CHROMATIC LHC OPTICS EFFECTS ON COLLIMATION PHASE SPACE CUTS

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Abstract

The different levels of LHC collimators must be set up by respecting a strict setting hierarchy in order to guarantee the required performance and protection during the different operational machine stages. Two different subsystems establish betatron and momentum collimation for the LHC. Collimator betatronic phase space cuts are defined for a central on-momentum particle. However, due to the chromatic features of the LHC optics and energy deviations of particles, the different phase space cuts become coupled. Starting from the basic equation of the transverse beam dynamics, the influence of off-momentum beta-beat and dispersion on the effective collimator settings has been calculated. The results are presented, defining the allowed phase space regions from LHC collimation. The impacts on collimation-related setting tolerances and the choice of an optimized LHC optics are discussed.

INTRODUCTION

Collimators in proton machines were historically used to reduce the radiation background at the experiments. The high energy and intensity reached in the LHC and the use of superconducting technologies require a sophisticated collimation system for beam cleaning and machine protection. Two straight sections of the LHC ring are dedicated to momentum (IR3) and betatron (IR7) cleaning. Their layout consists of primary (TCP) and secondary (TCSG) collimators plus absorbers (TCLA). Additional protection devices are installed upstream of the most sensitive components of the machine.

A strict setting hierarchy is fundamental to guarantee the required performance of the collimation system during the different operational stages of the machine. The collimator settings depend on the minimum machine available aperture which must be in the shade of the protection elements. The aperture of the secondary collimators must then be smaller than the aperture of the protection collimators. Finally primary collimators must be the closest element to the beam. A multi-stage cleaning system is implemented in this way and it should not be violated as an effect of setup errors, transient beam instabilities (e.g. transient orbit and beta-beat) or off-momentum beta-beat. For this reason, the mutual retraction between collimators of different families must be fixed taking into account a safety margin. Any violation (e.g. a secondary collimator acting as a primary) would indeed worsen the cleaning efficiency and compromise the required protection.

THE LHC CLEANING INSERTIONS

Primary and secondary collimators are used to scatter the beam halo particles and to constrain the losses in the cleaning insertions where normal conducting magnets are installed. The TCLA active absorbers are located downstream of the secondary collimators and have to intercept escaping particles and the showers produced by inelastic interactions of the protons inside the TCP and the TCSG jaws.

Conflicting optics requirements made necessary to use separate insertions for betatron and momentum collimation [1]. The two insertions were designed on the basis of theoretical conditions [2] and empirical optimization studies.

Betatron Cleaning Insertion

The betatron system allows to limit the transverse extension of the beam halo by “cleaning” particles with a large betatron oscillation amplitude. This is optimized by installing collimators in a low dispersion region.

The standard betatron collimator settings were defined according to the hierarchy rules presented above. The nominal half-gaps in σ_β units ($\sigma_\beta = \sqrt{\varepsilon\beta}$ is the betatron beam size) at injection and collision energy for TCP (n_1), TCSG (n_2) and TCLA (n_{abs}) are shown in Table 1.

Table 1: Nominal betatron and momentum collimator half-gaps at injection and collision energy.

	450 GeV		7 TeV	
	IR3	IR7	IR3	IR7
$n_1[\sigma_\beta]$	8	5.7	15	6
$n_2[\sigma_\beta]$	9.3	6.7	18	7
$n_{abs}[\sigma_\beta]$	10	10	20	10

At injection, the tightest aperture limitation is $\sim 7.5\sigma_\beta$ in the arcs. The injection protection elements are set to $6.8\sigma_\beta$ and the half-gap of the secondary collimators is $6.7\sigma_\beta$. A $1\sigma_\beta$ retraction is kept between TCP and TCSG. A three-stage cleaning system is then completed, by setting the TCLA to $10\sigma_\beta$, to protect the arc cold aperture.

The aperture of the triplets in the high luminosity insertions ($8.4\sigma_\beta$ in IR1 and IR5 for $\beta* = 0.55$ m [3]) imposes to close the tertiary collimators (TCT), installed upstream, to $n_3 = 8.3\sigma_\beta$. These collimators intercept particles escaping from the cleaning insertions and reduce the losses on the downstream magnets. The TCT strengthen the betatron system by introducing a fourth stage of cleaning.

Momentum Cleaning Insertion

The momentum cleaning system catches the longitudinal losses induced by off-momentum particles. While a pure betatron cleaning is achievable in regions of the machine with dispersion close to zero, off-momentum particles have generally a non negligible betatron component as well. Momentum collimators should not intercept particles which are in the RF-bucket (3.5·10^{-4} $\Delta p/p$ [3]) and have stable betatron oscillations below the cut of the betatron collimators. This is avoided by placing the momentum primary collimator at a place of maximum dispersion.
The openings of the momentum cleaning collimators are shown in Table 1 at injection and collision energy. Their openings were defined in order to intercept particles with a momentum deviation $\Delta p/p < -10^{-3}$.

