LHC CLEANING EFFICIENCY WITH IMPERFECTIONS

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Abstract

The performance reach of the LHC depends on the magnitude of beam losses and the achievable cleaning efficiency of its collimation system. The ideal performance reach for the nominal Phase 1 collimation system is reviewed. However, unavoidable imperfections affect any accelerator and can further deteriorate the collimation performance. Multiple static machine and collimator imperfections were included in the LHC tracking simulations. Error models for collimator jaw flatness, collimator setup accuracy, the LHC orbit and the LHC aperture were set up, based to the maximum extent possible on measurements and results of experimental beam tests. It is shown that combined "realistic" imperfections can reduce the LHC cleaning efficiency by about a factor 11 on average.

INTRODUCTION

Each LHC proton beam stores an energy of up to 360 MJ. The superconducting (sc) magnets of the LHC would quench after an energy deposition of 5 mJ/cm^3 [1]. A sophisticated system of collimators [2] has been designed to concentrate beam losses in dedicated cleaning insertions where more resistant room-temperature magnets are installed.

The performance of the collimation system is characterized by the local cleaning inefficiency η_c defined as:

$$\eta_c = \frac{N_{lost}^{\Delta s}}{\Delta s \cdot N_{abs}}, \tag{1}$$

where $N_{lost}^{\Delta s}$ is the number of particles lost within a longitudinal binning $\Delta s = 10$ cm and N_{abs} is the total number of particles absorbed at the collimators. η_c is derived by using detailed loss maps calculated with "SixTrack" and a realistic machine aperture model [4]. Local losses exceeding the quench limit of the sc magnets could imply a limitation in the maximum allowed beam current I_{max} [3]. The performance of the Phase 1 LHC collimation system [2] and possible collimator-induced constraints are analyzed, in the following, for the ideal machine and in case of multiple imperfections.

PERFORMANCE REACH FOR THE IDEAL MACHINE

The LHC collimation system must be active during the full machine cycle, from injection up to physics and extraction. Studies of cleaning efficiency have been performed for different optics in order to identify limitations in beam intensity for safe machine operation. Peak values of the maximum local cleaning inefficiency η_c^{max} are listed in Table 1 at injection and collision energy for the perfect machine.

Table 1: Peak values of η_c^{max} for the ideal machine at injection and collision energy. The quench limit is evaluated for a loss rate corresponding to a beam lifetime of 0.1 h at 450 GeV and 0.2 h at 7 TeV.

Energy [TeV]	η_c^{max} [10^{-5} m^{-1}]	Quench limit [10^{-5} m^{-1}]
0.45	19.2±1.8	78.3
7.00	4.6±0.9	1.7

The error on η_c^{max} is purely statistical and is given by:

$$\sigma_{\eta_c^{max}} = \frac{\sqrt{N_{lost}^{\Delta s}}}{\Delta s \cdot N_{abs}}. \tag{2}$$

Losses exceeding the quench limit at 7 TeV (see Table 1) are estimated to reduce I_{max} to about 40% of its nominal value ($I_{nom} = 3.22 \cdot 10^{34}$ protons) already in the ideal case. While these results are based on conservative assumptions (i.e. 0.2 h beam lifetime and 10 cm loss dilution length), no other margin has been applied. In the LHC, the dump threshold of the beam loss monitors (BLM) will be set to 30% of the quench limit [5]. Collimation therefore must be even more efficient to avoid beam-loss triggered aborts. Other safety margins could further reduce the allowable beam loss so that these predictions on I_{max} can be considered as realistic.

IMPACT OF IMPERFECTIONS ON THE MACHINE PERFORMANCE

It was seen in other accelerators and always expected for the LHC that imperfections strongly deteriorate cleaning efficiency. Early qualitative and semi-quantitative estimates indicated that the performance can be reduced by factors of 5-10. Here we present the first quantitative study that estimates in detail the effect of many (still not all) imperfections.

In order to give an evaluation of the "realistic" cleaning performance of the collimation system and consequent limitations to the maximum allowable beam intensity reach, several scenarios with combined imperfections were analyzed for the nominal collision optics, as shown in the following.

