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Research Article

## Operational Results with Fast Automatic Beam-Based LHC Collimator Alignment

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**Abstract.** The CERN Large Hadron Collider (LHC) is the largest and highest-energy particle accelerator ever built. It is designed to collide particles at a centre-of-mass energy of 14 TeV to explore the fundamental forces and constituents of matter. Due to the potentially destructive high-energy particle beams, with a total design energy of 362 MJ, the collider is equipped with a series of machine protection systems. The beam cleaning or collimation system is designed to passively intercept and absorb particles at large amplitudes. The cleaning efficiency depends heavily on the accurate positioning of the jaws with respect to the beam trajectory. Beam-based collimator alignment is currently the only feasible technique that can be used to determine the beam centre and beam size at the collimator locations. If the alignment is performed without any automation, it can require up to 30 hours to complete for all collimators. This reduces the beam time available for physics experiments. This article provides a brief recap of the algorithms and software developed to automate and speed up the alignment procedure, and presents the operational results achieved with fast automatic beam-based alignment in the 2011-2013 LHC runs.

**Keywords** Large Hadron Collider - Collimation system - Collimator alignment - Intelligent automation - Operational results.

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## 1 Introduction

The LHC at CERN is a 27 km long, state-of-the-art circular particle collider (Brüning *et al.* 2004). The injector chain accelerates protons or heavy ions from rest to a relativistic energy of 450 GeV, before injecting them in two counter-rotating beams into the LHC. After a further acceleration to the design energy of 7 TeV in the LHC (4 TeV in 2012), the particles in the two beams are brought in collisions at the locations of the four experimental detectors.

A complex beam cleaning system is installed to passively scatter and absorb particles which deviate from the beam core, before they are deposited in the superconducting magnets, thus protecting the LHC against normal and abnormal beam losses (Assmann *et al.* 2002). There are 54 beam-cleaning devices, called collimators, per beam. Each collimator is made up of two blocks or ‘jaws’ of carbon, tungsten or copper material. The jaws, identified conventionally as ‘left’ and ‘right’, are housed in a tank and kept under vacuum. The transverse rotation of the collimators follows a clockwise coordinate system, where the zero angle lies along the x-axis. Hence, for a vertical collimator, the ‘left’ jaw would be positioned above the beam, and the ‘right’ jaw would lie below the beam. The four jaw corners can be moved individually using stepping motors, with a precision of 5  $\mu\text{m}$ . The maximum movement speed is 2 mm/s (Masi and Losito, 2008).

The collimators are distributed in the LHC ring as illustrated in Fig.(1). The collider has an eight-fold symmetry. Arcs connect eight long straight sections or insertion regions (IRs), and at the centre of each IR lies an interaction point (IP). Focusing and defocusing quadrupole magnets are used to ensure that particles

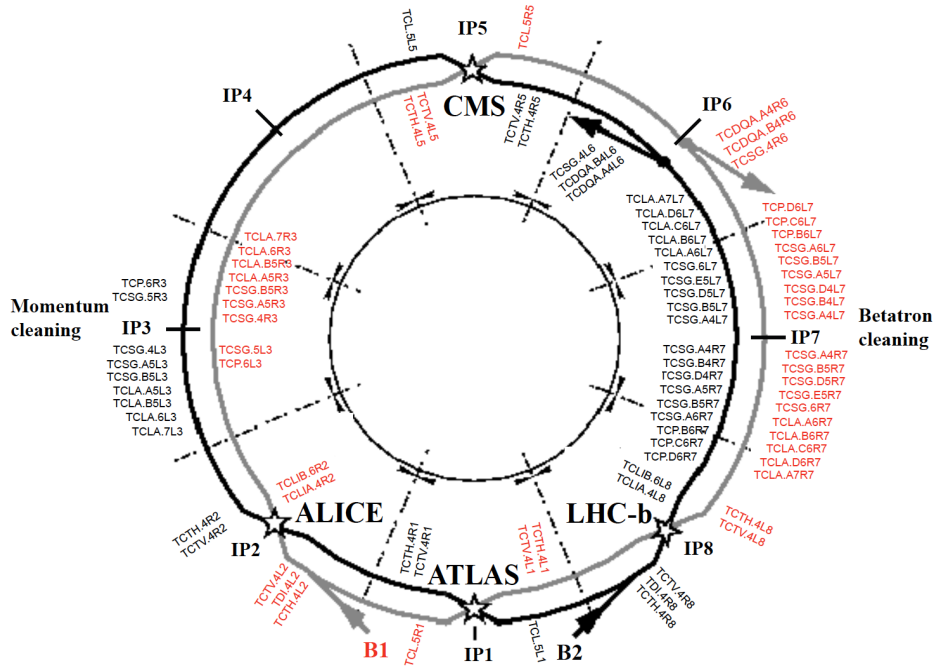


Figure 1: LHC collimation system layout (Bracco, 2009). The majority of the collimators are located in IR3 for momentum offset cleaning, and IR7 for betatron offset cleaning.

remain confined along the design orbit, and this causes them to perform so-called betatron oscillations around the design orbit. In addition, the particles have a certain momentum spread, and hence circulate in different orbits around the design orbit. The majority of the collimators are located in IR3 and IR7 to clean particles with large momentum and betatron offsets respectively. Dedicated collimation insertions are required due to space and radiation constraints, with the remaining IRs being taken up the experimental detectors, RF cavities and beam dump system.

The collimators are arranged in a four-stage hierarchy to reach the required level of cleaning efficiency, defined as the fraction of particles that escapes the collimators and are lost locally at any ring location. A graphical representation of the collimator hierarchy is shown in Fig.(2). The primary collimator (TCP) jaws are placed tightest around the beam, followed by the secondary collimators (TCSG), tertiary collimators (TCT) and absorbers (TCLA). The cleaning is carried out over hundreds of turns, and is hence referred to as multi-turn, multi-stage beam cleaning.

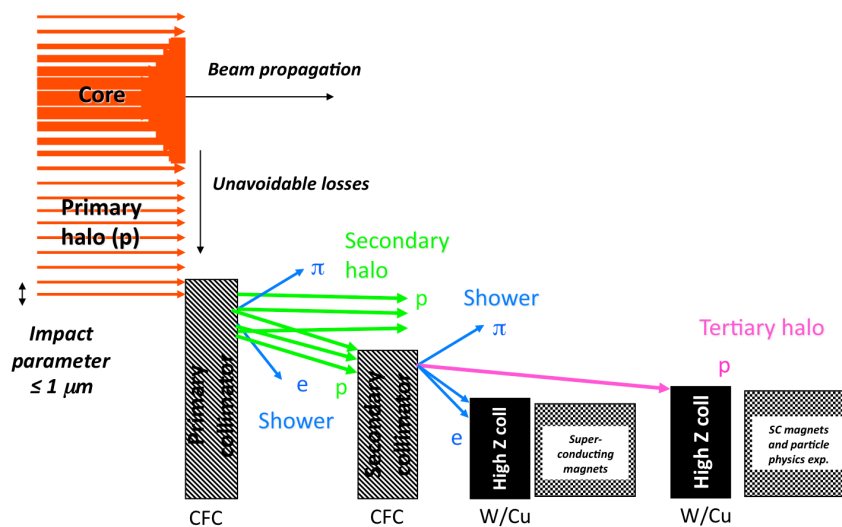


Figure 2: LHC multi-stage beam cleaning (Assmann, 2010). The primary halo is scattered by the TCPs. The secondary shower leaving the primary collimators is then scattered further by secondary TCSG and tertiary TCT collimators, until it is absorbed by TCLAs.

