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MD421: Electron cloud studies on 25 ns beam variants (BCMS, 8b+4e)

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Summary

This note describes a Machine Development session performed with the main goal of studying the e-cloud mitigation that can be obtained by injecting mixed trains of 8b+4e beam type and trains having the standard 25 ns structure. Additionally, in the course of the MD, the pure 8b+4e beam was also checked to be stable when injected with low chromaticity and octupole current settings. Subsequently, the operational BCMS 25 ns beam was also injected with the 8b+4e settings and found to be unstable. The operational settings for injection were re-found by gradually increasing the chromaticity and octupole knobs until all the bunches of the injected beam could remain stable after injection.

Contents

1 Motivation and description

The operational experience in 2015 and 2016 has shown that electron cloud effects can limit the performance of the LHC both in terms of heat load on the cryogenics system and in terms of beam stability [1,2]. Running the LHC with low electron cloud filling patterns (e.g. 8b+4e beams [3]) is envisioned as a viable option for the HL-LHC era, if operation until LS3 will show that the electron cloud in the LHC cannot be suppressed to a sufficiently low level with beam induced scrubbing. However, this entails a reduction of the number of bunches that can be injected into the LHC, with the consequent luminosity loss. Tests performed in the LHC in 2015 confirmed that the 8b+4e scheme can be used to significantly suppress the e-cloud formation in the arcs at the cost of about 30% less bunches circulating in the machine.

In this framework, we have explored the potential of reducing the electron cloud in the LHC by combining 8b+4e trains with standard 25 ns trains within the same filling scheme. The results of this exercise open to the option of tailoring the filling scheme such as to maximize the performance within the available cooling capacity from the cryogenics. Moreover, this experiment provides important input data to cross-check the existing modelling of the electron cloud formation, in particular concerning the rise and decay times of the build up. The filling scheme used for the test is shown in Fig. 1. It basically alternates standard 25 ns trains (2x48 bunches, BCMS), with 8b+4e trains of 56 bunches. All the bunches were injected with about the same intensity. After the fill with the mixed filling scheme, two more fills took place during MD421. They aimed at establishing the needed machine settings when injecting a pure 8b+4e beam into LHC and then proving that the standard LHC beam is unstable with the same settings, and remains unstable until the settings are basically returned to the operational values.

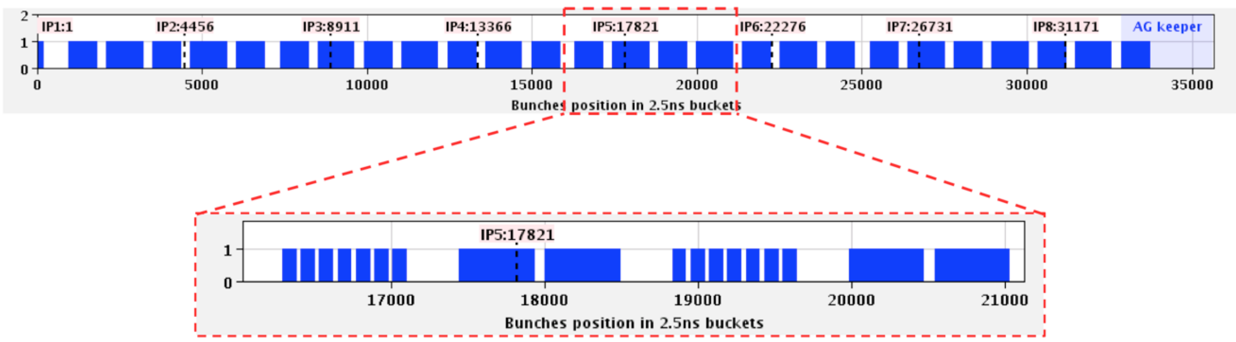

Figure 1: Filling scheme used for the MD. The zoom into two groups of adjacent trains highlights the different train structures.

