LONGITUDINAL PARAMETERS AND BEAM INDUCED HEATING

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Abstract

The longitudinal beam parameters are proposed for the LHC re-commissioning and operation in 2015, based on the experience obtained from operation and MD results during LHC Run 1. Controlled longitudinal emittance blow-up is necessary during the whole ramp to 6.5 TeV. The value of the longitudinal emittance is defined by beam stability and IBS, and bunch length and RF voltage by particle losses, beam induced heating and experiments requirements. The impact of the longitudinal parameters on luminosity will be also discussed here.

Beam induced heating limitations during LHC run 1 are reviewed and an update on the mitigation measures taken during LS1 is presented. The situation in 2015 is expected to be more favourable due to all improvements made and potential issues would be mainly caused by unexpected non-conformities. In addition, more devices are equipped with temperature sensors that will allow us to monitor beam induced heating and react early to try and prevent damage to the equipment. Since further increase of bunch length leads to beam lifetime degradation, a special controlled emittance blow-up that flattens the bunch profile is also considered for beam induced heating mitigation.

LONGITUDINAL PARAMETERS

The nominal LHC longitudinal parameters were defined in the LHC Design Report [1] and are shown in Table 1.

Table 1: Longitudinal parameters from LHC Design Report.

Energy	RF Voltage [MV]	Bunch length [ns]	Emittance [eVs]
450 GeV	8	1.5	0.8
7 TeV	16	1.05	2.5

At the end of the LHC Run 1, in 2012, the longitudinal emittance of the bunches extracted from the SPS was lower than in the DR, i.e, 0.5 eVs and 0.45 eVs for the Q26 and Q20 optics, respectively. The voltage at injection was 6 MV, which was enough to keep injection losses below 0.5 %. At 4 TeV, however, the bunch length had to be increased to ~ 1.25 ns (4 σ_t calculated from BQM FWHM for a Gaussian distribution) to reduce the beam induced heating. First issues started in 2011 when the beam intensity was pushed [2] (bunch intensity up to 1.6×10^{11}) and then problems continued during 2012 [3].

In this paper we analyse the possible range of the longitudinal parameters after LS1, taking into account the effects on beam stability, particle losses, synchrotron radiation, IBS, and beam induced heating. We also present the strategy to follow during the start up in 2015, a mitigation for the beam induced heating in case of problems, and a scheme for luminosity levelling via bunch length.

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Landau Damping

The single bunch stability threshold at 6.5 TeV will be similar to that at 4 TeV if the bunch length and the RF voltage V are the same as it follows from the scaling [4]:

$$N_b^{th} \propto \frac{\varepsilon^{5/2}}{E^{5/4}\,V^{1/4}}, \qquad (1)$$

where N_b^{th} is the threshold bunch intensity, ε is the longitudinal emittance, and E is the beam energy.

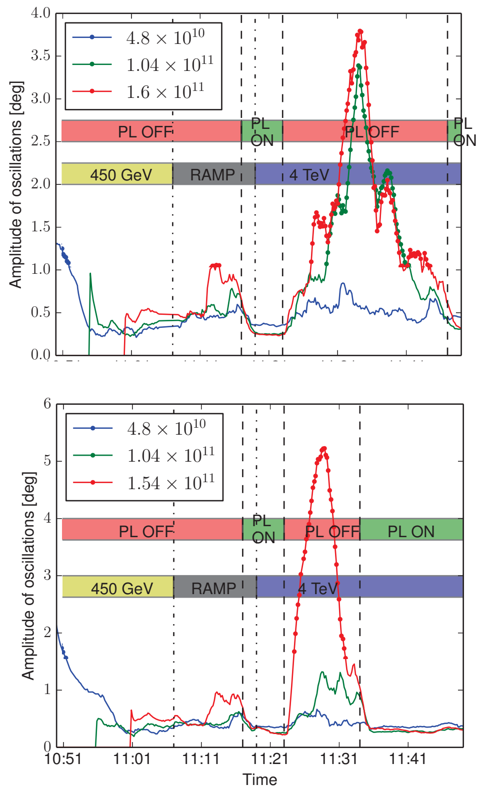

Figure 1: Amplitude of dipole oscillations during a fill with acceleration to 4 TeV for Beam 1 (top) and Beam 2 (bottom). At 4 TeV, all bunches had a longitudinal emittance of 1 eVs. The bunch with intensity of ~ 1.0×10^{11} was unstable in Beam 1 and at the limit of stability in Beam 2. Beam energy and Phase Loop status are indicated in the plots.