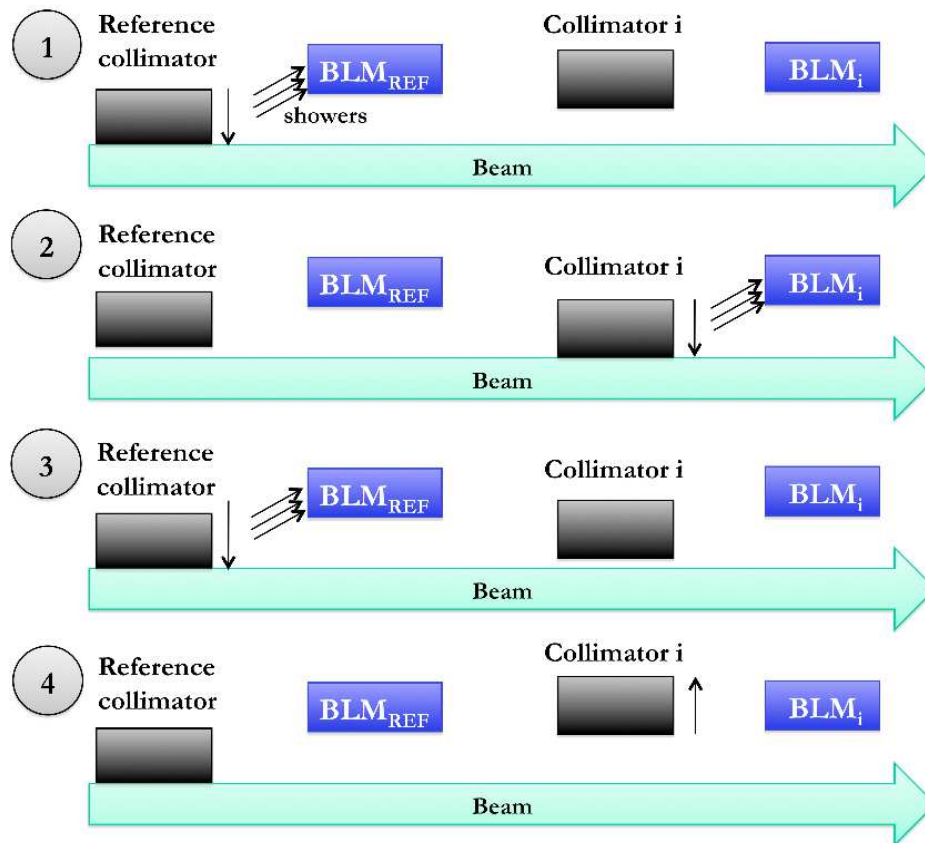


Figure 3: The four-stage beam-based alignment sequence for collimator  $i$ , using a primary collimator as a reference (Wollmann *et al.* 2010). A single jaw is shown for simplicity.

Beam losses in the LHC are measured using ionization chamber Beam Loss Monitors (BLMs) (Dehning, 2007). The approximately 3600 BLMs are placed at strategic points all around the collider, such as near the superconducting magnets, with some being positioned a few metres downstream of the collimators. A total of 1032 Beam Position Monitors (BPMs) measure the beam orbit in the horizontal and vertical planes at various positions around the ring (Jones, 2007), although often not close to the collimator locations.

The collimation hierarchy only be set up if the beam centre and beam size at the collimator locations is known. Beam-based collimator alignment is currently the only feasible technique that can be used to determine these parameters. The alignment procedure consists of moving both jaws of a collimator towards the beam, until they touch the beam halo and induce beam losses. This stage is reached when a characteristic spike is observed in the beam losses picked up by a BLM positioned downstream of the collimator.

Collimator alignment was performed ‘manually’ in the CERN Control Centre during the 2010 LHC run. This means that a collimation expert is required to intervene for each jaw step of a few micrometres, using a software application to set the new jaw position. The expert must

also simultaneously observe the BLM signals to ensure that the jaw is correctly aligned to the beam. For these reasons, a software tool was built to automate and speed up the alignment, and was used in the 2011-2013 LHC runs.

This paper is organized as follows. The collimator beam-based alignment procedure and the algorithms and software developed to automate it and speed it up are described in Sections II and III. The operational results achieved in the 2011-2013 LHC run are presented in Section IV, together with a comparison to the alignment results achieved in the previous run.

## 2 Collimator Beam-Based Alignment

Collimator alignments are part-and-parcel of the beam-commissioning period held at the start of each year of LHC operation. They are also performed throughout the year whenever the orbit and optics configuration parameters at the experimental IPs are changed, such as the beam crossing angles and  $\beta$ -functions at the experimental points (known as the  $\beta^*$ ), as well as for dedicated beam studies and the so-called Van der Meer scans (White *et al.* 2010).

