ANGULAR ALIGNMENT OF THE LHC INJECTION PROTECTION STOPPER

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Abstract

Machine safety depends critically on the correct setup of the protection elements. One of the injection protection elements consists of exceptionally long jaws (4 m). An angular offset of the jaws could affect significantly the measured beam size and, as a consequence, the correct setup with respect to the beam. Dedicated studies and cross-calibrations have been performed to quantify the effect of tilts and offsets on the setup of this stopper and to check the provided passive protection.

INTRODUCTION

Nominal LHC operation foresees the injection of up to 288 bunches of $1.15{\cdot}10^{11}$ protons at a time. The injection into the LHC takes place in point 2 (IP 2) for Beam 1 and 8 (IP 8) for Beam 2. A system of four injection kickers (MKI) deflects the beams coming from the transfer lines (TI 2 and TI 8) vertically on the machine central orbit.

Injection kicker failures can happen a few times per year. The MKIs can either fail to kick or fire erratically when not required. In the first case the injected beam is not deflected onto the LHC closed orbit, while in the second case the circulating beam can be kicked by mistake. The kickers can also experience high voltage breakdowns which can give a kick of any amplitude, for the firing kicker magnet, of up to twice the nominal one.

To protect against these incidents one beam stopper (TDI) per IP is installed at a phase advance of 90° downstream of the MKI to intercept any mis-kicked beam and shield the machine aperture.

THE TDI BEAM STOPPER

The TDI is a vertical collimator and consists of two jaws (upper and lower) with a length L_{TDI} of 4 m, made up of different materials (hBN, Al, Cu) [1]. The TDI jaws are designed to withstand the impact of 288 bunches, to stop the primary beams and absorb part of the induced showers of secondary particles in order to reduce the energy deposition onto the downstream elements.

The opening of the TDI is chosen as a function of the available machine aperture. At injection, an aperture limitation of $\pm 7.5\ \sigma$ in the arcs was assumed by design [2] and, as a consequence, a TDI half-gap of 6.8 σ (nominally $1\ \sigma = 0.57$ mm at the TDI) was chosen.

An aperture of 12.5 σ was measured in the LHC [3]. The available aperture is then calculated subtracting the tolerances for orbit bumps, injection oscillations, β-beat and TDI jaws setup accuracy from the measured aperture (see values in Table1). A gain of 0.5 σ and 2 σ is found, compared to the nominal design aperture, for the injected and the circulating beam, respectively. It was however decided to keep the TDI at the nominal setting to gain some margin for operation and setup accuracy and increase the protection.

Table 1: Parameters used to calculate the available machine aperture (in σ units). The different values have been defined according to operational experience.

	Inj. beam	Circ. beam
Design aperture	7.5	7.5
TDI half-gap	6.8	6.8
Measured aperture	12.5	12.5
Orbit bumps	1.5	1.5
Inj. oscillations	1.5	0
β-beat	0.5	0.5
Position accuracy	0.2	0.2
Angle accuracy	0.8	0.8
Available aperture	8	9.5

TDI SETUP

The TDI is the only defense in case of MKI failure; a bad setup could have serious consequences. In order to provide the required machine protection the TDI jaws have to be precisely centered with respect to the beam axis and aligned parallel to the beam envelope.

A critical point is the angular adjustment: an effective angle of 1 mrad results in an offset of 4 mm (7 σ!) between the two jaw ends. This reduces significantly the amount of material crossed by the beam and thus the stopping power of the TDI in case of kicker failures.

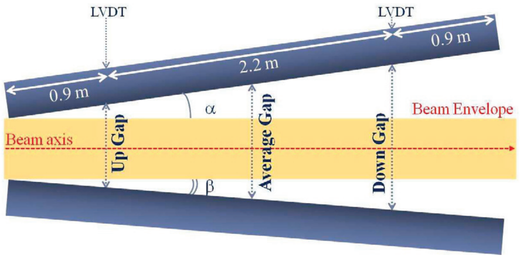

Figure 1: Schematic view of the upper and lower TDI jaws in case of a positive angle (for both jaws) with respect to the beam envelope.

