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EFFICIENCY FOR THE IMPERFECT LHC COLLIMATION SYSTEM

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Abstract

The LHC collimation system requires a high cleaning efficiency in order to prevent magnet quenches due to regular beam diffusion. The cleaning efficiency is significantly reduced due to imperfections of the collimator jaws and the machine optics. Tracking tools have been set up to predict the cleaning efficiency in presence of multiple imperfections. The deterioration of cleaning efficiency is quantified for different errors, including collimator surface non-flatness, collimator alignment errors, beta beating, orbit errors, non-linear field errors, and chromatic effects.

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Abstract

The LHC collimation system requires a high cleaning efficiency in order to prevent magnet quenches due to regular beam diffusion. The cleaning efficiency is significantly reduced due to imperfections of the collimator jaws and the machine optics. Tracking tools have been set up to predict the cleaning efficiency in presence of multiple imperfections. The deterioration of cleaning efficiency is quantified for different errors, including collimator surface non-flatness, collimator alignment errors, beta beating, orbit errors, non-linear field errors, and chromatic effects.

1 INTRODUCTION

The high intensity LHC beams require efficient collimation at all phases of a beam cycle. The regular proton losses due to diffusion and scattering processes will create a primary beam halo with enough intensity to quench and even damage the super-conducting magnets. The protons of the primary beam halo must therefore be intercepted at specifically designed collimators, so that they cannot reach the cold aperture of the magnets. The detailed requirements of the LHC collimation system are described in [1].

The particles in the beam halo are characterized by their normalized radial amplitudes $A_r = \sqrt{A_x^2 + A_y^2}$, where A_x is defined with the usual Twiss parameters α, β, γ as:

$$A_x = \left(\frac{\gamma_x x^2 + 2\alpha x x' + \beta_x x'^2}{\epsilon_x} \right)^{1/2} \quad (1)$$

The collimation system is then characterized for some cut amplitude A_{cut} by the cleaning inefficiency η_c:

$$\eta_c(A_{cut}) = \frac{\text{Number of protons}(A_r > A_{cut})}{\text{Number of impacting protons}} \quad (2)$$

The relevant cut amplitude A_{cut} is given by the available mechanical aperture downstream of the collimation system, which is specified to be about 10σ in the LHC. The available aperture is obtained after subtracting tolerances for mechanical alignment and closed orbit and its details depend on the installation and operation of the machine. The results have been obtained for nominal LHC parameters. The required collimation inefficiency at $A_{cut} = 10\sigma$ is about 10^{-3} for nominal LHC intensity and top energy, assuming in addition that the escaping protons are lost over 50 m of cold aperture [1, 2].

Two insertions in the LHC are dedicated to betatron and momentum collimation [3, 4]. The betatron cleaning system at top energy is most critical and is considered here. It includes 4 primary 0.2 m long Al collimators and 16 secondary 0.5 m long Cu collimators. These collimator materials cannot withstand the expected accidental proton losses in the LHC. However, until an improved system has been designed, the efficiency studies are performed with the existing system. The collimators are set to 6σ for the primary and 7σ for the secondary jaws. The scattering processes in the collimator jaws is calculated with the K2 [5] and alternatively the STRUCT [6] routine.

2 LINEAR TRACKING

A simple but fast linear, uncoupled, and non-chromatic tracking program was set up. Samples of up to 10^6 protons are tracked up to several hundred turns, when most particles have been lost in the collimators. The impact parameter was set to 1-2 μm. The normalized populations of secondary and tertiary beam halos have been calculated without imperfections. As shown in Fig. 1, the secondary halo extends to just below 10 σ. For calculating the inefficiency the tertiary halo is integrated above 10 σ_r. An ideal cleaning inefficiency of 6×10^{-4} is obtained. The phase space distribution in the tertiary halo is highly non-uniform, as particles originate at specific phase space locations.

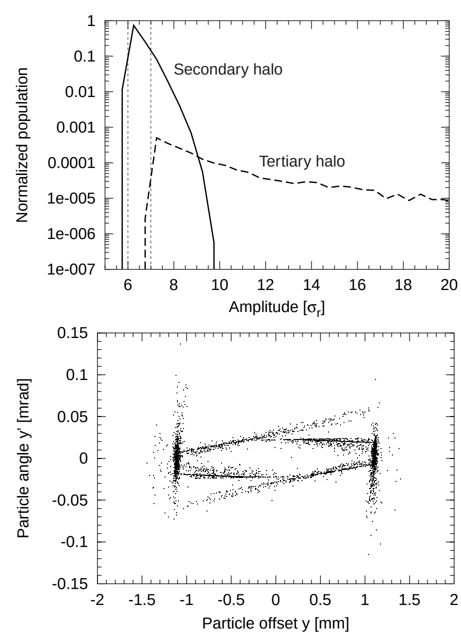

Figure 1: Transverse distribution of secondary and tertiary beam halos, normalized to the number of impacting protons (top). Vertical phase space of the tertiary halo (bottom).