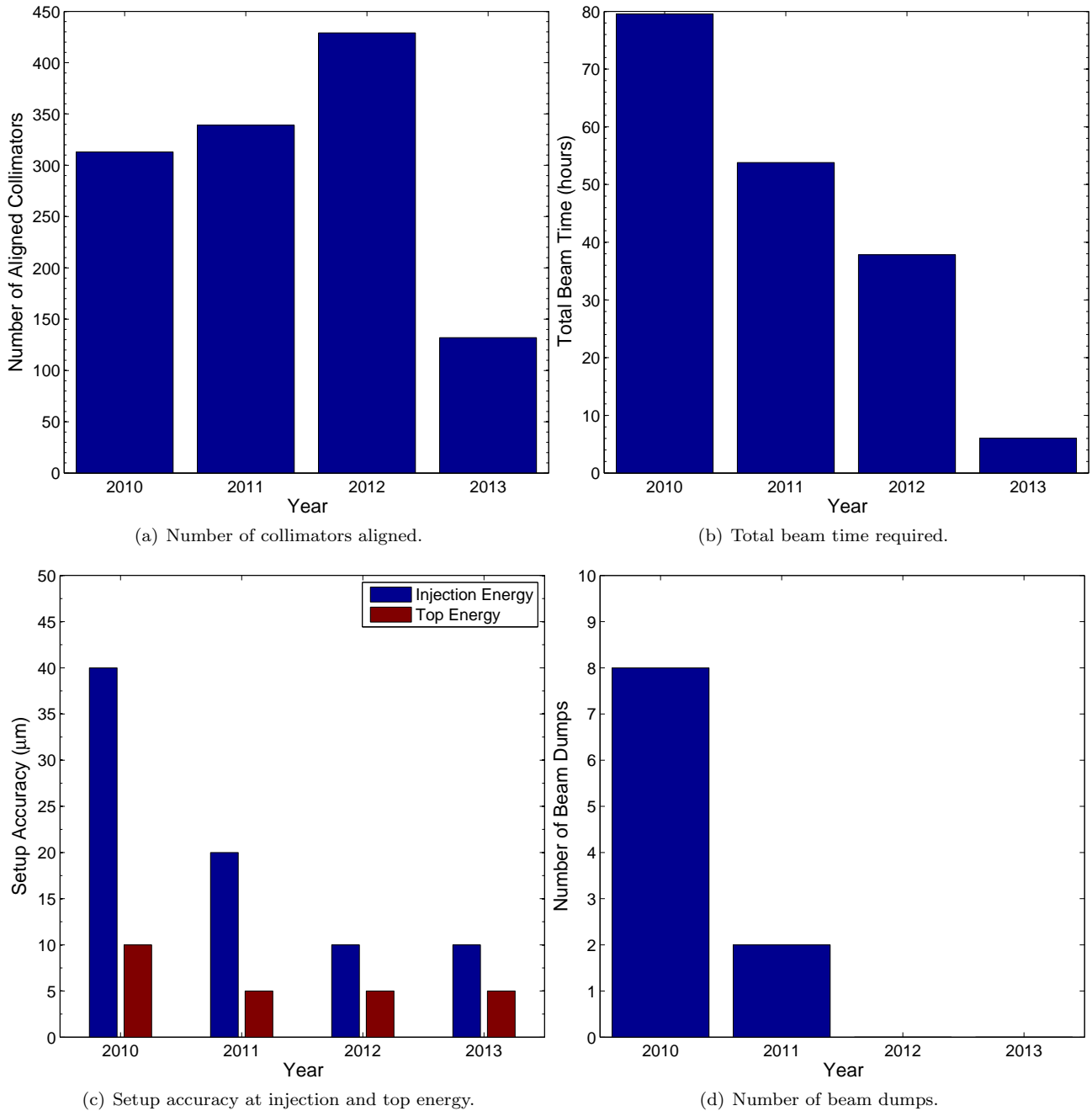


Figure 4: Collimator alignment statistics.

The collimators are aligned in a four-step procedure, which is illustrated in Fig.(3). Only one jaw is shown for simplicity. The jaw of a reference collimator is moved in steps towards the beam to make a reference cut in the beam (step 1). The reference collimator is normally taken to be the TCP in the same plane (horizontal, vertical or skew) as the collimator  $i$ .

A BLM signal spike can be attributed to a particular jaw movement if only that jaw was moving when the spike occurs. Therefore, the left and right jaws are

moved towards the beam separately. After aligning the reference collimator, the same procedure is performed for the collimator  $i$  (step 2) and the reference collimator is aligned once again (step 3). The beam centre  $\Delta x_i$  can then be determined from the final jaw positions of collimator  $i$ :

$$\Delta x_i = \frac{x_i^{L,m} + x_i^{R,m}}{2} \quad (1)$$

where  $x_i^{L,m}$  and  $x_i^{R,m}$  are the measured left and right jaw positions. The measured beam size at collimator  $i$ ,

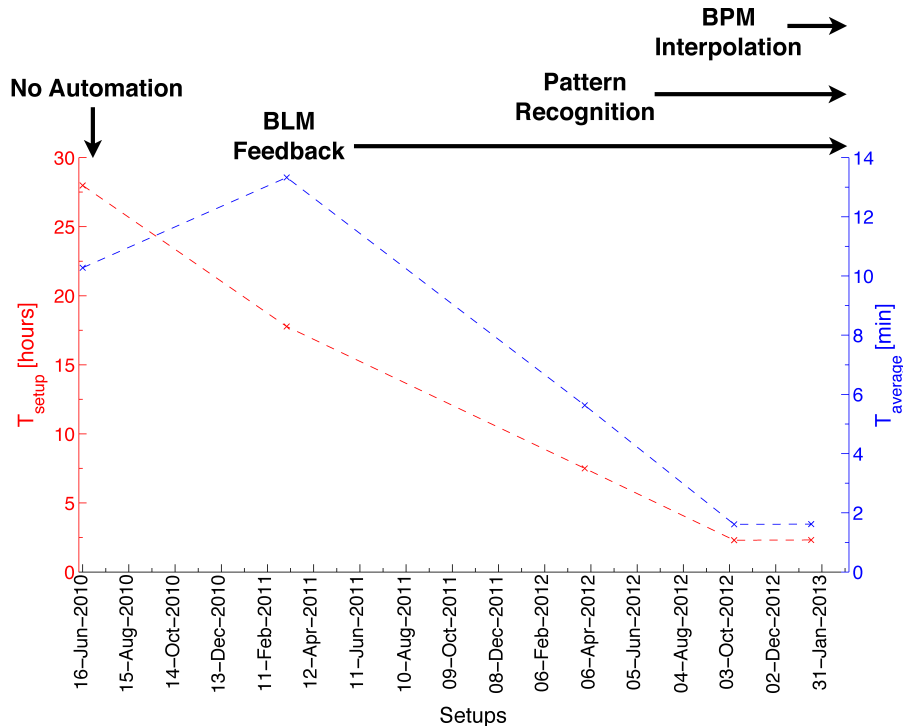


Figure 5: Evolution of the total setup time and average setup time per collimator at flat top in the 2010-2013 LHC runs. A timeline showing the introduction of the various algorithms is super-imposed.

$\sigma_i$ , is expressed as a function of the jaw half gap, with  $n_1$  being the cut made by the reference collimator in units of nominal beam standard deviations or  $\sigma$ :

$$\Delta x_i = \frac{x_i^{L,m} - x_i^{R,m}}{2n_1} \quad (2)$$

The nominal  $1\sigma$  beam size at each collimator is determined from the nominal geometrical emittance  $\varepsilon$ , the nominal beta functions  $\beta_{x,i}$  and  $\beta_{y,i}$  at the collimator  $i$ , and the rotation angle of the collimator jaws  $\psi_i$ :

$$\sigma_i^{nom} = \sqrt{\beta_{x,i}\varepsilon_x \cos^2 \psi_i + \beta_{y,i}\varepsilon_y \sin^2 \psi_i} \quad (3)$$

In step 4, the left and right jaws are set to the operational settings, with  $N_i$  being the half-gap opening specific to a collimator family:

$$x_i^{L,set} = \Delta x_i + N_i \sigma_i \quad (4)$$

$$x_i^{R,set} = \Delta x_i - N_i \sigma_i \quad (5)$$

### 3 Alignment Software

Over the 2010 - 2012 LHC runs, algorithms were developed and introduced in stages to speed up and automate the alignment procedure. The first step in 2011 was the introduction of a BLM feedback loop, that could allow for a single or parallelized movement of collimator jaws in steps towards the beam, until the losses exceeded a pre-defined BLM stopping threshold that was initially

