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LHC 3324: Counteracting coupling decay at injection

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Summary

The b_3 spool-pieces are corrector sextupole magnets (MCS), are designed to correct the b_3-error of the main dipoles. Changes in the settings of the MCS have been linked to changes in transverse coupling. This implies that there is a nonzero vertical orbit in the MCS which is feeding down to coupling. In this report we investigate if this is likely to be an effect of a non-centered orbit or if the MCS are misaligned with respect to the main dipole. The results indicate that the misalignments of the MCS are the dominant cause. A method to change the powering of the MCS in order to compensate for the chomaticity decay but without changing the global coupling is also tested and reported.

Contents

Arc	K_2[m^{-3}]	b_3 [unit]
RCS.A12B2	0.163325	-4.957045
RCS.A23B2	0.194105	-5.949433
RCS.A34B2	0.237377	-7.153934
RCS.A45B2	0.161282	-4.926429
RCS.A56B2	0.177219	-5.423144
RCS.A67B2	0.188144	-5.763623
RCS.A81B2	0.169408	-5.179697

Table 1: The static part of the setting of the MCS for Beam 2 at injeciton energy.

1 Introduction

A lot of effort has gone into controlling the transverse coupling in the LHC [1–5]. One of the main drivers to control the transverse coupling has been its impact on transverse instabilities [6, 7]. At injection, the transverse coupling has been observed to decay. This has been linked to the powering of the the b_3-spool pieces (MCS). The powering of the MCS has two parts at injection: static and dynamic. The static part is different for each arc, shown in Tab. 1 for Beam 2. The dynamic part depends mainly on the time since the main dipoles have reached the injection settings (b_3 decay). The strength of this correction has been experimentally obtained, and is equally distributed among the different arcs. This part is compensating for the b_3-decay in the dipoles.

In order to get a change in the transverse coupling from a normal sextupole, a transverse offset of the orbit relative to the magnetic center is needed. Conceptually, we can separate it into two potential reasons, or a combination thereof:

1. There is an offset between the MCS and the ideal orbit but the dipole and the MCS are well aligned.

2. The ideal orbit is passing through the center of the dipole but the MCS is vertically misaligned with respect to the dipole.

The two situations are conceptually shown in Fig. 1.

We can measure the effect on the transverse coupling by changing the strengths of the MCS. From this we conclude that the orbit was not going through the center of the MCS. These measurements are described in detail in Section 2. A way to mitigate the impact on the transverse coupling is presented in Section 3. In Section 4 different measurements and simulations are presented, to disentangle if it is only MCS which are misaligned or it is also the dipoles. The measurements presented were taken both during commissioning and normal MD periods. The dates for the different measurements can be found in Appendix B.

2 Change MCS powering arc-by-arc

The impact on the transverse coupling by changing the strength of the MCS for a given arc was measured during commissioning for the two beams and then repeated for Beam 2 during a MD (2018-09-16). The measurements were done by changing the strength of the MCS, as

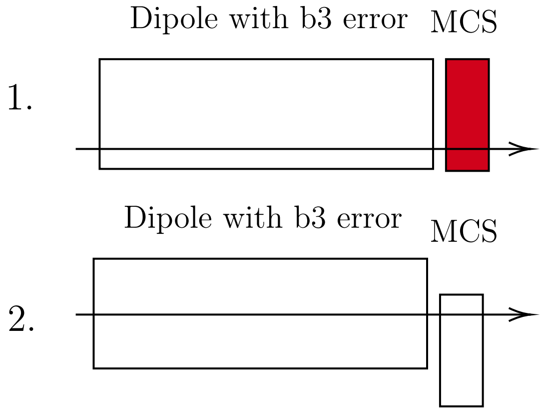


Figure 1: Two cases to create a change of the coupling from the MCS: 1. There is a systematic offset of the vertical orbit in combination with a non perfect b_3-correcttion. 2. There is a systematic offset of the MCS with respect to the dipole.

shown in Fig. 2. The C^- was measured using the AC-dipole. The results were fitted for the real and imaginary parts of the C^- to the equivalent strength of the knobs used in operation to correct the coupling. The results are shown in Fig. 3a. We notice that the impact on the coupling stayed approximately constant from the commissioning period to the MD. This is an important result in order to mitigate the effect, discussed in Section 3.

The missalignments were matched in MAD-X to reproduce the measurements. The results are shown in Tab. 2. It should be stressed that the MAD-X simulation assumes all of the MCS, for a given arc, are misaligned by the same amount. We observe that a similar offset is needed to reproduce the measurements for the two beams. It is worth noting that all the missalignments are in the same direction, indicating a systematic effect.

3 Mitigating the coupling decay

Since the influence of the powering of the MCS stayed constant throughout the year it might be possible to find a correction strategy that compensates globally the b_3-decay but distributes the correction unevenly, in order to keep the C^- constant. No assumption on where the change in C^- is deriving from is needed as long as the effect remains unchanged throughout the year.

Based on the measurement of each individual arc, a knob was calculated which allowed to change the b_3 without changing the C^-. In order to easily compare the results during the MD, two knobs were created, called: even and uneven. The even created an equal change on all the MCS while the uneven created a change different for the different sectors. When trimmed to -8 both correspond to a correction of approximately 2 hours of b_3-decay at injection or a change of $Q'_x = -40$ and $Q'_y = 32$. The strength of the knobs are given in Tab. 3. Only Beam 2 was available during this MD.