At injection the LHC collimators are set up using the beam size measured with respect to the beam edge defined by the primary collimators (n_{TCP}) [4]. The measured half-gap (HG_{meas}) is determined by the average of two LVDT position sensors located at 0.9 m from the jaw extremities (Fig. 1). An angle α varies the measured beam size (σ_{meas}) with respect to the case of a parallel jaw ($HG_{\parallel}$) by:

$$\sigma_{meas} = \frac{HG_{meas}}{n_{TCP}} = \frac{HG_{\parallel}}{n_{TCP}} \pm \frac{0.5 \cdot L_{TDI} \cdot \sin\alpha}{n_{TCP}}. \quad (1)$$

A wrong σ_{meas} affects the opening of the TDI and the protection of the arc aperture.

ANGULAR TDI ALIGNMENT

The method used to define the jaw angle consists in applying a tilt and close the jaw in steps until the circulating beam is fully scraped. The beam centre is defined as the average between the up and downstream corner position, taking into account the applied angle and the LVDT distance from the jaw corners (Fig. 1), corresponding to the beam losses at the TDI going to zero. The measurement is repeated for different tilts; the angle for which the jaw can be closed farthest into the beam (minimum beam centre for upper jaw and maximum beam centre for lower jaw) defines the real parallel position.

These measurements assume a possible error in the LVDT calibration; this is a well known issue for the TDI. Different beam centres can also be found for the two jaws if the LVDTs show an offset.

Angular Scan Results

The measurements were carried out using a pilot bunch (10^{10} protons), varying the applied angle from +1 mrad to -1 mrad (hardware limit) in 0.5 mrad steps and closing each jaw in steps of 150 μm.

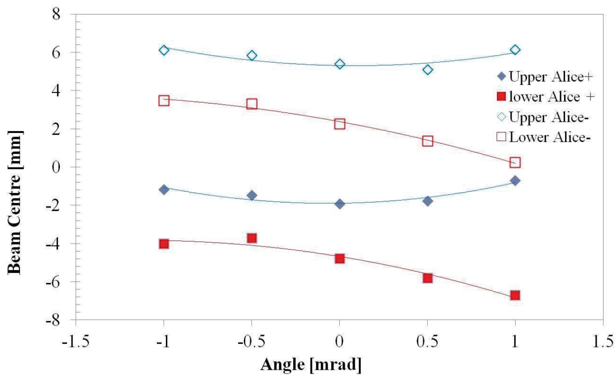

Figure 2: Results of angular scans performed for the TDI in IP 2 with different polarities of the vertical crossing angle in ALICE.

Several TDI angular scans were carried out over the last two years of the LHC operation. A first alignment was performed for the TDI in IP 2 and IP 8 at the beginning of the 2011 run (see results in Table 2).

Some months later it was decided to flip the polarity of the crossing angle in ALICE from positive to negative (MAD-X convention). The vertical orbit bump which is used to create this crossing angle starts ~95 m before the TDI and corresponds to a ~40 μrad beam angle at the TDI; a new angular alignment was performed in IP 2.

The results of these measurements are presented in Fig. 2. As expected, the beam centre is shifted by ~7 mm from negative to positive coordinates. New angles of 86 μrad and -1 mrad were measured for the upper and lower jaws, respectively.

The two TDI jaws show a systematic difference in the beam centre confirming the presence of an offset in the LVDT readouts.

Two new scans were made in 2012 (see Table 2). The first scan was part of the standard machine recommissioning after the winter technical stop.

Table 2: Results (in mrad) of angular scans performed over the last two years of the LHC operation.

	Beam 1		Beam 2	
	Upper	Lower	Upper	Lower
2011	-0.070	-0.750	-0.191	-0.111
2012	0.066	-0.750	-0.167	-0.136
2012 Def. check	-0.058	-1.000	-0.209	-0.226

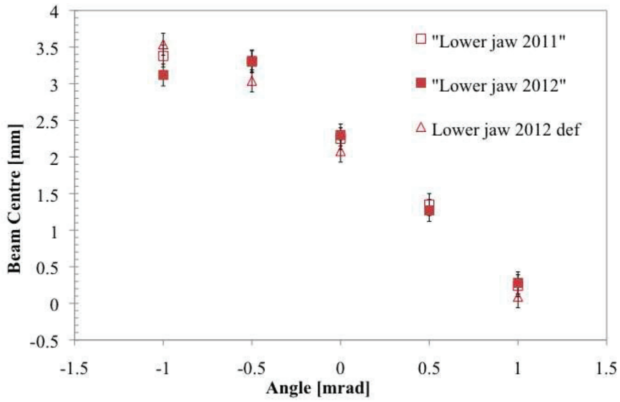

Figure 3: Results of angular scans performed over the last two years for the lower jaw of the TDI in IP 2.