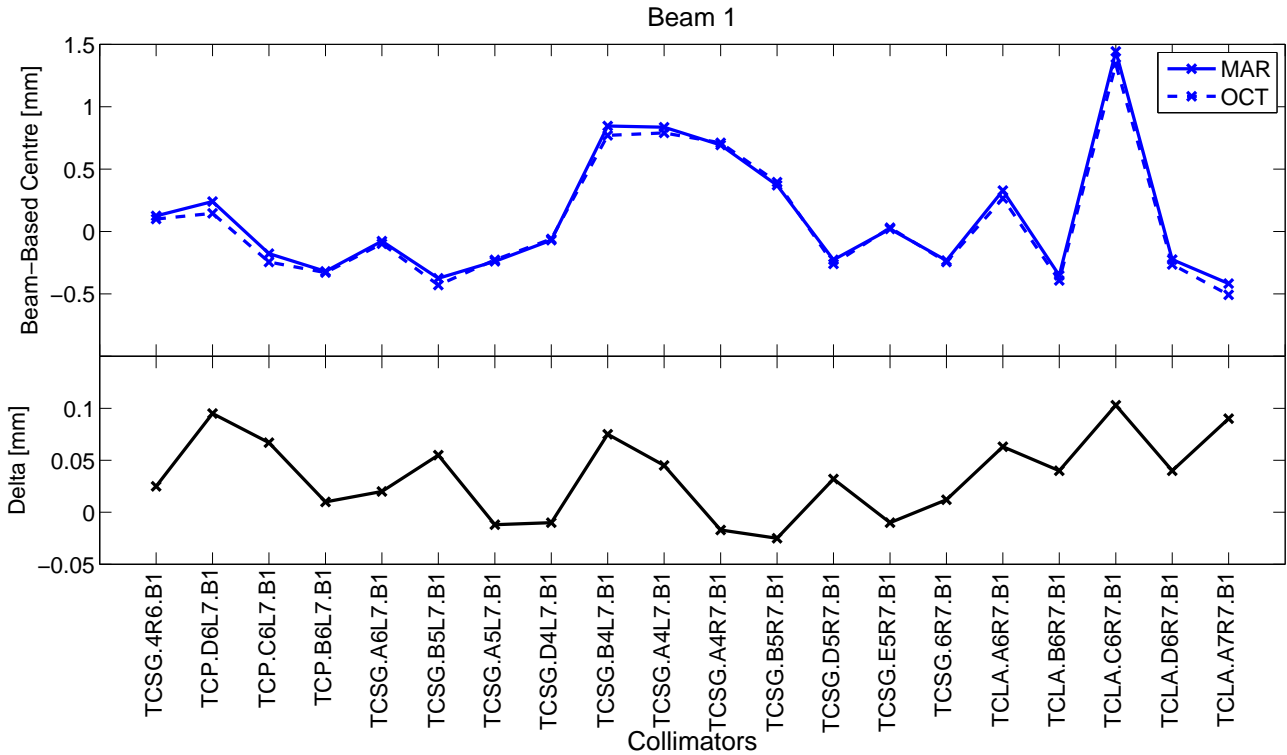
set manually (Valentino *et al.* 2012a).

For the start of the 2012 run, other improvements were introduced. Faster BLM data at a rate of 12 Hz allowed for the maximum collimator movement rate of 8 Hz to be used. Previously, the BLM feedback loop was limited by the acquisition of the BLM data at a 1 Hz frequency. Automatic selection of the BLM stopping threshold with every jaw movement reduces the need for expert intervention (Valentino *et al.* 2012b). Classification of the BLM loss signals based on Support Vector Machines (Valentino *et al.* 2012c) is used to determine whether the signal exhibits the typical loss spike and temporal decay characteristics when the threshold is exceeded, indicating that the jaw is aligned to the beam. A tool developed to centre the jaws at a safe and tighter gap around the BPM-interpolated orbit at the collimators at the start of alignment was tested in a dedicated beam study (Valentino *et al.* 2012d). These algorithms were implemented in the existing collimator control Java application (Redaelli *et al.* 2007) in the top-level of the LHC Software Architecture (LSA).

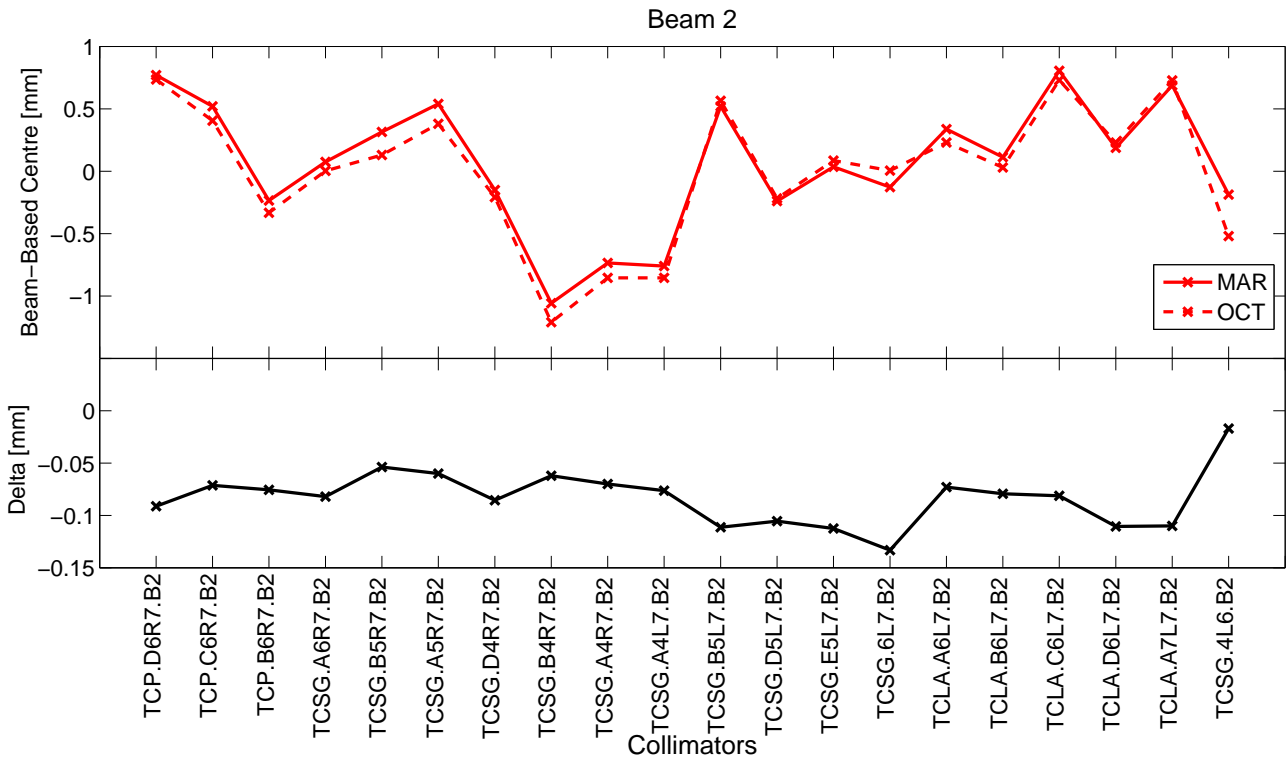
## 4 Operational Results

### 4.1 Alignment Times and Accuracy

Several highlight plots showing the collimator alignment operational results are shown in Fig.(4). The total number of collimators aligned per year has increased (see Fig.(4)(a)), while the total beam time required de-



(a) Measured B1 centres at the collimators.



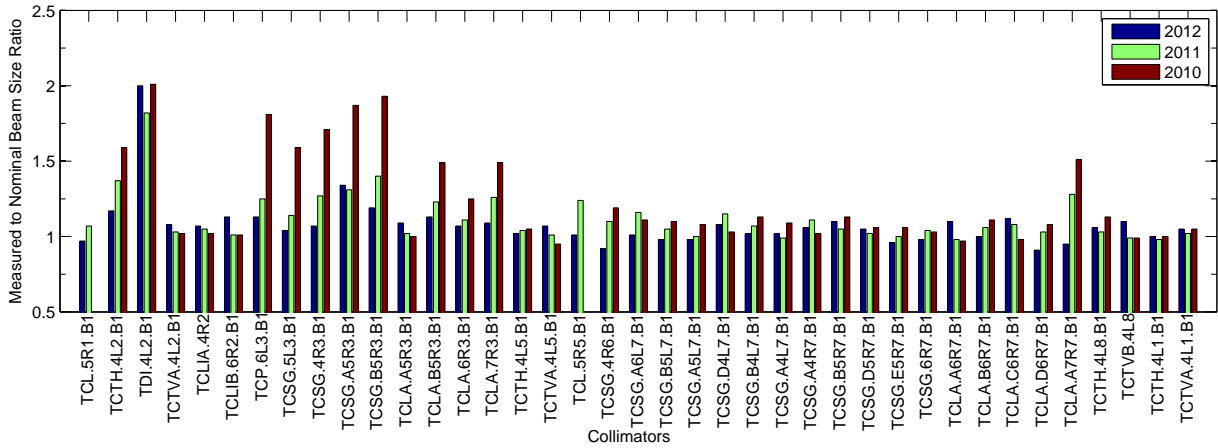
(b) Measured B2 centres at the collimators.