The procedure for the MD (2018-09-16) was as follows:

1. Measure the transverse coupling to have a reference value.

2. Trim in the Uneven knob to -8 and correct the chromaticity using the main sextupoles.

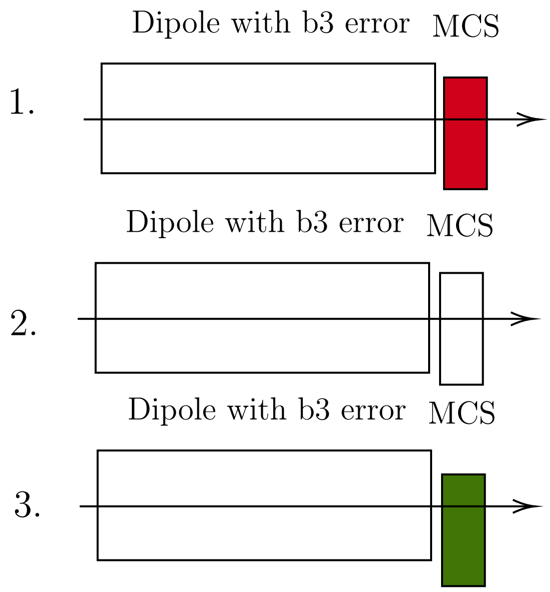
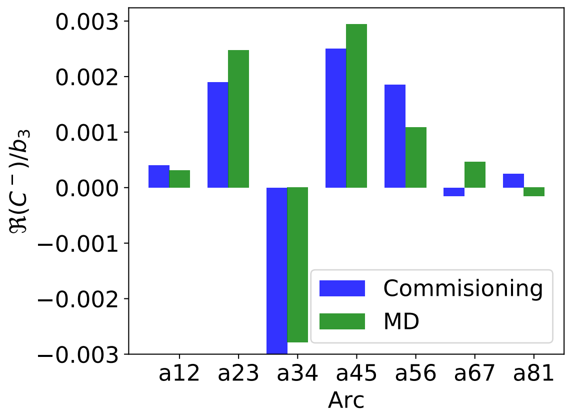
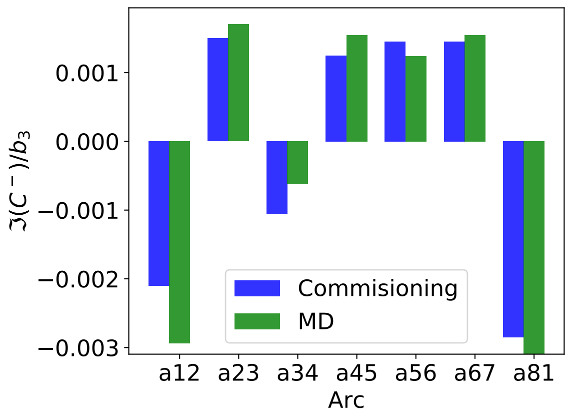


Figure 2: Conceptual figure of the 3 measurements that were performed. 1. With decreased b_3 in that arc by, 2. With nominal setting, 3. With increased b_3 setting strength.



(a) Real part of the C^-



(b) Imaginary part of the C^-

Figure 3: The change of the real part (a) and the imaginary part (b) of the C^- from changing the MCS strength equivalent to 1 unit of b_3. The blue bar shows the measurement during the commissioning and the green shows the results during the MD.

Arc	offset [mm]	$\Re(C^-)$	$\Im(C^-)$
RCS.A12B1	-0.30	0.00141	-0.00140
RCS.A23B1	-0.45	0.00116	0.00243
RCS.A34B1	-0.45	-0.00132	-0.00197
RCS.A45B1	-0.40	0.00086	0.00248
RCS.A56B1	-0.30	0.00065	0.00188
RCS.A67B1	-0.40	-0.00129	0.00220
RCS.A78B1	-0.25	-0.00056	-0.00149
RCS.A81B1	-0.35	0.00149	-0.00176
RCS.A12B2	-0.40	0.00063	-0.00256
RCS.A23B2	-0.40	0.00208	0.00131
RCS.A34B2	-0.55	-0.00299	-0.00097
RCS.A45B2	-0.50	0.00283	0.00175
RCS.A56B2	-0.30	0.00167	0.00103
RCS.A67B2	-0.20	0.00017	0.00128
RCS.A81B2	-0.45	0.00062	-0.00288

Table 2: The vertical offset of the MCS, arc-by-arc, needed in the simulation to reproduced the measured coupling.

Arc	Even K_2 [m^{-3}]	Uneven K_2 [m^{-3}]
RCS.A12B2	0.004	0.0030535
RCS.A23B2	0.004	0.0034902
RCS.A34B2	0.004	0.0070352
RCS.A45B2	0.004	0.0027526
RCS.A56B2	0.004	0.0035134
RCS.A67B2	0.004	0.0055220
RCS.A81B2	0.004	0.0027993

Table 3: The knobs used to test the change in chromaticity.

