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MD Test of a Ballistic Optics

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Summary

The ballistic optics is designed to improve the understanding of optical errors and BPM systematic effects in the critical triplet region. The particularity of that optics is that the triplet is switched off, effectively transforming the triplets on both sides of IR1 and IR5 into drift spaces. Advantage can be taken from that fact to localize better errors in the Q4-Q5-triplet region. During this MD this new optics was tested for the first time at injection with beam 2.

1 Introduction

A special optics without triplet powering was conceived in the construction phase of the LHC for the triplet alignment [1]. In the past this technique was investigated at LEP [2, 3]. It was not used in operation because the vertical misalignment of the low-β quadrupoles could be followed up easily with a sufficient accuracy by means of water levels.

In LHC two new motivations have arisen for the use of the ballistic optics where the triplets are switched off:

- more accurate reconstruction of errors in the Q4 and Q5 quadrupoles,
- the convenient phase advance between BPMs in the ballistic region allows an accurate measurement of the β function at the IR BPMs which can be used to calibrate BPMs by comparing to the β from amplitude measurement.

2 MD Preparation

The **ballistic** optics strengths with the triplets off for IR1 and IR5 were imported into the LHC optics model project. An injection optics was prepared from the standard injection: all strengths except for IR1 and IR5 remained identical to the standard injection optics. Since the total phase advance is reduced significantly the integer tunes had to be lowered by one unit in both planes. The fractional tunes were matched to the standard values (0.28,0.31) with the arc trim quadrupoles (RQTF and RQTD). In LSA the optics name is R2015a_A11mC11mA10mL10m_ALIGN, the betatron function along the ring is shown for beam 1 in Fig 1. Machine settings for injection and ramp to 6.5 TeV were generated in beam process **RAMP-6.5TeV-BalisticOptics-2015_V1**. The beam process was inserted into Hypercycle **6.5TeV_2015_Balistic_Optics**.

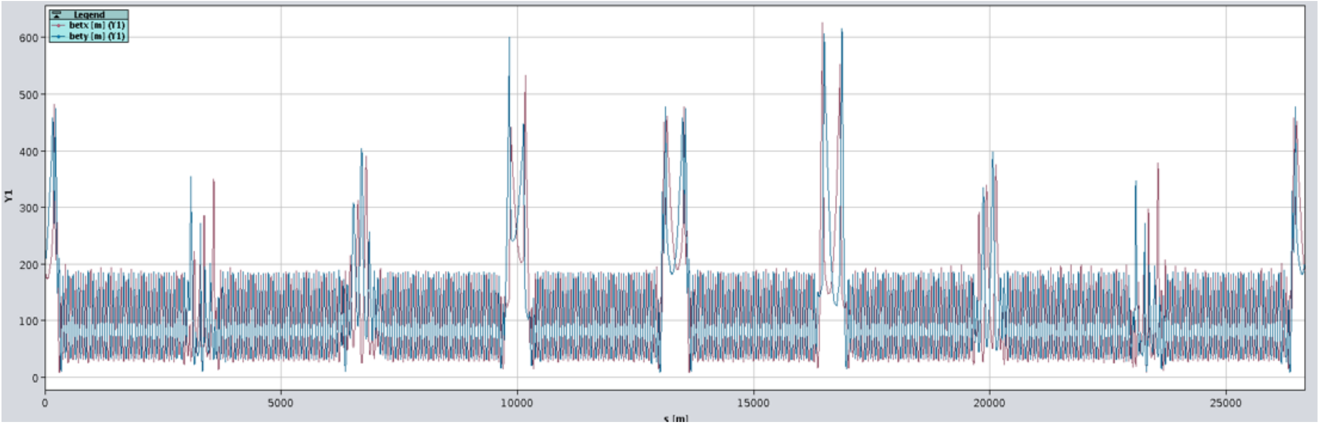

Figure 1: Balistic optics R2015a_A11mC11mA10mL10m_ALIGN betatron functions along the ring for B1.

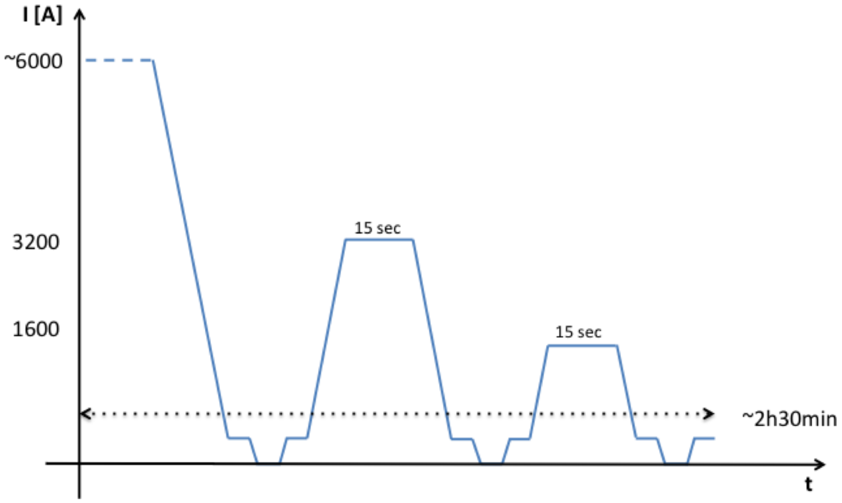

Figure 2: Degaussing cycle of the inner triplets as preparation of this MD.

