EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ACC-2013-0072

LIFETIME ANALYSIS AT HIGH INTENSITY COLLIDERS APPLIED TO THE LHC

B. Salvachua_, R. W. Assmann† , R. Bruce, F. Burkart, S. Redaelli,

G. Valentino, D. Wollmann , CERN, Geneva, Switzerland

Abstract

The beam lifetime is one of the main parameters to define the performance of a collider. In a super-conducting machine like the LHC, the lifetime determines the intensity reach for a given collimation cleaning. The beam lifetime can be calculated from the direct measurement of beam current. However, due to the noise in the beam current signal only an average lifetime over several seconds can be calculated. We propose here an alternative method, which uses the signal of the beam loss monitors in the vicinity of the primary collimators to get the instantaneous beam lifetime at the collimators. In this paper we compare the lifetime from the two methods and investigate the minimum lifetime over the LHC cycle for all the physics fills in 2011 and 2012. These data provide a reference for estimates of performance reach from collimator cleaning.

Presented at the International Particle Accelerator Conference (IPAC'13) –

May 12-17, 2012, Shanghai, China

Geneva, Switzerland, May 2013

LIFETIME ANALYSIS AT HIGH INTENSITY COLLIDERS APPLIED TO THE LHC

B. Salvachua*, R. W. Assmann†, R. Bruce, F. Burkart, S. Redaelli,
G. Valentino, D. Wollmann , CERN, Geneva, Switzerland

Abstract

The beam lifetime is one of the main parameters to define the performance of a collider. In a super-conducting machine like the LHC, the lifetime determines the intensity reach for a given collimation cleaning. The beam lifetime can be calculated from the direct measurement of beam current. However, due to the noise in the beam current signal only an average lifetime over several seconds can be calculated. We propose here an alternative method, which uses the signal of the beam loss monitors in the vicinity of the primary collimators to get the instantaneous beam lifetime at the collimators. In this paper we compare the lifetime from the two methods and investigate the minimum lifetime over the LHC cycle for all the physics fills in 2011 and 2012. These data provide a reference for estimates of performance reach from collimator cleaning.

INTRODUCTION

In collider machines like the LHC protons losses occur during regular operation. These losses could be due to beam dynamics such as diffusion or instabilities or to operation variations like changes of collimator settings during ramp, orbit changes during squeeze, etc. There is a continuous attempt to minimize these losses but they cannot be completely avoided and they set a limit to the maximum beam intensity without risk of quenching a magnet [1]. The beam lifetime is related to the maximum allowed intensity by the following equation [2]:

$$N_{\max} = \tau_{\min} \cdot \frac{dN}{dt} \approx \tau_{\min} \cdot R^{\mathrm{TCP}}_{\max} = \tau_{\min} \cdot \frac{R_{\mathrm{q}}}{\eta_c}$$

where $\tau_{\min}$ is the minimum beam lifetime, dN/dt is the particle loss rate which is approximated to the particle loss per second at the primary collimator $R^{\mathrm{TCP}}_{\max}$, R_{q} is the quench limit of the superconducting magnets and η_c is the collimation cleaning inefficiency which depends on the collimator settings but otherwise is stable during operations, see [3, 4].

The beam lifetime can be calculated from the direct measurement of beam current (BCT signal). However, due to the noise in the beam current signal only an average lifetime over few seconds can be calculated (an average over 30 s is used in regular LHC operation). On the other hand, beam loss monitors (BLMs) are placed all along the LHC and provide a measurement of the beam losses in Gy/s with 12 different integration times that range from $40\ \mu$s to about 84 s. The use of the BLMs, for example the ones downstream the primary collimators in IR7, is useful to provide a lifetime measurement [5] of specific type of losses, like fast betatron losses from protons impacting the primary collimators due to beam instabilities.

CALIBRATION OF THE BLM SIGNAL

The LHC cycle comprises several beam modes, we focus here in the beam modes ramp (beam energy is increased from 450 GeV to 3.5 or 4 TeV), flat top (no changes), squeeze (beams being squeezed at the colliding IRs), adjust (beams put in collisions) and stable (stable collisions are being produced). For the calculation of the calibration factor of the BLMs we have analyzed 297 fills in 2012 and 216 fills in 2011. All the fills analyzed here reached the stable beam mode. For each beam mode and fill, we calculate the number of protons lost per second as function of time (R^{bct}) from the BCT signal. Notice that the intensity lost due to luminosity burn-off is not subtracted. In order to smooth the BCT signal and average period of 5 s was used. Figure 1 shows the intensity (top) and proton loss rate (bottom) for fill 2479 during adjust beam mode.