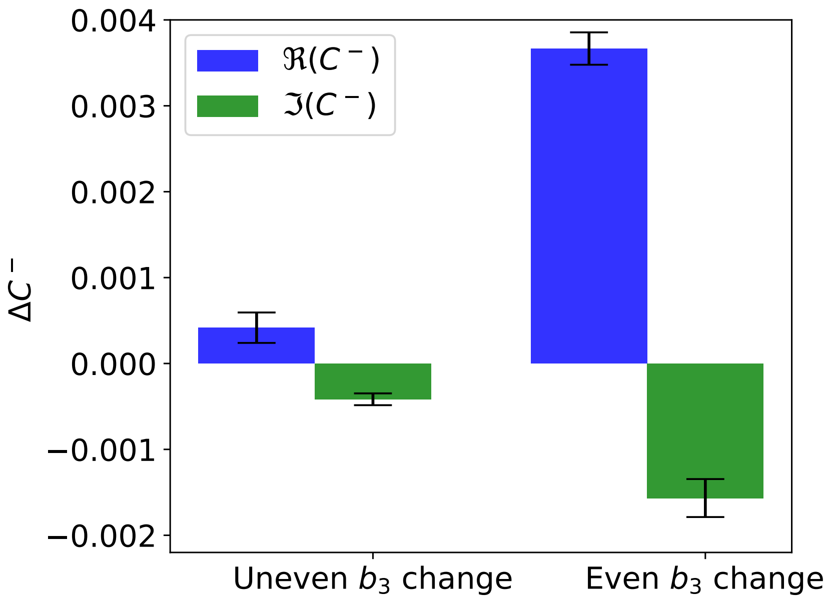


Figure 4: The change of C^- in Beam 2, from trimming in and out the two knobs to (-8) given in Tab. 3.

3. The coupling was measured and compared to the first step. No change in coupling was observed.
4. Change to the even powering of the MCS and measuring the coupling and chromaticity again. This was done by simultaneously trimming out the even knob, while trimming in the Uneven knob. The chromaticity stayed within one unit for the two measurements while the coupling changed by about 4×10^{-3}. The change to the C^- for the two knobs is shown in Fig. 4.

We can observe that the coupling is virtually unchanged with the new compensation scheme. However, it is also important to verify that this correction scheme does not have negative impacts on other important optics parameters. If we assume that in the previous scheme all the arcs were compensated perfectly, then we can compare the error introduced by the new compensation scheme, shown in Fig. 5. The tested correction corresponds to a b_3-decay at injection of approximately 2 hours. This can be compared with the compensation of the missing arc in Beam 2. We observe that the change of this new knob would be smaller than the effect of the missing MCS in arc78 for Beam 2. Simulation of the impact on the Montangue functions as well as the Q'' were done, and they showed negligible changes [8]. In addition, there was an MD which showed that even large changes in the powering of the MCS had a small impact on the dynamic aperture [9].

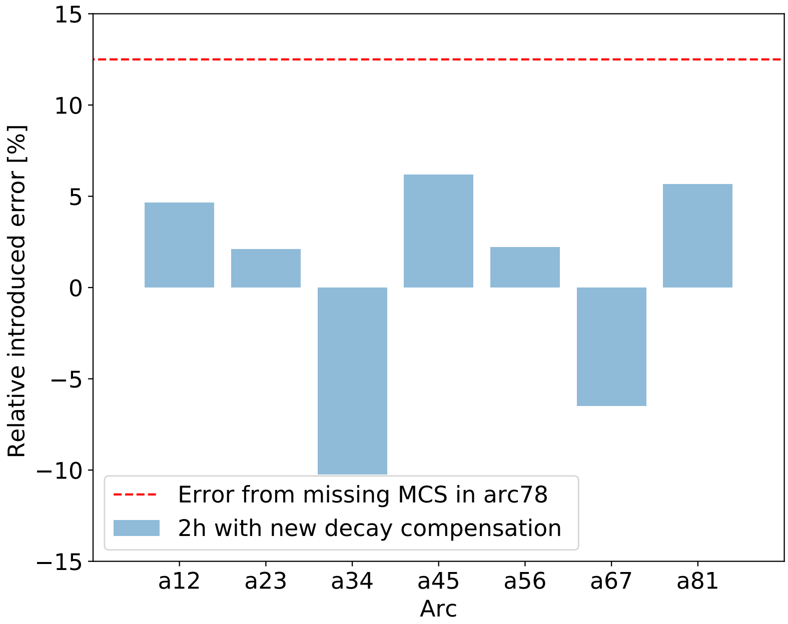


Figure 5: The relative error introduced after 2 h by the uneven knob in percentage of the static local over correction due to the missing MCS in arc78 for Beam 2.

4 Misalignment or orbit?

In order to create coupling from a normal sextupole, a vertical displacement is needed. As described in the introduction, this can be achieved by either an orbit offset through the dipole and MCS, or that there is a misalignment of the MCS relative to the b_3-error of the main dipole. In case there would be a perfect local correction of the b_3, then there would be no dependency on the orbit. There might be a small contribution from the orbit and the fact that the optics is not exactly the same through the b_3-error in the dipole and the MCS. This is investigated later in this section.

