FILLING SCHEMES AND E-CLOUD CONSTRAINTS FOR 2017

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Abstract

Several measures implemented in the 2016-17 Extended Year End Technical Stop (EYETS) should allow the increase of both the number of bunches per injection into the LHC and of the intensity per bunch for the 2017 Run.

This contribution reviews the possible filling patterns, in particular comparing the high brightness scheme (Batch Compression Merging and Splitting – BCMS – scheme in the PS) against the nominal production scheme. In particular we analyze possible limitations due to electron cloud induced heat load on the beam screens of the cryogenic magnets.

Scrubbing requirements for the 2017 Run are also presented, taking into account that one of the LHC sectors (S12) needs to be warmed-up and vented to exchange one of its main dipole magnets.

POSSIBLE FILLING SCHEMES FOR 2017

In 2016 the presence of a vacuum leak in the SPS high energy beam dump (TIDVG) limited the intensity that could be accelerated in the SPS [1]. For this reason the number of bunches per injection into the LHC was limited to 96, in the configuration with two batches of 48 bunches produced using the high brightness scheme (BCMS) in the PS. Under these conditions the maximum number of bunches that could be stored in the LHC was 2220, corresponding to the filling scheme in the top part of Fig. 1.

A new beam dump for the SPS is being manufactured and will be installed before the 2017 LHC startup. This will remove the present intensity limitations and allow the injection of [1, 2]:

- Trains of 288 bunches (in the configuration 4×72b) for the standard 25 ns beam (standard production scheme in the PS), as foreseen in the LHC design [3];
- Trains of 144 bunches (in the configuration 3×48b) for the high brightness 25 ns beam variant (BCMS production scheme in the PS).

Moreover, studies conducted in 2016 have shown that shorter rise-times can be achieved both for the SPS injection kickers (MKPs) and for the LHC injection kickers (MKIs), reducing the spacing between PS batches to 200 ns (it was 225 ns in 2016) and the spacing between injections in the LHC to 800 ns (it was 900 ns in 2016).

Profiting from these improvements and assuming that the abort-gap keeper is adjusted to the actual train length, optimized filling schemes can be prepared for the 2017 Run as shown in Fig. 1. In particular, for the high brightness case (BCMS), 2556 bunches can be stored in the LHC, i.e. 15% more compared to the maximum number of bunches reached in 2016. Using the standard scheme (low brightness) instead, the number of bunches can be increased to 2760 bunches, i.e. 7% more compared to the BCMS case.

The bunch intensity was limited to about 1.1×10^{11} p/bunch in 2016, due to the dynamic pressure rise in the injection kicker (MKI) area in Point 8 [4]. During the 2016-17 Extended Year End Technical Stop (EYETS) additional pumping modules are being added. Thanks to this improvement it should be possible to increase the bunch intensity to about 1.3×10^{11} p/bunch, which is presently the maximum achievable in the SPS with 25 ns bunch spacing [2].

HEAT LOAD CONSTRAINTS

To estimate the beam induced heat loads in the arcs we assume that the scrubbing status is the same as at the end of 2016 (given the very slow conditioning observed in the last part of the 2016 p-p run – see Fig. 2 [5]). This condition is not true right at the beginning of the year due to the need to recover the scrubbing of the beam screens in Sector 12, which was warmed-up and vented during the EYETS in order to change one of its main dipole magnets.

Heat loads are estimated for the sectors with the highest loads (i.e. S12 and S81), starting from the values that were measured at the end of 2016. Both the effect of the filling pattern (train length, number of gaps) and of the bunch intensity need to be taken into account.

The impact of the filling scheme can be estimated knowing the e-cloud rise-time from the RF stable phase measurements (see for example Fig. 3). Due to the e-cloud buildup along the trains, bunches at the head of each train generate very little heat load while bunches at the tail of long trains generate a significant load.

The heat load dependence on the bunch intensity was measured in a Machine Development (MD) session in 2016, with three consecutive fills performed with the same bunch length and filling scheme but with different bunch intensities. The results of these measurements are show in Fig. 4. The measured heat loads are fitted quite well with a linear dependence with an intensity threshold. Since the dependence is quite steep, a sizable effect can be observed when increasing the bunch charge from 1.1×10^{11} p/bunch to 1.3×10^{11} p/bunch. The intensity threshold is in the range from 0.4 to 0.7×10^{11} p/bunch, depending on the sector.

