LHC COLLIMATION CLEANING AND OPERATION OUTLOOK

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Abstract

An overview of the collimation system performance during 2012 is described. The collimator "tight" settings for the 60 cm $\beta^\star$ reach are introduced and the evolution of the cleaning inefficiency achieved throughout the year with one single collimator alignment is presented. The performance of the semi-automatic collimator alignment tools is discussed. We investigate the beam losses through the cycle with emphasis on the yearly evolution of the measured instantaneous beam lifetime in critical phases of the operational cycle.

The concept of collimators with integrated beam positions monitors (BPM) is presented here and their effect on the $\beta^\star$ reach after the long shutdown I is analyzed. The baseline settings strategy for the startup in 2015 is discussed based on the expected performance of the collimators with BPMs. New values of $\beta^\star$ reach are discussed.

THE LHC COLLIMATION SYSTEM

The LHC collimation system provides a multi-stage cleaning in the two warm cleaning insertions, IR3 for momentum cleaning and IR7 for betatron cleaning. The primary collimators (TCPs) are the closest to the beam in transverse normalized space, cutting the primary halo. The secondary collimators (TCSGs) cut the particles scattered by the primaries (secondary halo) and the absorbers (TCLAs) stop the showers from upstream collimators [1]. The tertiary collimators (TCT) protect directly the triplets at the colliding IRs. Together with the passive absorbers, the physics debris absorbers, transfer line collimators, injection and dump protection makes a total of 108 collimators, hundred of them movable that need to be aligned within $10 - 50\ \mu\mathrm{m}$ precision to achieve the required cleaning.

During 2012 running period with $4\ \mathrm{TeV}$ beam energy the collimator system was setup with the so-called "tight" collimator settings [2], illustrated in Fig. 1. The primary collimators are set to the nominal $7\ \mathrm{TeV}$ gap in mm which corresponds to $4.3\ \sigma$ at $4\ \mathrm{TeV}$, where σ is the transverse beam size assuming transverse normalized emittance of $\epsilon_{norm} = 3.5\ \mu\mathrm{m\ rad}$. We will assume in all the document the same normalized emittance unless explicitly quoted. The secondaries and absorbers in IR7 are placed at $6.3\ \sigma$ and $8.3\ \sigma$ respectively. The secondary collimator in IR6 (part of the dump protection system) is at $7.1\ \sigma$ and TCTs at $9\ \sigma$, protecting the tripet aperture of $10.5\ \sigma$ and allowing a $\beta^\star$ of $60\ \mathrm{cm}$. These settings were validated during MD's in 2011 [2] [3] [4]. In particular, it was verified that the proposed hierarchy could be achieved without additional alignment campaigns, indicating that the orbit and collimator settings are stable enough to ensure a good hierarchy with $2\ \sigma$ retraction between TCP's and TCSG's. Optimization of TCT settings and measurement of the aperture that can be protected are detailed in [5] [6] [7].

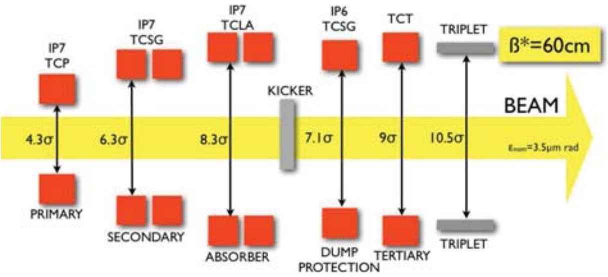

Figure 1: Tight collimator settings for $4\ \mathrm{TeV}$ beam energy and $\beta^\star = 60\ \mathrm{cm}$.

SYSTEM PERFORMANCE

All collimators are setup symmetrically around the beam orbit for each machine configuration (*i.e.* injection, flat top, squeeze and collisions) with full gap as small as $2\ \mathrm{mm}$. The alignment procedure aligns each collimator jaw independently based on the beam loss monitor (BLM) spike observed when touching the beam halo produced with the primary collimators. This is done only in dedicated low intensity fills with up to 3 nominal bunches in order to avoid any machine damage.

