CALCULATION METHOD FOR SAFE β^* IN THE LHC

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Abstract

One way of increasing the peak luminosity in the LHC is to decrease the beam size at the interaction points by squeezing to smaller values of β^*. The LHC is now in a regime where safety and stability determines the limit on β^*, as opposed to traditional optics limits. In this paper, we derive a calculation model to determine the safe β^*-values based on collimator settings and operational stability of the LHC. This model was used to calculate the settings for the LHC run in 2011. It was found that β^* could be decreased from 3.5 m to 1.5 m, which has now successfully been put into operation.

INTRODUCTION

After being put into operation in late 2009, the Large Hadron Collider (LHC) [1] at CERN has made remarkable progress. During 2010, the goal of a peak luminosity of 10^{32} cm^{-2}s^{-1} was reached and surpassed. For 2011 the ambitious goal of an integrated luminosity of 1 fb^{-1} was set [2] and reached already in June 2011. One method to increase the luminosity, which was an important part of the success in 2011, is to reduce β^*, the optical β-function at the interaction points (IPs), thus reducing the transverse size of the colliding beams.

The present operational lower limit on β^* is not given by the optics or the magnets but rather by machine protection. When squeezing β^* to smaller values, the beam blows up in the triplets, at the global aperture bottleneck of the LHC. With a nominal stored energy of 362 MJ, the LHC beams are highly destructive and even tiny local beam losses (a fraction of about 1.2×10^{-7} of the full beam) could quench a magnet [1], so it is essential to protect cold elements from losses. The limitation on β^* is given by the minimum aperture that can be protected by the collimation system.

In the LHC, a multi-stage collimation system is used [1, 3, 4], shown schematically in Fig. 1. The collimators in the cleaning insertions are primary (TCP), secondary (TCS) and absorbers (TCLA). In the experimental interaction regions (IRs), tertiary collimators (TCT) are in place for local protection of the triplets, and at the extraction in IR6, there are special dump protection devices (TCS6 and TCDQ). The collimators must at all times be positioned so that the cold aperture is protected and that the hierarchy is preserved. This means that the TCPs must be the primary aperture bottleneck and have a smaller aperture than the TCSs. The TCSs must shadow the dump protection, which in turn has to shadow the TCTs. For this to hold, margins are necessary between the collimators to account for drifts.

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After fixing the opening of the TCPs, the other collimators are successively fixed by the necessary retraction, which defines a minimum aperture that can be protected.

The calculation of the minimum possible β^* therefore consists of three steps: i) estimating the necessary margins between each step in the cleaning hierarchy, ii) estimating the aperture in the triplets for different β^* configurations, and iii) defining the minimum possible opening of the TCPs. We discuss these steps separately in the following sections. We show also some numerical examples from the runs in 2010 and 2011.

MARGINS IN THE CLEANING HIERARCHY

The collimators are aligned using a beam-based setup and afterwards qualified with loss maps [5]. This cannot be performed in every fill. The setup is therefore done a few times every year and, in the periods between, the operation relies on the machine reproducibility. The margins must thus account for orbit drifts (fill-to-fill, within fills and intentional drifts from luminosity optimization), β-beat, positioning errors (reproducibility of the collimator position between fills), and the inaccuracy of the collimation setup.

The β-beat was not measured continuously during operation but was studied in dedicated measurements [6]. We use an upper bound (10% in 2011) and consider the most pessimistic case (larger beam at the device to be protected, smaller beam size at the protecting device) to calculate a reduction of the margin. Positioning errors (40 μm) and setup errors (10 μm) [7], given by the step size used when aligning the collimators, are the same for all collimators.

Since orbit data is logged during operation we do a more elaborate calculation of the orbit margins, determined separately for every case. We define the aperture margin as the distance between the beam center and the closest aperture in units of σ (beam standard deviations based on the nominal emittance) and the margin, or retraction, between two devices (collimators or collimator to aperture) as the difference in aperture margin.

We calculate first the necessary retraction due to orbit movements between a TCT and the aperture of the closest triplet (upstream of the IP), for which we use the subscripts 1 and 2. We assume that the TCT is centered at a distance A_1 around the reference orbit during the qualification, while the triplet aperture A_2 is not. The aperture margin during the qualification is thus A_1 in the TCTs and $A_2 \pm x_{r2}$ in the triplet, where x_{r2} is the triplet reference orbit in the relevant plane ($-$ for the side where the x is defined positive, $+$ on the other side). The retraction between