The heat loads expected for the different filling schemes in Fig. 1 are shown for different bunch intensities in Fig. 5

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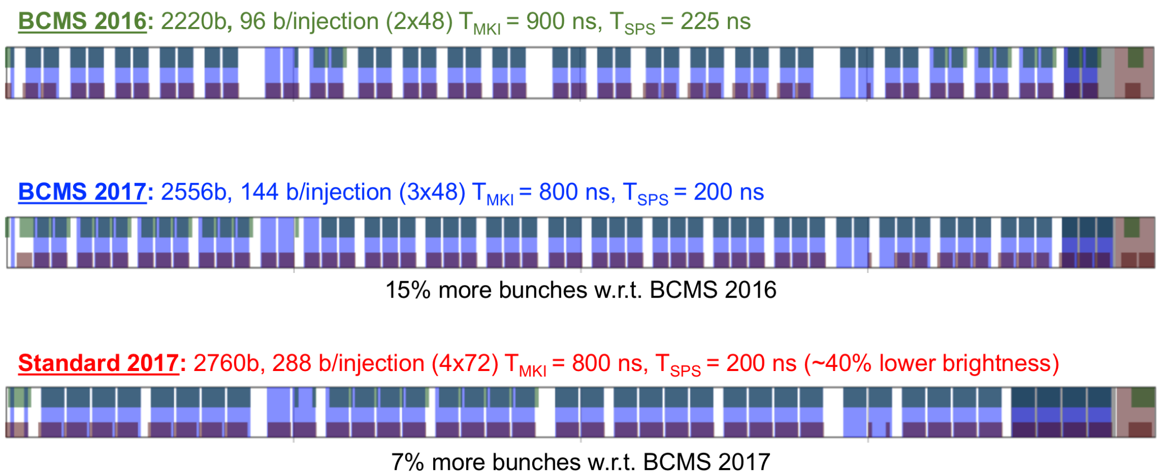

Figure 1: Filling scheme used for physics production at the end of 2016 (top) and possible options for 2017 operation, both for the BCMS scheme (middle) and for the standard scheme (bottom).

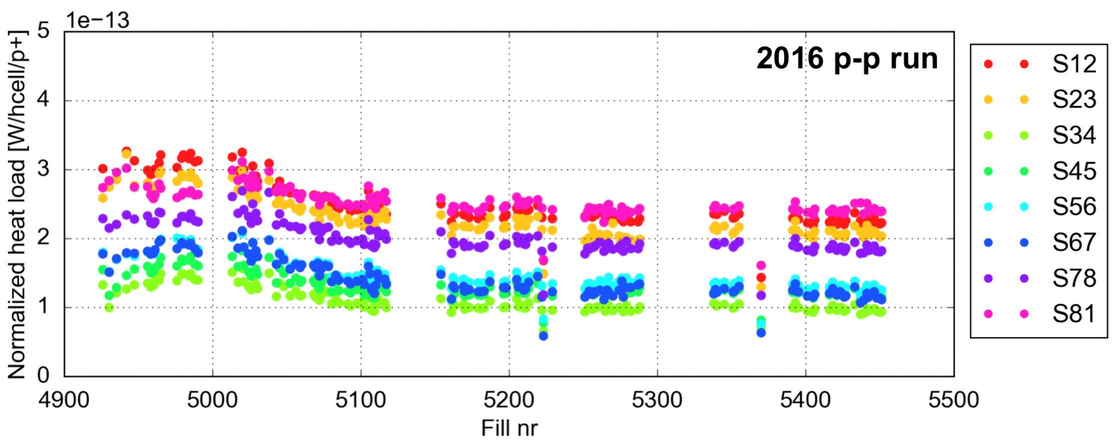

Figure 2: Evolution of the heat load at high energy normalized to the beam intensity during the 2016 p-p run.