In order to bootstrap the settings and speed up the commissioning all trims were copied from the standard injection and ramp beam processes. This includes tune, coupling, chromaticity and orbit corrector settings. Since this optics was operated without crossing angle and separation bumps, the contributions from those bumps were subtracted from the corrector settings. The triplet orbit corrector settings (RCBX at Q1, Q2 and Q3) were zeroed for IR1 and IR5.

In order to minimize the remanent the magnetic field, a process called de-gaussing is normally used. This consists of an excitation to very high positive value, followed by progressively decreasing magnitude of the field, while alternating its sign. This procedure was applied to the Inner Triplet magnets at the beginning of the MD to reduce the remaining field, with two limitations. As the main power converters are 1-quadrant, the current cycle was only performed on positive sign and a compromised was found reducing the number of cycles to three, due to the long time needed for ramping up and down the magnets. Moreover, it was decided to use the ramp-down from the previous MD as a first cycle. After this, two cycles at approximately 50% and 25% of nominal current were performed see Fig. 2. Each time the magnets were brought to zero current.

3 Injection

The MD took place on Saturday November 7^{th} 2015. Due to a WIC problem affecting the TI 2 injection line, only beam 2 was available during this MD. The fill number was 4596.

Since this was a new optics (at least in IR1 and IR5) and since it was not sure that the beam would circulate immediately, it was decided to check the quality of the first turn by stopping the beam on a collimator in IR3. A measurement of the trajectory excursion could then be used to decide if threading the first turn would be necessary or not. Unfortunately a TCP was selected to stop the beam, which turned out to be to thin to stop the beam sufficiently in IR3. Instead an important fraction of the beam escaped from IR3 and triggered the ATLAS BCM (beam dump trigger). It took around 1 hour to get the green light for injection from ATLAS (verification by an expert). Since however the trajectory was of good quality after passing through IR5, it was decided to attempt a direct injection into the ring. This was successful and beam 2 circulated immediately. The initial orbit is shown in Fig. 3 before and after correction.

Figure 3: Raw beam 2 orbit after the first injection (before any correction, top) and after correction (bottom). The rms of the corrected orbit is very similar to the rms of the standard orbit (without the crossing and separation bumps).

Tunes, coupling and chromaticity were slightly off, but the correction proceeded rapidly as can be seen in Fig. 4. In roughly 30 minutes all key parameters were corrected and the optics measurements could start.

A ramp attempt was initiated towards the end of the MD, unfortunately due to a bad manipulation the triplet magnets were accidentally switched back on during the ramp preparation when a standby command was sent to all machine PCs.

Fill 4596 2015-11-07 08:05:32
Q1 = .3107 Qx = .3110
Q2 = .3203 Qy = .3200
|C-| = ??? 450. GeV
Q-Stab: ??? ???
S/N ratio: .000 .000
Trim Stab: .000 .000
Clock OK

Fill 4596 2015-11-07 08:05:32
Q1 = .2797 Qx = .2798
Q2 = .3101 Qy = .3100
|C-| = .0116 450. GeV
Q-Stab: .000 .000
S/N ratio: 23.180 25.372
Trim Stab: .000 .000
Clock OK

Fill 4596 2015-11-07 08:19:26
Q1 = .3107 Qx = .3110
Q2 = .3203 Qy = .3200
|C-| = ??? 450. GeV
Q-Stab: ??? ???
S/N ratio: .000 .000
Trim Stab: .000 .000
Clock OK

Fill 4596 2015-11-07 08:19:26
Q1 = .2806 Qx = .2806
Q2 = .3095 Qy = .3094
|C-| = .0019 450. GeV
Q-Stab: .000 .000
S/N ratio: 47.277 27.526
Trim Stab: .000 .000
Clock OK

Figure 4: Iterative correction of tunes, chromaticity and coupling of beam 2.