During an MD (2018-10-29), a measurement was done to establish the magnitude of the uncorrected b_3. Due to time constraints and limited availability, only a single arc and beam was investigated. We first turned off the main sextupoles in the arc of interest, a34 for Beam 2 since any orbit in these would also feed-down to coupling. We then created a vertical orbit bump in the arc and by changing the orbit (Δy) and measuring the coupling, we could obtain the strength of the uncorrected b_3-error. This measurement is shown in Fig. 6. It is important to note that this is independent of the relative alignment of the dipole and the MCS. It was found that the MCS were powered at 17% stronger than the b_3-error for that arc. This is close to the expected values since the missing MCS in arc78 results in a local over correction of $\frac{8}{7}$ (14%).

From this measurement we conclude that for this arc there is a non perfect local compensation of the b_3 but the magnitude is in accordance with expectation, considering the missing arc. This is also inline with previous attempt to measure the residual b_3-error arc-by-arc

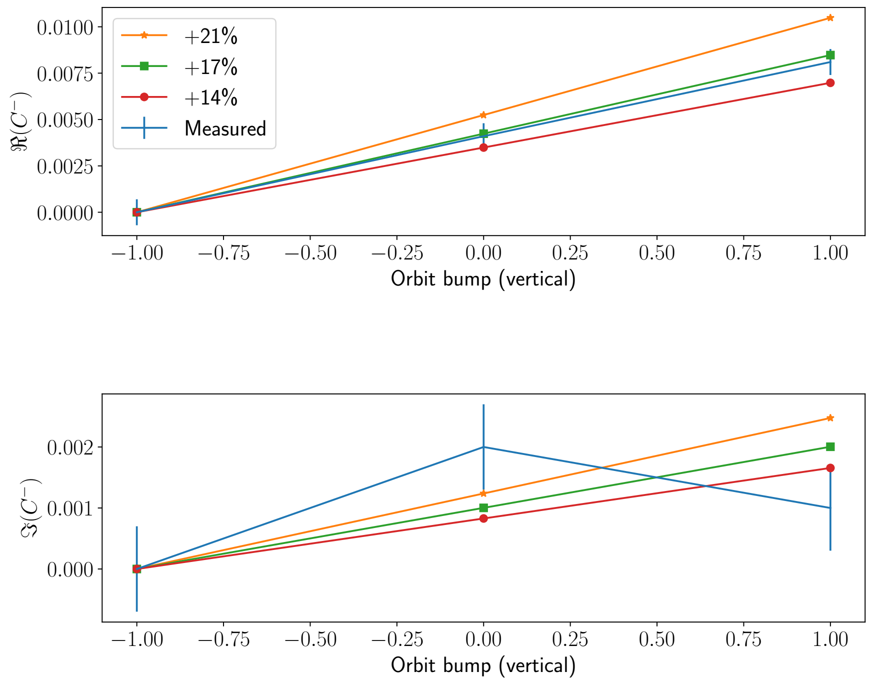


Figure 6: The percentage of error in the correction needed to reproduce the correct change in C^-.

using feed-down to tune [10].

4.1 Analytical Investigation

In the first part we will look at the effect from a single dipole with a b_3-error and MCS, and in the following parts we will investigate it for a more realistic system where all the bends and MCS are included.

We start with some well known relations: The impact of a skew quadrupolar term $K1_s$ on the C^- [11]:

$$C^- = \frac{1}{2\pi r} \int \sqrt{\beta_x \beta_y} k1_s(s) e^{i(\phi(s)_x - \phi(s)_y)} ds \tag{1}$$

where r, is the radius of the accelerator. In the following calculations, we will will treat the elements as thin. We use the following relation and notation: $k_s = K1_s L$, where L is the length of the magnet.

The feed-down to k_s from thin sextupole is given by:

$$\Delta k_s = k_2 \Delta y, \tag{2}$$

where Δy is the vertical distance to the middle of the sextupole.

The contribution to coupling from one MCS and a dipole with a b_3-error can therefore be written as:

$$C^- = \Delta y^{bend} k_2^{bend} \sqrt{\beta_x^{bend} \beta_y^{bend}} e^{i(\phi_x^{bend} - \phi_y^{bend})} - \Delta y^{mcs} k_2^{mcs} \sqrt{\beta_x^{mcs} \beta_y^{mcs}} e^{i(\phi_x^{mcs} - \phi_y^{mcs})} \tag{3}$$

1. Inspecting formula Eqn. 3 we observe the following: that there is no contribution to the coupling when $\Delta y^{bend} = \Delta y^{mcs} = 0$.

2. Let us divide the k_2 into a static part and a dynamic part $k_2 = k_2^{static} + \Delta k_2$. We can observe that in case the orbit (Δy) and the optics do not change, the static part will only give a fixed contribution. Since we are interested in the dynamic part, we can factor this out. This means that the decay part will be given by:

$$C^- = \Delta y^{bend} \Delta k_2^{bend} \sqrt{\beta_x^{bend} \beta_y^{bend}} e^{i(\phi_x^{bend} - \phi_y^{bend})} - \Delta y^{mcs} \Delta k_2^{mcs} \sqrt{\beta_x^{mcs} \beta_y^{mcs}} e^{i(\phi_x^{mcs} - \phi_y^{mcs})} \tag{4}$$

This is important because it means that any static difference between the two will have no impact on the coupling decay as long as no other parameters are changing.

