50 NS BACKUP SOLUTION

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Abstract

The baseline bunch spacing for LHC high luminosity proton-proton operation after LS3 is 25 ns to maximize the integrated luminosity while keeping the pile-up low. The success of this mode of operation is not guaranteed. Electron cloud, UFOs, long-range beam-beam, heating and other effects might make 25 ns operation in the LHC and/or the injectors difficult. This talk will review possible showstoppers in the LHC and injectors for 25 ns operation and discuss possible remedies. An alternative would be re-considering 50 ns operation. An estimate of the 50 ns performance will be given. The question of whether a different upgrade path would have to be chosen in case of 50 ns operation will also be addressed.

INTRODUCTION

The integrated luminosity goal during the LHC High Luminosity (HL) era is 275 fb^{-1} per year. The standard scenario to achieve this ambitious goal is to run with a levelled luminosity of 5×10^{34} cm^{-2}s^{-1} with 25 ns bunch spacing. This configuration respects the HL LHC experiments' limit of event pile-up of $\mu = 140$. The HL LHC parameters with 25 ns can almost give this performance with a physics efficiency slightly increased with respect to the 2012 efficiency [1].

This paper will investigate whether there could be showstoppers for 25 ns operation in the LHC or in the injectors and what the possible mitigations could be. The main topic will then be whether 50 ns could be a valid alternative to 25 ns and whether there would be any differences in the upgrade path if 50 ns beam had to become the operational beam.

The LHC configuration and beam parameters assumed for 25 ns and 50 ns in this paper are the standard HL parameters, see Table 1.

INJECTOR PERFORMANCE AFTER LS2

Fig. 1 and Fig. 2 show the expected performance in the SPS at 450 GeV as normalized emittance for a given bunch population in the case where all proposed injector upgrades are implemented (after LS2). The white zones in the plots show the achievable combinations of emittance versus bunch intensity and the coloured areas refer to exclusion zones due to various instabilities in the injectors and other limitations. The injector upgrades include Linac4 connection, upgrade of PSB extraction energy to 2 GeV and full SPS uprade and e-cloud suppression [2].

25 ns after LS2

An emittance growth of 20 % and intensity loss of 5 % through the LHC cycle is assumed. Thus the HL 25 ns target parameters at the end of the injector chain are supposed to be a bunch intensity of $N_b = 2.32 \times 10^{11}$ p+ and a normalized emittance of 2.08 μm. According to Fig. 1 the expected performance after LS2 is 2×10^{11} p+ in an emittance of 1.88 μm. The main limitation for reaching the target parameters is the available SPS RF power. It appears however that this is not necessarily a hard limit [3] and that the required bunch intensity is almost within reach.

Table 1: HL parameters for 25 and 50 ns

Parameter	25 ns	50 ns
N_b [$\times 10^{11}$]	2.2	3.5
n_b	2808	1404
ε_n [μm]	2.5	3
Bunch length [cm]	7.5	7.5
Crossing angle [μm]	590	590
Events per crossing	140	140

50 ns after LS2

Valuable experience with 50 ns has been gained during LHC run 1 with bunch intensities up to 1.8×10^{11} protons. The remarkable 50 ns performance in the injectors in 2012 is shown in Fig. 2.

The target HL performance of the injectors for this beam is 3.68×10^{11} p+ per bunch in an emittance of 2.5 μm. As can be seen in Fig. 3 the achievable parameters for 50 ns in the injectors with all the upgrades in place are 2.7×10^{11} p+ in an emittance of 1.95 μm. The bunch intensity will only be about 70 % of the target value, limited by PS longitudinal stability.

POSSIBLE SHOWSTOPPERS FOR 25 NS IN THE LHC

With the HL beam parameters for both 25 ns and 50 ns, the LHC will become more challenging to operate than what was experienced during LHC run 1 or will be experienced during LHC run 2. A number of possible issues specifically for 25 ns will be discussed in the following section. According to the experience with the LHC so far, the only real threat for 25 ns beams will be electron cloud.

Machine Protection Absorbers

The energy deposition in material is proportional to the energy density of the beam

$$\Delta E \propto \frac{N_b \cdot n_b}{\varepsilon} \qquad (1)$$

where N_b is the number of protons per bunch, n_b the number of bunches and ε the normalized transverse emittance.