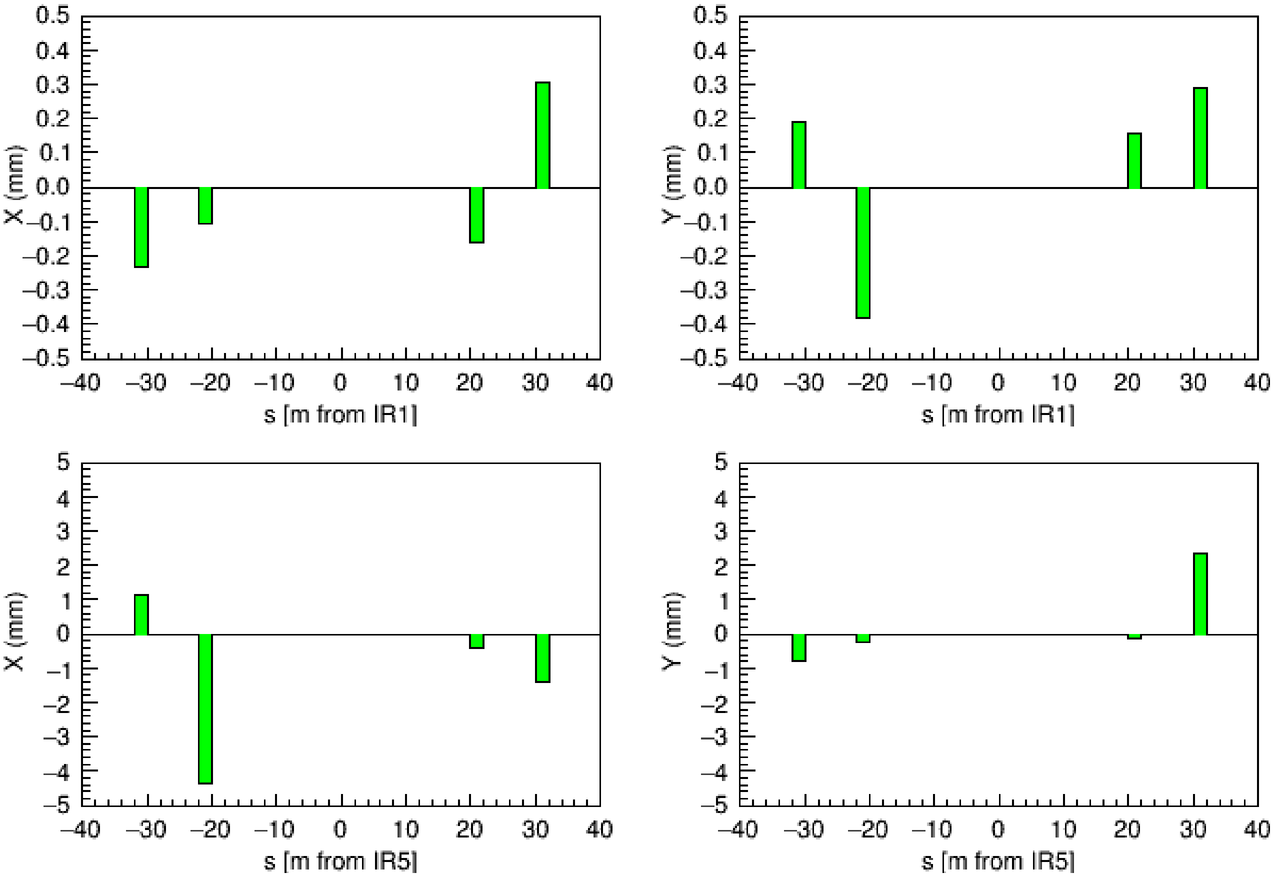

Figure 5: Q1 and Q2 BPM readings for the horizontal (top left) and vertical (top right) plane of IR1 and for the horizontal (bottom left) and vertical (bottom right) plane of IR5. The horizontal scale corresponds to the distance from the IP. Those readings correspond to the corrected orbit, Fig. 3. Note the difference of the vertical scales for IR1 and IR5. It is evident from the figure that some BPM readings have offset of many mm.

4 Triplet BPM alignment

Since the triplet is switched off for the ballistic optics and the beam feels a pure drift space when passing through the triplets on the left ad right of IR1 and IR5, the BPM readings should ideally be aligned on a straight line. Deviations from a straight line give an indication of measurement offsets to due to BPM electronics or to the BPM alignment. The readings of the BPMs at Q1 and Q2 are shown in Fig. 5 for the corrected orbit (Fig. 3 bottom). It is clear that some BPMs have large offsets, well beyond 1 mm. But the majority of the readings lie on a straight line within 0.2 mm even through it is not always possible to determine which reading is affected by an offset.

The relative changes of the same readings between the raw and the corrected orbit (difference between Fig. 3 top and bottom) give an indication of the quality of the BPM calibration and the accuracy over a time scale of 30 minutes. The readings differences are shown in Fig. 6: most of the differences agree within 0.1 mm, but it must be noted that some changes are rather small. The short term accuracy of the reading, as determined by a dispersion measurement, is at the level of 0.01 mm.