3. After step 2 we split the $\Delta y = \Delta y_m + \Delta y_{co}$, where Δy_m is the relative misalignment between the b_3-error and the MCS, Δy_{co} the common closed orbit for both the bend and the MCS. We can now again make an interesting observation. Let us assume that the optics and orbit have stayed constant in time. We can now compare the impact on having a Δy_{co} to a Δy_m. For simplicity, we can assume that

$$\sqrt{\beta_x \beta_y} e^{i(\phi(s)_x^{bend} - \phi(s)_y^{bend})} = \sqrt{\beta_x \beta_y} e^{i(\phi(s)_x^{mcs} - \phi(s)_y^{mcs})} = k_c. \tag{5}$$

The impact of an closed orbit plus a non perfect correction can then be written as:

$$C^- = (\Delta k_2^{bend} - \Delta k_2^{mcs}) \Delta y_{co} k_c \tag{6}$$

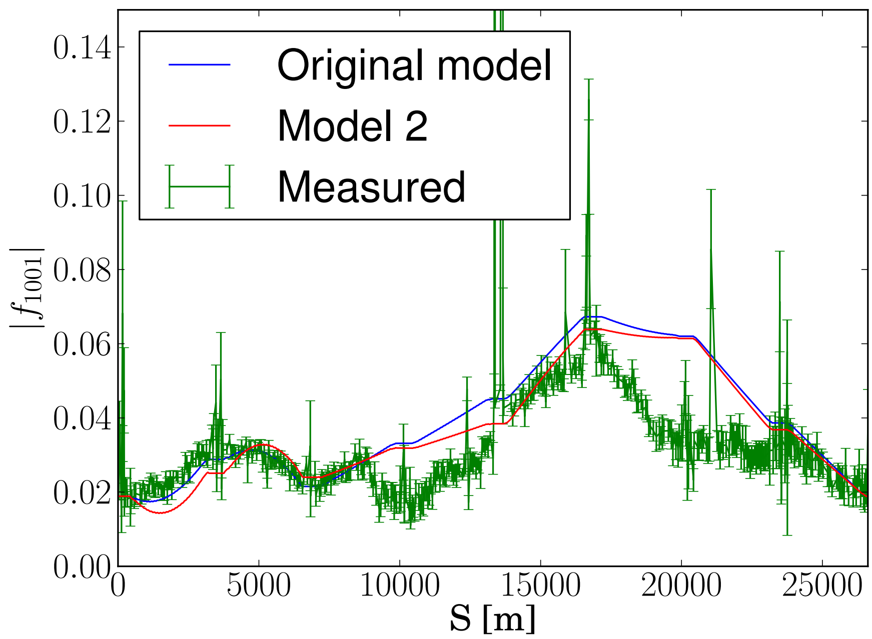


Figure 7: The measured f_{1001} at injection for Beam 1 compared to a simulation where the MCS have been misaligned with -0.40 mm (Original), and with the measured misalignment as shown in Tab. 2 (Model 2).

This can be compared to a perfect closed orbit, $\Delta y_m^{bend} = 0$ but misaligned MCS which would give:

$$C^- = (-\Delta k_2^{mcs})\Delta y_m^{MCS} k_c \tag{7}$$

This shows that a misaligned MCS creates a coupling change proportional to the powering, while a common offset of orbit only generates a coupling proportional to the error in the correction. We will in the following sections see how big such an error would have to be in order to explain the observations.

4.2 Coupling pattern along the machine

In the commissioning of the ATS optics it was observed that there was a pyramid-like coupling structure, in particular for Beam 1. This was corrected using the arc skew quadrupoles. The nominal optics did not show this structure due to the larger integer tune split between the horizontal and vertical plane. In Fig. 7 the coupling structure at injection for Beam 1 is shown and compared to a simulation where the MCS are misaligned with -0.4 mm as well as with measured misalignment. There is a good agreement for the pattern and the amplitude of the structure.

The same comparison is done for Beam 2 and is shown in Fig. 8. The agreement for Beam 2 is not as good as for Beam 1, but it is not surprising, since the model does not include any additional errors other than the misalignment of the MCS. A simulation of the effect of a misaligned orbit through both the dipole and the MCS was performed. This was

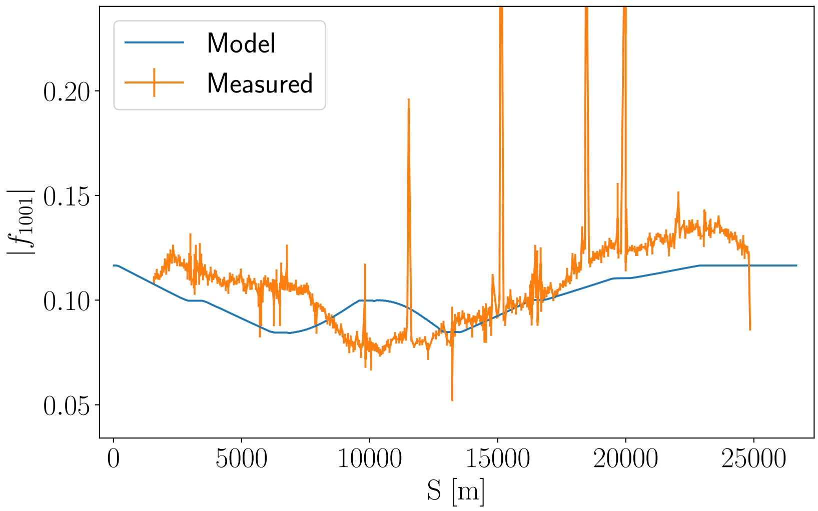


Figure 8: The measured f_{1001} at injection for Beam 2 compared to a simulation where the MCS have been misaligned with -0.40 mm