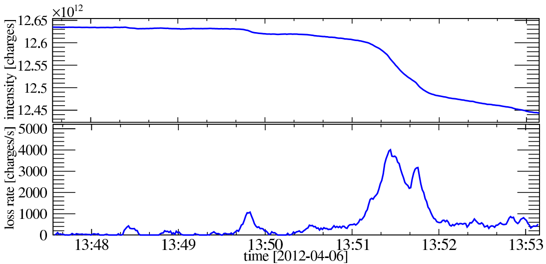

Figure 1: Intensity (top) and loss rate (bottom) during the adjust of fill 2479 for Beam 1 as a function of time.

The signal from one or several BLMs can be calibrated to provide the same number of protons lost. In this paper, we calculate the calibration factor for the BLM downstream of the primary collimators in IR7 (TCP.A) that can measure horizontal, vertical and skew primary losses in IR7 and use the BLM running sum of 1.3 s, therefore losses in other locations (such as IR3) will not be taken into account for this analysis.

The calibration is calculated by doing a minimization of the quantity $\chi^2 = \sum_{i=0}^{n} \left(R_i^{\mathrm{bct}} - \lambda R_i^{\mathrm{blm}}\right)^2$, where the sum runs from the first to the last second of the selected beam mode ($i = 0, n$) and λ is the calibration factor that will minimize the χ^2 for every beam mode. This minimization is done for every stable beam fill (2011 and 2012) independently. For example, the result is shown in Figure 2 during squeeze in 2012 as function of time. The top part shows the

---

* belen.salvachua@cern.ch
† Present address: DESY, Germany

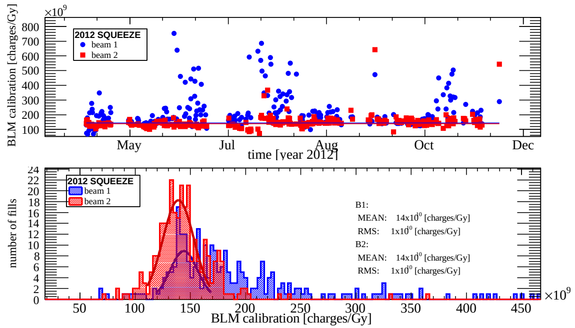

Figure 2: BLM calibration as a function of time (top) and histogram of those factors (bottom) for all stable fills of 2012 during squeeze beam mode.

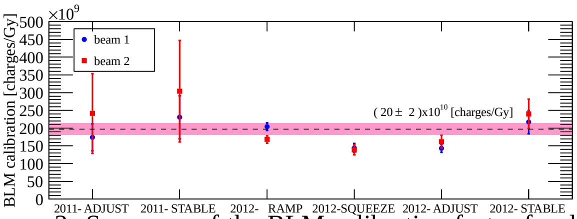

Figure 3: Summary of the BLM calibration factor for different beam modes in 2011 and 2012.

calibration factor λ over time and the bottom a projection of all the calibrations. A Gaussian fit was used to fit these values.

Figure 3 summarizes the result for all the beam modes and periods analyzed. From these values one can derive an average calibration factor for 2011 and 2012 for the BLM TCP.A of $(20 \pm 2) \cdot 10^{10}$ $[\mathrm{protons/Gy}]$.

LIFETIME THROUGH THE CYCLES

Figure 4 shows the protons lost per second as a function of time for fill 2479 during adjust, in blue the BCT signal, in dashed-red the BLM signal calibrated with the factor calculated specifically for that fill and in dashed-black line the BLM signal calibrated with the average calibration factor. The three distributions show a good agreement within 20%. We will use the average calibration and the BLM signal to compute the lifetime in the rest of the paper.

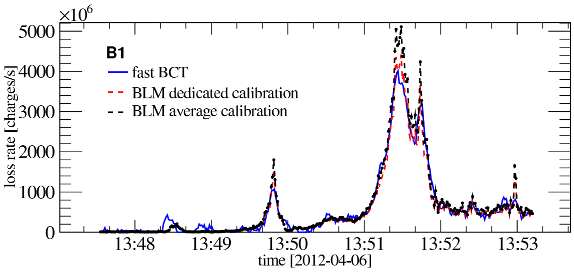

Figure 4: Protons lost per second as function of time for fill 2479 during adjust (BCT average: 5 s, BLM: 1.3 s).