The operational strategy during 2011 and 2012 run periods was to perform one full alignment of the main cleaning insertions (IR3 and IR7) and monitor regularly the losses along the ring to validate if a new alignment was needed by looking at the cleaning and the collimator hierarchy. For new physics configurations only the 16 TCTs collimators at the colliding IRs need to be re-aligned.

Since 2010 several improvements have been implemented in the alignment software towards a faster and more reproducible alignment [8] [9] [10]. The main improvement on the alignment speed was the use of the $12.5\ \mathrm{Hz}$ BLM data, available from the start of 2012 run. This allowed to use the maximum collimator movement rate of $8\ \mathrm{Hz}$ that before was limited by the $1\ \mathrm{Hz}$ BLM data. In

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addition, currently, it is possible to align in parallel several collimators and the algorithm routine automatically identifies the loss spike and decides if the collimator is completely aligned. Fig. 2 shows the setup time per collimator as function of time. Nowadays, all collimators in IR7 (19 collimators per beam) and IR6 (2 collimators per beam), a total of 42 collimators, can be re-aligned in about 50 min. Ever since the semi-automatic alignment was set in place, no more beam dumps at top energy happened during alignments [10].

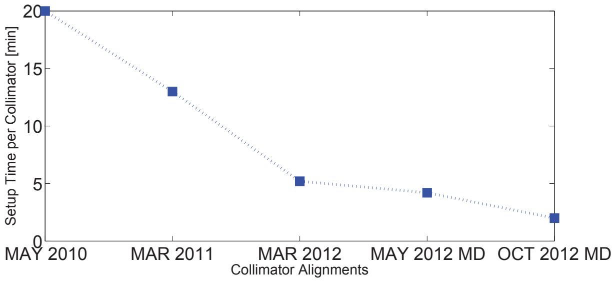

Figure 2: Setup time per collimator versus alignment date.

Losses along the ring

In order to validate the cleaning hierarchy and study the performance of the collimator system, loss maps are performed. Beam losses are recorded along the ring while exciting the beam with the transverse damper (ADT) [11] and are compared with the peak losses at the primary collimators to compute the cleaning inefficiency. The ADT introduces white noise in vertical or horizontal plane that can be gated to selected bunches. When the ADT is working on this mode the excited bunch is blown up and interacts with the collimators producing beam losses along the ring. Fig. 3 shows the losses, noise subtracted and normalized to the highest loss, for beam 1 (beam is going from left to right) blown up in the horizontal plane. The highest peak occurs at the betatron cleaning insertion (IR7). The minimum cleaning inefficiency is defined as the highest leakage at the cold magnets, which is in the dispersion suppressor region of IR7. Fig. 4 shows a zoom into IR7, the cleaning hierarchy appears as decreasing losses from the primary collimators (left IR7) to the absorbers (right IR7). The local cleaning inefficiency is measured at Q8 magnet, in this case right of IR7.

The local cleaning inefficiency from 2010 to 2013 is provided in Fig. 5. In 2010 and 2011 the beam energy was 3.5 TeV and the relaxed collimator settings were used [12] while in 2012 the beam energy was increased to 4 TeV and the tighter collimators settings described in previous section were used. The figure shows an excellent stability of the cleaning performance which was achieved with only one alignment campaign per year at the beginning of each run period. In 2012, with the “tight” settings the cleaning improved from 99.97 % to 99.993 %. This was observed also during a machine development test in 2011 [3] which is included in Fig. 5. The performance shown in the plot has been calculated taking into a account all top energy cycles, and no significant differences on the cleaning in IR7 were found. This confirms that the IR7 cleaning is not much affected by changes in the colliding IRs [13].

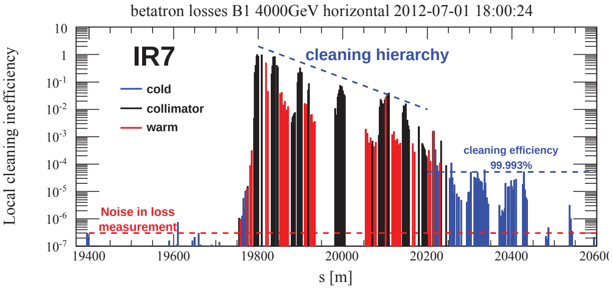

Figure 4: Distribution of the losses in the betatron cleaning insertion (IR7) while exciting beam 1 in the horizontal plane.