done using virtual correctors to match the orbit to an offset of 0.4 mm (that would mean that MCS are below the reference orbit with -0.4 mm). The b_3-errors for the dipoles from WISE and the nominal MCS corrections were applied. By this, basically no coupling was created (as expected from the previous section), however, by assuming a 10% error in the correction, some structure developed as seen in Fig. 9. However, this is still not big enough to explain the observation and the pattern also appears to be slightly different. The 10% error of the static part is also most likely an overestimation, since previous performed measurements have indicated that the powering is within 5% [10]. Note that the measurement presented in the previou section stating the 17% difference was for Beam 2 and was due to the missing arc. All this together provides a strong indication that there is no systematic orbit offset causing the feed-down to coupling.

4.3 Coupling decay at injection

There have been in total 3 measurements of the coupling decay. The first one was only for Beam 2 and was performed parasitically during an MD (2016-10-31) [3]. The second measurement was also performed for Beam 2 (2017-05-15), but in this case the dynamic correction part for the MCS was initially turned off, while the static powering was still on. This measurement is shown in Fig.10. The total time was around 2 h, which corresponds to about 0.90 b_3 units of decay in the dipoles. We notice that when the chromaticity was corrected using the Magnet Sextupoles (MS), there was only a small impact on the C^- (a few 10^{-4}). The total drift in the coupling when the MCS were off was 1.2×10^{-3}, including the effect of the orbit correction which was responsible for around 25% of the change. The fact that a small drift is observed could indicate that there is an offset of the orbit compared to the b_3-error of the main dipole, or that something else drifted in the meanwhile. However,

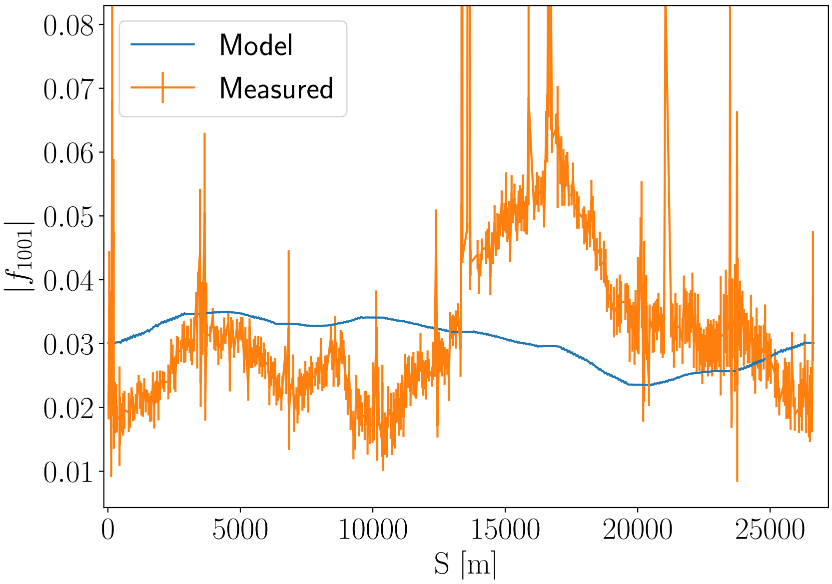


Figure 9: The measured f_{1001} at injection for Beam 1 compared to a simulation where the b_3-errors have been taken from WISE and assigned to the dipoles and corrected using the MCS. An error of 10% of the correction is assumed.

when we redistributed the correction from the MS (which we know had a very small effect when they were used for correction) we saw a change of 3.4×10^{-3}, so approximately a factor 3 higher. This clearly indicates that the MCS are more misaligned with respect to the closed orbit than the b_3-error of the main dipoles. This is because in this case the b_3 in the dipoles are changing with the same amount as done by the MCS but with the difference that we do not see the same impact on the coupling.

The third measurement was done for both Beam 1 and Beam 2. We do not expect any systematic errors of the b_3-correcttion for Beam 1 since all the arcs had operational MCS. The measurement is shown in Fig. 11 and we can observe that a shift of the coupling is also observed for Beam 1. The timescale of the measurement is shorter, so the total change is therefore also lower, but the curves are similar to Beam 2 shown in Fig. 12.

In the following part we will try to explain the drift from the third measurement seen in Fig.11. We focus on Beam 1 because all the MCS were operational.

We will, in the following sections, investigate if there is a systematic difference between the error in the dipole and the correction in the MCS which could explain the observed decay. We assume that the error is effectively located in the middle of the dipole, while the spool piece is placed in the end of the magnet. The different potential reasons are investigated quantitatively through simulations in the following sections.

