COLLIMATION DEPENDENT BEAM LIFETIME AND LOSS RATES IN THE LHC

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Abstract

The four primary collimators in each LHC beam define the smallest aperture. Particles with high betatron amplitudes or momentum offsets will therefore hit first a primary collimator. The instantaneous particle loss rate at primary collimators measured by precise beam loss monitors (BLM) is an important measure for the global lifetime of the beams and a major ingredient to identify collimation induced performance limitations in the LHC. These loss rates have been measured during a number of LHC fills, featuring both"good"fills with high luminosity and"bad"fills with beam instabilities. The beam lifetime at the collimators was then calculated from these data for different cases. The results are presented and interpreted within this paper.

INTRODUCTION

At nominal particle momentum (7 TeV/c) and intensity ($\sim 3\times10^{14}$ p) the LHC will have a stored energy of 362 MJ per beam. Uncontrolled losses of just a small fraction of beam at the superconducting magnets of the LHC can cause a loss of their superconducting state (quench limit at 7 TeV/c: $R_q = 7.6\times10^6\,\mathrm{ps^{-1}m^{-1}}$) [1, 2]. Therefore a powerful collimation system is needed to intercept these unavoidable beam losses.

For installing the full LHC collimation system a phased approach has been taken. The collimators of the current phase-I system are mainly installed in two dedicated cleaning insertions. IR3 collimators are used for the cleaning of off-momentum particles and IR7 to intercept particles with too large betatron amplitudes. In addition the collimators provide a passive machine protection [3, 4, 5].

The four primary collimators (TCPs) define the smallest aperture. Particles with high betatron amplitudes or momentum offset will therefore hit first a primary collimator [6]. The instantaneous particle loss rate at primary collimators is an important measure for the global lifetime of the beams and a major ingredient to identify collimation induced performance limitations in the LHC. The phase-I collimation system was expected to significantly limit the maximal possible beam intensity stored in the LHC at 7 TeV/c and at intermediate particle momenta as the current 3.5 TeV/c [6, 7]. Therefore the instantaneous loss rates at the primary collimators have been measured during a number of LHC fills, featuring both"good"fills with high luminosity and"bad"fills with beam instabilities. The beam lifetime at the collimators was then calculated from these data for different cases.

During the physics running period in 2010 the LHC was operated at 3.5 TeV/c with a maximum of 368 proton bunches per beam (i.e. $\sim 4.2\times10^{13}$ p) and a bunch spacing of 150 ns providing collisions to the particle physics experiments. In 2011 the bunch spacing was reduced to 50 ns which lead to a maximum of 1380 bunches per beam (i.e. $\sim 1.5\times10^{14}$ p).

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COLLIMATION BEAM LOSSES

The instantaneous particle loss rate on a collimator can be calculated from the signal of the corresponding beam loss monitor (BLM) i as

$$R_{loss}(t) = f^i_{calib} S^i_{blm}(t). \quad (1)$$

The calibration factors f^i_{calib} were achieved by correlating the BLM signals, S^i_{blm}, to the beam intensity signals from the fast beam current transformers (FBCT). As the calibration factors vary from fill to fill the correlation has been performed for each analysed fill. Only periods when the LHC was in the machine status *stable beams*, i.e. the two beams were in collision and the experiments were taking data, were included for the correlation. About 90 % of the losses recorded by the BLMs during *stable beams* operation appear in the two cleaning insertions IR3 and IR7. Therefore collimation related losses are clearly dominating. The instantenous loss rates $R_{loss}(t)$ presented below were calculated from the signal of a BLM, which is sensitive to the losses in the vertical and horizontal primary collimators. The estimated error in the conversion of beam loss signals to loss rates was smaller than 20%. The instantaneous beam lifetime can be calculated from the loss rate and beam intensity N at the time t [8] as

$$\tau(t) \approx \frac{N(t)}{R_{loss}(t)}. \quad (2)$$

Losses during high luminosity runs

Twenty high luminosity fills have been analyzed: 3 runs with 312 bunches ($\sim 3.6\times10^{13}$ p), 5 runs with 368 bunches ($\sim 4.2\times10^{13}$ p) (from the running period 2010 with a bunch spacing of 150 ns), and runs with 912, 1092 and 1380 bunches (from the intensity ramp up during the running period 2011 with a bunch spacing of 50 ns), each with 4 fills. Instantaneous loss rates have been calculated for four different integration times of the BLM signals: 80 μs, 640 μs, 10.24 ms and 1.3 s. Losses that appear only in the first two integration times can be assumed as transient losses, as these correspond to 1 - 7 LHC turns. Losses that appear also in the latter can be considered as steady state losses (115 - 14600 turns).