Transient orbit errors and beta beat The collimator settings are adjusted to the values required from static orbit and beta beat errors. A transient change in the machine settings or natural drifts will then change the orbit or the beta beat without the collimators being re-optimized. The loss of cleaning inefficiency is shown in Fig. 2 for a transient orbit error and in Fig.3 for a transient beta beat. The worst phase of orbit and beta beat error is assumed. It is seen that the inefficiency is increased by 50% for transient beta beat of 8% or an orbit change of 0.6 σ (120 μm).

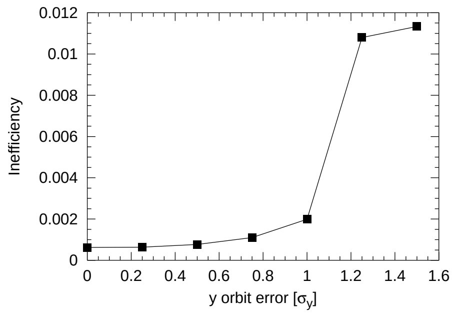

Figure 2: Dependence of the collimation inefficiency on an uncontrolled change in vertical orbit. The impact parameter at the primary vertical collimator was kept constant and the orbit change was supposed to be out of phase with the primary collimator.

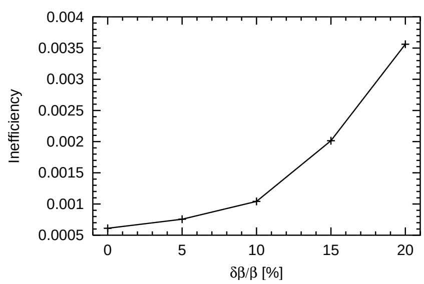

Figure 3: Dependence of the collimation inefficiency on an uncontrolled transient beta beat, considering the worst phase. Beta beat was modelled as a modulation of collimation depth.

Required accuracy for collimator adjustments The inefficiency is shown in Fig. 4 for different collimator settings. A shallow minimum exists and the settings of collimation depth need to be accurate on the level of $\pm$ 0.5-σ or $\pm$ 100 μm (secondary settings relative to primary settings). This is a rough estimate, as the dependence is quite non-linear and there is more room for some cases.

Collinearity errors and surface flatness The efficiency of the collimation system depends strongly on the active length of collimator jaws. This is the length of matter that the beam traverses. The active length of a jaw can be shorter than its real length, for example due to angular misalignment or flatness errors. The dependence of inefficiency on the rms angle between the jaw surface and the longitudinal beam direction is illustrated in Fig. 5. Angle errors were randomly assigned with several seeds per point. There is a quite steep dependence with a tolerance of about 50 μrad for a 50% increase in inefficiency.

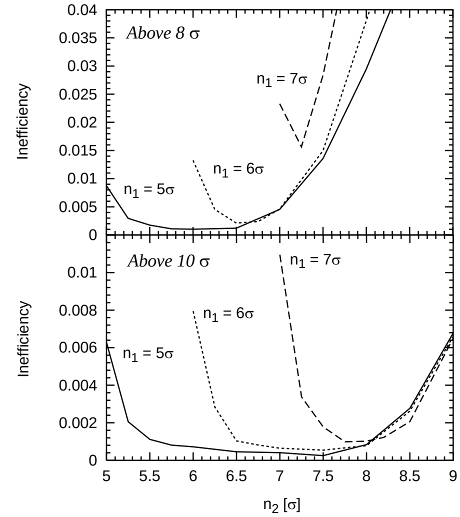

Figure 4: Dependence of the collimation inefficiency on the collimator settings for n_1 (primary collimation depth) and n_2 (secondary collimation depth).

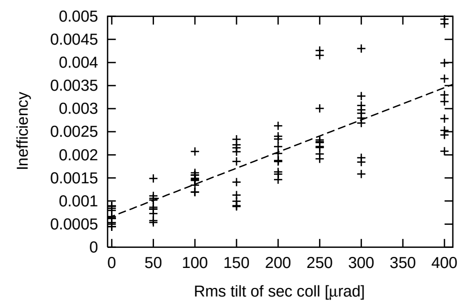

Figure 5: Dependence of the collimation inefficiency on the rms angle between jaw surface and longitudinal beam direction.

The small impact parameter at the collimator imposes strict tolerances on the surface flatness of the jaws. The typical impact parameter at primary collimators is expected to be about 1-2 μm. Errors in surface non-flatness can reduce the effective length of the primary collimator. This has two effects: 1) The cleaning half time (time until half the impacting protons are lost) is dramatically increased, being ten times longer ($\approx$100 turns), if the active length is only 10% of the actual length. 2) The cleaning inefficiency is increased, as shown in Fig. 6. Note, that only the secondary collimators show a strong dependence of cleaning inefficiency on the active jaw length. This is expected and to some extent compensated by the larger impact parameter of about 200 μm.