2 Performed tests

The MD consisted of three consecutive fills (fill numbers: 5370, 5371 and 5372) performed with different filling patterns. The main steps of the tests were the following:

- During fill 5370, trains of 56 bunches with 8b+4e filling pattern (duly prepared in the injectors) and 2x48 bunches of 25 ns beam (BCMS) were injected into LHC in an interleaved fashion. The machine was filled with 45% of the bunches in 8b+4e trains and 55% in BCMS 25 ns trains, amounting to a total of 1908 bunches per beam. The beams were accelerated and brought to collision using the operational machine settings (in particular at injection: Q'=20 in both planes and octupole knob set to -3.0, corresponding to a current of 40 A in

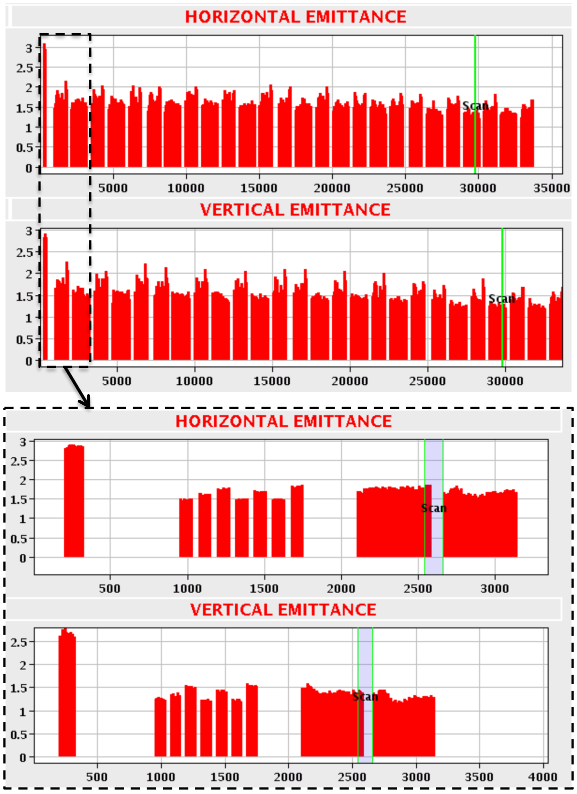

Figure 2: Bunch-by-bunch horizontal and vertical emittances for Beam1 measured by the BSRT.

the octupole magnets). After declaration of stable beams, the beams were kept in collision for about 45 minutes. Data of heat load, bunch-by-bunch emittances and stable phase shift were collected all throughout the cycle;

- During fill 5371, the machine was filled with pure 8b+4e trains, but with much reduced chromaticity and weaker octupoles. In particular, chromaticity (Q') was set to 5 units in both planes and the octupole knob was set to -0.5 (i.e. about 6.5 A);
- During fill 5372, 25 ns beams (BCMS) were injected into the LHC with the same settings as for the 8b+4e of the previous fill. Since the beam was unstable at injection, leading to quick emittance degradation, the settings were gradually increased for the successive injections until reaching the point of keeping the beam stable and without visible degradation at injection.

3 Main results

3.1 Fill 5370

Fill 5370 (6 October 2016) was the first instance in which a hybrid filling pattern, alternating injections of 8b+4e trains with BCMS 25 ns trains, was used to fill LHC. The bunch intensity was about nominal for both, i.e. 1.1×10^{11} p/b, and similar transverse emittances of about 1.5 μm at injection. Figure 2 shows a snapshot from the BSRT display for Beam 1 and a zoom on the first two trains (plus the train of twelve bunches at the beginning) showing the mixed train structure.

The measured bunch-by-bunch stable phase shift data [4] for Beam 2 in Fig. 3 clearly show a 'rising' electron cloud pattern along the 25 ns trains and a flatter structure, corresponding to negligible stable phase shift due to electron cloud, for the 8b+4e trains. A zoom on the bunch-by-bunch stable phase is also displayed. It is clear that the electron cloud build-up from the 25 ns beam does not continue into the 8b+4e trains and restarts from scratch at the beginning of every 25 ns train not preserving any memory from the previous train.