From measurements performed during an MD in 2012 and shown in Fig. 1, the threshold at 4 TeV and with 12 MV was found to be around 1 eVs for a bunch intensity of 1×10^{11} [5]. However, only three bunches were measured and therefore measurements with more bunches are needed to obtain more statistics and a more precise threshold. Using Eq. (1), we can scale to the operational parameters of 6.5 TeV and 10 MV and obtain an intensity threshold of 6×10^{11} for a bunch with 1.25 ns length (same as in 2012), and 2.8×10^{11} for the nominal bunch length of 1.05 ns. In both cases, the threshold is well above the nominal bunch intensity of 1.15×10^{11}. The minimum emittance required for stability for a bunch with nominal intensity is 1.32 eVs (0.85 ns).

The coupled bunch instability has not yet been observed for the operational parameters during Run 1 (50 ns beams, total beam current up to 0.4 A), neither at injection energy nor at 4 TeV. It was not observed either for 25 ns beams during the scrubbing run at 450 GeV, when the total beam current was increased to 0.5 A. The scaling to higher energy is not trivial, but it can be approximated for the case of equally spaced bunches and constant bunch length. In that case, the intensity threshold scales as $I_{th} \propto V^{1/4}$ [4] and therefore the beam would be stable at 6.5 TeV. For shorter bunches, the threshold cannot be estimated as it depends on the resonant frequency of the driving impedance.

Particle Losses

Two particle loss mechanisms that are related to the bunch length were observed during LHC Run 1. The first one is due to particles escaping from the RF bucket. It was proven during an LHC MD in 2011 that the loss rate increases for longer bunches, as it can be seen in Fig. 2 [6].

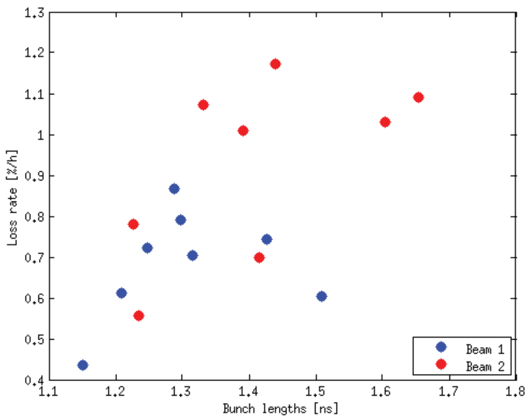

Figure 2: Measured particle loss rate at 3.5 TeV as a function of bunch length for 8 non-colliding bunches in Beam 1 (blue) and Beam 2 (red). Bunch intensity of $(1.15 \pm 0.15) \times 10^{11}$.

The second loss mechanism is caused by the beam-beam interaction and it was observed as a longitudinal shaving. In 2012, this effect was limiting the maximum bunch length to about ~ 1.3 ns, as shown in Fig. 3. At the end of the Run 1, from 29 October 2012, the voltage program was modified to the following: the RF voltage was increased during the ramp to 10 MV instead of 12 MV, and then to 12 MV after 2-3 h of collisions to improve the integrated luminosity. The voltage increase seems to enhance this effect, as the maximum bunch length is reduced. This could mean that the losses are related rather to the energy spread than to the bunch length. If that is the case, lower voltage and smaller emittance would be desirable in operation.

