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COMPARISON OF BEAM SIZES AT THE COLLIMATOR LOCATIONS FROM MEASURED OPTICS AND BEAM-BASED COLLIMATOR ALIGNMENT AT THE LHC

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Abstract

At the Large Hadron Collider (LHC), the collimation hierarchy is defined in units of the betatron beam size using the sizes at each collimator location. The beam size at a given collimator can be inferred from the gap measurement during beam-based alignment campaigns, when the collimator touches a reference beam halo defined with the primary collimators. On the other hand, the beta functions at each collimator are also measured as a part of the standard LHC optics validation. This paper presents a comparison of the beam size measurements at the collimator locations applying these two techniques for different machine configurations. This work aims at determining which is the most reliable method for setting the collimator gaps at the LHC.

INTRODUCTION

The LHC accelerates two counter-rotating beams to a nominal energy of 7 TeV, corresponding to 362 MJ of stored energy per beam. An uncontrolled beam loss of only 7.6×10^6 p s^{-1}m^{-1} in a superconducting magnet can induce enough heating to cause a quench. In Run 1, a multi-stage system composed of 43 collimators per beam was operated to protect the LHC against losses of circulating beam [1]. Each collimator is composed of two jaws which need to be positioned equidistant from the beam, based on the beam centre and beam size at the collimator location. The upstream and downstream corners of each jaw can be moved independently by dedicated stepper motors. Most of the LHC collimators are located in Insertion Region (IR) 3 and IR 7 to clean particles with large momentum and betatron offsets, respectively. The IR7 horizontal aperture is shown in Fig. 1. The collimators are installed in the horizontal, vertical and skew planes to ensure the best coverage of the transverse phase space.

COLLIMATOR ALIGNMENT

The beam center and the beam size at each collimator are measured during a commissioning period at the start of the run. These values are measured for four machine modes: injection, flat top, squeezed separated, and colliding beams, and are used to calculate the operational jaw settings for the whole run. Thanks to the reproducibility of the beam orbit, one set up per machine mode per year has proven to be sufficient for now. Alignments are repeated if the machine configuration (e.g. β^*, crossing angle) is changed.

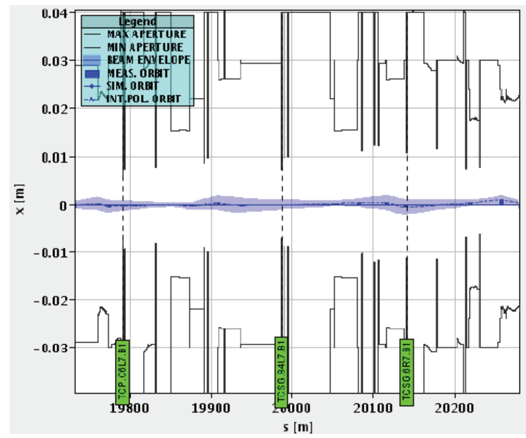

Figure 1: The IR7 horizontal aperture and beam orbit, with the envelope denoting the 1-σ beam size. The green text boxes show names of a few IR7 horizontal collimators.

Each collimator is set up using a four-step procedure [2]. The jaw of a reference collimator, taken to be the IR7 primary collimator (TCP) in the same plane as the collimator to be aligned, is first moved in steps of 5 μm (top energy) or 20 μm (injection energy). A feedback loop is used to stop the movement when the beam losses from a downstream Beam Loss Monitor (BLM) exceed a pre-defined threshold [3] (step 1). The opposite jaw is then aligned to the beam. After the reference cut in the halo is established, the i^{th} collimator i can be aligned (step 2). The reference collimator is re-aligned to the beam to account for halo depletion during the previous alignment (step 3). Finally, the collimator is retracted to the hierarchy positions (step 4).