Lifetime through the cycle

The maximum number of charges that can be injected in the machine without risk of quenching a magnet is determined by

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

where τ_{beam} 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 $R^{\text{TCP}}_{\max}$. R_{q} is the quench limit and η_c is the collimation cleaning inefficiency [14]. We have studied the beam lifetime through the LHC cycles by analyzing the measured beam intensity from the BCT signal (LHC.BCTFR.A6R4.B1 and LHC.BCTFR.4R6.B2). For each cycle and fill the BCT signal was smoothed using a running average of 5 s. Afterwards the beam intensity lifetime was calculated by performing linear fits to the smoothed intensity signal. As an example, the intensity and lifetime distribution of a random fill (#2469) during ADJUST [1] beam mode are shown in Fig. 6.

The minimum beam lifetime is shown in Figs. 7 and 8 for every fill and cycle of 2012 run period during SQUEEZE and ADJUST beam modes respectively. The plots include all the fills that were setup for physics, with a filter on the total injected intensity of $\text{I}_{\text{tot}} > 10^{13}$ protons to exclude low intensity fills not relevant for the performance reach. The fills with lifetime below 0.2 h were dumped. 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,

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[1] ADJUST is the beam mode that follows SQUEEZE, used when the beams are collapsed to produce collisions.

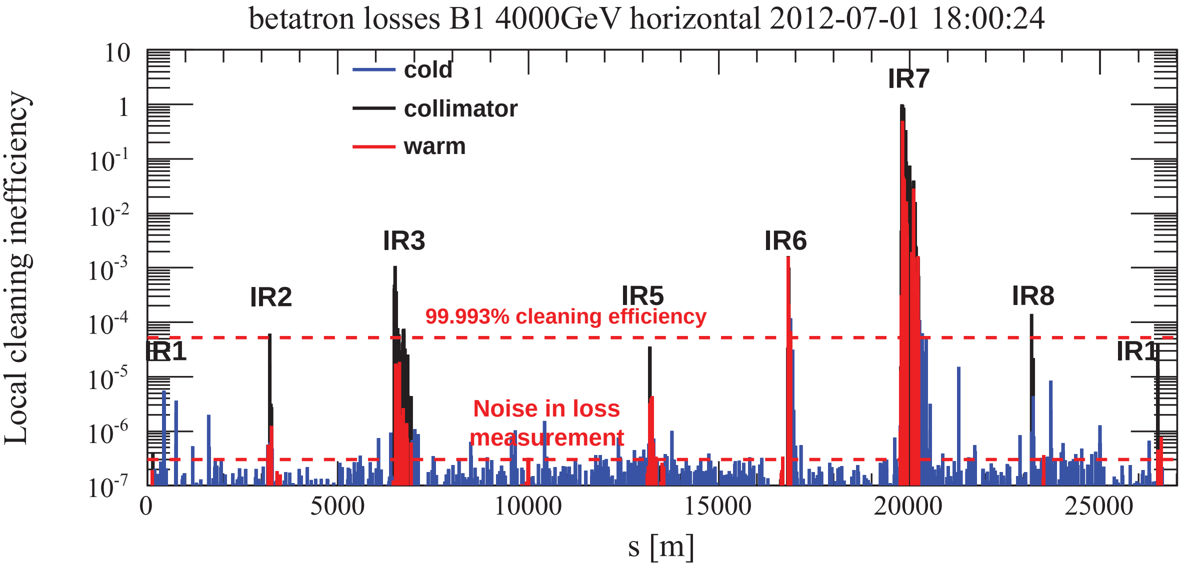

Figure 3: Distribution of the losses in the LHC ring while exciting beam 1 in the horizontal plane.