The lifetime, assuming an exponential decay, is calculated with the following equation [6] [7]:

$$\tau_i = \frac{-1}{\ln\left(1 - \frac{R_i^{\mathrm{blm,bct}}}{N_i}\right)}$$

where i is an iterator over time, $R_i^{\mathrm{blm,bct}}$ is the proton loss rate from BLMs or BCT and N_i the beam intensity. Figure 5 shows as an example the lifetime as a function of time for fill 2479 during adjust, calculated with the BCT and with the calibrated BLM.

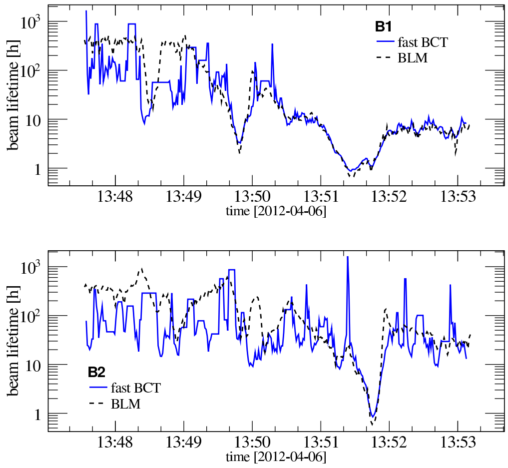

Figure 5: Beam lifetime as a function of time for fill 2479 during adjust for Beam 1 (top) and Beam 2 (bottom).

Figure 6 shows the calculated lifetime using the BLM signal for a random fill in 2011 and in 2012 over the full cycle excluding the start of ramp. One can see that in 2011 there was only one steep decrease of the lifetime in adjust when beams were put in collision. In 2012 the lifetime behavior changed with respect to 2011. We observe major drops of lifetime, one comes at the end of ramp when the collimators are moving closer to the beam (primaries go to $4.3\ \sigma$ assuming normalized transverse emittance of $3.5\ \mu\mathrm{m\,rad}$). These are slow losses which are not dramatic for operation, see [8]. The second lifetime drop occurs when the beam are being prepared for collisions in adjust. In between there is also a period with reduced beam lifetime this corresponds to squeeze.

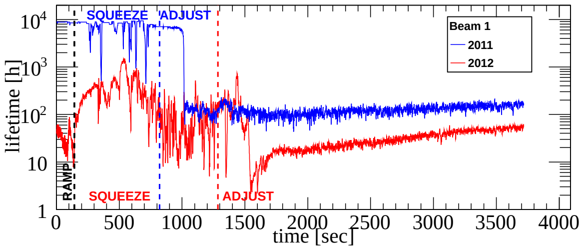

Figure 6: Lifetime as function of time for a typical fill in 2012 and 2011 (fill numbers 2712 and 1732).

LHC LIFETIME PERFORMANCE

The fraction of fills with lifetime smaller than 1, 5 and 10 hours is shown in Figure 8 for Beam 1 (top) and Beam 2 (bottom) for different beam modes in 2011 and 2012. The figure shows how in 2012 more than $90\ \%$ of the fills had lifetime below $5\ \mathrm{h}$ during adjust while in 2011 only about