Energy deposition studies for the injection protection absorbers have shown that the current design choice of materials for transfer line collimators and the TDI injection absorber would not survive the LIU 25 ns beams after LS2. The energy density will be increased by about a factor 4. The main limitation comes from tensile stresses for shallow impact parameters.

The solution for the transfer line collimators could be disposable collimators with quick plug-in supports, as full beam impact on these devices is supposed to be rare and has not happened so far. For the TDI injection absorber however a material has to be found that can survive beam impact. It is designed to protect against injection kicker failures and these failures occur several times per run. The beam was lost 3 times on the TDI in 2012.

50 ns LIU beams would have the advantage of 50 % less energy density in a full injected SPS batch and hence provide significant margin with respect to 25 ns LIU beams for the design choice of protection absorbers.
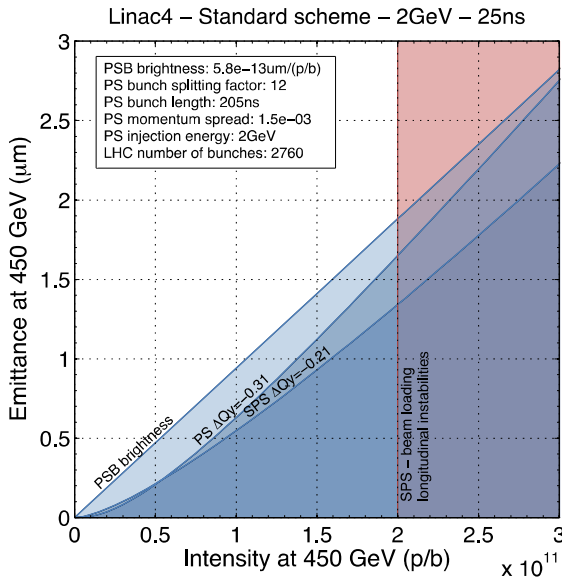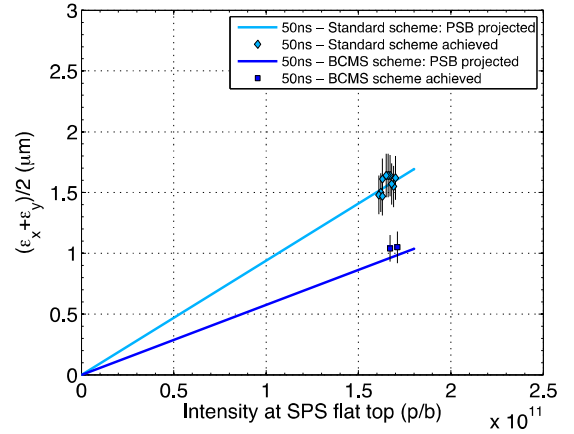

Figure 2: Emittance and intensity for 50 ns beams in the injectors at the exit of the SPS. This plot shows the remarkable performance of the 50 ns beam in the LHC injectors during LHC run 1. The projection from the PSB includes the emittance growth and intensity loss budget through the chain.
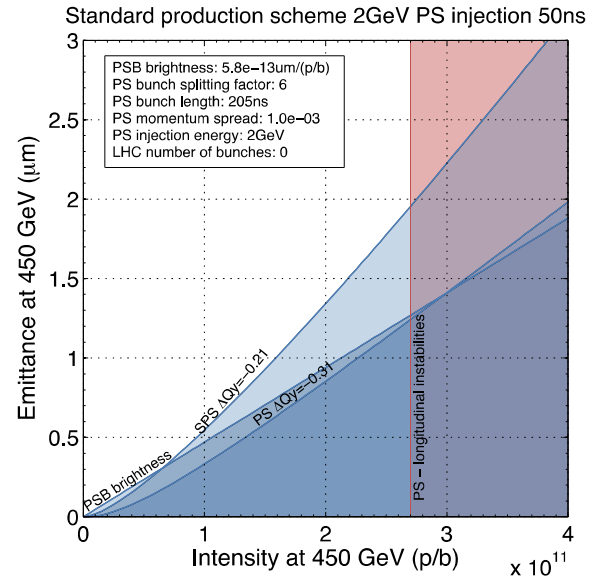

Figure 3: 50 ns performance after LS2.