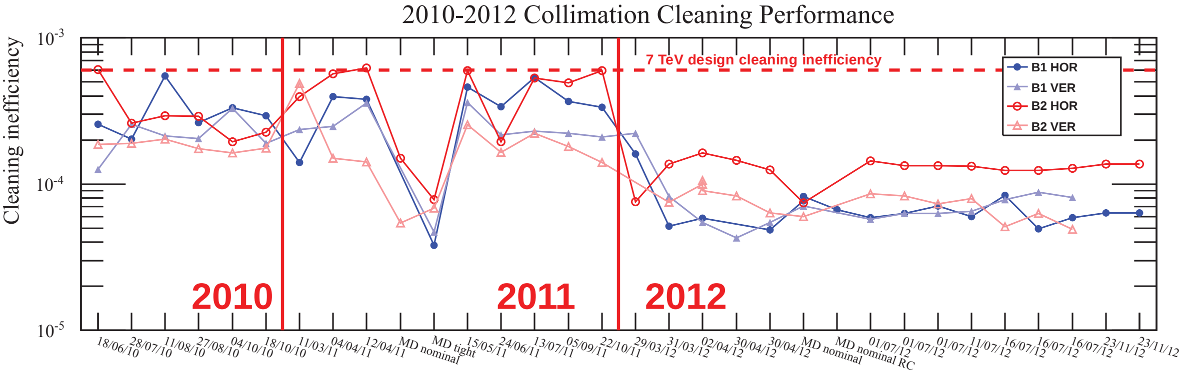

Figure 5: Collimation cleaning inefficiency as function of time since 2010 until end of 2012 run.

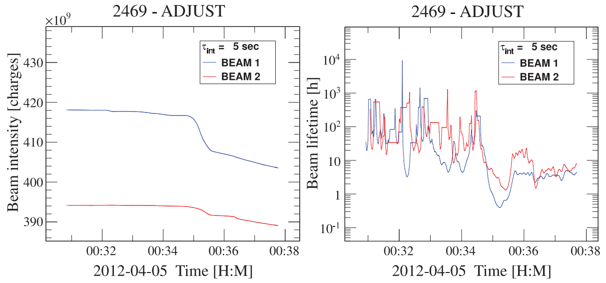

Figure 6: Measured beam intensity (left) and calculated beam lifetime (right) for fill 2469 during ADJUST beam mode.

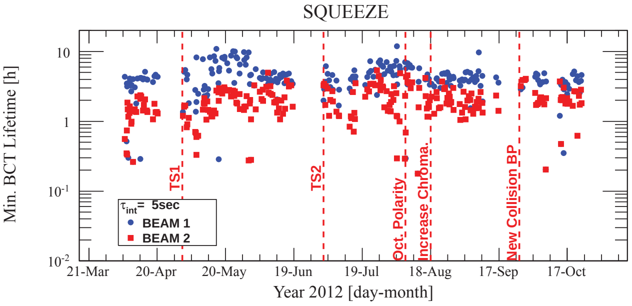

Figure 7: Minimum beam lifetime over 5 seconds during SQUEEZE beam mode.

the chromaticity was increased and the lifetime came 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 ADJUST beam mode.

The most critical phase is when the beams are going to collide, the average minimum lifetime along the year is found to be between 0.5 and 10 h, worse than during the ramp of energy or squeeze. Contrary to the operation in 2011 when the losses are starting only from collisions, in 2012 the instability occurred during the full adjust mode.