4.3.1 Orbit Difference between MCS and bend

In Fig. 13 the differences between the orbit in the MCS and the bends are shown. The orbit in the locations of the MCS and the dipoles are obtained by reading the measured

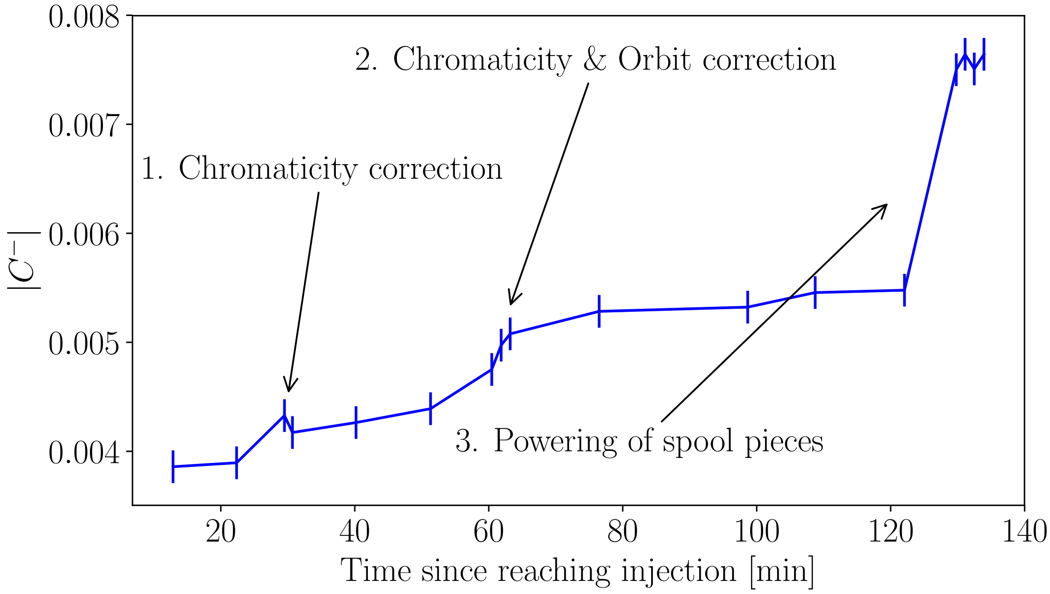


Figure 10: Coupling as a function of time after reaching injection. Note that until minute 120 all the b_3-decay was corrected with the MS at the two marked occasions. Measurement taken 2017-05-15.

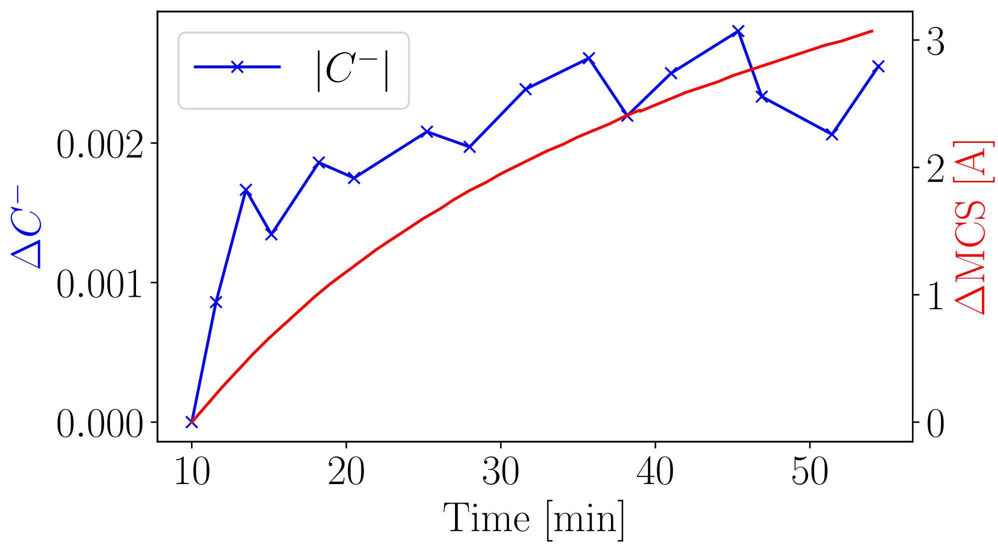


Figure 11: The measured change in coupling as a function of time since injection for Beam 1. The right scale shows the change in the powering of the MCS for the given time period. (2018-04-04)

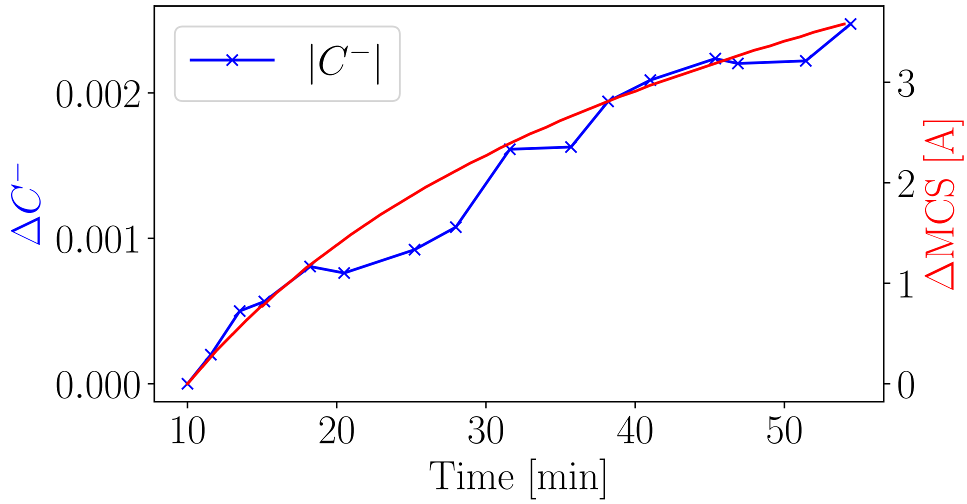


Figure 12: The measured change in coupling as a function of time since injection for Beam 1. The right scale shows the change in the powering of the MCS for the given time period. (2018-04-04)