At the start of the horizontal collimator alignment, the momentum halo is cut using the primary collimator in the high-dispersion region in IR3. This ensures that the halo intercepted by the other collimators is dominated by the betatron contribution, and has proved to give more stable and reliable results [6] for the beam centres. The inferred beam size at the collimator i is expressed in terms of the jaw half gap and the reference cut in units of σ, n_1:

$$\sigma_i^{\text{inf}} = \frac{x_i^{\text{L}} - x_i^{\text{R}}}{n_1^{k-1} + n_1^k} \quad (1)$$

where x_i^{L} and x_i^{R} are the left and right aligned jaw positions, and k is an index for the number of reference collimator alignments. The half-gap opening n_1 in units of σ for the two reference collimator alignments is calculated

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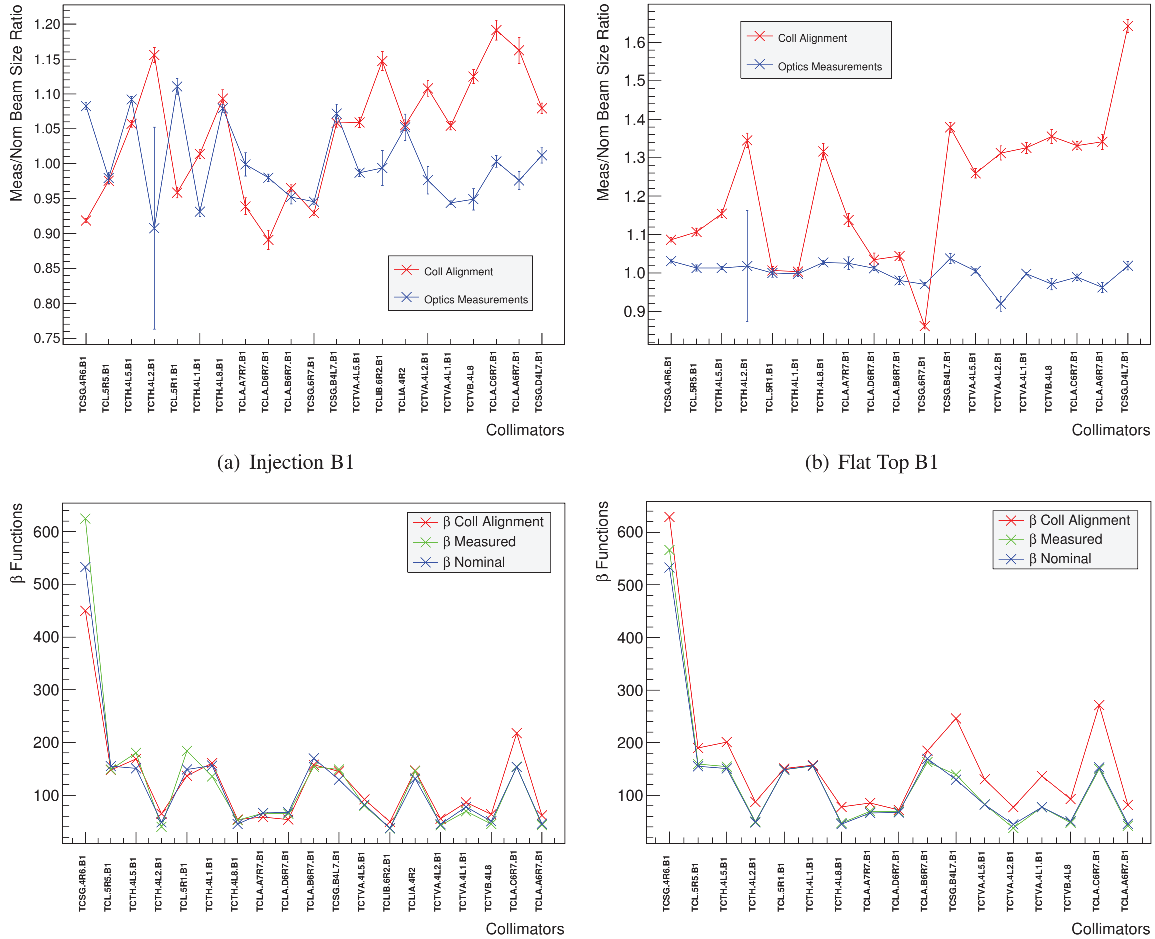

(a) Injection B1 (b) Flat Top B1

(c) Injection B1 (d) Flat Top B1

Figure 2: Beam size ratios and β-functions at injection and flat top for H and V collimators (except IR3).

as the average of the TCP cuts in steps (1) and (3) of the alignment procedure to define the normalized halo width for the i^{th} collimator in order to account for cut of the halo in step 2:

$$n_1^{k-1} = \frac{x_{k-1}^{\mathrm{L}} - x_{k-1}^{\mathrm{R}}}{2\sigma_{\mathrm{TCP}}^{\mathrm{nom}}}, \qquad n_1^{k} = \frac{x_{k}^{\mathrm{L}} - x_{k}^{\mathrm{R}}}{2\sigma_{\mathrm{TCP}}^{\mathrm{nom}}}. \tag{2}$$

This provides the relative hierarchy. The calculation relies on the nominal TCP β-functions.