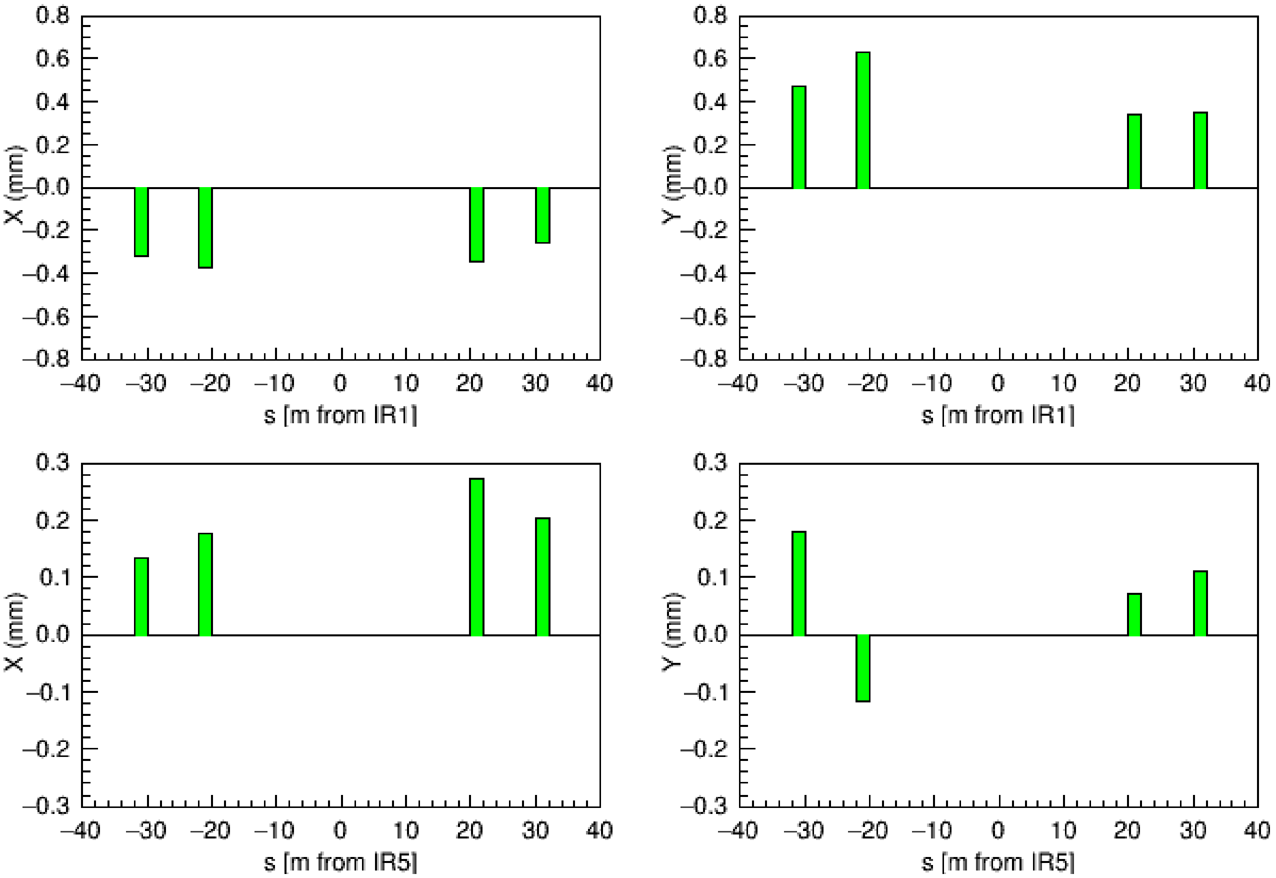

Figure 6: Difference of the Q1 and Q2 BPM reading before and after orbit correction (Fig. 3) for the horizontal (top left) and vertical (top right) plane of IR1 and for the horizontal (bottom left) and vertical (bottom right) plane of IR5. The horizontal scale correspond to the distance from the IP. Note the difference of the vertical scales for IR1 and IR5. The relative accuracy is at the level of 0.1 mm, while the short term accuracy of the BPMs is at the level of 0.01 mm.

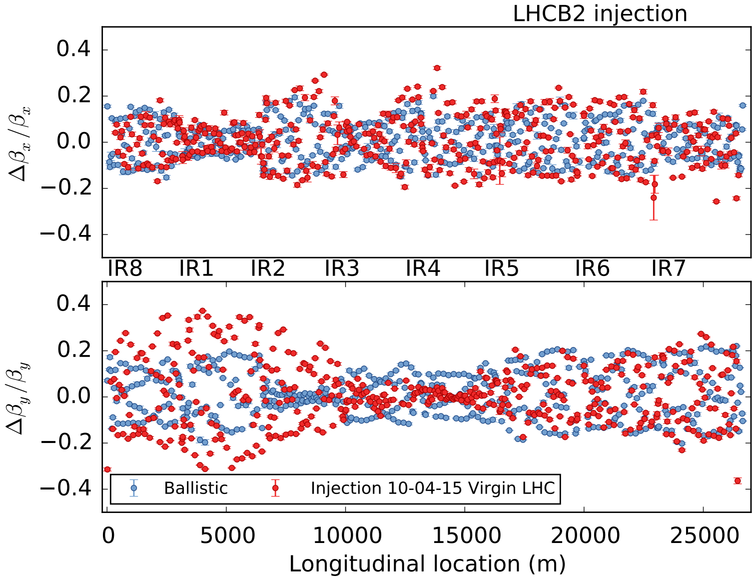

Figure 7: Beam 2 horizontal and vertical β-beating for the virgin nominal and ballistic optics at injection energy.

5 Optics measurements

5.1 β-beating in the ballistic optics

Optics measurements were carried out with the AC dipole following the usual procedure [4] and using the N-BPM method [5]. Figure 7 compares the ballistic to the nominal LHC β-beating without corrections. The ballistic optics feature lower β-beating than the nominal. This can be attributed to the removal of the optics errors in the IR1 and IR5 triplets.

5.2 Optics errors in the ballistic optics

Figure 8 shows the measured horizontal phase advance deviations from the ballistic model in IR1 and IR5 as usually done for identifying local errors [6]. A clear discrepancy is observed and it features a very similar pattern in IR1 and IR5. The optics errors are outside the main triplets since the phase deviation cannot be reproduced only with errors in the triplet area. The errors could be matched for example by lowering Q5L strength by about 0.7% and lowering Q5R strength about 0.4% for both IRs. Additionally, for a better matching, the strength of Q4L1 and Q8R5 should be changed in the order of few permil. An upper limit of the remaining magnetization in the triplet gradients is estimated to be 2×10^{-5} m^{-2}.

5.3 Optics-measurement-based BPM calibration

The motivation of this study is to compute the calibration factor of the beam position monitors (BPM) at the interaction regions (IR) 1 and 5. This analysis has been done comparing the β from phase and the β from amplitude. Traditionally, in the LHC, β from amplitude is only used for the measurement of normalized dispersion to remove the dependence on the BPM calibration [7].

