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EXPERIMENTAL TEST OF A NEW METHOD TO VERIFY RETRACTION MARGINS BETWEEN DUMP ABSORBERS AND TERTIARY COLLIMATORS AT THE LHC

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Abstract

The protection of the tertiary collimators (TCTs) and the LHC triplet aperture in case of a so-called asynchronous beam dump relies on the correct retraction between the TCTs and the dump region absorbers. A new method to validate this retraction has been proposed, and a proof-of-principle experiment was performed at the LHC. The method uses a long orbit bump to mimic the change of the beam trajectory caused by an asynchronous firing of the extraction kickers. It can, thus, be performed with circulating beam. This paper reports on the performed beam measurements, compares them with expectations and discusses the potential benefits of the new method for machine protection.

INTRODUCTION AND MOTIVATION

The unprecedented stored energy in the two beams of the Large Hadron Collider (LHC) requires a sophisticated beam dump system [1]. In case of a beam abort request, fast ramping magnets are used to extract the beam into the dump line. To avoid excessive beam losses during the rise time of these extraction kickers magnets (MKD), a 3 µs long abort gap in the circulating beam is kept free of particles. If the correct synchronisation of the MKD rise time with the abort gap is lost, a so-called asynchronous beam dump is produced and the beam is swept over the machine aperture by the rising edge of the kicker field [1, 2].

To protect the downstream elements from the impact of such an asynchronous beam dump, dedicated absorbers, named TCDQ and TCSP, are installed in the extraction region, which is located in the Insertion Region (IR) 6 of the LHC. In addition, tertiary collimators (TCTs) are installed around the four LHC experiments to protect the superconducting inner triplet quadrupoles that provide the final beam focus for the collision points. The 1-meter long, tungsten TCTs are installed to stop the tertiary halo particles from impacting the triplet magnets, reduce beam backgrounds, and protect the triplets in case of failures such as asynchronous beam dumps, but they are not designed to directly intercept high intensities of primary beam particles [3, 4].

The protection of the triplet aperture and the TCTs relies on the correct horizontal position of the TCTs and of the IR6 absorbers (TCDQ/TCSP) with respect to the beam [5, 6]. These retraction margins have to be verified experimentally for all relevant collimator settings and optics. Therefore, asynchronous beam dump tests are regularly performed at the LHC. During these tests, the extraction kickers are fired on a debunched particle distribution inside the abort gap and the observed beam losses are analysed [2, 7]. The new, complementary method discussed in this paper allows the validation of the aperture margins by using a long orbit bump [8], and therefore without the need of dumping the beam, which requires considerably more machine time.

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BEAM EXPERIMENT

Method Overview

A proof-of-principle experiment for the new method was performed in October 2018 at the LHC (MD2186) [9]. The method consisted of the following main steps:

- The collimators and beam parameters are set to the configuration that should be validated.
- An orbit bump with four corrector magnets is implemented to mimic the trajectory caused by the asynchronous firing of the MKDs, making the IR6 absorbers the ring aperture bottleneck.
- The horizontal beam envelope is defined by blowing up the emittance until beam losses are observed at the IR6 absorbers.
- The horizontal TCT in IR5 is moved inwards until the first jaw starts touching the beam envelope.
- It is verified that the measured stop position of the TCT matches the expected retraction to the IR6 absorbers.

Experimental Set-up and Procedure

For the experiment, three low-intensity bunches with approximately 1×10^{10} protons per bunch were injected into Ring 2 of the LHC. The beam was accelerated to an energy of 6.5 TeV. Collision optics with a β function at the collision point of $\beta^* = 30$ cm and a half crossing angle of 160 µrad were used. The most critical retraction margins are between the IR6 collimators and the TCTs at the adjacent IR5 (CMS experiment) for the counter-clockwise rotating Beam 2 [8]. Therefore, the beam test was performed for this configuration, using a long orbit bump from IR6 to the downstream interaction point of IR5. Figure 1 shows the bump shape as simulated with MAD-X [10]. It matches closely the expected MKD trajectory [8, 11].