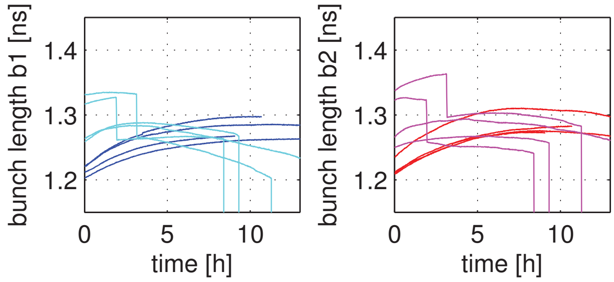

Figure 3: Bunch length evolution for several fills in 2012, for Beam 1 (left) and Beam 2 (right). Two different voltage settings: constant 12 MV (blue and red) and 10 MV increased to 12 MV after 2-3 hours (cyan and pink). Courtesy G. Papotti.

Synchrotron Radiation

Synchrotron radiation will be stronger at 6.5 TeV as compared to 4 TeV, with an increase in the energy loss per particle from 0.7 keV to 5 keV per turn. If synchrotron radiation damping rate were higher than the blow-up from RF noise and IBS, bunches would shrink and if it leads to any problems it should be compensated by controlled longitudinal emittance blow-up [7]. Otherwise this gives a luminosity increase through the geometric factor.

In addition, particles lost from the RF bucket will all move in the same azimuthal direction much faster than at 4 TeV.

Intra Beam Scattering (IBS)

Simulations using MAD-X show no emittance growth in the vertical plane, but a growth in the horizontal plane that increases for shorter bunches and for smaller longitudinal emittances [8], as shown in Fig. 4. Nevertheless, Fig. 5 presents a calculation done for a transverse emittance of 1.7 µm, RF voltage of 12 MV and $\beta^* = 40$ cm that shows that reducing the bunch length from 1.25 ns to 1.0 ns results in a higher integrated luminosity. The approximation was done assuming constant bunch length and emittance growth rate, although the growth rate is strongly dependent on the transverse emittance and it is slower for larger emittances. In practice, the gain in luminosity would be probably higher.

Luminosity Levelling via Bunch Length

Bunch length levelling could be used in case of excessive beam induced heating or too high pile-up density. The acceleration would be done with constant 6 MV or increasing it to 8 MV if needed, and with controlled longitudinal emittance blow-up to get bunches with ~ 1.25 ns at the beginning of physics. Then they will be shrunk slowly by increasing the voltage up to 16 MV. Taking into account that the bunch length τ dependence on voltage V is $\tau \propto V^{1/4}$, a factor 2 increase in voltage translates to a 20% reduction in bunch length. The lower synchrotron frequency could be detrimental for the transverse stability and its effect should be studied as well as the effect of synchrotron radiation.

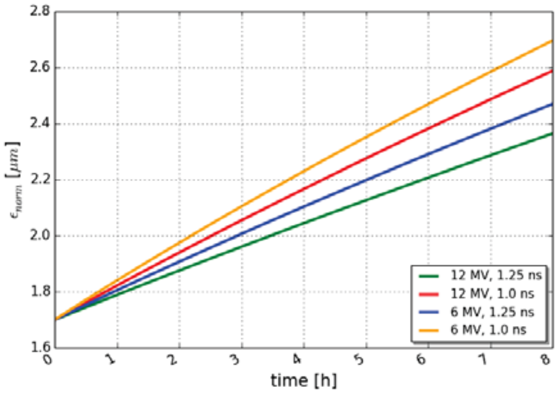

Figure 4: Horizontal emittance growth due to IBS for different voltages and bunch lengths. The growth rate is faster for shorter bunches and for lower voltage [8].