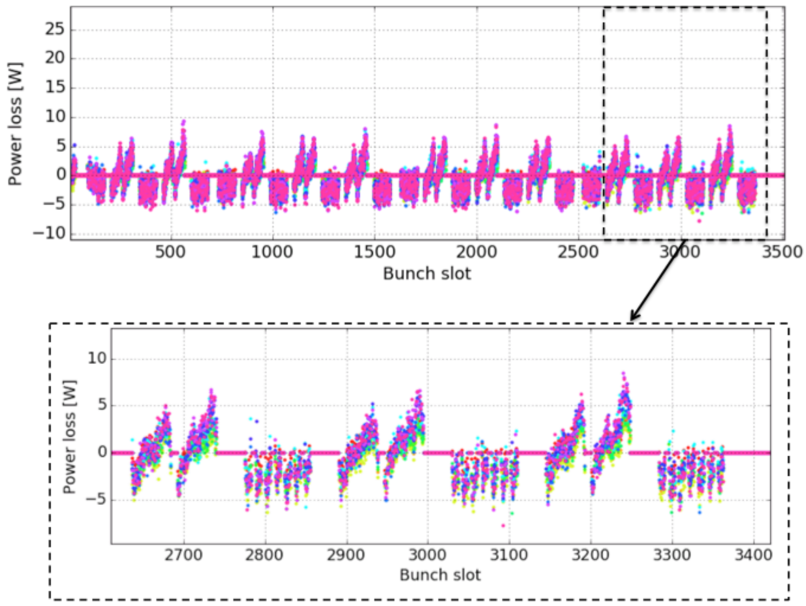

Figure 3: Bunch-by-bunch stable phase shift for Beam2 on a selected part of the full train.

Finally the average heat load measured in the different LHC sectors is shown in Fig. 4 (different sectors in different colours, as labelled) and compared with the values measured for a fill with a similar number of bunches but with a pure 25 ns beam (Fill 5351 from 30 Sep 2016). While it is clear that in both cases the electron cloud is still an important contributor to the heat load in all sectors both at injection and top energy (all coloured lines lie above the dashed line, representing the heat load in the arcs from impedance and synchrotron radiation, throughout the machine cycle), a reduction of the heat load by 40% was observed in the most critical sector at the price of 15% loss in number of bunches.

3.2 Fills 5371 and 5372

As described in Sec. 2, the fills 5371 and 5372 were devoted to investigating whether chromaticity and octupoles could be lowered when injecting a low electron cloud beam like the 8b+4e. During fill 5371, chromaticity was set to 5 units in both planes and the octupole knob was set to 0.5 (i.e. 6.5 A octupole current) at injection. In these conditions, the machine was filled with 8b+4e trains. Figure 5 shows the injection process in the top left plot, as well as superimposed scans of horizontal and vertical emittance measurements from the BSRT, which were made in the coloured ranges highlighted in both left plots. It is clear that no instability or fast emittance blow up affecting the last bunches of the trains can be identified during this fill. Only a slow emittance growth in both planes, uniformly distributed over all the bunches injected at the same time, is revealed by the fact that in later scans the trains injected earlier exhibit larger emittances than those freshly injected.