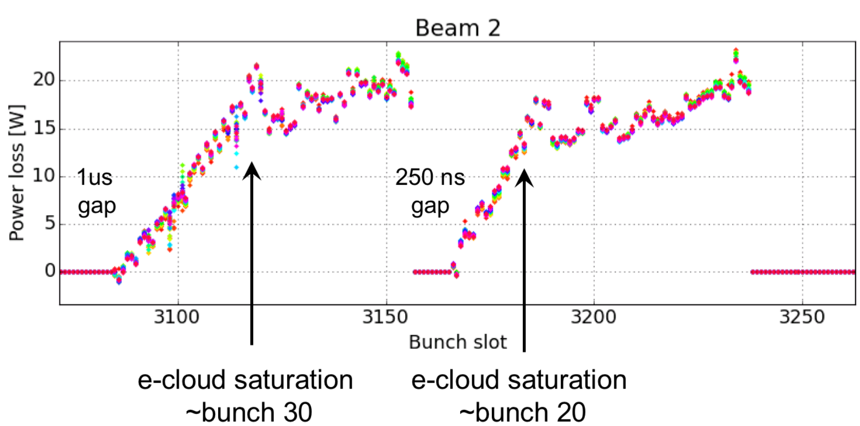

Figure 3: Bunch-by-bunch energy loss along two trains of 72 bunches, as measured from the RF stable phase (data courtesy of J. Esteban Muller).

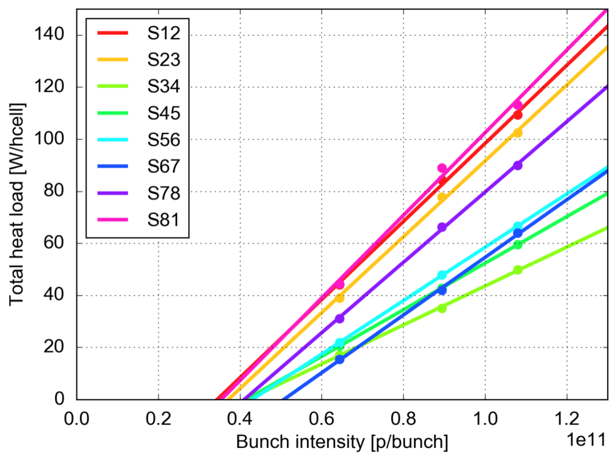

Figure 4: Dependence of the arc heat loads on the bunch intensity as measured in a Machine Development session in 2016. Measured points and corresponding linear fit.

(top). By comparing the heat load values with the maximum available cooling capacity from the cryogenic system, namely 160 W/hcell [6], we can estimate the number of bunches that can actually be stored in the machine for the different configurations, as shown by the full bars in Fig. 5 (bottom), in comparison with the maximum allowed by the filling scheme (dashed bars).

The prospect for the different schemes can be summarized and follows:

- **BCMS 2016:** filling scheme allowing for a maximum of 2220 bunches in injections of 2×48b. This is the filling scheme used in 2016 and will have to be kept for 2017 operation in case the faulty beam dump in the SPS cannot be replaced. As observed in 2016, with this filling scheme and with a bunch intensity of 1.1×10^{11} p/bunch, some margin is available with respect to the available cooling capacity. This can be used to increase the bunch intensity up to 1.3×10^{11} p/bunch without limitations on the number of bunches.
- **BCMS 2017:** filling scheme allowing for a maximum of 2556 bunches in injections of 3×48b. For this filling scheme, allowing for 15% more bunches with respect to the "BCMS 2016" case, it should be possible to operate without limitations from heat loads with bunch intensities up to 1.2×10^{11} p/bunch, while the limit is exceeded by about 10% if the bunch intensity is increased to 1.3×10^{11} p/bunch.
- **Standard 2017:** filling scheme allowing for a maximum of 2760 bunches in injections of 4×72b. Due to the longer bunch trains and to the smaller number of gaps, the average heat load per bunch with this scheme tends to be significantly larger than for the BCMS cases. For this reason the heat load reaches the available cooling capacity already for 1.1×10^{11} p/bunch. For larger bunch intensities this scheme is limited to a number of bunches that is even lower than for BCMS.