Beam Induced Heating

The power loss from beam is proportional to the N_b^2. The number of bunches contributes differently depending on narrow band or broad band impedances. In the case of a broad band impedance the power loss is proportional to

$$P_{loss} \propto M \times N_b^2 \qquad (2)$$

where M is the number of bunches. In the case of a narrow band impedance (peaked at a multiple of 20 or 40 MHz) the power loss is proportional to

$$P_{loss} \propto (M \times N_b)^2 \qquad (3)$$

The power loss will be much increased for the high luminosity beams. 50 ns beams will be slightly worse

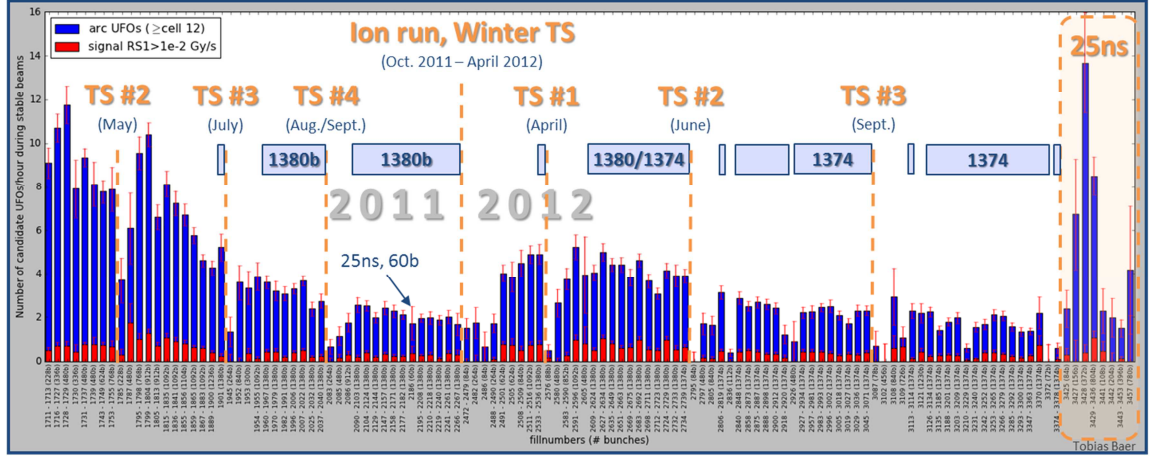Figure 1: 25 ns performance after LS2.

Figure 4: Evolution of number of arc UFOs during stable beams for the years 2011 and 2012. *Courtesy T. Baer*.

for broad band impedance, but 25 ns significantly worse for narrow band ones. A summary is given in Table 2.

Table 2: Power loss scaling with respect to 2012 50 ns beam (1374 bunches, 1.6×10^{11} ppb)

	25 ns nominal	50 ns 2012	50 ns HL- LHC	25 ns HL-LHC
Broad band	×1.05	×1	×4.9	×3.9
Narrow band	×2.1	×1	×5	×7.9

UFOs

The evolution of the UFO events detected during stable beams was monitored during the physics production runs 2011/2012 [4]. In 2012 there were periods with 50 ns and 25 ns physics. A summary is given in Fig. 4. Extrapolating from 2012 using the same assumptions for quench limits and hence beam loss thresholds, roughly 100 beam dumps a year from UFOs can be expected at 7 TeV[*].

With 25 ns beams the LHC might see even more UFOs. During the 25 ns operation in 2012, the UFO rate increased by factor 5 to 10 in the arcs. However a fast conditioning back to the 50 ns rate levels was observed. The mechanisms involved are not fully understood.

To give realistic predictions for the HL era, UFO rate data from LHC run 2 with 25 ns physics at 6.5 TeV is required.

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[*] The results from the 2013 quench tests indicate that the assumed quench limits for the UFO-like time scales might have been too pessimistic.