The β that is being computed directly using the amplitude of the oscillations has a strong dependence with the BPM calibration. Denoting C as the calibration factor of each BPM, the position that is measured is then given by the equation:

$$x_{measured} = C \cdot x_{correct} \tag{1}$$

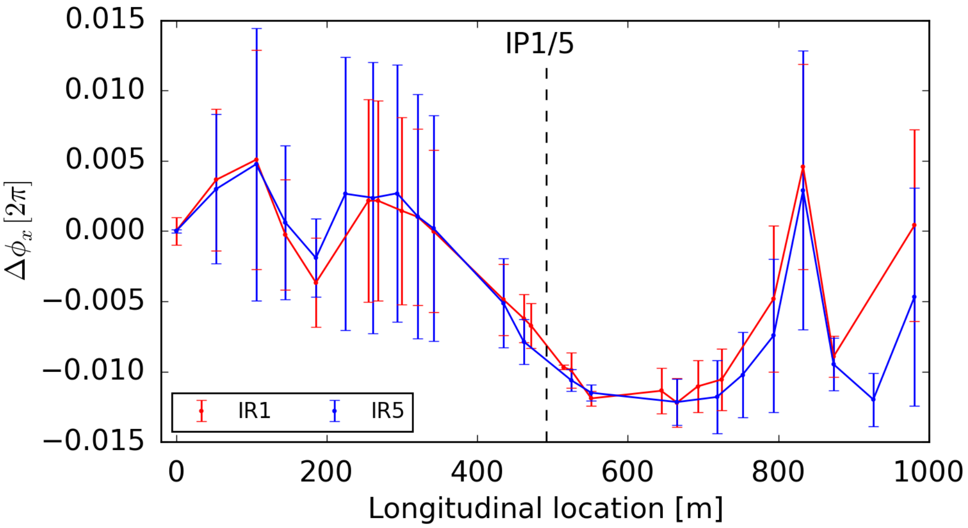

Figure 8: Beam 2 propagated horizontal phase advance deviations from the ballistic model in IR1 and IR5 measured at injection energy.

IR1				
	Horizontal		Vertical	
	Model	Measurement	Model	Measurement
β^* [m]	$189.4 \pm 9 \cdot 10^{-5}$	182.4 ± 0.3	$182.5 \pm 6 \cdot 10^{-3}$	162 ± 1
ω [m]	$3129.0 \pm 6 \cdot 10^{-5}$	3140.7 ± 0.3	$3250.5 \pm 4 \cdot 10^{-3}$	3256.5 ± 0.2

IR5				
	Horizontal		Vertical	
	Model	Measurement	Model	Measurement
β^* [m]	$176.2 \pm 1.2 \cdot 10^{-3}$	186.6 ± 0.6	$184.86 \pm 1.3 \cdot 10^{-3}$	161.05 ± 0.13
ω [m]	$16957.5 \pm 8 \cdot 10^{-4}$	16450.2 ± 0.8	$16580.5 \pm 9 \cdot 10^{-4}$	16583.5 ± 0.2

Table 1: Fit results of Eq. 3 for model and measurements over IR1 and IR5.

This calibration factor also relates the $\beta_{measured}$ with the $\beta_{correct}$ through the equation:

$$\beta_{measured} = C^2 \cdot \beta_{correct} \tag{2}$$

Since in the ballistic configuration the triplets are switched off, the β function over the IR follows a parabola given by equation:

$$\beta(s) = \beta^* + \frac{(s-\omega)^2}{\beta^*} \tag{3}$$

where β^* is the β function at the waist ω. This behavior can be used to obtain an accurate measurement of the β function via a fit to the β from phase measurements. The IR dipoles, however, produce a weak focusing that might distort the parabola. An estimation of the impact of this focusing effect of the beam has been made by fitting the β from the model to the Eq. (3). As can be seen in Fig. 9 and Table 1 the data from the model fits very well Eq. (3). Therefore, the weak focusing effects can be safely neglected.

In the following we compare the β from phase (including the fit) and β from amplitude. Figures 10 and 11 show, respectively, the horizontal and vertical measurements for IR1. Figures 12 and 13 correspond to IR5.

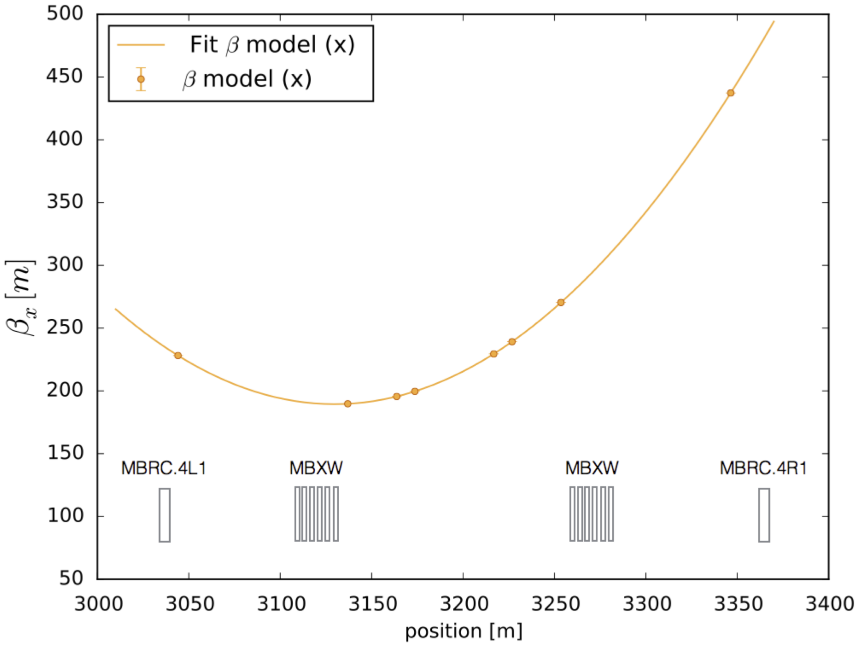

Figure 9: β_x from model at IR1 together with a parabolic fit according to Eq. (3). The MBXW dipoles have a negligible effect on the β function.