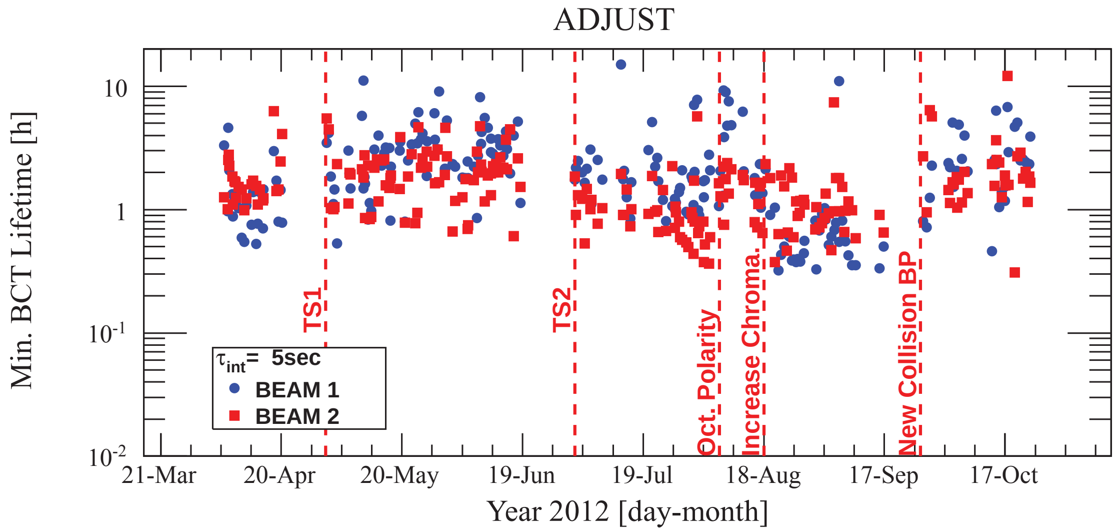

Figure 8: Minimum beam lifetime over 5 seconds during ADJUST beam mode.

COLLIMATOR HARDWARE: IMPROVEMENTS FOR LS1

During the LHC long shutdown I , 16 Tungsten tertiary collimators in all colliding interaction regions and 2 Carbon secondary collimators in IR6 will be replaced by new collimators with integrated beam positions monitors buttons. The layout will not be changed, the collimators will stay in the same positions along the ring (with the exception of IR8 where the 2-beam design TCTVB will be replaced with 1-beam design collimators) but with the gain of

- alignment without touching the beam,
- reducing orbit margins allowing more room to squeeze and
- allowing regular monitoring during operation at high intensity (with possibility to improve interlocking strategy).

Fig. 9 shows the schematic view of a collimator with integrated BPM buttons in the jaws. Since 2010, several tests on the CERN SPS accelerator were performed in order to validate this concept [15]. The beam orbit was measured with the BPM buttons with an accuracy of up to 10 μm and a fully automatic alignment algorithm was tested achieving a 10 s alignment (centering both jaws with respect to the beam) without touching the beam core [16]. Fig. 10 shows the measured beam orbit with respect to the collimator jaws (for upstream and downstream BPMs) as a function of time during one the alignment tests. The figure shows how in about 10 s the beam is centered with respect to the collimator, this corresponds to beam position equal to 0 mm.

Proposed collimator settings

The evolution of collimator settings followed the improved knowledge of the machine: tighter and tighter settings for improved $\beta^\star$ were achieved every year. A similar evolution is expected for the recommissioning at higher energy after LS1. Fig. 11 shows the evolution of the collimator settings from 2010 until now extrapolated to 6.5 TeV in beam sigma size with normalized emittance of 3.5 μm rad. The solid black line represents the collimator relaxed settings used in 2011 in mm. The solid blue line represents the achieved tight collimator settings in 2012 without BPMs in

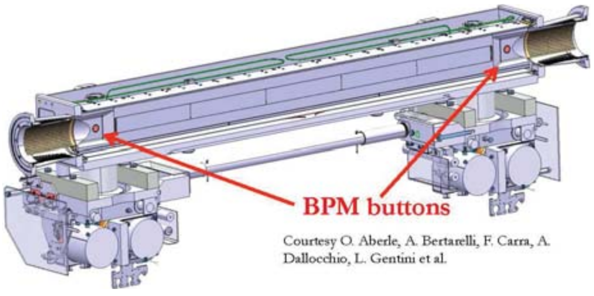

Figure 9: Schematic view of a collimator with integrated BPM buttons.