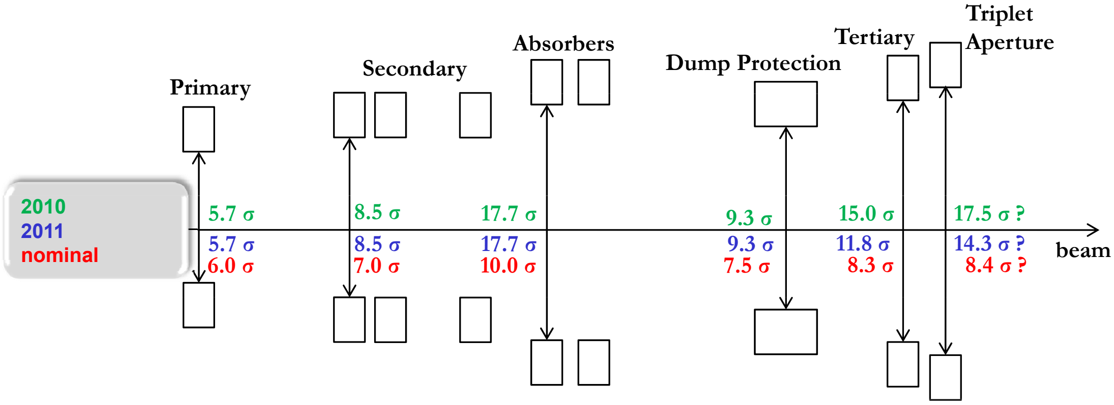

Figure 1: Schematic illustration (not to scale) of the collimator settings used during the 2010 run with $\beta^* = 3.5$ m (green), 2011 run with $\beta^* = 1.5$ m (blue), and the nominal settings with $\beta^* = 0.55$ m (red) together with the aperture estimates they were based on.

triplet and TCT is thus $A_2 \pm x_{r2} - A_1$, meaning that the minimum margin M_{min} over the two sides is

$$M_{min} = \min\{A_2 - A_1 - x_{r2}, A_2 - A_1 + x_{r2}\} = A_2 - A_1 - |x_{r2}|. \quad (1)$$

We assume that this configuration has been successfully qualified and consider now a later time where the orbit has drifted by Δx_1 at the TCT and Δx_2 at the triplet. If $\Delta x_1 > 0$, there is an *increase* in retraction to the triplet on the positive side and a *decrease* on the negative side. On the other hand, $\Delta x_2 > 0$ means *decreased* margin on the positive side. The new margin therefore becomes $A_2 - (x_{r2} + \Delta x_2) - (A_1 - \Delta x_2)$ and $A_2 + (x_{r2} + \Delta x_2) - (A_1 + \Delta x_2)$ on the negative side. The new minimum margin becomes

$$\tilde{M}_{min} = \min\{A_2 - A_1 - (x_{r2} + \Delta x_2 - \Delta x_1), A_2 - A_1 + (x_{r2} + \Delta x_2 - \Delta x_1)\} = A_2 - A_1 - |x_{r2} + \Delta x_2 - \Delta x_1|. \quad (2)$$

The change in the minimum margin is

$$\Delta M_{min} = \tilde{M}_{min} - M_{min} = |x_{r2}| - |x_{r2} + \Delta x_2 - \Delta x_1|. \quad (3)$$

In this calculation, we assumed that a TCT jaw protects the triplet aperture on the same side, as is the case for the closest triplet (phase advance $\Delta\mu \approx 0$). At the other triplet, a TCT jaw protects the opposite side since $\Delta\mu \approx \pi$. Eq. (3) then has to be modified to

$$\Delta M_{min} = \tilde{M}_{min} - M_{min} = |x_{r2}| - |x_{r2} + \Delta x_2 + \Delta x_1|. \quad (4)$$

If we instead take the margin between two collimators, where the orbit was centered in both devices during the setup, we set $x_{r2} = 0$ in Eqs. (3) and (4). We see that if $x_{r2} = 0$, any change in orbit causes a reduction in margin, while if $x_{r2} \neq 0$, the margin can also increase. Note that the the unit of all quantities in Eqs. (3) and (4) is σ based on the *nominal* emittance.

To decide the necessary orbit margin between two devices, we quantify the risk connected with a given orbit movement. Our approach is to demand that the assigned margin should be respected during at least 99% of the time spent in stable beams and use Eqs. (3) and (4) to calculate ΔM_{min} at all times. This means that if we expect one asynchronous beam dump per year, and that 1/3 of the time is spent in stable beams, we expect one beam dump in 300 years where the margin TCT-IR6 is violated. If the violation of the margin TCT-triplet is assumed to be uncorrelated to the margin TCT-IR6, we expect a beam dump that is dangerous for the triplet once every 30000 years.

The collimator settings used in 2010 are shown in Fig 1. Based on 2010 data, new 2011 settings could be determined [7]. Starting from a 5.7 σ TCP setting, the minimum aperture that can be protected was calculated to 14.1 σ.