Assuming end-2016 scrubbing status, due to heat load constraints, the standard scheme does not really allow for a larger number of bunches compared to the BCMS case. For this reason the BCMS beam seems to be the natural choice for luminosity production in 2017, profiting from the increased brightness (see [7] for detailed performance comparison). In this scenario, the intensity ramp-up will probably be fast (as in 2016) and it will be easier to deal with the scrubbing recovery for Sector 12, if needed. But most likely further conditioning of the beam screens, and the consequent reduction of the heat loads, will be very limited. This will not have much impact on performance in 2017-18, since we have enough cooling capacity to practically profit from the full performance reach of the BCMS beam. Nevertheless e-cloud induced heat loads might come back as a performance limitation for Run 3 and HL-LHC.

SCRUBBING RUN

After the 2015-16 Year End Technical Stop (YETS) deconditioning of the beam screens was clearly observed [5, 8], inducing instabilities and strong emittance blow-up. The reconditioning was very fast and the 2016 beam quality was recovered with about 24 h of scrubbing at 450 GeV. Based on these observations, it might be convenient to allocate 1-2 days for scrubbing at the beginning of each year, mainly to recover an acceptable beam quality before starting the intensity ramp-up in physics.

The situation for the 2016-17 EYETS will be different since the sector 12 has to be warmed-up and vented to replace a dipole suspected to have an inter-turn short. Based on the experience from the Long Shutdown 1 (2013-14) the Secondary Electron Yield (SEY) of the beam screen surfaces will be reset. Nevertheless scrubbing preservation might be better thanks to the larger accumulated dose compared to Run 1, but no direct experience is available in this respect.

In any case compared to 2015 it should be easier to preserve an acceptable beam quality since only one out of eight arcs has been exposed to air and our knowledge on how to stabilize the beam has significantly improved [5, 9, 10]. Moreover the cryogenics system will be less sensitive to heat load transients thanks to improvements on the feed-forward control deployed in 2016 and to increased interlock levels on the beam screen temperatures. The intensity increase during the 2017 scrubbing could also be limited by pressure rise in one of the injection kickers in Point 2, which was exchanged before the 2016 ion run and has never been conditioned with high intensity 25 ns beams.

Taking all these aspects into account, seven days have been allocated for scrubbing at the beginning of the 2017 Run. The Scrubbing Run will be performed at 450 GeV, using exclusively 25 ns beams. The standard production