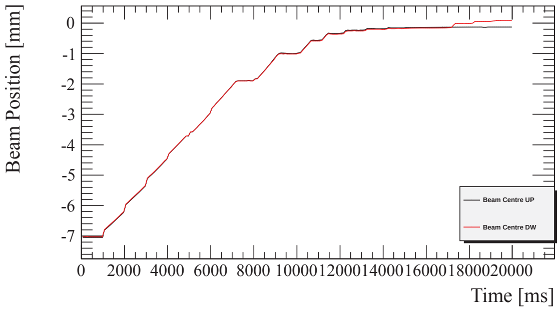

Figure 10: Measured beam position with respect to the collimator jaws with embedded beam position monitor buttons as a function of time during an alignment test on the CERN SPS.

mm. The solid red line represents the nominal collimator settings. The dashed lines represent 2 proposals of collimator settings without exploiting the collimators with integrated BPM potential. Option black-dashed is the relaxed approach, with collimator gaps around 20% larger than the current tight settings in mm, while option blue-dashed, tighter than the 2012 "tight" settings, proposes 5.5 σ opening for the primary collimators (the same as the nominal settings) and 2 σ retraction for secondaries.

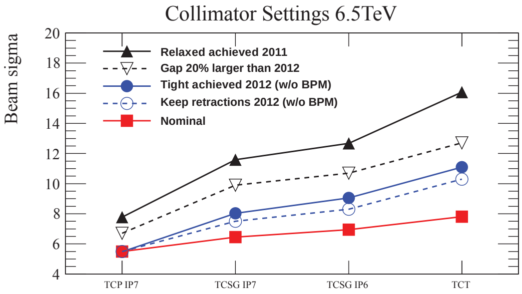

Figure 11: Proposed collimator settings in beam sigma size with normalized emittance ($\epsilon_{\text{norm}} = 3.5\ \mu$m rad).

The last point of each line identifies the setting in sigma of the TCTs at the main colliding IRs, in order to push the $\beta^{\star}$ limit the opening of the TCTs need to be reduced to protect the triplet aperture. However, this imposes tighter tolerances which may require frequent alignments. The cleaning hierarchy must be respected in order to guarantee the required cleaning, this is illustrated in the line trend that should be always positive. With collimator gaps as small as few mm, this can be only achieved if collimators are precisely aligned around the correct orbit.

Table 1 compares the 2012 "tight" settings with the 2 proposed approaches. The relaxed approach of gaps about 20 % larger than in 2012 and the tighter approach of nominal settings at the primary and 2 σ retraction at the secondaries. The collimator settings in beam sigma as well as the allowed apertures at the triplets are listened for the case of using and not using the integrated BPMs information. The use of collimators with BPMs allows smaller apertures at the triplets and thus smaller $\beta^{\star}$. The more ambitious approach of keeping the 2 σ retraction at the secondaries allows almost 1 σ larger aperture at the triplet than the 2012 "tight" settings.

Beta-star reach after LS1

One of the limitations when going to smaller $\beta^{\star}$ is the aperture limit at the triplet, which is the fact that the margins at the triplet aperture decreases when decreasing $\beta^{\star}$. The assumptions for calculating new $\beta^{\star}$ reach and aperture after LS1 are:

- same excellent apertures, orbit and beta-beat as in 2012,
- primary collimator in betatron cleaning insertion at the same position in mm,

Table 1: Proposed collimator settings expressed in beam sigma size at 6.5 TeV [17].

Collimator	**Gap** 20% **larger than 2012**	**Tight 2012 in mm**		**Keeping retractions in** σ	
TCP 7	6.7	5.5		5.5	
TCSG 7	9.9	8.0		7.5	
TCLA 7	12.5	10.6		9.5	
TCSG 6	10.7	9.1		8.3	
TCDQ 6	11.2	9.6		8.8	
BPM	no	no	yes	no	yes
TCT Aperture	12.7 14.3	11.1 12.6	10.0 11.2	10.3 11.7	9.1 10.3

- and BPM buttons with collimators providing orbit measurement with 50 μm precision at the TCTs in the colliding IRs and TCSG in IR6.

The last item on the list do not fully exploit the potential of the BPMs, since the results on the SPS showed better precision. However this scenario represents already a big improvement from the present orbit precision of 0.5 to 1 mm and we assume that for the start up we will start with a more relaxed approach on the use of the BPMs until we gain enough operational experience to fully exploit them.