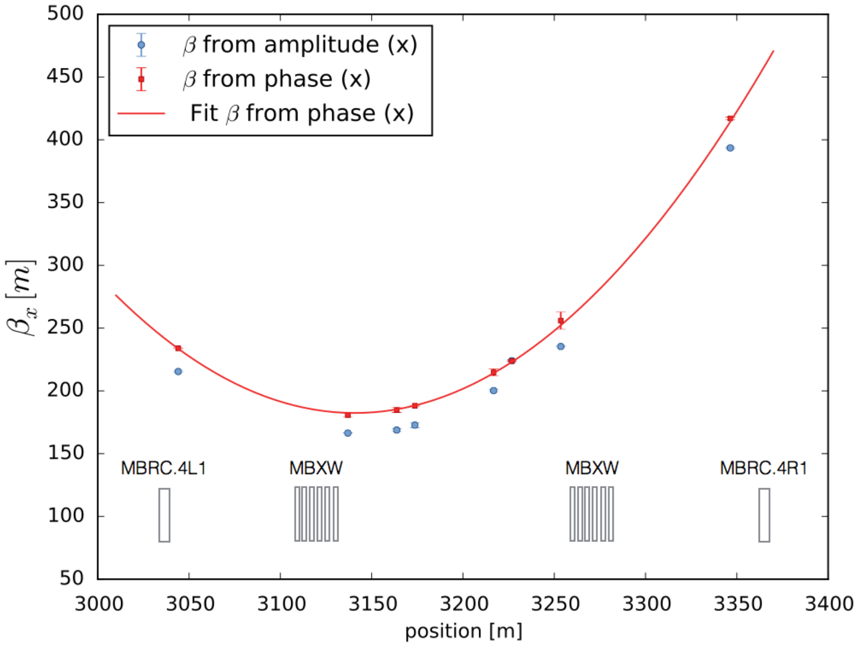

Figure 10: IR1 measured horizontal β from amplitude and β from phase including the fit to Eq. (3). β from amplitude is consistently below β from phase except for one BPM right from the IP.

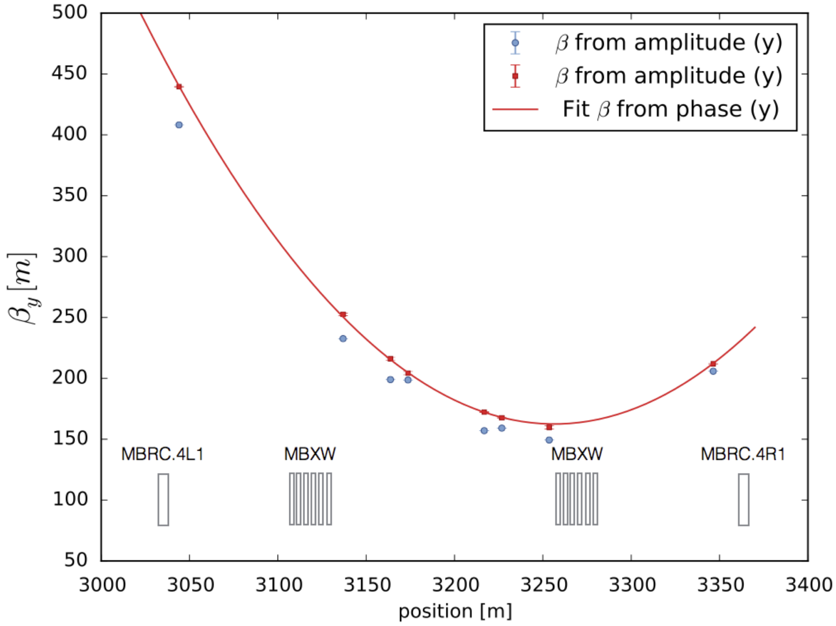

Figure 11: IR1 measured vertical β from amplitude and β from phase including the fit to Eq. (3). β from amplitude is consistently below β from phase.

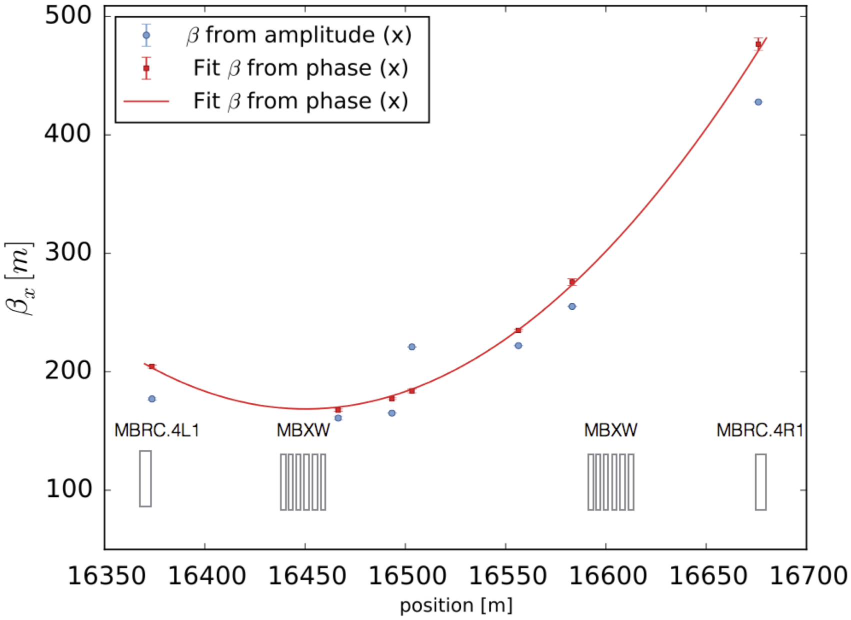

Figure 12: IR5 measured horizontal β from amplitude and β from phase including the fit to Eq. (3). As in IR1 β from amplitude is consistently below β from phase except for one BPM left from the IP.