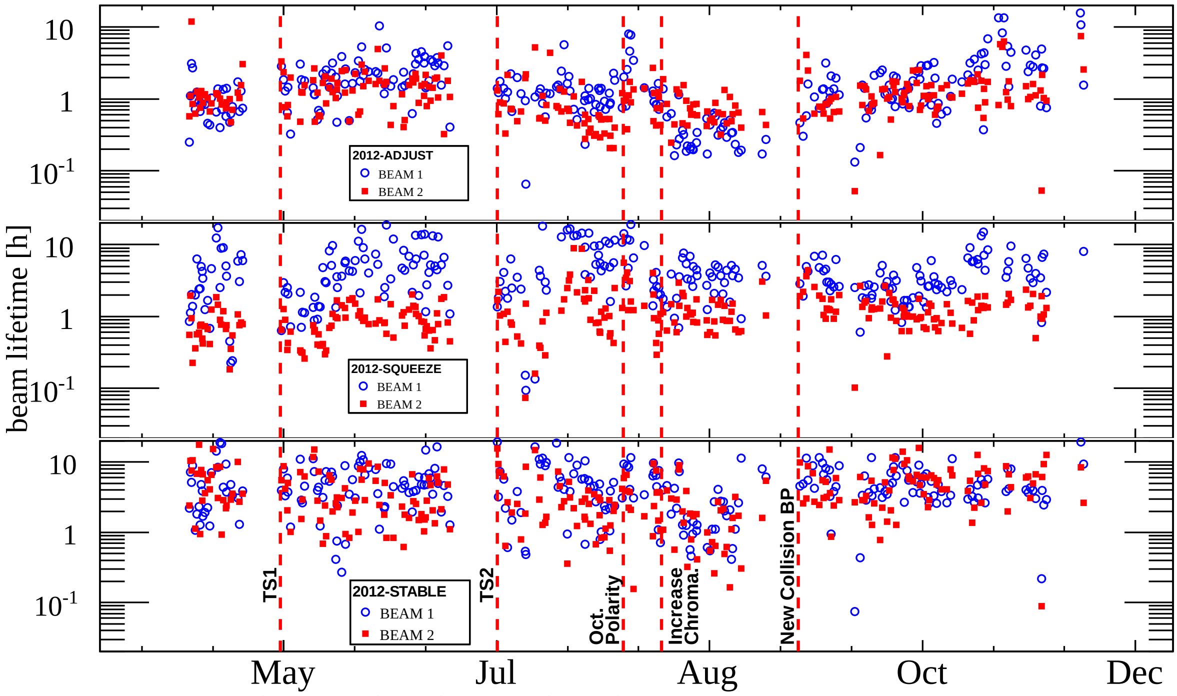

Figure 7: Minimum beam lifetime per fill as function of time for squeeze (top), adjust (middle) and stable beam (bottom).

30 % (10 %) for Beam 1 (2) went below 5 h. About 30 % of the fills in 2012 had lifetime below 1 h.

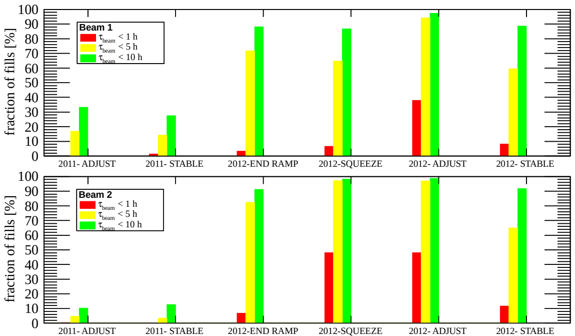

Figure 8: Fraction of fills with minimum beam lifetime below 1, 5 and 10 hours sorted by beam mode.

The minimum lifetime for every fill in that made it to stable mode in 2012 is shown in Figure 7 for 3 beam modes (squeeze, adjust and stable beams) as a function of time. The vertical red dashed lines show changes of running periods or significant machine configurations. TS1 and TS2 are the first and second technical stops of 2012. On August 7th, 2012, the octupoles polarity was changed and seemed to improved the beam lifetime. However on August 18th, the chromaticity was increased and the lifetime decreased again. On September 26th, the collision beam process was changed to bring collisions in IP8 after IP1 and IP5, this seems to improve the lifetime during the adjust beam mode. Abut 45 fills were lost in 2012 due to losses before putting the beams in collisions due to instabilities during squeeze and adjust, these fills have been neglected in the present analysis.

CONCLUSIONS

The BLMs provide a measurement of the beam losses. Here we described a method to calibrate these BLMs to get the total number of protons lost per unit time. Using this calibration we calculated the minimum beam lifetime in 2011 and 2012, which is one of the required parameters to estimate the LHC intensity reach. It was found that the most critical phase is when the separation bumps are collapsed to collide, with minimum lifetimes in 2012 between 0.5 and 10 h depending on the fill conditions. Unlike what was experienced in the low-loss operation in 2011 during squeeze, some 45 fills were lost in 2012 due to losses before putting the beams in collision (due to instabilities during squeeze and adjust).

ACKNOWLEDGMENT

The authors would like to acknowledge the BLM and operation team of the LHC as well as the members from the LHC collimation group.

REFERENCES

[1] The LHC Design Report, CERN-2004-003 (2004).

[2] C.Bracco, CERN-THESIS-2009-031.

[3] B. Salvachua *et al.*, LHC Evian Workshop (2012).

[4] B. Salvachua *et al.*, MOPWO048, IPAC13, China (2013).

[5] F. Burkart, CERN-THESIS-2012-046.

[6] R.W.Assmann, LHC Chamonix Workshop (2003).

[7] D. Wollmann *et al.*, THPZ026, IPAC11, Spain (2011).

[8] S. Redaelli *et al.*, MOPWO038, IPAC13, China (2013).