After a long physics fill with 1380 bunches, it was observed that the LVDTs were drifting outside the jaw position interlock limits [5]. This behavior is caused by a temporary jaw deformation which is induced by heating due to the high intensity beams (presumably driven by excitation of higher order modes [6]). An angular scan was done to check a potential change produced by the jaw warmup. The measured angles (see Table 2, 2012 Def. check) show variations of the order of 100 μrad which is the estimated

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accuracy measurement.

The measurements show a good reproducibility in time (an example in Fig. 3, case with the largest angle variation). The error on the beam centre position depends on the alignment step size (150 μm) and the LVDT accuracy ($\pm$10 μm). The beam size measured after applying the defined angles agrees with the nominal values within few percent. This proves the reliability of the method used to measure the jaw angle with respect to the beam.

MACHINE PROTECTION VALIDATION TESTS

Once the TDI settings are defined according to the measured beam centre position and jaw angle, dedicated tests are performed to validate the system and prove that it is providing the needed protection.

The protection against MKI failures is verified injecting pilot intensity and using a knob which simulates MKI kicks with a strength different from nominal. The maximum amplitudes of the escaping particles should be below 7.5 σ and no primary beam loss should occur anywhere else but on the injection protection devices.

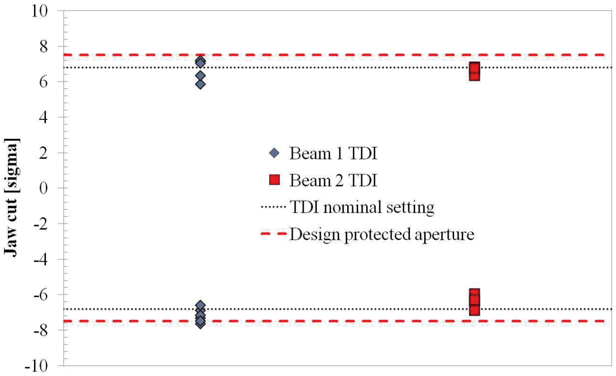

Figure 4: Results of machine protection validation tests for the 2012 TDI settings.

The measurements were done varying the kick amplitude from 0 to $\pm$10 σ.

A numerical algorithm combines the kick amplitude with the beam loss at the TDI and allows the calculation of the amplitude which is cut by the TDI jaws. The results of the validation tests performed for the 2012 settings are shown in Fig. 4. The points on the graph represent the real cut provided by the TDI jaws while the dotted and the dashed lines define the nominal TDI setting and the aperture to protect, respectively. The measurements confirm the required protection level.

Three major MKI failures (two in 2011 and one in 2012) occurred over the last two years of the LHC operation [7]. In all cases some of the mis-kicked beam grazed the TDI with the result that a few superconducting magnets quenched. Quenches in case of injection failure are expected and not critical: the machine fully recovers in 2-4 hours.

As a consequence of one of these events (2011), the Silicon Drift Detector (SDD) of ALICE suffered permanent effects since it was not in a fully safe state during the beam injection. In addition three higher order field corrector circuits in the IP 2 inner triplet were affected [8]. Studies are ongoing to understand if the circuits were damaged due to the beam impact or as a consequence of the magnet quench.

CONCLUSIONS

The TDI absorber provides the only protection in case of injection failure and has therefore to be precisely set up. The angular alignment is particularly critical due to the length of the jaws and the small beam size at this element. A dedicated method has been defined for measuring the TDI jaw angles with an accuracy of 100 μrad. Several measurements have been performed over the last two years of the LHC operation showing good reproducibility.

Machine protection validation checks confirmed the correct setup of the TDI and the assurance of the required aperture shading. Also during operation the TDI proved to protect the arc magnets in case of MKI failure. Studies are ongoing to understand the energy deposition in the experimental regions downstream of the injection points.

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