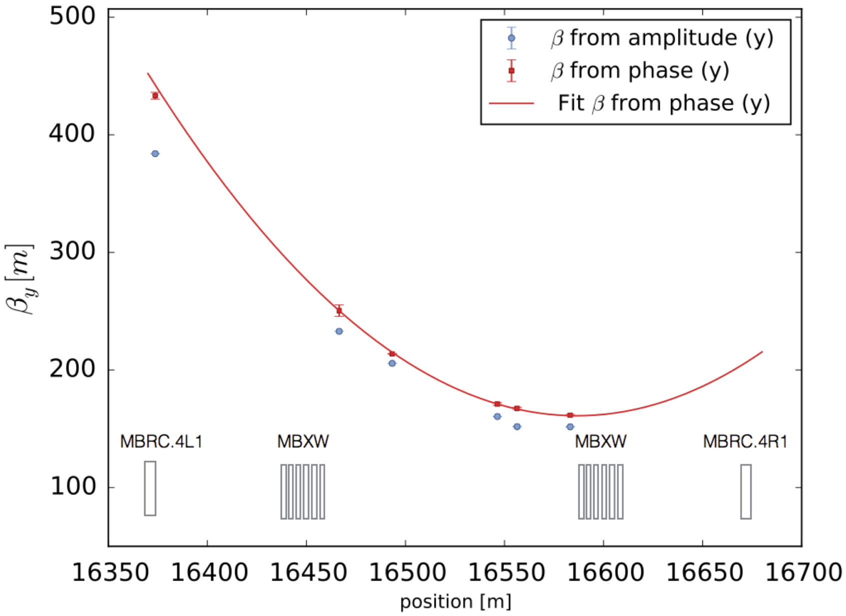

Figure 13: IR5 measured vertical β from amplitude and β from phase including the fit to Eq. (3). As in IR1 β from amplitude is consistently below β from phase except for one BPM left from the IP featuring a significantly larger deviation than the other points.

For both IRs and both planes most of the BPMs feature a larger β from phase than β from amplitude except for BPMSW.1L5.B2 (left from IP5). This deviation might be related to the orbit offset of several mm at this BPM, see Fig. 14.

The parameters obtained in the previous fits are used to compute β_{fit} by evaluating Eq. (3) at the position of the BPMs. The BPM calibration factor is computed using the following equation,

$$C^2 = \frac{\beta_{fit}}{\beta_{amp}} \tag{4}$$

This ratio together with the corresponding uncertainty is shown in Figs. 15 and 16 for IR1 and IR5 BPMs.

Figure 17 shows a histogram of the C^2 uncertainty revealing an accuracy below 1.2%. Therefore the BPM calibration C is measured with an accuracy below 0.6%.

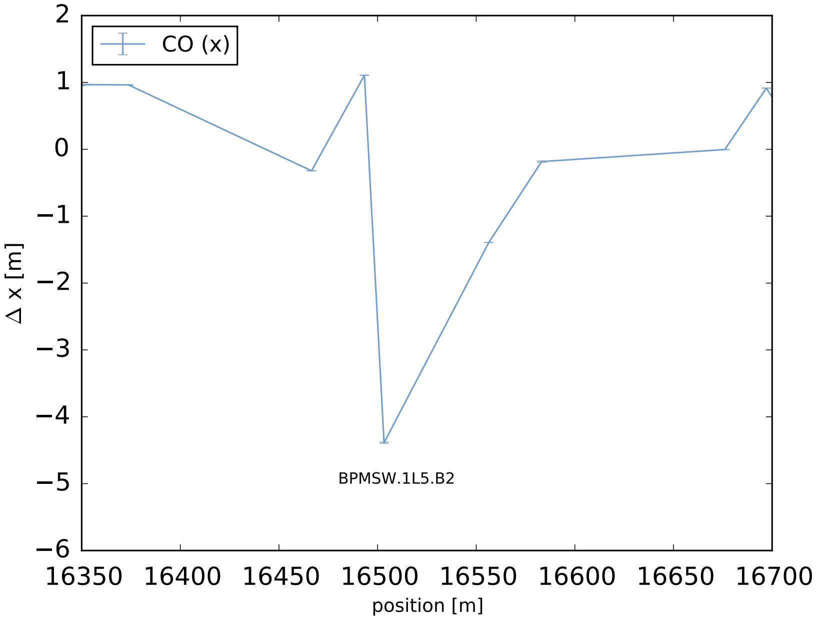

Figure 14: Horizontal closed orbit at IR5 showing a large offset at the same BPM that featured a lower β from phase than β from amplitude in Fig. 12.