Figure 6: Measured beam centres comparison between March and October 2012.

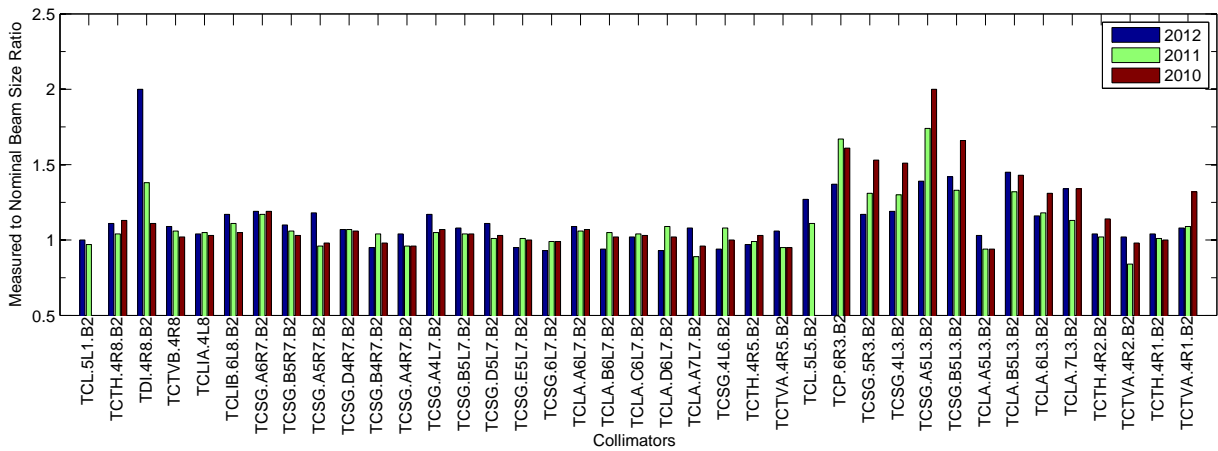
creased (see Fig.(4)(b)). The reduction in time can be attributed to the phased automation of the alignment

procedure described earlier in Section III.

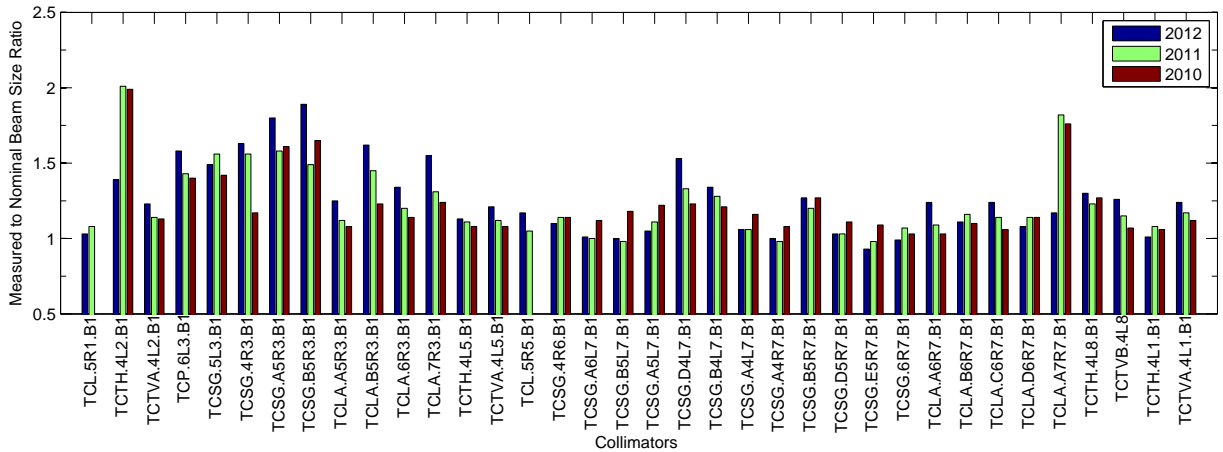
The gains in time could allow for smaller jaw step sizes



(a) B1 collimators, alignments at injection energy.



(b) B2 collimators, alignments at injection energy.



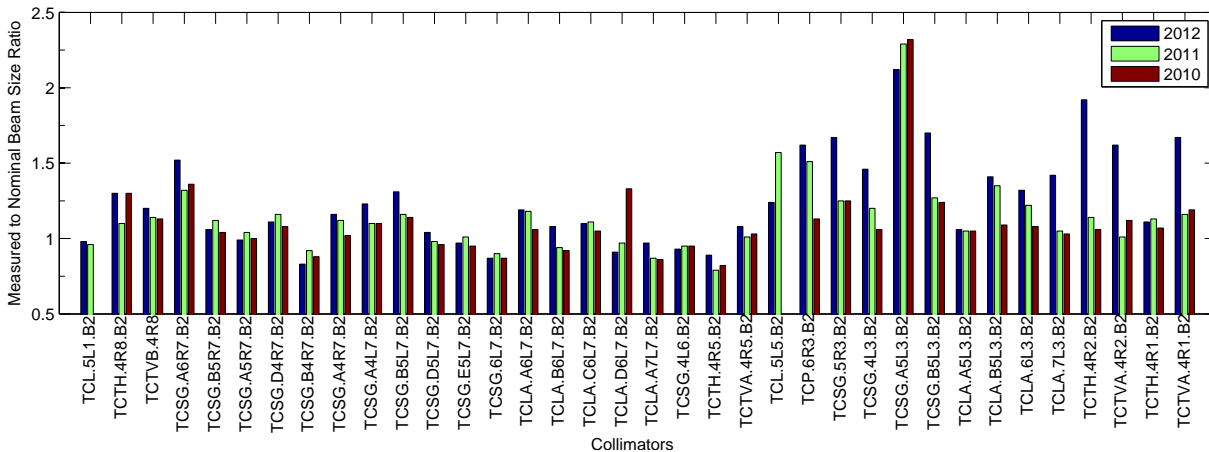
(c) B1 collimators, alignments at top energy.

to be used during the alignment (see Fig.(4)(c)). The beam size shrinks as a function of energy, meaning that a smaller step size is required to avoid over-scraping of the beam. For alignments at top energy in 2011-2013, therefore, the minimum jaw step size of 5  $\mu\text{m}$  was used.

In addition, no more beam dumps have been triggered due to human error during the alignment, as a result of the alignment automation (see Fig.(4)(d)).

The time required for individual alignments of the full system over the last four LHC runs is given in Fig.(5).





