ESTIMATE OF WARM MAGNETS LIFETIME IN THE BETATRON AND MOMENTUM CLEANING INSERTIONS OF THE LHC

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Abstract

The CERN LHC collimation system is designed to perform momentum and betatron cleaning in different insertions, respectively IR3 and IR7. The insertions are not perfectly decoupled because the dispersion in IR7 is not null and the beta function in IR3 is not zero. The detailed sharing of losses between the two insertions depends on the relative collimator settings as observed by the change between 2011 and 2012 LHC operation. In this report, using the beam loss measurements at the primary collimators of IR3 and IR7, the total BLM losses in the two insertions are calculated and compared to each other. These studies are also used to quantify the total dose to warm magnets in those IRs with the aim to understand better their lifetime and the implications of the radiation to electronics. This will be of particular importance in view of LHC operating at nominal performance after several years of operation.

INTRODUCTION

The LHC magnets have a limited lifetime which depends strongly on the radiation received. Measurements of the resin degradation and comparisons of stress analysis with irradiated and non-irradiating samples provide an estimation of the dose limit of about $10\ \mathrm{MGy}$ for the quadrupoles MQW and $50\ \mathrm{MGy}$ for the dipoles MBW. However, these measurements are performed at high-dose rates and are thus likely to be conservative [1, 2].

In September 2012, we reviewed the need of additional absorbers in IR3 upstream the quadrupoles MQWA [3]. These magnets intercept a significant fraction of the showers from the momentum losses. We present here the estimation of the expected radiation dose in the betatron and momentum cleaning insertions (IR7 and IR3 respectively) and extrapolate to the maximum luminosity before the maximum dose is reached after the LHC long shutdown 1 (LS1).

The radiation dose has been estimated by analyzing the beam losses during 2011 and 2012 LHC operation period at the primary collimators. The sharing between IR3 and IR7, in terms of losses measured by the beam loss monitors (BLMs), is analyzed and compared between 2011 proton-proton (pp) operation, when "relaxed" collimator settings were used at $3.5\ \mathrm{TeV}$ [4], and 2012 pp run operating at $4\ \mathrm{TeV}$ with "tight" collimator settings [5].

During the second technical stop (June 27th, 2012) dosimeters located close to the magnets and collimators were read out [6]. Using the measurement from the dosimeters and the result from the analysis of the losses, one can extrapolate the maximum reach on total cumulated luminosity at 6.5 TeV beam energy based on the lifetime limit of the warm magnets in IR3 and IR7.

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COLLIMATOR SETTINGS

The LHC has a multi-stage collimation system. It is optimized to clean particles with high betatron amplitudes in IR7 and off-momentum particles in IR3, but the cleaning is not completely decoupled and depends strongly on the selection of collimator settings. Table 1 shows the half-gap openings of the primary collimators in IR3 and IR7 expressed in units of transverse beam sigma size assuming $3.5\ \mu\mathrm{m\,rad}$ normalized emittance. Notice the difference of settings in IR7, in 2012 the primaries in IR7 were closer to beam, at 4.3σ. This has to be done in order to clean more aggressively the beam halo and allow more room to squeeze at the main colliding IRs [7, 8]. As a result of this change, the ratio of losses between IR3 and IR7 changed.

Table 1: Collimator Settings for Primary Collimators, Assuming Normalized Emittance of $3.5\ \mu\mathrm{m\,rad}$

	IR3	IR7
2011 at 3.5 TeV	12.0	5.7
2012 at 4.0 TeV	12.0	4.3

Figure 1 illustrates this sharing. The figures show the linear cuts of the primary collimators (TCPs) in IR3 and IR7, in the space spanned by betatron amplitude and relative energy offset. Both axes have been normalized by the corresponding standard deviations. In 2012 the TCPs in IR7 were placed closer to the beam and therefore caught off-momentum losses with smaller betatron amplitudes than in 2011, meaning that we expect the relative loss fraction in IR7 to increase.

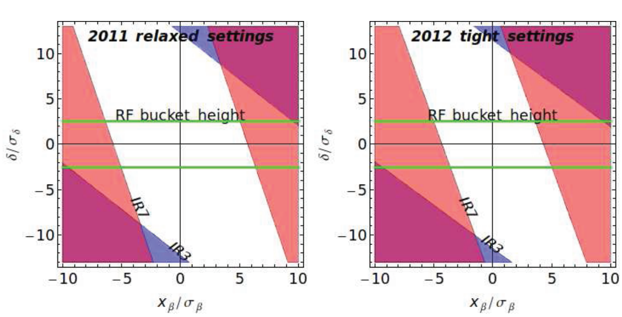

Figure 1: Relative momentum and betatron cuts in 2011 (left) and 2012 (right).