Figure 12 shows the beta-star reach for 5 different collimator settings and 4 different scenarios [17] :

- **case 1**: 25 ns bunch spacing, 12 σ beam-beam separation and normalized emittance of 3.75 μm rad,
- **case 2**: 25 ns bunch spacing, 12 σ beam-beam separation and normalized emittance of 1.9 μm rad,
- **case 3**: 50 ns bunch spacing, 9.3 σ beam-beam separation and normalized emittance of 2.5 μm rad and
- **case 4**: 50 ns bunch spacing, 9.3 σ beam-beam separation and normalized emittance of 1.6 μm rad.

On one hand, the more pessimistic scenario corresponds of collimator settings with gap 20% larger than in 2012 and no use of BPM buttons, this will allow $\beta^{\star} \geq 70$ cm at 25 ns or $\beta^{\star} \geq 57$ cm at 50 ns. On the other hand, the more optimistic scenario of keeping same retractions in sigma as in 2012 and using the BPM buttons will allow $\beta^{\star} \geq 37$ cm at 25 ns or $\beta^{\star} \geq 30$ cm at 50 ns. The final choice of collimator settings should take into account also the impedance constrains. This might require larger collimator gaps than the proposed here and thus worse $\beta^{\star}$.

Clearly, we will only exploit the full potential of the BPMs after we gain the needed operational experience with them. Thus, at the start-up after LS1 we propose to start with the 2012 "tight" settings, assuming the machine impedance is still under control, and move towards the tighter approach of keeping 2 σ retraction at the secondaries at 6.5 TeV.

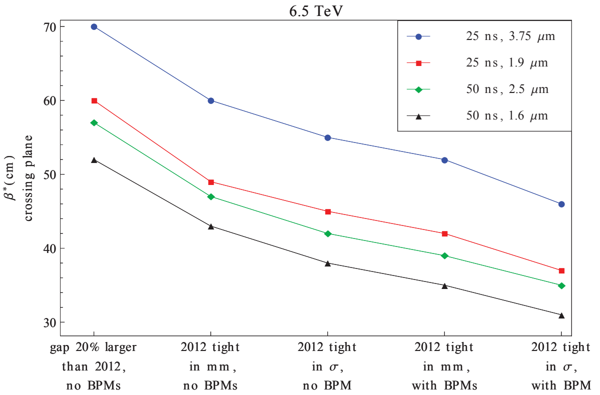

Figure 12: $\beta^\star$ reach in the crossing plane at 6.5 TeV as a function of collimator settings.

SUMMARY

The performance of the collimation system was discussed. The improvements on the alignment tool decreased the collimation setup time from 20 min to few minutes per collimator. The cleaning stability in the dispersion suppressor region of IR7 along the LHC running periods was analyzed and was shown to be excellent. In 2012, with the "tight" collimator settings the average leakage at Q8 cell in IR7 was about $\eta_c = 7 \cdot 10^{-5}$ for beam 1 (both horizontal and vertical halo cleaning) and beam 2 vertical and around $\eta_c = 10^{-4}$ for beam 2 horizontal. No quenches with circulating beams were experienced with up to 140 MJ at 4 TeV. The minimum beam lifetimes, that is one of the required parameters to estimate the intensity reach was also discussed. It was found that the most critical phase is when the beams are collapsed to collide, with minimum lifetimes along the year between 0.5 and 10 h depending on the fill conditions. Unlike what was experienced in the "loss-free" operation in 2011, some 45 fills were lost in 2012 due to losses before putting the beams in collision (due to instabilities during squeeze and adjust). This analysis must be continued to understand better the implications for the operation after LS1.

The concept of collimators with integrated BPM buttons is introduced and we showed the expected $\beta^\star$ reach after LS1 for different proposed collimator settings at 6.5 TeV, with special emphasis on the $\beta^\star$ limit if we exploit the potential of the collimators with BPMs. Assuming 50 ns bunch spacing and normalized emittance of 1.6 μm rad the $\beta^\star$ limit with BPMs is $\beta^\star \geq 30$ cm. However, this will only come after gaining some experience with the embedded BPMs, until then we propose to start with the 2012 "tight" collimator settings as baseline and approach to the 2 σ retraction settings and full use of the BPMs after improving the knowledge of the machine at higher energy.

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