Figure 1 shows the calculated loss rates for BLM signals with different integration times at the horizontal primary

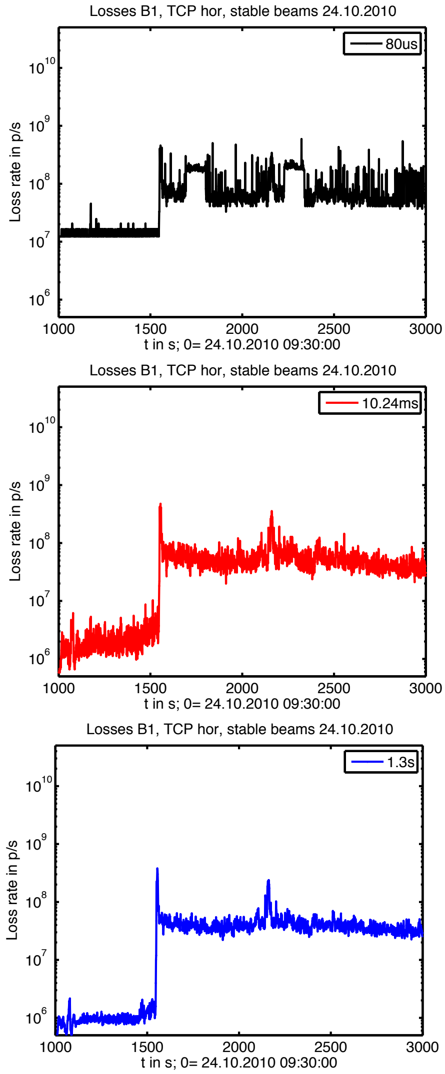

Figure 1: Loss rate at the horizontal primary collimator in the betatron cleaning insertion of beam 1 during 33 mins of a high luminosity LHC run. The plots show the loss rates calculated from BLM signals with the integration times 80 μs, 10.24 ms and 1.3 s.

collimator in the betatron cleaning insertion of beam 1 during a high luminosity run. In all integration times the loss rates showed a spike and the loss rate levels were significantly increased when the two beams were put into collision ($t > 1500$ s). They stayed at this levels until the beams were dumped. This shows that the losses are mainly induced by beam-beam interactions. Additional loss spikes appeared for the different signals in most cases at the same time. Especially for the 80 μs integration time there were additional transient losses, which were nearly as high as the losses caused by bringing both beams into collision.

In figure 2 the highest measured loss rates of the fills with the same bunch numbers are compared to the specified maximum loss rate $R_{spec} = 4.5 \times 10^{11}$ p/s, specified during the design phase of the LHC collimation system. It was defined for losses on collimators over several seconds at the nominal intensity ($\sim 3 \cdot 10^{14}$ p), 7 TeV/c and for a life time of $\tau_{spec} = 0.2$ h. This loss rate indicates the limit above

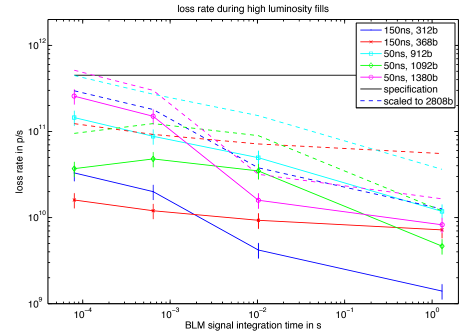

Figure 2: Highest loss rates found in LHC runs with 312, 368, 912, 1092 and 1380 bunches versus BLM signal integration time compared to $R_{spec} = 4.5 \times 10^{11}$ p/s. The dashed lines show a linear scaling to the nominal number of bunches (2808).

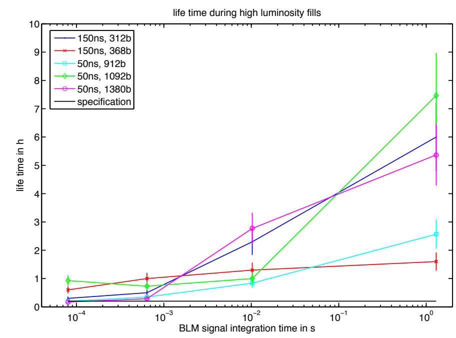

Figure 3: Lowest instantaneous life times found in LHC runs with 312, 368, 912, 1092 and 1380 bunches versus BLM signal integration time compared to τ_{spec}.

which the leakage of particles from the cleaning insertions into the cold dispersion suppressor magnets could reach a critical level and could cause quenches of cold magnets at 7 TeV/c. It can be clearly seen that the loss rates were below the specifications for all integration times. This still holds when the loss rates are linearly scaled to nominal intensity (dashed lines) in most of the cases. Only the scaled loss rate from the runs with 1380 bunches is slightly exceeding the specified loss rate in the 80 μs integration time. As these would be transient losses (one single turn) they are not expected to cause collimation related intensity limitations for the LHC. Figure 3 shows that the lowest measured instantaneous life times of the high intensity runs are above the specified life time of $\tau_{spec} = 0.2$ h for all integration intervals, except for 80 μs in the 1380 bunch runs.