Preliminary estimate of tolerances Based on the results shown above, preliminary tolerances on the different imperfections were defined, for each with a 50% increase in cleaning inefficiency. The tolerances are summarized in Table 1. Note that the flatness tolerances were determined to be equivalent to a 50 μrad angle error between beam

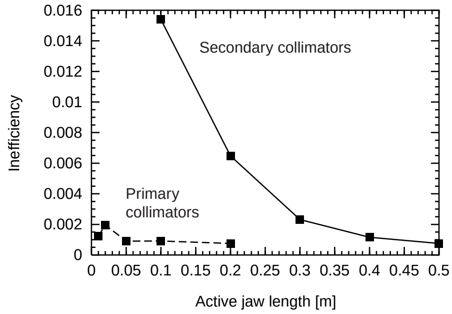

Figure 6: Dependence of the collimation inefficiency on the active jaw length for primary and secondary collimators. The lengths of jaws of one type were reduced together.

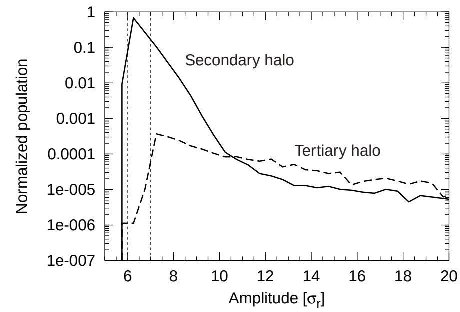

Figure 7: Transverse distribution (in normalized units) of secondary and tertiary beam halos, normalized to the number of impacting protons. This is like Fig. 1 but here takes into account the dispersive horizontal offsets due the off-momentum nature of halo particles.

Table 1: Preliminary tolerances, each for a 50% increase in cleaning inefficiency. The setting accuracy of secondary collimators is relative to the primary collimators. The flatness tolerances assume impact parameters of 10 μm and 200 μm. Interdependencies between errors are not yet taken into account.

Error	Tolerance
Orbit	0.6 σ
Beta beat	8%
Longitudinal angle	50 μrad
$\Delta L/L$ (prim)	75%
Surface flatness (prim)	10 μm
$\Delta L/L$ (sec)	20%
Surface flatness (sec)	25 μm
Setting accuracy (prim)	-1.0/+0.5 σ
Setting accuracy (sec)	$\geq \pm$ 0.5 σ

and jaw surface (in terms of active jaw length). Further refinements are required and a full model must simulate all effects concurrently.

3 CHROMATIC EFFECTS

The off-momentum nature of the beam halos requires for the cleaning inefficiency to include the dispersive offset at locations of non-zero dispersion and for the tracking to include full chromatic effects. The simple and fast tracking approach was not designed to include all chromatic effects. However, the maximum arc dispersion can be included into the definition of cleaning inefficiency. This was done and Fig. 7 shows the modified normalized distributions of secondary and tertiary halo. Comparing the result to the on-momentum halos in Fig. 1 it is seen that the tertiary halo is essentially unchanged. However, the secondary halo is no longer cut at 10 σ but extends much further. The protons beyond 10 σ now originate in roughly equal numbers from the secondary and tertiary halo. The cleaning inefficiency is about doubled.

The collimation scattering routines were implemented into the standard tracking programs DIMAD (STRUCT scattering routine) and SIXTRACK (K2 scattering routine). A preliminary comparison of the DIMAD result with the fast linear tracking showed that the results are basically comparable with a factor of five disagreement at 10 σ. This is true even for non-chromatic tracking in DIMAD, when the momentum loss in collimators is suppressed. The origin of this disagreement is under study.

4 CONCLUSION

The efficiency of the LHC betatron collimation system was studied for top energy including imperfections, as they are expected in the LHC. Different tools were employed, showing results different by about a factor of five. As the studies involve the detailed understanding of proton-matter interaction at 7 TeV and the accelerator physics of large amplitude halos, the observed disagreement seems reasonable. Nevertheless work is continuing to understand the origin of discrepancies and to further improve the predictive power of the numerical tools.

The existing tools were used to calculate the expected secondary and tertiary beam halos at locations of zero and maximum dispersion. The off-momentum secondary beam halo was found to extend far beyond 10 σ, doubling the cleaning inefficiency. For a number of imperfections preliminary tolerances were specified with the criterion of a 50% increase of cleaning inefficiency for each error.

The future work will aim at further improving the predictive power of the numerical tools and at establishing a complete and fully interdependent error model for the LHC collimation system.

5 REFERENCES

[1] R. Aßmann et al. These proceedings.
[2] J.B. Jeanneret, Proc. Chamonix X, CERN SL 2000-007 DI, R. Le Roux et al. Eds, February 2000, p. 162.
[3] J.B. Jeanneret, Phys. Rev. ST-AB, **1**,081001, 1998.
[4] D.I. Kaltchev et al., Proc. PAC99. CERN LHC Project Report 305 (1999).
[5] N. Catalan Lasheras et al., CERN LHC Project Report 156 (1998).
[6] I. Baishev et al., SSCL-MAN-0034, Dallas, 1994.