In this paper, we express the collimator half-gaps and beam positions in units of the local betatron beam size $\sigma = \sqrt{\beta \cdot \epsilon_n / \gamma_{rel}}$, with the nominal β function at the element, the relativistic factor γ_{rel} and assuming a normalized emittance of $\epsilon_n = 3.5$ µm.

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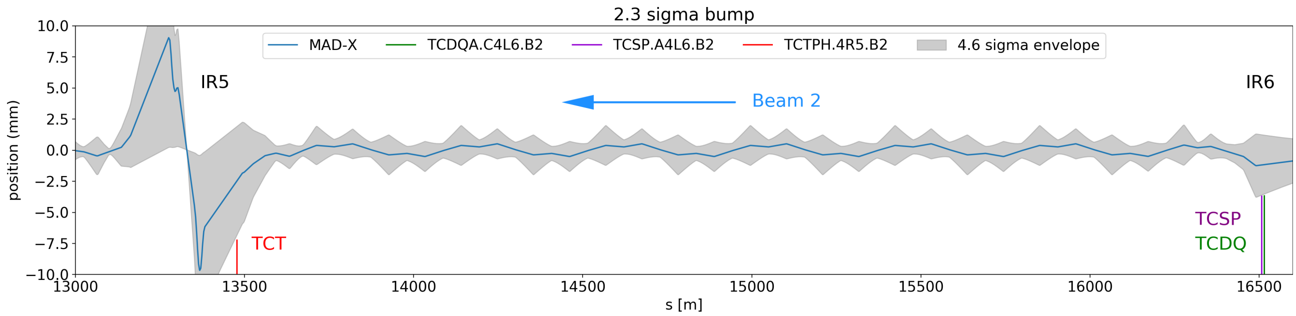

Figure 1: Bump shape computed with MAD-X for a bump strength of 2.3 σ at the TCDQ, including a 4.6 σ beam envelope. The positions of TCDQ, TCSP and TCTPH are indicated. Beam 2 travels from right to left.

The new method was tested with two different orbit bump strengths. An overview of the measured beam and collimator positions in σ throughout the tests is shown in Fig. 2.

Test 1: TCDQ at Nominal Position and 2.3 σ Bump The IR6 absorbers TCDQ/TCSP and the TCTs were positioned at their nominal settings (see Table 1). After introducing an orbit bump of 2.3 σ at the TCDQ, the emittance of the first bunch, and thus its beam size, was increased using the Transverse Damper (ADT) until losses were observed at the beam loss monitors close to the TCDQ/TCSP. Before, the horizontal and skew primary collimators (TCPs) had been retracted to 7 σ to avoid an aperture bottleneck in the collimation region in IR7.

The horizontal TCT was then moved towards the beam center using the beam based alignment (BBA) procedure [12]. The collimator jaws were moved inwards in steps of 10 µm. They automatically stopped when the first jaw touched the beam envelope and generated beam losses, such that the position of the beam envelope could be determined.

Table 1: Nominal Collimator Settings for Beam 2 (Collisions, $\beta^* = 30$ cm) [13] and Nominal Beam Sigma

Element	Collimator Setting	Beam Sigma
TCDQA.A4L6.B2	7.24 σ	0.51 mm
TCSP.A4L6.B2	7.24 σ	0.53 mm
TCTPH.4R5.B2	8.5 σ	0.95 mm

Test 2: TCDQ Retracted and 3.5 σ Bump After moving the TCT out again, the IR6 absorbers TCDQ/TCSP were retracted by approximately 1 σ. The orbit bump was then increased to 3.5 σ and the emittance of the second bunch was blown-up until beam losses were observed at the TCDQ/TCSP. Again, the TCT was moved inwards, using BBA to determine the position of the beam envelope.