(d) B2 collimators, alignments at top energy.

Figure 7: Nominal to measured beam size ratios for each collimator in the LHC proton runs from 2010 to 2012.

A timeline is superimposed to show the contributions of the different algorithms. Recall also that the BLM data rate was increase from 1 Hz to 12 Hz for the 2012 run onwards. The setup time is observed to decrease from almost 30 hours with manual alignment in May 2010 down to less than 4 hours in a beam test held in January 2013. Similarly, the setup time per collimator decreases from 20 minutes to approximately two minutes.

## 4.2 Comparison of Measured Beam Centres and Beam Sizes

In 2012, the IR6 and IR7 collimators in both beams were aligned on two occasions: at the start of the LHC run in March, and for a beam study in October. The beam centres and beam sizes measured during the beam study were compared to the values achieved in the March alignment. The results are shown in Figs.(6, 7), where the collimator names shown on the x-axis are arranged in order of longitudinal position in the LHC.

The largest change in the beam centre is of 0.185 mm (corresponding to  $0.507\sigma$ ), with the average change being 0.043 mm ( $0.146\sigma$ ) for beam 1 (B1) and 0.089 mm ( $0.243\sigma$ ) for beam 2 (B2). The similarity in the measured values is a reflection of the excellent stability of the LHC, and is the reason why a full collimation system alignment needs to be performed only yearly.

The differences between the nominal and the measured beam sizes can indicate the accuracy of the alignment, quality of the optics correction or misalignment angles of the collimator jaws or the tanks housing the jaws themselves. However, this is true only if certain machine parameters remain constant, such as the  $\beta$ -beat, which is the error in the optical  $\beta$ -function with respect to its design value. The proximity of the measured beam size to the nominal beam size can hence be expressed as the ratio of the two parameters. Fig.(7)

shows the beam size ratios at each collimator for alignments occurring in the 2010-2012 LHC runs. The alignments were performed at injection energy (450 GeV) and top energy (3.5 TeV in 2011 and 4 TeV in 2012).

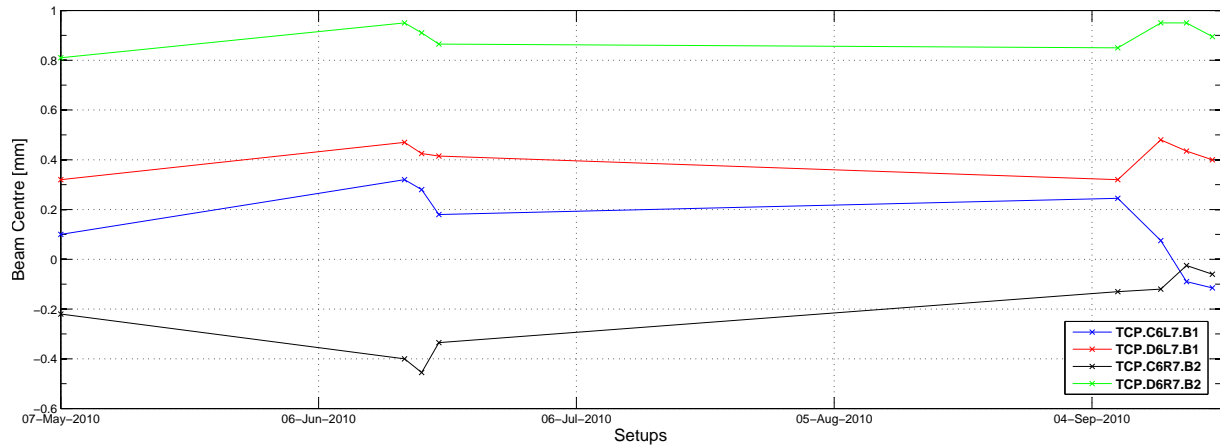
The beam size ratios in IR3 are generally larger than 1. This could be due to the fact that there is a high dispersion in IR3, which means that, independent of the alignment, the small energy errors on all particles give a significant contribution to the measured beam size. The tanks of three collimators having a larger beam size ratio than expected (TCLA.A7R7.B1, TCTH.4L2.B1 and TCSG.A5L3.B2) were re-aligned in the tunnel in after the 2011 alignments (Valentino *et al.* 2012a), and the effect on the beam size ratio is visible in the values obtained in 2012.

## 4.3 Orbit stability at the TCPs

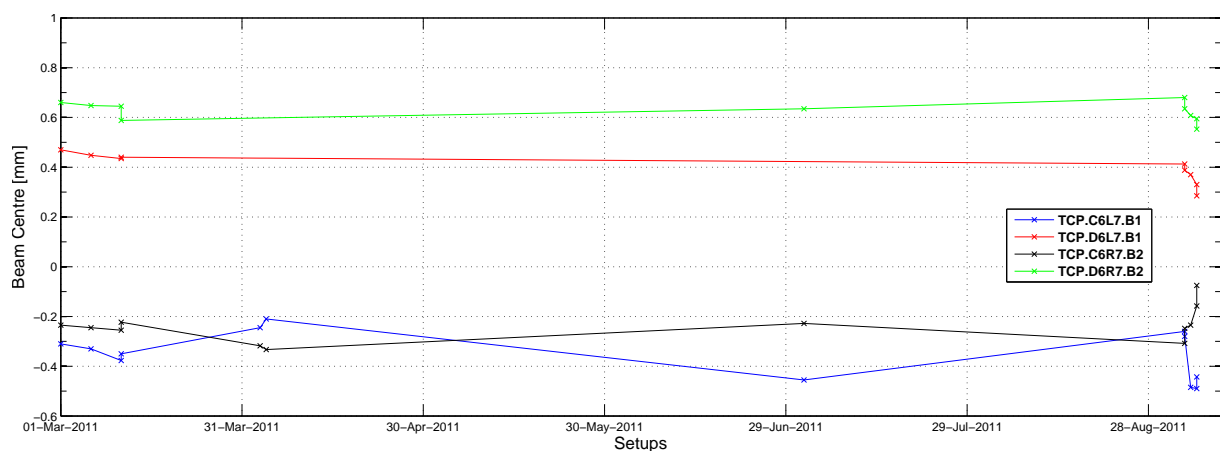
The horizontal and vertical primary collimators in IR7 are the collimators that are aligned most frequently during the year, being the reference collimators used to align other collimators. The beam centres measured at the TCPs during all alignments held in the 2010-2012 period are shown in Fig.(8). The reference beam orbit at the IR7 TCPs is not changed throughout the year, unlike in the experimental regions, and hence is expected to remain constant. However, orbit drifts can occur due to various effects, including ground motion and the ambient temperature in the tunnel (Steinhagen, 2007).

Certain patterns are noticed in the data. For example, there appear to be correlated shifts in the measured centres in one plane or one beam. This could be the effect of systematic misalignments of the quadrupole magnets over time. The variations in the orbit are of the order of a few hundred micrometers, which can be attributed to various effects described above.