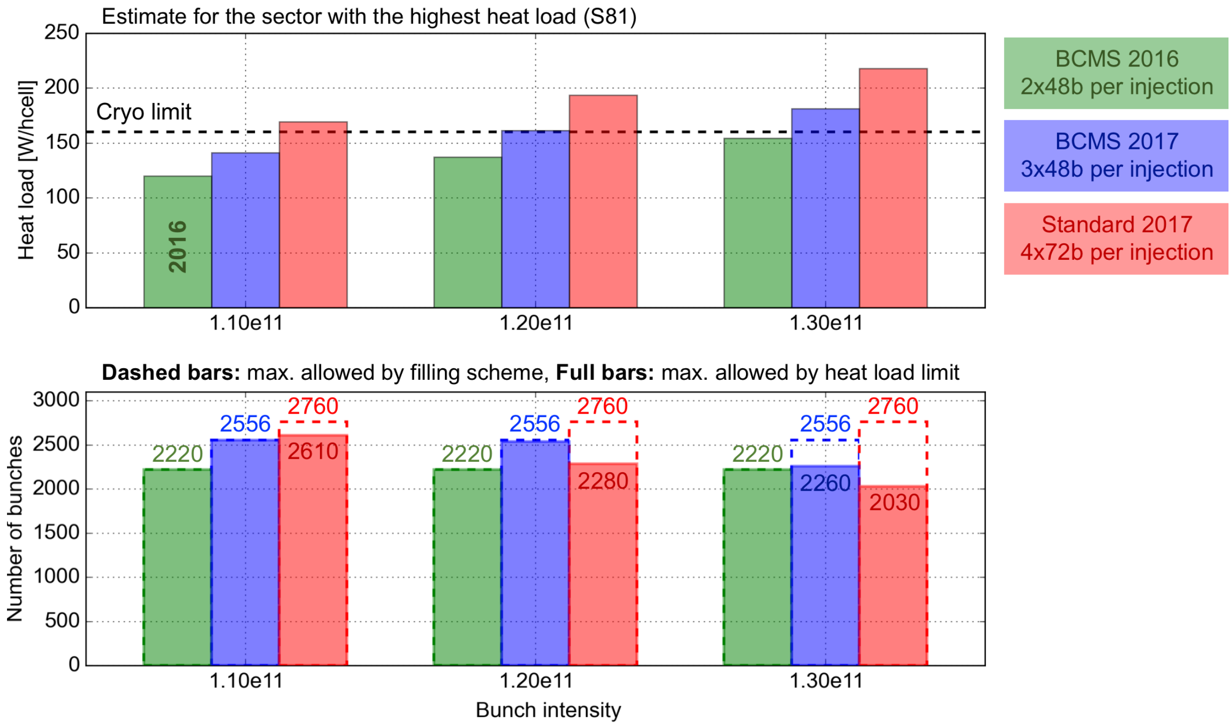

Figure 5: Estimated heat load for the filling schemes presented in Fig. 1 for different bunch intensities (top) and corresponding limitation to the number of stored bunches (bottom).

scheme (low brightness) will be used in order to have longer bunch trains. In particular in 2017 it should be possible, for the first time in Run 2, to inject and store trains of 288 bunches from the SPS. This will provide important information on the scrubbing efficiency which can be achieved with this scheme.

Doublet beams [9, 11] will not be used during the 2017 Scrubbing Run, mainly due to the lack of time for preparation in the injectors. In 2016 doublets were not available for injection into the LHC due to the aforementioned limitation from the SPS TIDVG. In 2015, due to strong transverse instabilities, it was possible to accumulate only trains of 24 doublets (up to 250 doublets in total). This was sufficient to prove the enhancement on the heat load per bunch compared to normal 25 ns trains but to achieve a significant scrubbing efficiency we need to store significantly more bunches (in the order of 1000 doublets) and in longer trains (48-72 doublets/train).

Studies on doublet beams will restart in MD with the main goal of identifying optimal settings to stabilize the beam, profiting from the scrubbing accumulated in 2015 and 2016 and from tune settings optimized for the e-cloud spread. This will allow assessing the possible intensity reach. In case of a positive outcome, a longer test period to probe the scrubbing efficiency of doublet beams could be envisaged for 2017 or later.

SUMMARY AND CONCLUSIONS

In 2017 it should be possible to increase the number of bunches in the LHC with respect to 2016, thanks to the replacement of the faulty beam dump in the SPS, and to faster kicker rise-times in the SPS and in the LHC. From pure filling scheme constraints it should be possible to inject up to 2556 bunches for BCMS (about 15% more than 2016) and up to 2760 bunches for the standard scheme (7% more than BCMS).

Nevertheless, limitations from e-cloud induced heat loads are quite different for the two schemes. Assuming the same situation as at the end of 2016, the BCMS option shows no limitation on the number of bunches for bunch intensities up to 1.2×10^{11} p/bunch while the standard scheme is limited to the same number of bunches as the BCMS, or even less, already for 1.1×10^{11} p/bunch.

For this reason the BCMS option seems to be the natural choice for 2017, also allowing for a faster intensity ramp-up. In this scenario, most likely we will not see more conditioning than in 2016. This will not have much impact on the performance in Run 2, but concerns remain for Run 3 and HL-LHC.

A scrubbing run of seven days has been allocated for 2017. It will be performed with 25 ns beams in long bunch trains, up to 288 bunches per injection. This will allow the recovery of some scrubbing in sector 12, which was vented to exchange one of its main dipoles, and condition the injection kicker in point 2 (MKI2D), which was exchanged before the 2016 ion run and has never been conditioned with high intensity beams. This will also be an occasion to test (for the first time in Run 2) the scrubbing efficiency with trains of 288 bunches.

Studies with doublet beams are planned to restart during MD time in 2017, with the main goal of evaluating stability margins and intensity reach. In case of a positive outcome, these studies could be followed-up with a longer period to assess the scrubbing efficiency.

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