IMPACT OF OFF-MOMENTUM BETA-BEAT

Analytical studies were carried out to assess the consequences of off-momentum beta-beat on the effective collimator settings. The collimator jaws are ideally always centered around the closed orbit and intercept all particles which, at their phase location, have an oscillation amplitude A_z greater than the half gap z_{cut} (z refers to transverse coordinates x and y). A_z is determined by the sum of two contributions:

1. the betatron oscillation amplitude: $n \cdot \sqrt{\varepsilon_z \beta_z(\delta)}$
2. the dispersion function: $D_z(\delta) \cdot \delta$

where D_z is the dispersion and $\delta = \Delta p/p$.

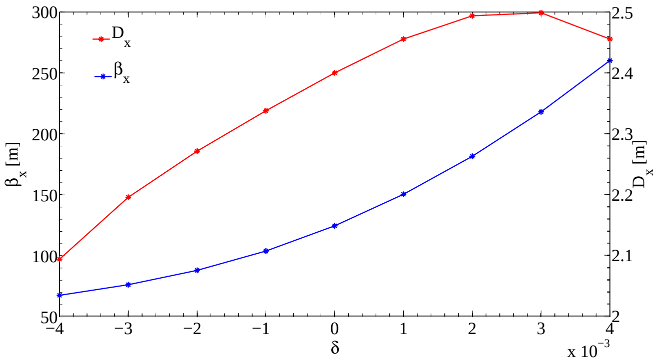

Figure 1: Variation of β_x and D_x as a function of particle momentum offset δ at the location of the horizontal primary collimator in the momentum cleaning insertion.

The half gaps (in mm) of the nominal collimator settings are calculated considering a central on-momentum particle. If $\delta \neq 0$ for a given particle the effective betatron amplitude cut $n_{\beta_z cut}(i)$ at each collimator i changes as a function of δ, β_z and D_z.

The cut in phase space produced by the nominal collimator settings can then be defined for each collimator as:

$$z_{cut}(i) = n_{\beta_z cut}(i,\delta) \cdot \sqrt{\varepsilon_z \beta_z(i,\delta)} + D_z(i,\delta) \cdot \delta \qquad (1)$$

from which, considering both collimator jaws and sufficient time for phase space mixing, it is possible to derive explicitly $n_{\beta_z cut}(i,\delta)$ as:

$$n_{\beta_z cut}(i,\delta) = \frac{\pm z_{cut}(i) - D_z(i,\delta) \cdot \delta}{\sqrt{\varepsilon_z \beta_z(i,\delta)}}. \qquad (2)$$

Ideally the β-function is independent of beam energy, meaning that the off-momentum beta-beat is zero. However, in reality there is always some dependance of β_z on δ, which is minimized during the accelerator design. An example is shown for the location of the IR3 horizontal primary collimator in Fig. 1. The effect of the off-momentum beta-beat on $n_{\beta_z cut}$ for this collimator is shown in Fig. 2 (red lines, 7 TeV settings). The blue lines show the phase space cut produced by the two jaws if the dispersion and the β-function are independent of δ.

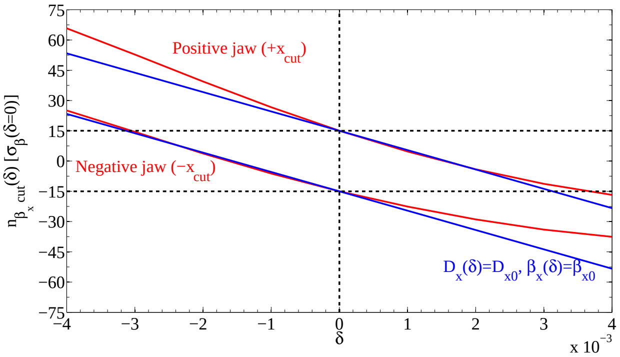

Figure 2: Phase space cut $n_{\beta_x cut}$ as a function of particle momentum offset δ for the IR3 horizontal primary collimator (red lines). The blue lines show $n_{\beta_x cut}$ in case of D_x and β_x being independent of δ, which is not the case for this location in the LHC.

Overlapping the δ-dependent phase cuts for all horizontal collimators and taking into account the energy spread of the nominal LHC RF-bucket, the allowed phase space region for the circulating beam can be defined, as shown in Fig. 3. Due to the off-momentum beta-beat the IR7 primary collimators, though set at 6σ_β ($\delta = 0$), cut the betatron halo down at 3 σ_β for δ = -0.13%. Primary collimator in IR3 intercepts all particles with $\delta \leq -0.16\%$. The dashed lines represents the reflections of the calculated curves with respect to the $n_{\beta_z cut} = 0$ axis. They define, for a fixed δ, the maximum possible betatron oscillation amplitude as imposed by phase space mixing. This is valid if the amplitude increase per turn is $\ll \sigma_\beta$ (stable beam) and if synchrotron oscillations are much slower than betatron oscillations. This is fully valid in the LHC [4].