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BEAM LOSSES

Beam loss monitors are placed all along the LHC ring. For this analysis we used the ionization chambers downstream the collimators that measure the energy depositions of secondary shower particles. Their signal is linear with the number of impacting protons at the collimators. In IR3 there is only one primary collimator per beam and it has horizontal orientation, however, in IR7 there are 3 primary collimators: one vertical, one horizontal and one skew. The BLM downstream the primary skew collimator in IR7 will also measure the showering from the upstream collimators, for this reason we will use this monitor to compare the losses in between IR3 and IR7 during 2011 and 2012 [9].

Figure 2 shows the cumulated losses calculated using the BLM downstream of the IR7 skew primary collimator that catches losses in all planes as a function of the LHC delivered integrated luminosity to ATLAS. The losses increase linearly with the integrated luminosity, however we see a period in 2011 were the loss rate is higher, this corresponds to July-September 2011 (between the 3rd and the 4th technical stop). Afterwards the initial loss rate was recovered to similar level. In 2012, there are clearly two regimes, before and after the second technical stop (end of June 2012):

- **Before TS2**: or until about 7 fb^{-1} of luminosity, where the loss rate is similar to 2011 (slighter higher for Beam 2).
- **After TS2:** the losses for both beams increase more rapidly with luminosity.

There was no change of collimator settings in the TS2 when the behavior changed. The reason for the different slopes of the figures could not yet be identified.

The losses in the momentum cleaning insertion (IR3) are shown in Figure 3. Notice here that the losses measured by BLMs in IR3 are about 7 to 9 times lower in 2012 than in 2011.

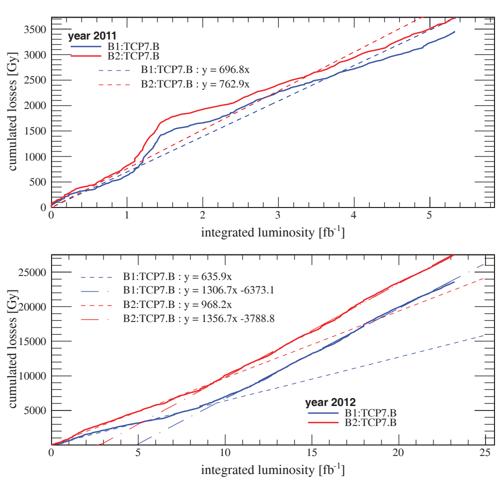

Figure 2: Cumulated losses at the BLM located downstream the primary skew collimator in IR7 during 2011 (top) and 2012 (bottom) as a function of the LHC delivered integrated luminosity to ATLAS.

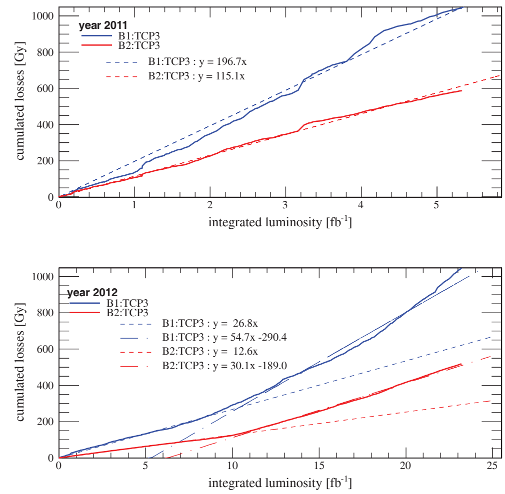

Figure 3: Cumulated losses at the BLM located downstream the primary collimator in IR3 during 2011 (top) and 2012 (bottom) as a function of the LHC delivered integrated luminosity to ATLAS.

SHARING BETWEEN MOMENTUM AND BETATRON CLEANING

The sharing of the losses between the momentum and betatron cleaning insertions can be analyzed by comparing the linear fits from Figures 2 and 3 shown also in Table 2.

However, the BLM response in the selected monitor on IR7 depends on the origin of the losses. For example, considering the TCP.B BLM (downstream skew collimator), a proton lost in the TCP.C (horizontal) collimator generates a signal 2.5 A, which is higher than the signal from a proton lost in the TCP.D (vertical) collimator (equal to 2.1 A). Therefore the comparison on the losses in IR3 and IR7 is just qualitative at this stage, as it is in terms of measured BLM signal and not in total number of protons lost.

We observed that the BLM losses in IR3 for Beam 1 are about a factor of 2 larger than for Beam 2 for both, 2011 and 2012. If we compare the 2 years of operation, in 2011 the percentage of losses in IR3 with respect to IR7 was between 6 to 12 times larger than in 2012. This could be explained by the smaller margin between IR3 and IR7 primary collimators, than in 2011 was 6.3σ as opposed to 7.7σ in 2012. As it is shown here, the choice of collimator settings is a key factor for the estimation of the radiation in IR3 (see Figure 1).