Beam-beam effect

The bunch spacing of 25 ns will create more long-range beam-beam encounters than the LHC run 1 physics beam with 50 ns bunch spacing. Large crossing angles of 590 μrad for HL 25 ns as well as 50 ns with its high bunch intensity are foreseen. Simulations suggest that enough dynamic aperture can be guaranteed with this crossing angle. β*-levelling and different optics (e.g. flat beams instead of round beams) will offer sufficient flexibility to optimise performance, see Fig. 5.
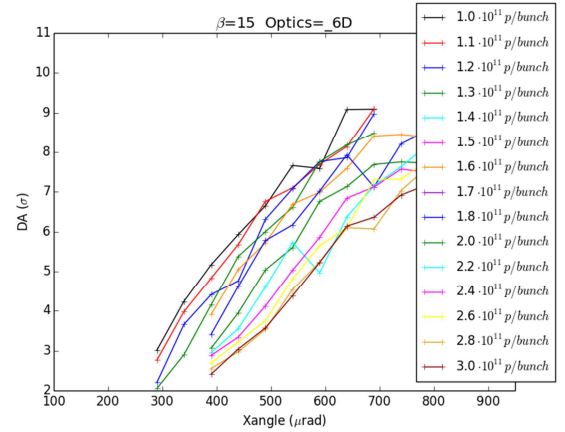

Figure 5: Dynamic aperture with beam-beam at β*=15 m, round optics, as a function of crossing angle for different bunch intensities. The collimators will be at 7 σ (beam sigma). The dynamic aperture with beam-beam should be larger than the collimator aperture.

With β* levelling, 15 m β* is reached only with smaller bunch intensities and 590 μrad crossing angle should hence be sufficient. (Imperfections have not been taken into account for this simulation.) *Courtesy T. Pieloni, D. Banfi, J. Barranco*

With the HL design parameters the head-on beam-beam tune shift ξ will be very high. And HL 50 ns ξ_{50} will be even higher than ξ_{25} for HL 25 ns.

$$\frac{\xi_{50}}{\xi_{25}} = \frac{\dfrac{N_{50}}{\varepsilon_{50}}}{\dfrac{N_{25}}{\varepsilon_{25}}} \approx 1.3 \qquad (4)$$

A total tune shift of $\xi \sim 0.02$ to 0.03 was achieved in the LHC during experiments without deterioration of the beam [5]. Long-range effects were however not present. With the HL parameters, a tune shift of $\xi \sim 0.0098$ per IP for 25 ns and $\xi \sim 0.013$ per IP for 50 ns can be expected. In case of problems with the very high tune shift, one could resolve to offset levelling for IP 8 instead of $\beta*$ levelling to reduce the total tune shift. Presently no insurmountable problems are expected from beam-beam.
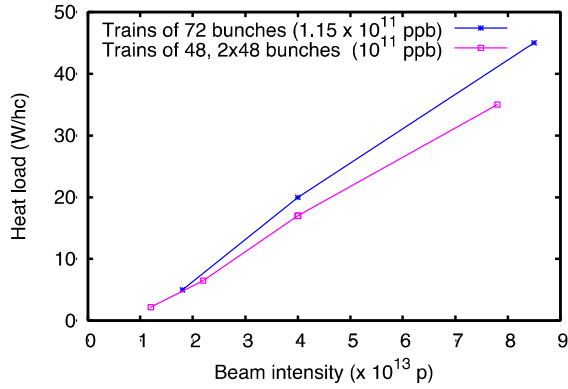

Figure 6: Heat load per arc half cell as function of beam intensity for different bunch train structures.

Electron Cloud

Substantial experience with e-cloud and scrubbing could be gained during LHC run 1, specifically during 2012. A résumé of the 2012 results with 50 ns and 25 ns beams is given in the following:

- Scrubbing has been demonstrated to be efficient at 450 GeV. It lowers the e-cloud in the dipoles. Scrubbing is less evident in the quadrupoles due to a significantly lower threshold SEY.
- Despite the 2-beam-50 ns operation in the triplet for 2 years (very high electron dose), the electron cloud is still present in the triplets.
- A significant increase (~ factor 4) of the heat load from electron cloud was observed in the arcs during the ramp. It only comes from the e-cloud in the dipoles and does not decrease over time at flattop. Scrubbing at flattop does not seem to take place. The underlying mechanism still needs to be understood.
- The heat load increases ~linearly with the number of bunches (less effect from bunch intensity above threshold intensity), see Fig. 6. This could put a limit to number of 25 ns spaced bunches in the LHC.