OPTICS MEASUREMENTS

The local optics at the collimators is measured using the N-BPM method [4]. The BPM turn-by-turn measurements are used to derive the phase advance of the betatron oscillation between BPMs, from which the β-function can be calculated at the BPM positions:

$$\beta_i = \frac{\epsilon_{ijk}\cot(\phi_{i,j}) + \epsilon_{ikj}\cot(\phi_{i,k})}{\epsilon_{ijk}\frac{M_{11(i,j)}}{M_{12(i,j)}} + \epsilon_{ijk}\frac{M_{11(i,k)}}{M_{12(i,k)}}} \tag{3}$$

where $\phi_{i,j} = \phi_j - \phi_i$ is the phase advance, ϵ is the Levi-Civita symbol and $M_{mn(i,j)}$ are the transfer matrix elements from BPM (i) to (j). The N-BPM method allows to analyze more BPM combinations together to calculate the β-function by considering systematic and statistical errors as well as correlations. In our case 10 BPM combinations within a range of 11 BPMs have been used per probed BPM. The measured optical functions at the BPM positions are then propagated to other elements, such as the collimators, via MADX [5].

RESULTS COMPARISON

The 1-σ nominal beam size at the collimator is calculated from the betatronic and dispersive contributions:

$$\sigma_i^{nom} = \sqrt{(\beta_{x,i}\epsilon_x + (D_i\delta_p)^2)\cos^2\psi_i + \beta_{y,i}\epsilon_y\sin^2\psi_i} \tag{4}$$

where ψ_i is the azimuthal angle of the collimator, ϵ is the geometrical beam emittance, D_i is the dispersion function and δp is the r.m.s. energy spread. Vertical dispersion is neglected. The comparison of the measured to nominal beam size ratios calculated from the alignment of collimators in low-dispersion regions and the measured optics, as well as the calculated and measured β-functions at injection and flat top is shown for B1 in Fig. 2. Similar results were obtained for B2 collimators. The skew collimators were neglected from the analysis due to further errors introduced