Jaw Flatness Errors

The LHC collimators are produced with stringent requirements on the flatness of the jaws: ~40 μm for the

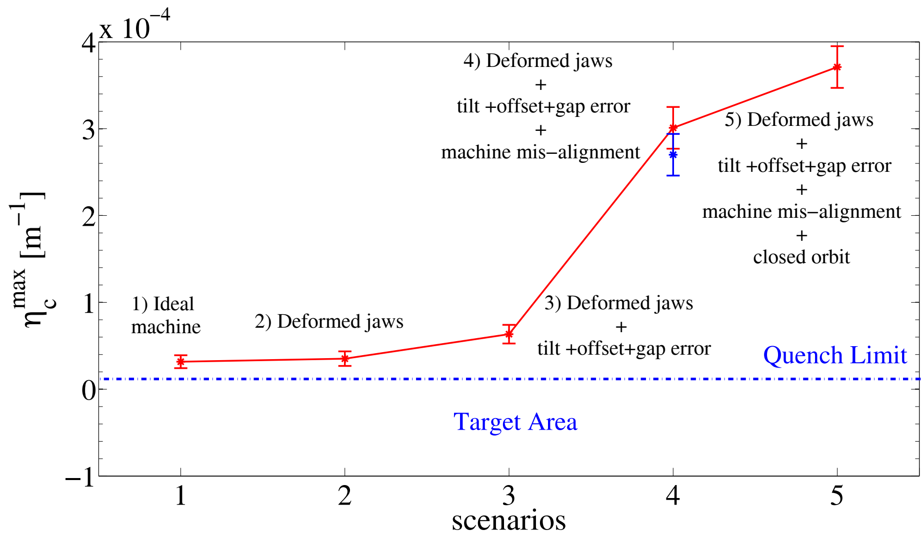

Figure 1: η_c^{max} for multiple combinations of collimator and machine imperfections at collision energy. The blue point refers to machine alignment errors as defined by measurements. The cleaning efficiency gets worse up to a factor of 11 by reducing I_{max} to <5% of I_{nom}.

1 m long graphite jaws. Any large deformation of the jaws would create a reduction of the material traversed by the halo particles (active length) and worsen the cleaning efficiency. However, the achievable flatness is technically limited and measurements performed on different collimator families show an average deformation of $40.3 \pm 22.2\,\mu$m [6].
Simulations were carried out by using the same systematic non-flatness, inwards and outwards, for jaws with equal length:

- 100 μm for 1 m long jaws (absorbers, secondary and tertiary collimators)
- 60 μm for 0.6 m long jaws (primary collimators).

A 10% increase in η_c^{max} was found with respect to the ideal machine at top energy (see Fig. 1 scenario 2).

Collimator Setup Errors

Ideally, the collimator jaws should be centered and aligned with respect to the beam. In reality the setup of the collimators is affected by unavoidable offsets and tilts with respect to the ideal position.
Results of experimental beam tests, performed with a prototype collimator installed in the SPS ring [6], were used to simulate this scenario. Random errors with a Gaussian distribution cut at 3σ were used and the following imperfections were combined:

1. Jaw flatness as described
2. R.m.s. error on gap centre with respect to the beam centre: 50 μm
3. R.m.s. error on gap size: 0.1 σ
4. R.m.s. error on jaw angle with respect to the beam envelope: 200 μrad

A factor of 2 loss in cleaning efficiency was found with respect to the perfect case (see Fig. 1 scenario 3).

Machine Alignment Errors

The collimation simulation package [4] allows taking into account magnet and beam screen misalignments of the LHC elements (beam screens are first aperture limitations).

Table 2: Horizontal and vertical r.m.s magnet misalignments at beam screen level for different families of machine elements. The numbers are based on design values and measurements performed in the LHC tunnel [7].

Description	Design		Measured	
	$\sigma_{\Delta x}$ [mm]	$\sigma_{\Delta y}$ [mm]	$\sigma_{\Delta x}$ [mm]	$\sigma_{\Delta y}$ [mm]
main dipole	2.40	1.56	1.83	1.10
arc quadrupole	2.00	1.20	1.36	0.76
triplet quadrupole	1.00	1.00	1.53	1.53
warm quadrupole	2.00	1.20	0.67	0.41
warm dipole	1.50	1.50	1.96	1.49
beam pos. monitor	0.50	0.50	1.36	0.76

