This is an excellent performance considering the additional challenges such as lower Beta*, and the limited length of trains that could be injected (thus requiring additional injections). The results show efficiency improvements during each beam mode. The data also indicates a high consistency between fills, with the tails in the distributions generally attributed to special studies or problem solving. Further, no strong pattern could be observed in the cause of the problems encountered.

In light of the good performance of the beam modes in 2016, in general only marginal gains in efficiency are possible. The challenge may in fact be to conserve the same performance. There are however some significant potential gains available by changing the playing field. For example injection of longer trains will reduce the total time at injection, and pushing the CRS to 1m Beta*, and colliding all IPs simultaneously will all contribute time savings. With the beams modes before stable beams representing on average 129 min in 2016, there is a realistic possibility of achieving less than 100 min in 2017.

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