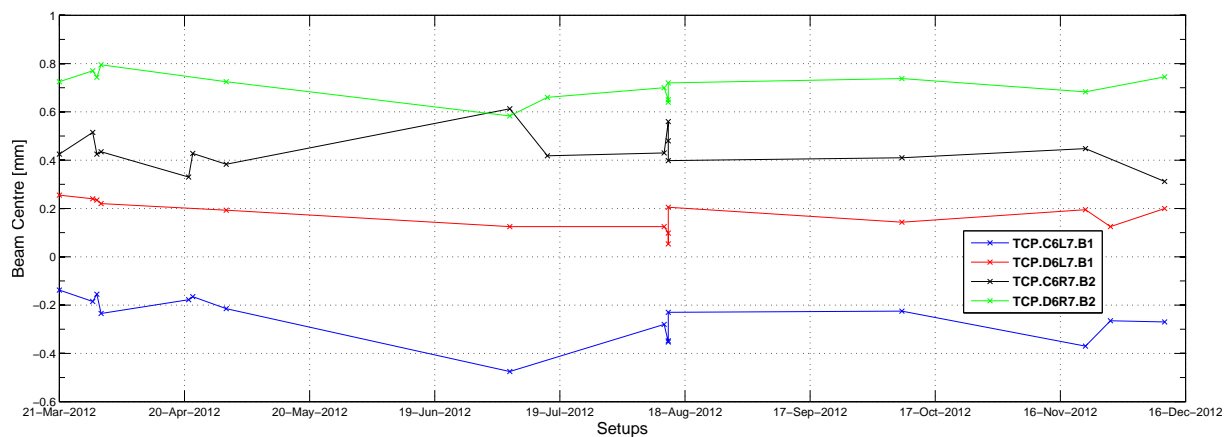




(a) TCP measured centres in the 2010 alignments.



(b) TCP measured centres in the 2011 alignments.



(c) TCP measured centres in the 2012 alignments.

Figure 8: Beam centres measured at the primary collimators in beam-based alignments from 2010 to 2012.

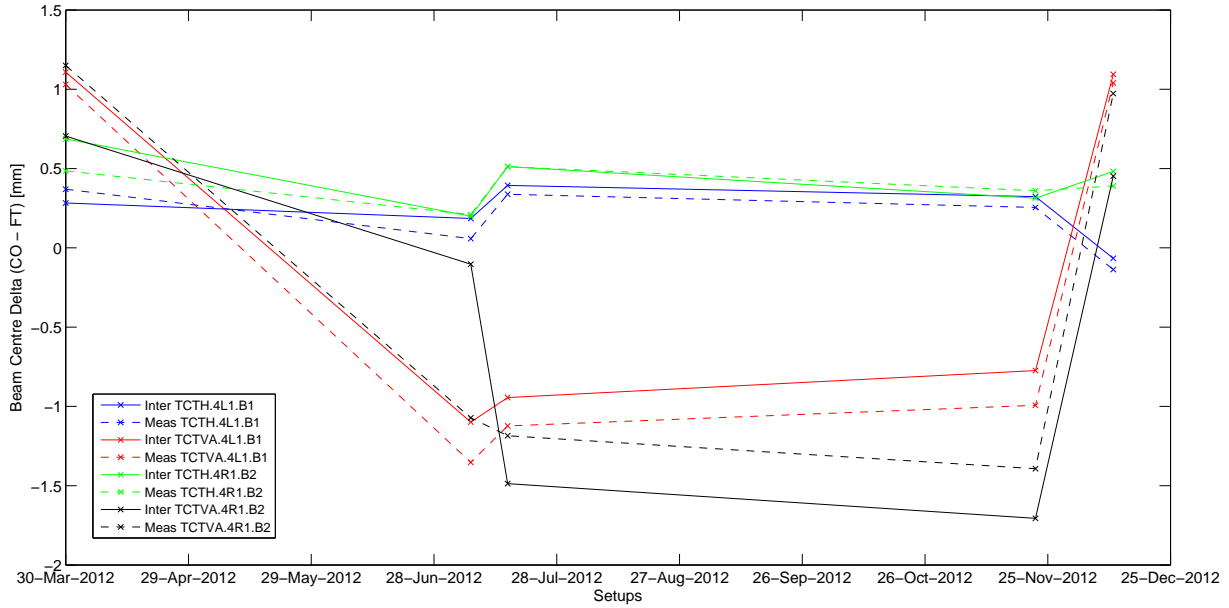
#### 4.4 Orbit changes at the TCTs

The TCTs need to be re-aligned whenever the orbit or optics configurations at the experimental IPs are

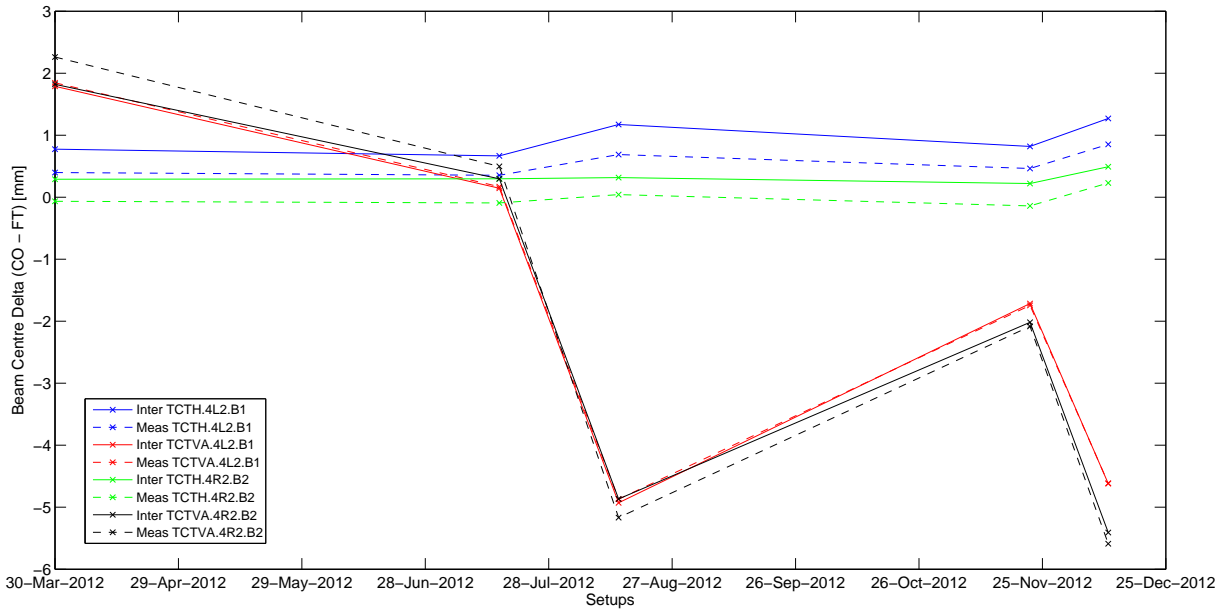
changed. Table I lists the configuration changes performed for the collisions beam process in the 2012 LHC run.

**Table 1: Configuration changes performed for the collisions beam process in the 2012 run.**

Date	Reason for Alignment	Crossing angle [ $\mu rad$ ] in IP1V / 2V / 5H / 8H / 8V	Optics [m] in IP1/2/5/8
30/03/2012	Start of run	-145 / -90 / 145 / 0 / 90	0.6 / 3.0 / 0.6 / 3.0
07/07/2012	$\beta^* = 90m$	0 / -90 / 0 / -220 / 0	90 / 10 / 90 / 10
16/07/2012	Van der Meer scans	0 / -90 / 0 / 200 / 0	11 / 10 / 11 / 10
22/11/2012	Van der Meer scans	0 / 145 / 0 / -220 / 0	11 / 10 / 11 / 10
11/12/2012	25 ns bunch spacing	-145 / 145 / 145 / 220 / 0	1 / 3 / 1 / 3



(a) Interpolated and measured beam centre deltas at the TCTs in IR1.