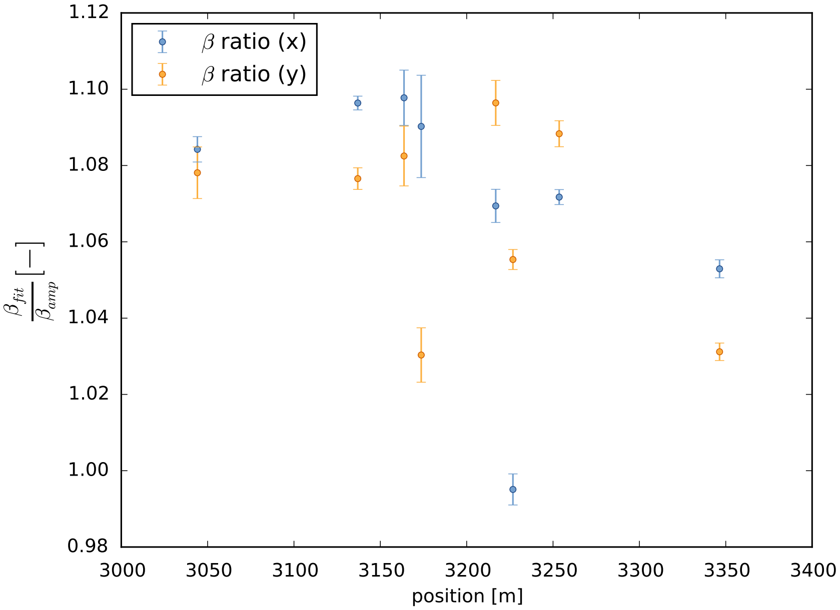

Figure 15: C^2 for horizontal and vertical BPMs in IR1

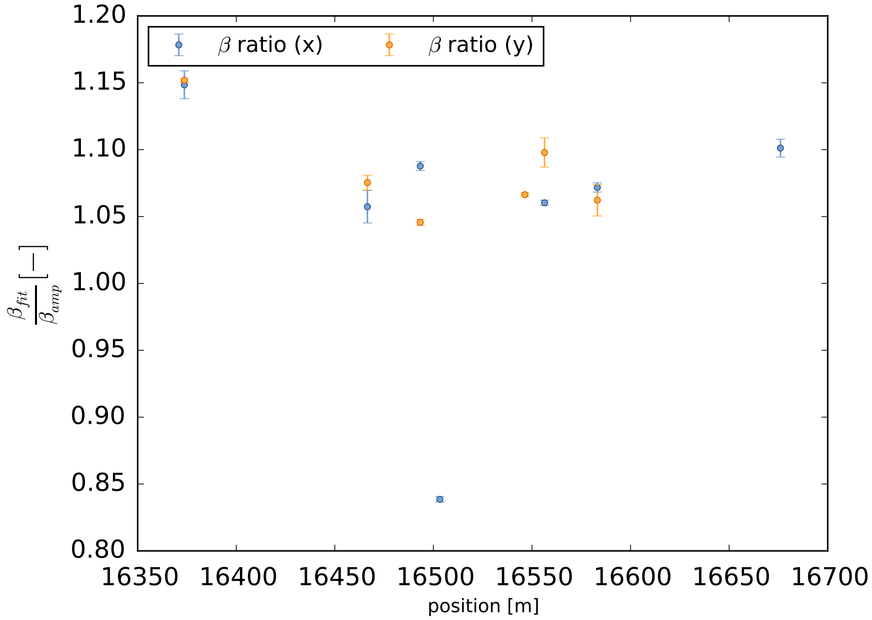

Figure 16: C^2 for horizontal and vertical BPMs in IR5

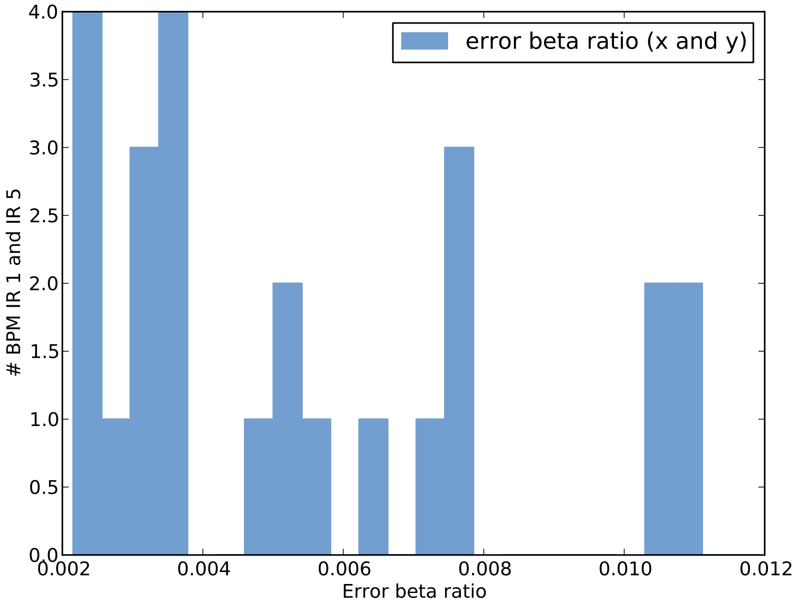

Figure 17: Histogram of the measured uncertainty of C^2 for all BPMs in IR1 and IR5.

6 Summary and outlook

The ballistic optics has allowed to estimate Q5 errors and BPM calibrations with unprecedented accuracy. In particular Q5L and Q5R strengths seem to be lower by about 0.7% and 0.4%, respectively. An upper limit of the remaining magnetization in the triplet gradients is estimated to be about 2×10^{-5} m^{-2}. At top energy this should be a factor 14 lower.

In the future it will be required to measure both beams at injection and at top energy. It will be fundamental to study the calibration dependence with beam offsets in the BPMs since a strong deviation on C has been observed in the horizontal BPMSW.1L5.B2, the only BPM with more than 4 mm beam offset.

7 Acknowledgements

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