If the electron cloud in the arcs from the dipoles at flattop cannot be suppressed, the 25 ns total number of bunches could be limited to about half the nominal number of bunches due to the limited cooling power available in the arcs, see Table 3. Different electron cloud mitigation possibilities have been discussed. The most promising one would obviously be scrubbing at 450 GeV to "completely" remove the electron cloud in the dipoles. A special scrubbing beam - the so-called doublet beam - with partly even shorter bunch spacing than 25 ns - will be tested in 2015 [6]. Simulations suggest that this beam will increase the e-cloud significantly and thus enhance the scrubbing efficiency. In case the electron cloud from the dipoles can be removed completely, no cooling power limitation in the arcs is expected, see Table 4.

Table 3: Heat load per arc half-cell. Projection to the HL era

	Available colling [W]	Fill 3429 meas [W]	HL 7 TeV, 25 ns, 2012 SEY [W]
Arc half-cell	255	45	438

Table 4: Heat load per arc half-cell. Projection to the HL era with full suppression of e-cloud in dipoles

	Available colling [W]	HL 7 TeV, 25 ns [W]
Arc half-cell	255	4.4

If it turns out that it is not possible to scrub the LHC dipoles sufficiently, an upgrade of the cooling power for the LHC arcs by a factor 2 would have to be considered assuming the degradation of the beam quality due to electron cloud is still acceptable.

New equipment to be installed in the LHC for the HL era should foresee e-cloud mitigation. E.g. the new triplets should be equipped with electron clearing electrodes or be coated.

THE 50 NS ALTERNATIVE

An estimate of the performance with 50 ns beams as alternative to the 25 ns scheme during the HL era will be given.

Assumptions

The following assumptions and definitions have been used to give an integrated luminosity estimate:

- The efficiency parameter used for the calculations and simulations in this paper is "physics efficiency" ε_{SB}. It corresponds to the ratio of the total time spent in stable beams T_{SB} over the total allocated time for operation T_{run}. The 2012 efficiency was 37 %.

$$\varepsilon_{SB} = \frac{T_{SB}}{T_{run}} \qquad (5)$$

- An exponential fill length distribution is assumed. The fill lengths of the fills in 2011 and 2012 followed exponential distributions [7][†]. The average fill length in 2012 was ~ 6 h.
- Assumed luminosity lifetime: 9 h (const.)
- 160 days of physics operation
- Pile-up limit of μ = 140 as for 25 ns. The level luminosity for 50 ns is thus half the level luminosity for 25 ns.

Estimated performance with HL 50 ns

The yearly expected integrated luminosity has been simulated according to the assumptions in the previous paragraph. Fig. 7 summarizes the results for 50 ns and 25 ns with and without crab cavities as integrated luminosity per year versus physics efficiency. An efficiency of ~ 47 % would be needed to meet the target of 275 fb[-1] per year for 25 ns with crab cavities. For HL 50 ns the required efficiency would be ~ 80 % due to the long optimum levelling times and the low level luminosity. Running with or without crab cavities does not change the result significantly with efficiencies < 50 % for 50 ns. Expecting a physics efficiency of > 50 % is very certainly unrealistic. On a short term basis 50 % efficiency could be achieved in 2012, see Fig. 8. To reach 50 % efficiency on average for the entire run is already a challenge. Assuming now 50 % efficiency, the runs would still have to be longer by > 50 % to reach the integrated luminosity goal with 50 ns beams, see Fig. 9.
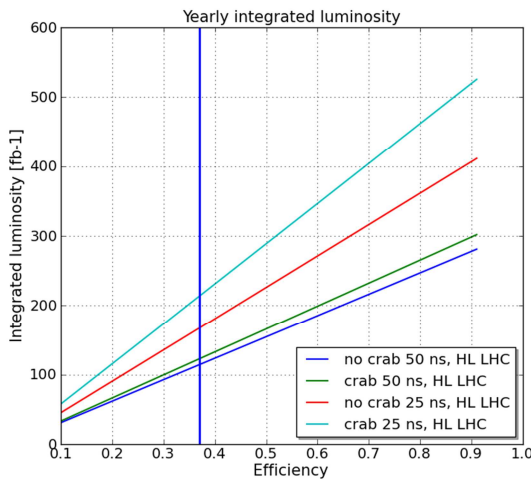