Measurement Results

Since the emittance blow-up is performed until the beam is scraped at the IR6 collimators, the horizontal beam envelope in IR6 $a^{\mathrm{IR6}}_{\mathrm{beam}}$ can be directly calculated as the difference between the measured resolver position of the left collimator jaw $n_{\mathrm{tcdq/tcsp}}$ and the measured horizontal position of the beam centre $x^{\mathrm{tcdq/tcsp}}_{\sigma}$:

$$a^{\mathrm{IR6}}_{\mathrm{beam}} = n_{\mathrm{tcdq/tcsp}} - x^{\mathrm{tcdq/tcsp}}_{\sigma}. \tag{1}$$

Here, all values are expressed in units of local beam sigma. Since the beam is scraped at the innermost collimator, the value $a^{\mathrm{IR6}}_{\mathrm{beam}}$ is calculated independently for the TCDQ as well as for the TCSP. The smaller value of the two is then used for further analysis.

To check the consistency of the measurement, the beam envelope in both IRs can be compared. For this purpose, the beam envelope in IR5 $a^{\mathrm{IR5}}_{\mathrm{beam}}$ is calculated from the measured beam position at the TCT $x^{\mathrm{tct}}_{\sigma}$ and the end position n_{tct} of the left TCT jaw after the BBA: $a^{\mathrm{IR5}}_{\mathrm{beam}} = n_{\mathrm{tct}} - x^{\mathrm{tct}}_{\sigma}$.

The results are summarised in Table 2. For the comparison, it was assumed that the beam is scraped at the IR6 collimator that is closer to the beam, i.e. the TCSP for Test 1 and the TCDQ for Test 2.

Table 2: Comparison of the Measured Beam Envelope at the TCDQ/TCSP in IR6 and at the TCT in IR5

Beam Envelope (at Element)	Test 1	Test 2
$a^{\mathrm{IR6}}_{\mathrm{beam}}$(TCDQ)	$(4.80 \pm 0.24)\ \sigma$	$(4.58 \pm 0.25)\ \sigma$
$a^{\mathrm{IR6}}_{\mathrm{beam}}$(TCSP)	$(4.64 \pm 0.08)\ \sigma$	$(4.76 \pm 0.09)\ \sigma$
$a^{\mathrm{IR5}}_{\mathrm{beam}}$(TCT)	$(4.61 \pm 0.06)\ \sigma$	$(4.63 \pm 0.06)\ \sigma$
$a^{\mathrm{IR6}}_{\mathrm{beam}} - a^{\mathrm{IR5}}_{\mathrm{beam}}$	$(0.03 \pm 0.14)\ \sigma$	$(-0.05 \pm 0.31)\ \sigma$

The uncertainty of the beam-envelope measurement is given by the sum of the uncertainties from the corresponding BPM readings and collimator positions. The uncertainty of the DOROS BPMs was estimated to be ±10 µm ± 1 % of the beam offset from the centre [14]. The collimator alignment tolerances were assumed to be ±20 µm for the 1 m long TCSP and TCT jaws and ±100 µm for the 9 m long TCDQ.

For both tests, the measured beam envelope at the TCT in IR5 agrees very well with the measurement in IR6. The deviations are 0.03 σ and -0.05 σ and thus clearly lie within the expected uncertainties.

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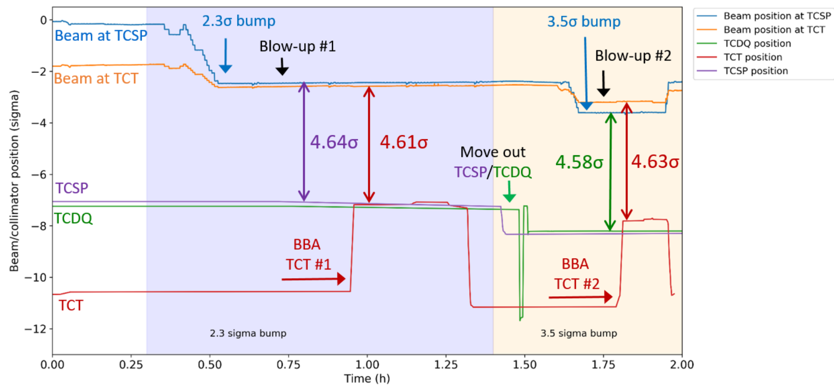

Figure 2: Overview of measured beam and collimator positions in local beam sigma during the two beam tests. The measured beam envelopes at the TCDQ/TCSP and at the TCT, as summarised in Table 2, are indicated with arrows.