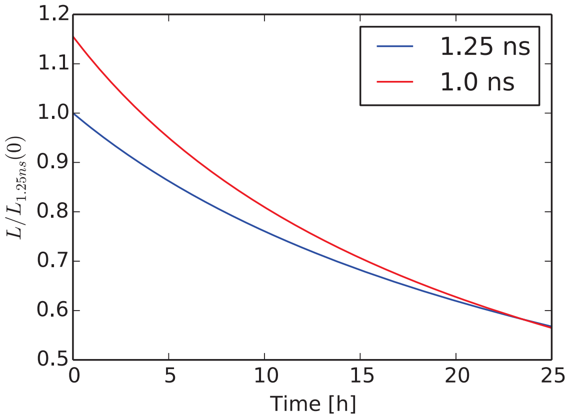

Figure 5: Instantaneous luminosity evolution for 1.25 ns (blue) and 1.0 ns (red) bunch lengths, relative to the initial luminosity with 1.25 ns, taking into account the transverse emittance growth due to IBS.

BEAM INDUCED HEATING

Beam induced heating was one of the main performance limitations in the LHC with 50 ns beams during Run 1. The consequences were damages to equipment, undesired beam dumps, and delays to re-inject. [9]

The power dissipated P in a device with a longitudinal impedance $Z(\omega)$ depends on the single bunch spectrum j_k according to:

$$P = \sum_{k=-\infty}^{\infty} j_k^2 \, \mathrm{Re}\, Z(k\,\omega_0) \left[\frac{\sin(M\,k\,\omega_0\,t_{bb}/2)}{\sin(k\,\omega_0\,t_{bb}/2)} \right]^2, \qquad (2)$$

where ω_0 is the revolution frequency, M is the number of bunches, and t_{bb} is the bunch spacing in the train. For a broadband impedance increasing the bunch length usually reduces the beam induced heating. For that reason, the bunch length was increased in few occasions up to 1.25 ns during Run 1.

Several mitigations were put in place by equipment groups before and during LS1 and they are summarized in the following list:

- All the VMTSA double bellows were removed.
- All non-conforming RF fingers were repaired during LS1 and a new design is being developed [10].
- The TDI beam screen was stiffened and more support was installed during LS1. The copper coating on the TDI jaw that was planned had to be abandoned due to technical issues. This means that the beam will deposit the same power in the consolidated TDI compared to the old TDI, but the consolidated TDI is expected to sustain better this heat load. It is important to note that the cooling was simulated to be inefficient but could not be upgraded during LS1 [11].
- The injection kicker MKI screening was significantly improved and the two non-conforming magnets that were causing heating problems were repaired (MKI8C and, in particular, MKI8D) [12].
- The primary collimator that was overheating, TCP.B6L7.B1, was exchanged during LS1 and the non-conformity should have been removed. The cooling system was suspected of being the issue, but investigations will be performed in September, to allow for sufficient radiation cool-down.
- All the 2-beam-collimators TCTVBs were removed, one half in 2012 and the other half during LS1.
- The valves of the standalone quadrupoles were upgraded to allow higher cooling of the beam screen [13].
- A shielding was installed on the ATLAS-ALFA and TOTEM detectors during LS1 to reduce heating, however the TOTEM plans to approach high luminosity beams may increase the heating to their pot [14].
- A new design of the BSRT mirror was installed during LS1 to reduce the heating [15].

In addition to these mitigation measures, an efficient monitoring of the elements with potential heating issues is necessary. Many systems have been requested to be equipped with additional temperature sensors during LS1 and the measurements to be be logged in the logging database. The implementation of a fixed display in the control room CCC is planned, together with alarms for fast reaction to prevent damages.

Figure 6 shows simulations of heating in the ALFA roman pot for the old and the new designs. The dependence on bunch length is very strong. The beam induced heating should be largely reduced with the new design, and less heating than in 2012 is foreseen even for nominal bunch length. The same behaviour is also expected in several other upgraded equipment.