Figure 7: Integrated luminosity per year for 25 ns and 50 ns HL beams with and without crab cavities as function of physics efficiency. The blue vertical line indicates the 2012 achieved efficiency. The HL goal is 275 fb[-1] per year.

[†] A uniform fill length distribution increases the performance estimate for integrated luminosity per year by ~ 15 %.

Additional upgrades for 50 ns?

All the previous performance estimates were assuming the 50 ns HL target parameters. With the currently foreseen injector upgrades the achievable parameters at the exit of the SPS will only be 2.7×10^{11} in an emittance of 1.95 μm, as already stated earlier. Fig. 10 compares the performance for HL 25 ns, HL 50 ns and 50 ns as achievable after injector upgrades after LS2 with and without crab cavities. With the assumptions from above for fill length distribution and efficiency but an emittance growth through the LHC cycle of 40 % instead of 20 % due to the higher brightness, the integrated luminosity per year with crab cavities for the achievable 50 ns beam would be ~ 113 fb[-1], compared to 123 fb[-1] for the 50 ns HL target parameters and crab cavities. The difference is less than 10 % and does not justify another upgrade scenario in the injectors in case of 50 ns operation.
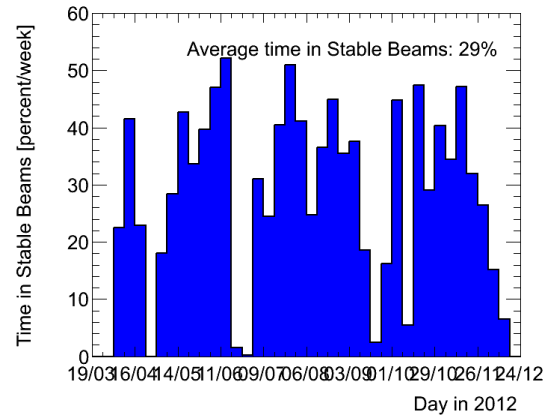

Figure 8: Average time in stable beams per week in 2012. 50 % physics efficiency per week was reached twice in 2012. *Courtesy ATLAS*
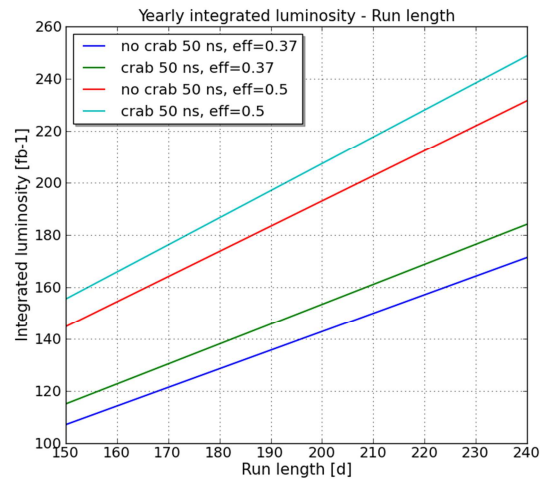

Figure 9: Integrated luminosity per year versus run length for 50 ns with and without crab cavities for efficiency of 37 % and 50 %. To reach the integrated luminosity goal of > 250 fb[-1] per year, the runs would

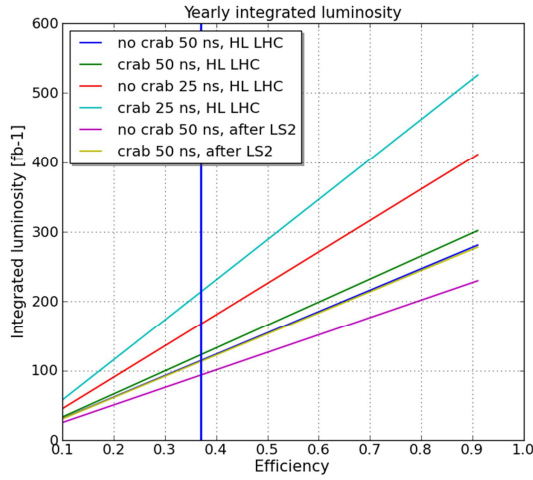have to be at least 50 % longer in case of 50 % efficiency.