Finally, to verify the correct retraction margin, the expected position $n_{\mathrm{tct}}^{\mathrm{expec}}$ where the left TCT jaw should encounter the beam is calculated. It is given by the sum of the beam centre position as computed with MAD-X $x_{\sigma}^{\mathrm{tct,madx}}$ and the beam envelope as measured in IR6:

$$n_{\mathrm{tct}}^{\mathrm{expec}} = x_{\sigma}^{\mathrm{tct,madx}} + a_{\mathrm{beam}}^{\mathrm{IR6}}. \qquad (2)$$

Note that this procedure, in contrast to the consistency check presented in Table 2, is sensitive to a variation in the phase advance or to a beam centre offset at the TCT, and therefore suited to validate the retraction margin.

The expected and measured TCT positions for the two tests are compared in Table 3. The uncertainty of $n_{\mathrm{tct}}^{\mathrm{expec}}$ is directly given by the uncertainty of the beam envelope measurement in IR6 (see Table 2). The uncertainty of $n_{\mathrm{tct}}^{\mathrm{meas}}$ is derived from the assumed alignment tolerances as discussed above. The expected and measured positions agree very well for both tests and only differ by -0.07 σ and 0.1 σ, respectively. The tested method is, therefore, suited to validate the retraction margin with sufficient accuracy.

Table 3: Comparison of Expected Position of the Beam Envelope at the TCT $n_{\mathrm{tct}}^{\mathrm{expec}}$ and Measured TCT Position During BBA $n_{\mathrm{tct}}^{\mathrm{meas}}$

TCT Position	Test 1	Test 2
$n_{\mathrm{tct}}^{\mathrm{expec}}$	$(-7.25 \pm 0.08)\ \sigma$	$(-7.72 \pm 0.22)\ \sigma$
$n_{\mathrm{tct}}^{\mathrm{meas}}$	$(-7.18 \pm 0.02)\ \sigma$	$(-7.82 \pm 0.02)\ \sigma$
$n_{\mathrm{tct}}^{\mathrm{expec}} - n_{\mathrm{tct}}^{\mathrm{meas}}$	$(-0.07 \pm 0.1)\ \sigma$	$(0.10 \pm 0.24)\ \sigma$

USE OF THE METHOD FOR MACHINE PROTECTION

During Run 2 of the LHC (2015-2018), new collimator settings with reduced margins between TCDQ and TCTs allowed reducing β^* below its design value [6], which contributed significantly to surpass the LHC design luminosity. The tighter TCT settings required constraining the acceptable phase advance between MKDs and TCTs [6, 15].

During the upcoming Run 3, the bunch intensity will be increased up to 1.8×10^{11} protons, increasing the importance of the asynchronous beam dump failure case and the risk of damaging a TCT. Therefore, we propose to validate the relative alignment and the phase advance between TCSP and the TCTs with the new method. This is complementary to the routinely performed asynchronous beam dump tests.

For increased operational flexibility, the two main elements of the method, i.e. the use of a long orbit bump as well as the direct aperture measurement with BBA, can be decoupled and used at different times.

It is proposed that during a regular collimator alignment campaign, an additional BBA measurement would be used to validate directly the relative alignment between TCSP and TCTs, in addition to measuring the alignment of both TCSP and TCT with respect to the TCPs in IR7. This measurement could be performed with the nominal beam orbit.

Separately, the long orbit bump can be used to determine the phase advance between the MKDs and the TCTs by directly measuring the observed orbit change at the DOROS BPMs at the TCTs. This refined procedure could, in principle, be used for both beams. It would not require moving the TCTs, and includes the option to maintain the bump during parts of a cycle to validate more than one configuration during a test fill with low-intensity beam.

CONCLUSIONS

A new method to measure aperture margins between the IR6 absorbers and the tertiary collimators in IR5 has been successfully tested with Beam 2 of the LHC. The operational margin was experimentally validated for two different collimator settings within a deviation of 0.1 σ from the expected value. Based on the achieved results, a refined validation method for operational use is proposed.

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