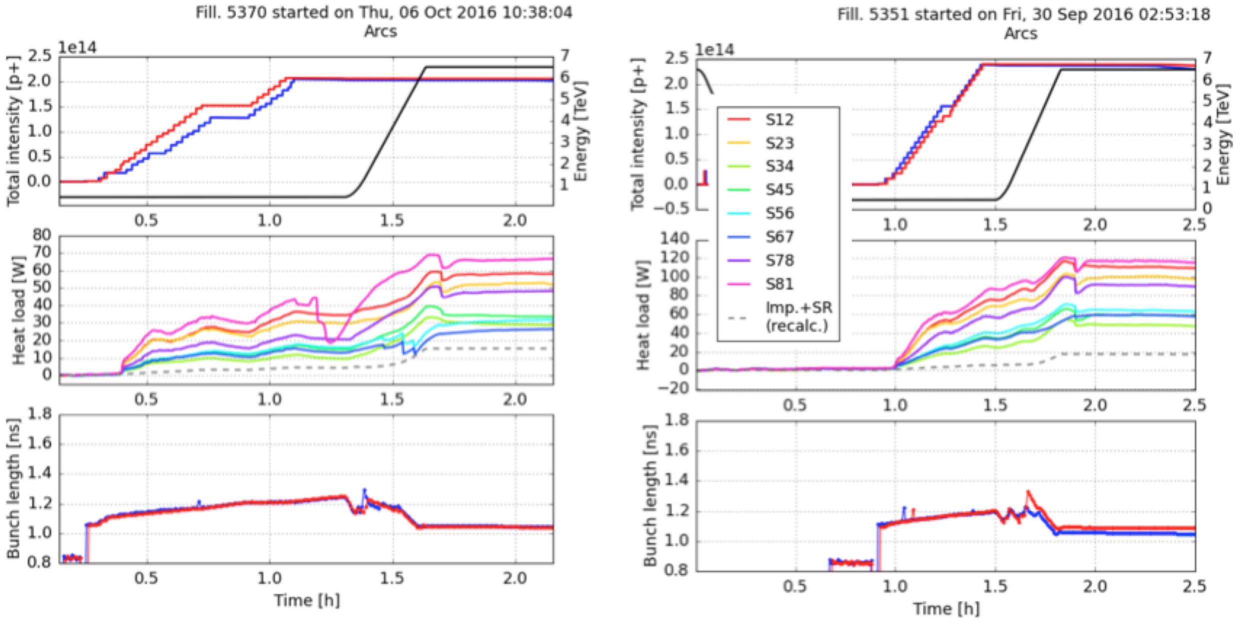

Figure 4: Top row: total intensity in Beam 1 (blue) and Beam 2 (red). Middle row: average heat load in each of the eight LHC sectors, as labeled, and calculated value of the heat load due to impedance and synchrotron radiation. Bottom row: bunch lengths for both beams.

During fill 5372, the chromaticity and octupole settings were initially kept as during the previous fill and injection of the operational BCMS 25 ns beam began. The injection of the first train resulted immediately into strong emittance blow-up at the end of the trains in both planes. Consequently, the chromaticity and octupole knob values were then gradually increased before the injection of each successive train with the goal of reaching the situation in which the injected train would not exhibit any degradation. Figure 6 shows the injections and the bunches acquired on the subsequent BSRT scans on the left side, as well as BSRT scans of the injected bunch-by-bunch horizontal and vertical emittances on the right side. The background colours associated to the different trains in the emittance plots indicate the chromaticity and octupole settings when each train was injected, using the table reported in the upper part of Fig. 6. It is clear that the first train that did not suffer degradation after injection was the one injected with Q' set to 20/15 in the two beams and octupole knob set to -4.0 (corresponding to 50 A octupole current). These are very close to the operational settings at injection for 25 ns BCMS beams.

3.3 Conclusions

To conclude, the measurements collected in this MD session have been instrumental to:

- demonstrate the viability of mixed injection schemes to reduce electron cloud effects for the future HL-LHC operation, in case of persisting electron cloud even after extended scrubbing;
- demonstrate that electron cloud free beams can be stably injected into LHC with reasonably low values of chromaticity (5/5) and octupole current (6.5 A);
- experimentally validate once again the machine settings needed to preserve the stability and quality of 25 ns beams at injection as they were assessed during the 2015 scrubbing runs and