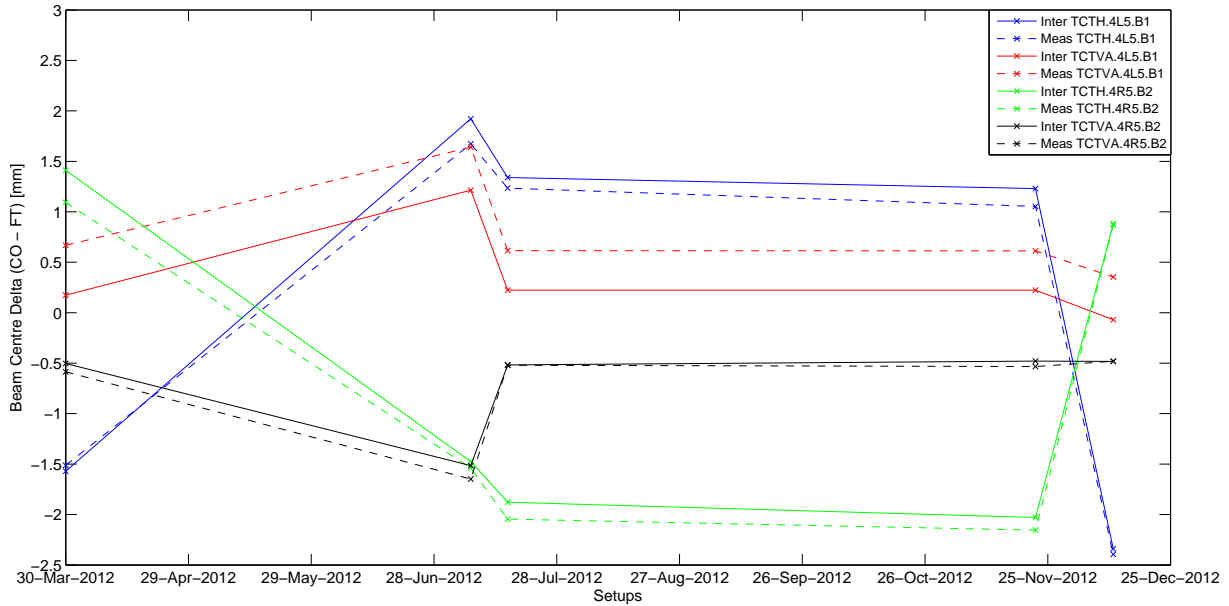


(b) Interpolated and measured beam centre deltas at the TCTs in IR2.

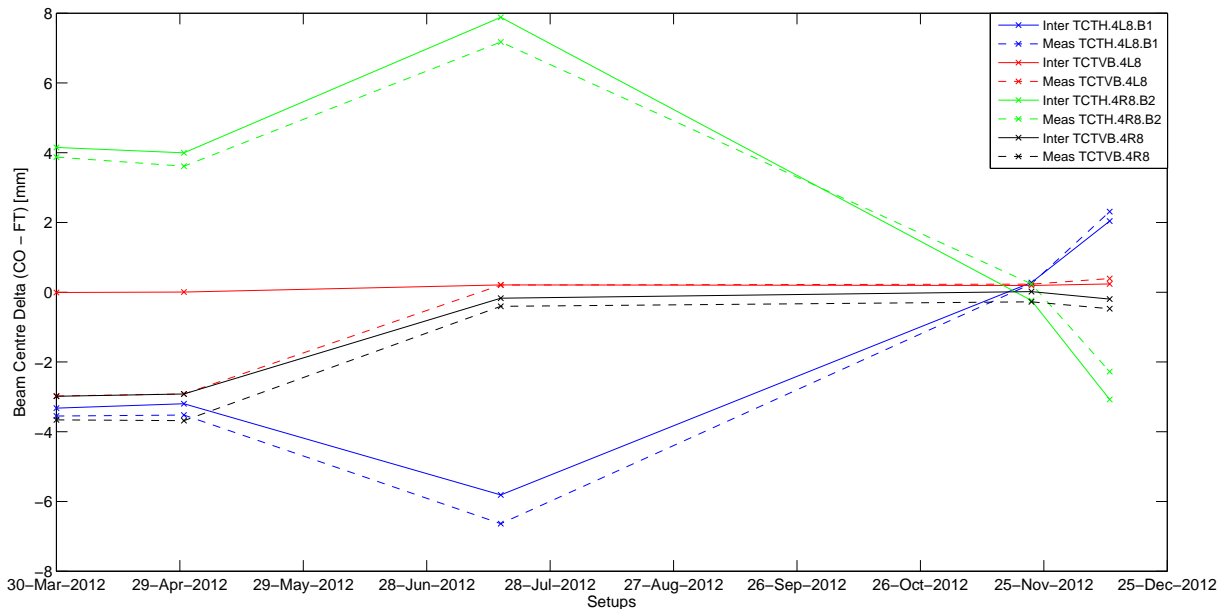
In this analysis, the BPM-interpolated orbit at the TCTs is extracted using the LHC Aperture Meter (Müller *et al.* 2011). As the absolute interpolated orbit is poor at the TCT locations due to errors introduced by BPMs in the IRs (Valentino *et al.* 2012e), the change between the interpolated orbit at flat top (FT) and collisions (CO) were compared with the change in the measured orbit at the same operating points in the

machine cycle. The comparison results are shown in Fig.(9), with separate plots for the TCTs in each IR. A very good comparison is observed between the measured and the interpolated orbit changes between FT and CO.

As expected, the beam centres at the TCTs shown in Figs.(9)(a-d) change as a function of the crossing angles in Table I. For instance, van der Meer scans were performed on the 16/07/2012 and on the 22/11/2012.



(c) Interpolated and measured beam centre deltas at the TCTs in IR5.



(d) Interpolated and measured beam centre deltas at the TCTs in IR8.

Figure 9: Comparison of the deltas in the measured and BPM-interpolated orbit at the TCT collimators between collisions and flat top in the 2012 LHC run.

In between these dates, the IP2 vertical crossing angle was changed from  $-90 \mu\text{rad}$  to  $145 \mu\text{rad}$ , while the IP8 horizontal crossing angle was changed from  $200 \mu\text{rad}$  to  $-220 \mu\text{rad}$ . The beam centres measured on the 22/11/2012 at all TCTs, except the IP2 TCTVs and the IP8 TCTHs, remained the same as the values measured on the 16/07/2012 (within  $100 \mu\text{m}$ ). A direct comparison between the measured centres and the crossing angles would require inclusion of other effects such as luminosity orbit bumps, and is beyond the scope of this

paper.

## 5 Conclusion

The Large Hadron Collider is passively protected against potentially destructive particle losses by a collimation system. The required jaw positions to establish an efficient four-stage hierarchy are determined via a beam-based alignment procedure. This article presented the operational results achieved with collimator alignment during the first few years of LHC operation. The

various algorithms introduced to automate the alignment procedure have had a significant impact, reducing the beam time required for a full alignment by more than a factor 6. Other alignment statistics, including the number of collimators aligned and the number of beam dumps per year, were presented. The similarity in the beam centres measured at subsets of collimators is an indication of the excellent reproducibility and stability of the LHC.

## 6 Acknowledgements

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