Figure 10: Integrated luminosity per year as a function of physics efficiency for 25 ns HL target parameters, 50 ns HL target parameters and 50 ns parameters as achievable after LS2 with and without crab cavities. The vertical line indicates the efficiency achieved in 2012.

Remark: Can we operate with HL 50 ns bunch intensities?

In 2012 the LHC was operating with 50 ns bunch spacing and bunch intensities up to 1.8×10^{11} p$^+$. Beam stability had become a permanent concern during 2012 operation with tight collimator settings. Fig. 11 shows the result of a stability classification analysis of all fills during 2012 based on logged data of BBQ amplitudes, emittance growth and losses. The red dots indicate fills with instabilities and the black ones without instabilities. In the second half of 2012 the fills were systematically suffering from instabilities at the end of the betatron squeeze degrading the beam parameters and creating increased loss rates at the collimators. The underlying mechanism is not understood. The additional impedance from the collimators with the smaller gaps in 2012 most probably played an important role together with beam-beam.

With the 50 ns HL bunch intensities, understanding the LHC stability limitations and the impedance model will become even more important. Beam instabilities with high bunch intensities might be a possible limitation for the HL 50 ns beam and could make it even less attractive with its already reduced performance compared to 25 ns.
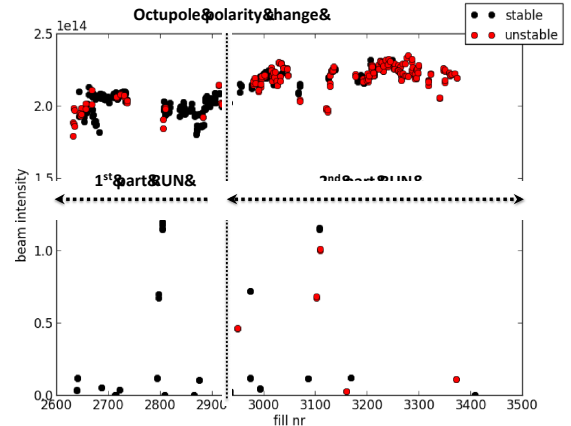

Figure 11: Stability classification of all LHC fills during 2012. Signatures of instabilities are detected from the logged data of losses, BBQ amplitudes and emittance growth. *Courtesy T. Pieloni, D. Banfi.*

CONCLUSIONS

The performance goal during the high luminosity era of the LHC will be to deliver 275 fb^{-1} of integrated luminosity a year. The 25 ns option with the high luminosity beam parameters, a fill length distribution as in 2012 and physics efficiency of close to 50 % could deliver this performance within the pile-up constraints given by the LHC experiments. Electron cloud could however be a showstopper and mitigation possibilities will have to be found in the next LHC run to prepare for the high luminosity era.

A bunch spacing of 50 ns could be an alternative. Valuable experience with this beam has been gained during LHC run 1 with bunch intensities up to 1.8×10^{11} protons. For the high luminosity ear after LS3 the 50 ns beam has significant disadvantages. With a fixed pile-up limit of 140 for the LHC experiments, only about 50 % of the integrated luminosity compared to 25 ns would be collected per year. In order to become comparable to 25 ns, unrealistic physics efficiencies of 70 – 80 % would be required.

Intermediate schemes with more bunches than the 50 ns scheme, but less electron cloud than for 25 ns, could be more attractive than 50 ns. An example is the 8b-4e beam as mentioned in [3].

No alternative upgrade paths have been identified in case 50 ns became the only valid option to operate the LHC with during the high luminosity era. Even more emphasis would however have to be put on understanding the LHC beam stability limits with high bunch intensities and the LHC impedance model. The proposed high luminosity 50 ns bunch intensities might be close to the bunch intensity limits of the LHC.

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