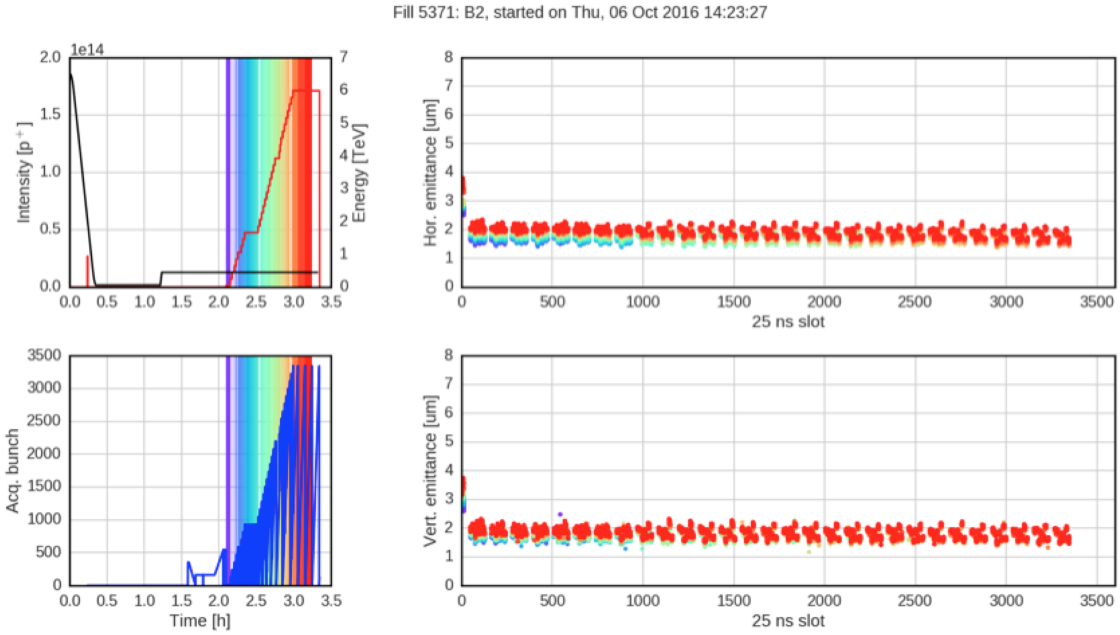

Figure 5: Left: total intensity in Beam 2 (red) in the upper plot and bunch acquisition for the BSRT in the lower plot. Right: snapshots of bunch-by-bunch horizontal emittance (top) and vertical emittance (bottom) coloured according to the convention shown in the left plots.

operation (except that the octupole current had to be increased when moving from standard 25 ns beams to BMCS) and have not changed much even after the important scrubbing accumulated during the 2015 and 2016 physics runs.

The natural follow-up of this study is to test more optimized filling schemes, for which the combination of 8b+4e and standard trains takes place in the SPS, allowing for shorter gaps between batches of the two kinds. It would be also important to test 8b+8e beams with the largest available bunch intensity, to continue the validation of this scheme as backup scenario for the HL-LHC upgrade.

4 Acknowledgments

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Octupole knob	-0.5	-1.0	-1.0	-1.0	-2.0	-4.0	-4.0	-4.0
Chromaticity	5/5	5/5	10/10	15/15	15/15	15/15	10/15	20/15

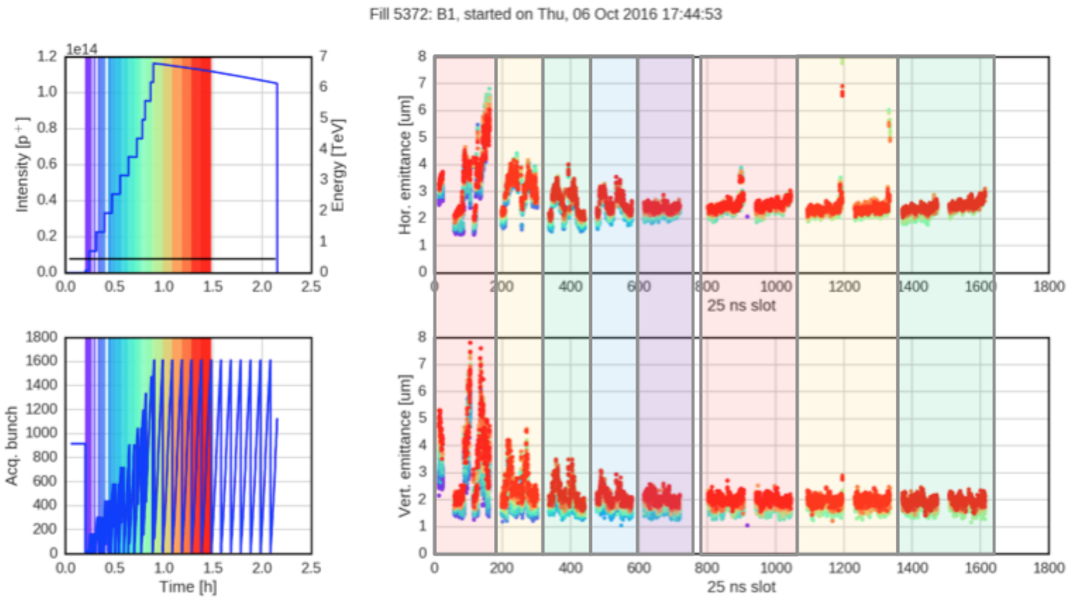

Figure 6: Table: values of chromaticity and octupole knob settings at the different stages of the injection of the 25 ns beam. In combination with the bottom plots, the coloured backgrounds associate the setting values to the different injections into the LHC. Left: total intensity in Beam 2 (red) in the upper plot and bunch acquisition for the BSRT in the lower plot. Right: snapshots of bunch-by-bunch horizontal emittance (top) and vertical emittance (bottom) coloured according to the convention shown in the left plots and with coloured background as explained above.

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