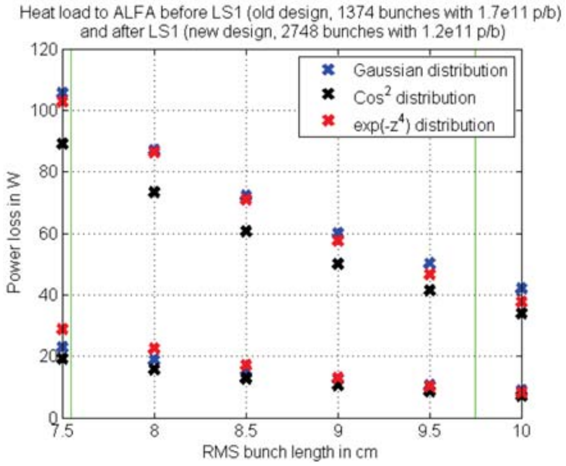

Figure 6: Simulated beam induced heating in the ALFA roman pot as a function of bunch length, for three different particle distributions. The points that have higher heating correspond to the old design, and the ones with lower heating are for the new design.

Flat Bunches

Another option to reduce the beam induced heating is to flatten the bunches [16]. In the absence of a 2^{nd} RF system in the LHC, this can be done by applying a phase modulation close to the synchrotron frequency. This method was already tested in the LHC and Fig. 7 shows that the beam spectrum was considerably reduced for frequencies below 1.2 GHz, but increased above that frequency (for 1.25 ns bunch length). A beneficial effect was observed on the monitored devices, but further tests would be required to check that there are no devices with impedance at a frequency higher than 1.2 GHz that could overheat as a result.

Another advantage of using this method is that the pile-up density would be more uniform.

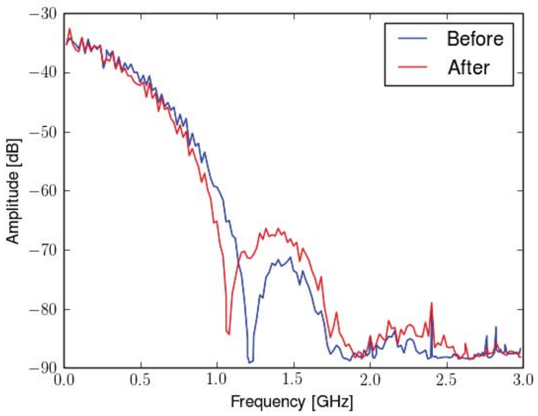

Figure 7: Envelope of the beam spectrum before (blue) and after (red) the RF modulation. The spectrum amplitude is reduced for frequencies below 1.2 GHz, but increased above.

PROPOSED STRATEGY

The LHC will run with 50 ns beams only for a short period during the start-up in 2015 and the same RF parameters as before LS1 will be used. The rest of the run, the LHC will operate with 25 ns beams. Beam induced heating should be carefully monitored as the total beam intensity will be higher (0.55 A).

The SPS can currently deliver the 25 ns beam with a bunch intensity up to 1.35×10^{11} and a longitudinal emittance similar to that obtained with 50 ns beams, i.e 0.47 eVs using Q20 optics.

The RF voltage in the LHC at injection energy is suggested to be set to 6 MV, the same as in 2012, in order to achieve similar transmission and beam stability. Then the beam is accelerated to 6.5 TeV with controlled longitudinal emittance blow-up, with an initial bunch length target of 1.25 ns.

Two options are possible to increase the luminosity at 6.5 TeV. The first one consists in reducing the bunch length to the nominal 1.05 ns, keeping the RF voltage constant to 10 MV or 12 MV. In this case, the reduction of the blow-up target during the ramp must be done in small steps and with careful monitoring of the beam induced heating and the transverse stability. The second option is to reduce the controlled longitudinal emittance blow-up and the RF voltage at 6.5 TeV, which would give the potential for luminosity levelling by increasing the voltage during the physics.

SUMMARY

Lower emittances at 6.5 TeV are tolerable thanks to the expected margin in longitudinal stability. This could have a positive impact on the beam lifetime and luminosity. It would also allow to use luminosity levelling via bunch length variation. The effect of IBS is not predicted to be significant.

The known issues with beam induced heating should be solved during LS1. More temperature monitoring and alarms will be available in 2015, and will help preventing damages if there are any unexpected issues. Flat bunches and bunch length levelling could be used as mitigations if necessary.

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