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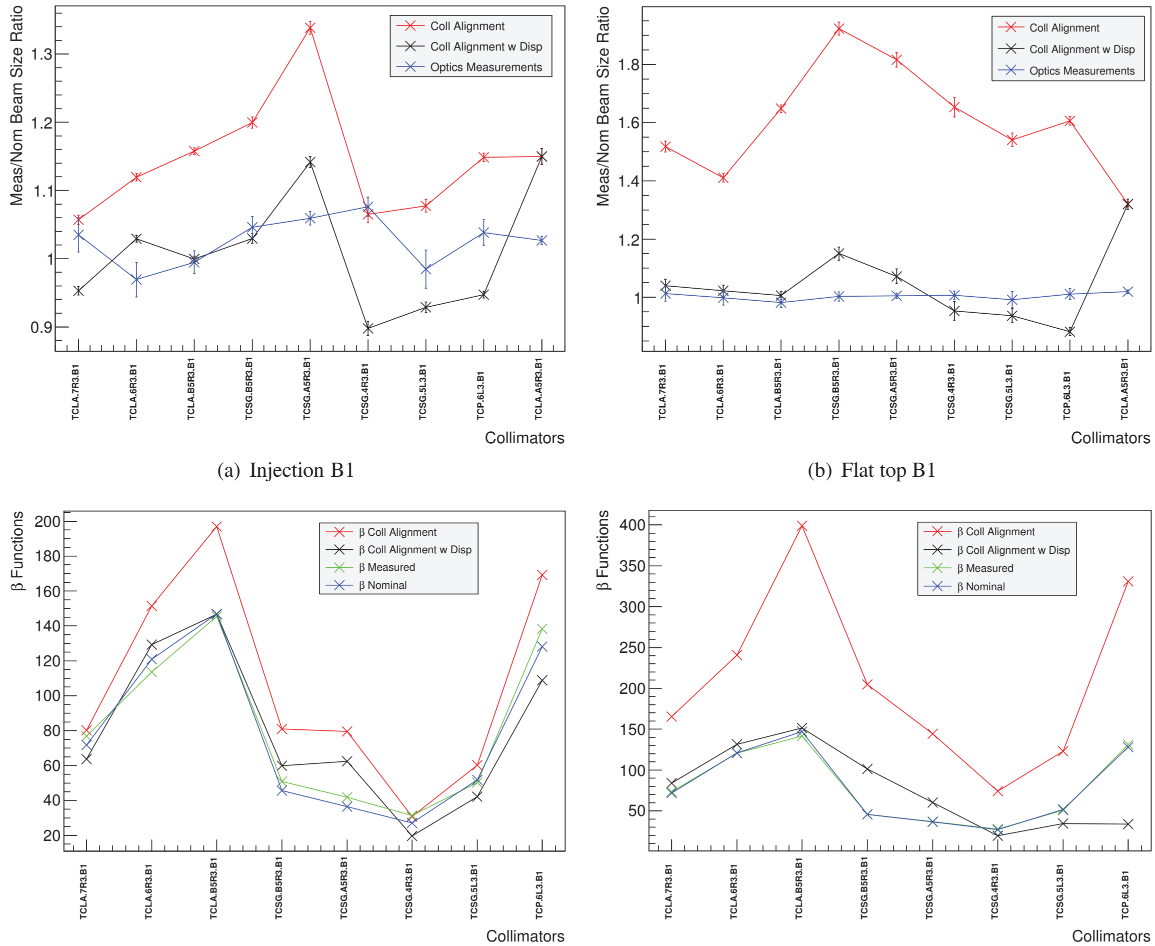

(a) Injection B1 (b) Flat top B1
(c) Injection B1 (d) Flat top B1

Figure 3: Beam size ratios and β-functions at injection and flat top for IR3 collimators.

by the non-round beams. The β-functions are calculated from the alignments via:

$$\beta_x = \frac{(\sigma_i^{inf})^2 - (D_x \delta p/p)^2}{\epsilon_x}, \qquad \beta_y = \frac{(\sigma_i^{inf})^2}{\epsilon_y} \tag{5}$$

The combination of collimator tank tilts with respect to the longitudinal direction of the beam [7] (<350 μm worst case) and offsets between the requested motor steps and LVDT readout (<50 μm) result in a larger measured gap in mm [3]:

$$\sigma_i^r = \frac{G_i + \Delta_{LVDT} + \Delta_{tilt}}{2n_1} \tag{6}$$

Hence, higher ratios are expected for the alignments done at top energy due to the smaller beam sizes. As the reference cut is made to the betatronic halo, a direct measurement of the dispersive contribution is not possible at the high-dispersion IR3 collimators, where it is larger. A similar comparison is shown in Fig. 3. The red line corresponds to the beam size ratios and β-functions calculated ignoring dispersion, while the black line was calculated by estimating the factor to be multiplied to the dispersive contribution $D_i\delta_p$ as 1 and 1.8 at injection and flat top, respectively.

CONCLUSIONS AND OUTLOOK

The beam size at each LHC collimator is necessary to calculate the operational settings and establish the collimation hierarchy. As the collimator gaps are smaller in mm at top energy, the setup procedure is more sensitive to gap measurement errors. Hence, in Run 1 the nominal betatron beam size was used to determine the settings at top energy, while the measured beam size was used for the injection settings. There is a good comparison of the beam sizes at 450 GeV within the expected error margin, while at flat top, the beam sizes from collimator alignment are larger than nominal. The dispersive contribution to the beam size was indirectly estimated, but a more detailed understanding is needed. The collimator operational settings are qualified regularly via beam loss maps [8]. During Run 2, loss maps with the beam sizes calculated from the measured optics could be performed and compared with loss maps done using with the settings calculated from the nominal optics to determine the best strategy for operation.

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