Recently the minimum beam lifetimes measured by the FBCTs could be increased by a factor 4 to 5 due to a change of the transverse tunes when putting the two beams into collision.

Losses due to instabilities

Two runs with exceptionally high losses due to instabilities, which finally caused a beam dump, have been analysed. Both runs had 108 bunches per beam with a bunch spacing of 50 ns. In the first the beam became unstable at the end of the so-called squeeze, when the beta functions in the interaction points (IPs) are reduced to collision values. The second fill showed high losses before the squeeze,

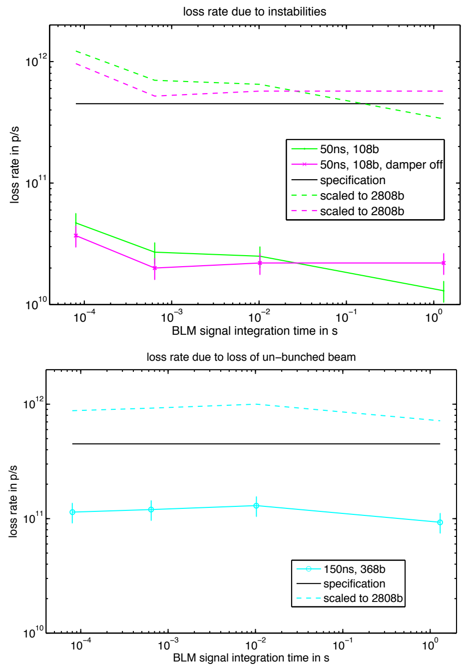

Figure 4: Highest loss rates versus BLM signal integration time compared to $R_{spec} = 4.5 \times 10^{11}$ p/s. The dashed lines show a linear scaling to the nominal number of bunches (2808). **Top:** LHC runs with instabilities. The first fill (108 b, 50 ns bunch spacing) became unstable at the end of the squeeze, the second due to turning of the tranverse damper. **Bottom:** Loss of un-bunched beam at the beginning of the ramp (27.10.2010). Within $\sim$ 6 s 2.8 % ($\sim 1.3 \times 10^{13}$ p) were lost in the momentum cleaning insertion (IR3). The fill had 368 bunches.

when the transverse damper was turned off. The top of figure 4 compares the highest instantaneous loss rates found during these two runs with the specified loss rate. In both cases the loss rates for all integration times were below the specifications. This does not hold any longer, if the loss rates are linearly scaled to nominal intensity.

These examples show that instabilities could cause a collimation indicated limitation of the achievable beam intensity in the LHC.

Losses due to un-captured beam

Particles which were not captured correctly in the RF bucket, or moved out of it due to an RF failure, will get lost in the momentum cleaning insertion (IR3) as soon as the particle energy is ramped up from 450 GeV/c. In a run with 368 bunches 1.3×10^{12} un-captured protons were lost in beam 1 within 6 s at the beginning of the ramp. This was equivalent to about 2.8 % of the total beam intensity. The bottom of figure 4 shows the instantaneous loss rate compared to the specified loss rate. For all integration times this was below the specifications. Scaling the measured loss rate linearly to nominal intensity shows that this would exceed the specifications.

Note that the scaling of the measured instantaneous loss rates was performed linearly with beam intensity in all cases discussed above (dashed lines). This approach may be a too optimistic. Higher bunch charges, a shorter bunch spacing (currently 50 ns in the future 25 ns), an increasing impedance due to tighter collimator settings, additional beam-beam effects due a fully filled machine (25ns), higher particle momenta and other effects could cause a further increase of the loss rates at collimators. Furthermore possible limitations due to collimation like radiation to electronics (R2E) have also not been taken into account here.

CONCLUSION

The highest measured instantaneous loss rates at primary collimators have been significantly below the specified loss rates. This still holds when the loss rates are linearly scaled to nominal intensity (dashed lines) if only integration times which represent multi turn losses are considered ($\geq$ 640 ms). Considering only the most relevant 1.3 s integration time of the BLM signals, the minimal instantaneous life times were found to be about a factor 9 higher than specified. As cleaning with the current collimation system works as expected [9] these results indicate that a limitation of the LHC intensity due to collimation is unlikely. Note that other issues such as radiation to electronics (R2E) have not been considered here.

As presented for some exceptional cases instabilities can significantly cause an increase of the instantaneous loss rates at collimators to a level above the specifications, if scaled to the nominal intensity. As instabilities could appear at higher intensities and particle momenta these limitations need to be taken into account. Also losses due to un-captured beam could limit the possible maximum intensity. Note that these are no hard limits, as they will cause beam dumps. The frequency of instability-induced beam dumps could then decrease the performance of the LHC.

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