Table 2: Result from the linear fit to the cumulated losses during each fill in 2011 and 2012 as a function of the LHC delivered integrated luminosity to ATLAS.

Fit results (slope)	IR7		IR3	
[Gy fb]	**B1**	**B2**	**B1**	**B2**
2011	696.8	762.9	196.7	115.1
2012 before TS2	635.9	968.2	26.8	12.6
2012 after TS2	1306.7	1356.7	54.7	30.1

EXPECTATION FOR AFTER LS1

Dosimeter Readings

During TS2, dosimeters that were installed during the 2011 Christmas shutdown and were located on the coil of the MQWA.E magnets (Q5) and the MBW dipole (D3) downstream the collimators in IR3 and IR7 were taken out and analyzed [6], the readings are shown in Table 3. We can estimate the expected dose after the primary collimators by scaling linearly the dosimeter reading with the assumed luminosity and energy as indicated in the following equation:

Table 3: Dosimeters Reading in 2012 at TS2 [6]

[kGy]	IR7 B1	IR7 B2	IR3 B1	IR3 B2
MQW	60.0	45.0	6.5	2.5
MBW	100-400	330-490	9-16	2-5

$$\left[\left(\frac{E}{4\ \mathrm{TeV}}\right)\cdot\left(\int \mathcal{L}dt\right)\cdot\left(\frac{\mathrm{BLM}}{\int \mathcal{L}\mathrm{dt}}\right)_{\mathrm{slope}}\right]\cdot\left[\frac{\mathrm{Dose}}{\mathrm{BLM}}\right]_{\mathrm{TS2}}$$

where E denotes the new beam energy (6.5 TeV), $\int \mathcal{L}dt$ the expected integrated luminosity, $\left(\mathrm{BLM}/\int \mathcal{L}\mathrm{dt}\right)_{\mathrm{slope}}$ the result from the linear losses versus luminosity (Table 2), Dose is the dosimeter reading after the second technical stop (Table 3) and BLM the cumulated losses for the corresponding time (at 6.5 fb^{-1}). Using this equation one takes into account changes on the dose rate along the year.

Assuming a total dose limit of $10\ \mathrm{MGy}$ ($50\ \mathrm{MGy}$) for MQW (MBW), the approximated integrated luminosity reached at $6.5\ \mathrm{TeV}$ would be limited by the quadrupoles and dipoles in IR7 to about $300\ \mathrm{fb}^{-1}$ for Beam 1 (see Table 4), using the loss rate (fit slope) after TS2. The minimum and the maximum limit for the dipoles are derived using the readings from 2 different dosimeters, while for the quadrupoles there was only one dosimeter in the coil (see Table 3). The reader should take into account that these numbers are just approximated since the extrapolation suffers from large uncertainties such as the scaling with beam energy, the final choice of collimator settings and the possibility of different loss rate as it was shown in 2012.

Table 4: Estimate of the maximum luminosity when the dose limit for the MQW and MBW is reached scaled linearly for $6.5\ \mathrm{TeV}$ beam energy.

$\int \mathcal{L}dt\ [\mathrm{fb}^{-1}]$	IR7 B1	IR7 B2	IR3 B1	IR3 B2
MQW	300	600	3 000	6 600
MBW min	250	300	6 000	17 000
MBW max	900	400	10 000	40 000

CONCLUSIONS

The losses at the primary collimators in IR3 and IR7 were analyzed. The total losses are shown to be linear with the integrated luminosity, however a change of slope is observed after the second technical stop, around June 2012. The sharing between IR3 and IR7 was investigated. For 2011 it was found that IR3 receives between 6 to 12 times more losses than in 2012. The origin of this difference could be explained by the change on collimator settings. In 2012 a more aggressive betatron cleaning was adopted for IR7 in order to achieve a smaller $\beta^{\star} = 0.6\ \mathrm{cm}$, reducing the total dose in IR3.

We extrapolated the expected dose for 6.5 TeV beam energy after the long shutdown 1 in 2013 and calculate an estimation of the maximum integrated luminosity that could be allowed before the maximum dose of $10\ \mathrm{MGy}$ $(50\ \mathrm{MGy})$ is deposited in the MQW (MBW) coil.

Assuming the use of the present “tight” collimator settings and a linear scaling with the beam energy, we would be limited at about $300\mathrm{fb}^{-1}$ in IR7 and $3000\mathrm{fb}^{-1}$ in IR3. The general strategy is to protect the magnets as much as possible and since the sharing between the 2 IRs varies significantly with the collimator settings, the installation of additional protection of warm magnets in IR3 is justified in order to keep the operational flexibility of the collimation system. The analysis of the cumulative doses should be continued in order to provide a better estimate of when limits will be reached based on operation data.

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