Two different optics are possible in the LHC with the off-momentum beta-beat corrected either in the first (IP1→IP5) or in the second (IP5→IP1) half of the ring. In

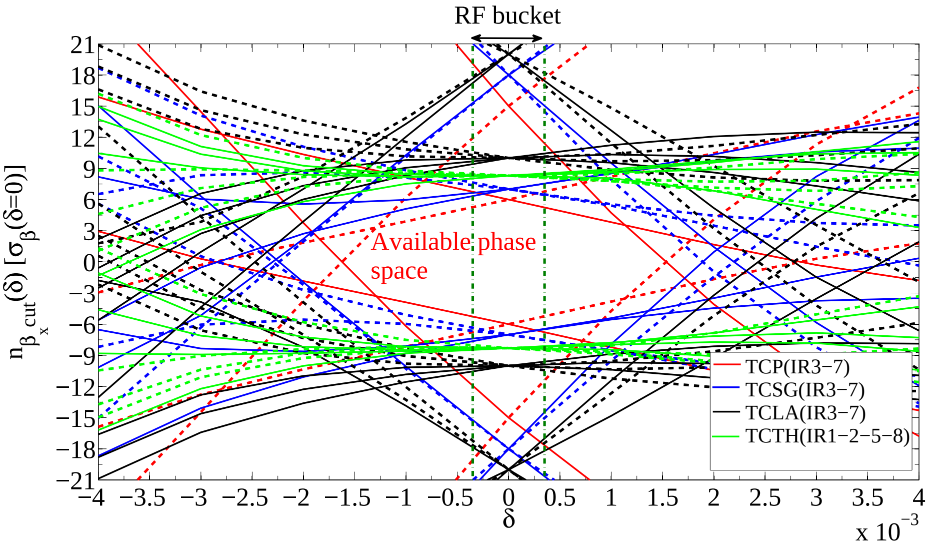

Figure 3: Phase space cut from all horizontal collimators in LHC, including IR3, IR7 and tertiary collimators. The region which can be populated by the beam halo is indicated. Note, that there is no mechanism to populate the phase space above the RF bucket while it can be populated below (synchrotron radiation).

Table 2: Minimum mutual retraction between collimators (betatron primary n_1, betatron secondary n_2 and tertiary collimators n_3) in case of beta-beat corrected in the first (IP1→IP5) or in the second (IP5→IP1) half of the ring.

	IP1→IP5	IP5→IP1
$n_2 - n_1$	$0.3\,\sigma_\beta$	$0.7\,\sigma_\beta$
$n_3 - n_2$	$1.8\,\sigma_\beta$	$1.9\,\sigma_\beta$

both cases, for $|\delta| \leq 0.2\%$, the collimators keep their roles while the retractions between collimators become smaller (see Table 2). A similar 22% reduction is found for the two optics when considering the retraction between tertiary and betatron secondary collimators. On the other hand, the difference between TCSG and TCP half-gaps in IR7 is reduced up to 30% if beta-beat takes place in the first half of the machine, whereas a 70% reduction is found for the other optics. The tolerance budget $T_b = n_2 - n_1$ [5] at top energy is then reduced, in the best case to $0.7\,\sigma_\beta$. Off-momentum beta-beat will make operation more delicate.

The results presented in this paper refer to the optics with beta-beat corrected in the half of the ring containing the betatron cleaning insertion (IP5→IP1). This option is in fact the most favorable from the point of view of the collimation since it gives a minimal reduction in terms of setting tolerances and has been adopted as LHC standard optics.

CONCLUSIONS

The high intensity beams of the Large Hadron Collider advance the state-of-the art in stored beam energy by two-three orders of magnitude. A sophisticated four-stage collimation system has been designed to intercept and absorb unavoidable fractional beam losses. Collimators are installed around the LHC ring and mainly in two straight sections dedicated to momentum and betatron cleaning.

The LHC collimation system shall provide a cleaning efficiency (absorption of particles) better than 99.99% for the 7 TeV LHC beams. Such a performance and the required machine protections can be obtained only by respecting a strictly defined setting hierarchy between different families of collimators. Several factors can influence the effective collimator settings. The consequences of off-momentum beta-beat have been assessed via analytical study and are presented in this paper. The studies were performed using optics configurations such that the beta-beat is corrected either in the first or in the second half of the machine. The outcome of the studies is that the preferred configuration is that one with the off-momentum beta-beat minimized in the betatron cleaning insertion. This option has a smaller effect on the collimation-related tolerance budget that is anyhow decreased by 30% (more demanding operation).

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