Starting from the standard aperture model used to derive the loss maps, up to 20 seeds of misaligned apertures can be applied to a set of halo trajectories produced by "SixTrack". An r.m.s. offset in the horizontal ($\sigma_{\Delta x}$) and vertical ($\sigma_{\Delta y}$) planes has been defined for different families of elements on the basis of design values and measurements performed in the LHC tunnel [7]. The applied imperfections are listed in Table 2. Misalignment errors are simulated with a Gaussian distribution cut at 1.5σ to the geometric centre of each magnet in the LHC. This is only carried out at the level of the aperture model. Particle tracking is done with the ideal machine orbit and fields. The reduced aperture has different bottlenecks (one-sided) which lead to loss peaks in unusual locations and an increase in the cleaning inefficiency. Fig. 2 summarizes the η_c^{max} values found for 20 different seeds of machine alignment errors (design values): the local cleaning inefficiency varies by up to a factor of four for different seeds. The cleaning efficiency is degraded by about one order of magnitude.

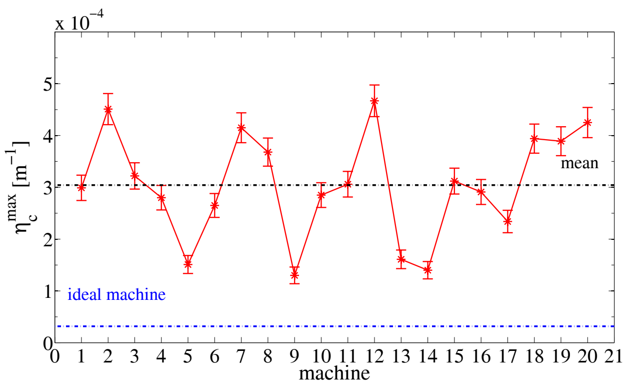

Figure 2: Cleaning inefficiency η_c^{max} for 20 different seeds of machine alignment errors (design values). η_c^{max} is increased on average by a factor of 9.5 with respect to the ideal machine.

The calculated maximum cleaning inefficiency averaged over the simulated seeds is:

1. $\overline{\eta_c^{max}} = (3.0 \pm 0.2) \cdot 10^{-4}\,\mathrm{m}^{-1}$ for machine alignment errors from design values.

2. $\overline{\eta_c^{max}} = (2.7 \pm 0.2) \cdot 10^{-4}\,\mathrm{m}^{-1}$ for machine alignment errors from measurements.

Results are in agreement within the simulation error. Both values are indicated in the summary plot shown in Fig. 1 (scenario 4: red point for design values, blue point for measured values).

Non Ideal Closed Orbit

The effect of a non-ideal horizontal closed orbit is added for the study of collimation system performance.

Previous in-depth studies on orbit perturbations [8] defined a conservative scenario in compliance with the specified LHC orbit for the collision optics. On the basis of these results two kickers were used to generate a static horizontal closed orbit oscillation with maximum amplitude of ± 4 mm in the arcs. The orbit was corrected to the specified ± 3 mm maximum amplitude in the straight sections. Simulations were carried out by using the standard initial halo distributions and the errors defined above. Tracking was performed with collimators centered on the non-ideal orbit. This resulted in a further increase in the local cleaning inefficiency by a factor of 1.16 (see Fig. 1).
To date this scenario (scenario 5 in Fig. 1) is considered as the most realistic one, and could limit the maximum intensity reach to $<5\%$ of I_{nom}.

CONCLUSIONS

The LHC collimation system shall provide a cleaning efficiency (absorption of losses) of better than 99.99% for the 7 TeV LHC beams.

This work extends the earlier studies on the achievable cleaning efficiency taking into account realistic static imperfections. Simulations include, in particular, manufacturing errors on flatness of collimators, collimator setup errors, design orbit errors and magnet alignment errors. As expected, it was found that combining these imperfections has a strong effect on the achievable cleaning efficiency. The performance loss was simulated for the first time for multiple imperfections, finding a factor of 11 reduction in cleaning efficiency if compared to the ideal performance.

The LHC beam intensity reachable with the Phase 1 collimation system is therefore predicted to be below 5% of the nominal value. This prediction is based on critical assumptions for the sc magnet quench limit and a minimal beam lifetime of 0.2 h. Nevertheless, since several imperfections are not yet taken into account (namely effects from beta-beat, coupling and non-linearities in the LHC), we expect these estimates to be representative of the LHC operation. It is then concluded that these are strong hints at possible limitations of the LHC intensity from cleaning of losses. Higher beam intensities would require lower peak loss than specified, better collimator setup, reduced machine imperfections or collimation upgrade.

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