ESTIMATION OF COLD APERTURE

The aperture margin in the triplet depends both on the optics, the crossing angle (the lower limit is given by beam-beam considerations and increases for smaller β^*), parallel separation and on the tolerances assumed on these parameters and the mechanical installation. Apertures have traditionally been estimated with the $n1$-method in the MAD-X program [8], which assumes the worst case for all variables. This approach is safe and well suited for the design stage of a machine but could lead to pessimistic aperture estimates. Once a machine is built, the installation tolerances are fixed and the aperture can be measured using a variety of methods. Several measurements have been performed in the LHC in the past [9, 10, 11, 12].

If the measurements are not done in the machine configuration where the aperture should be calculated, we can extrapolate the desired value from the measurements—e.g. we can use aperture measurements at injection energy to estimate the top-energy aperture after squeeze. We call this method *aperture scaling*. If the aperture at injection (subscript i) is known, we estimate the aperture at pre-collision (subscript p, after squeeze but before the beams are brought into collision) in units of σ as [7]

$$n_p = \frac{|u_i| - |u_p| - \delta u}{\sqrt{\beta_{up}\lambda_p\epsilon_n/\gamma_p}} + n_i\sqrt{\frac{\lambda_i\beta_{ui}\gamma_p}{\lambda_p\beta_{up}\gamma_i}} \quad (5)$$

where u is the ideal orbit, δ_u an additional shift in closed orbit, γ the relativistic factor, β the optical function, λ the worst-case β-beat, and ϵ_n the normalized emittance. The ideal β and orbit are taken from MAD-X and the other parameters are based on observed machine performance.

It has been shown [7, 13] that the scaling method gives larger apertures than the $n1$ method if the standard tolerances are used. However, an agreement can be found between the two methods if the momentum offset is reduced to about 1 σ instead of the full bucket height, and the orbit uncertainty is reduced to 2.3 mm. It should be noted that the aperture scaling does not include the effect of spurious dispersion, which becomes relevant when an energy offset is introduced to the whole beam (e.g. during chromaticity measurements).

Scaling the measured 2010 aperture [11], the aperture for $\beta^* = 1.5$ m and a crossing angle of 120 μrad was found to be about 14.3 σ. Using instead the 2011 measurement [12], the aperture in this configuration goes down to 13.8 σ.

MINIMUM TCP OPENING

The stability of the beam is highly dependent on the impedance of the machine, which is changed when the collimation system is moved in [1]. Furthermore, as the TCP opening is made smaller, the beam is cut closer to the core which decreases the lifetime. This determines the minimum TCP opening. The calculations involve many uncertainties so a detailed determination of the minimum setting must rely on experiments.

The emittance used during operation is smaller than nominal, and all collimator settings are expressed using the nominal emittance. This motivates smaller collimator gaps. During experiments in 2011, it was shown that cleaning works properly with so-called tight settings, with the TCPs at 4 nominal σ [14]. It still has to be demonstrated that a high-intensity beam remains stable using the tight settings.

2011 RUNNING CONDITIONS

An analysis of the running conditions was performed in the end of 2010 according to the outline described above, based on the 2010 running conditions [7]. It was shown among other things that the margin between IR6 and TCTs could be decreased from 5.7 σ to 2.3 σ.

The 14.1 σ aperture that can be protected corresponds well to $\beta^* = 1.5$ m and a half crossing angle of 120 μrad, sufficient to suppress beam-beam. Although the 2011 aperture measurement is slightly more pessimistic (implying $\beta^* = 1.6$ m), it was decided to accept a somewhat higher operational risk. Thus β^* was successfully reduced from 3.5 m to 1.5 m, which in 2011 has become the standard operational setting. The following factor 2.3 gain in instantaneous luminosity has played a very important role in the operational success during 2011 and was crucial for the early achievement of the 2011 luminosity goal.

CONCLUSIONS

We have shown a calculation model for the determination of the minimum safe β^* in the LHC in terms of cleaning machine protection—other limitations are not included. The margins between families in the collimation system, which must account for drifts in optics and orbit, together with the minimum opening of the primary collimator, define a minimum triplet aperture that can be protected. If the aperture is known as a function of β^*, for the minimum allowed crossing angle and parallel separation, we can infer the minimum β^*. We have shown both how to determine the necessary margins, based on operational stability, and a method to estimate the triplet aperture from measurements. The minimum opening of the TCPs have to be studied experimentally, guided by calculations.

Using our method, it has been shown that β^* could be reduced from 3.5 m in 2010 to 1.5 m in 2011, which has been successfully been put into operation. The resulting gain in luminosity, a factor 2.3, has been crucial to the success of reaching the 2011 goal for integrated luminosity.

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