orbit at the BPMs and then fitting the orbit in the model using the virtual correctors. This functionality is provided by the online-model [12]. The difference in vertical orbit is below 0.1 mm in most cases and we cannot observe any systematic shift. The mean difference was 0.2μm and the RMS was 0.061 mm.

The MCS were changed by 3A or ≈0.45 b_3 units to compensate for the b_3-decay in the dipole. Assuming that the local b_3-decay was locally compensated with the MCS the predicted change to coupling is: $|C^-| = 4 \times 10^{-5}$. This clearly shows that this cannot have been the main cause for the observed decay.

4.4 Difference in $\beta-$unctions and phase advance

If there would be a systematic difference in $\sqrt{\beta_x \beta_y}$ between the MCS and the bending magnet, this would also cause a change in coupling in conjunction with a non-local b_3-correcttion. The difference is shown in Fig. 14 and again, there is no systematic difference between the $\sqrt{\beta_x \beta_y}$ for any of the arcs. The mean value for the $\sqrt{\beta_x \beta_y}$ between the middle of the dipole and the consecutive MCS is -0.3 % and the $\sigma = 0.34\%$.

There is also a difference in the phase advance MCS and the error in the dipole. This is of significant importance, due to how the coupling errors add up to the global C^-. The $(\Delta\psi^{mcs}_{x-y} - \Delta\psi^{bends}_{x-y})$ is shown in Fig. 15. The mean difference in phase advance was 0.14 deg between the MCS and the middle of the bend. If we combine this with the difference β-function, assuming perfect sextupole correction and no orbit offset, we get a change in $|C^-| < 10^{-4}$, which is significantly smaller than the observations.

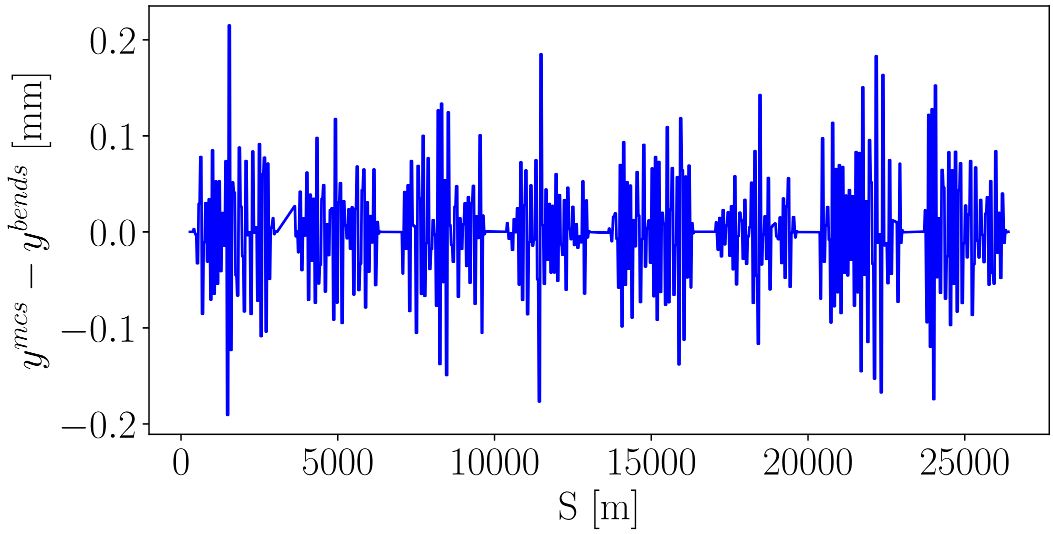


Figure 13: The difference between the fitted orbit in the middle of the bending magnets and in the MCS.

4.5 Orbit or misalignment?

Even though all the previous given effects are small, they are included in the model that is used in the following. We know the relative misalignment of the orbit and the MCS from previous measurements, see Section 2. If we introduce the offset through misalignment, the prediction of the coupling change comes out around 2×10^{-3}, while the measured was around 2.5×10^{-3}. There is also a good agreement of the phase of the C^- between measurement and the simulation.

We have seen in the previous sections that the small differences in orbit, phase advance and β-function between the magnetic error and the MCS are not sufficient to explain the drift in coupling. In the following all the effects are included. The orbit is also matched to measured and, in addition, the fitted orbit is added. This is not enough to explain the observation, so we also add an error in the correction of the b_3-decay. However, we know that globally the b_3 is kept well under control since there was no change in the chromaticity. This means that globally the b_3-decay in the dipoles is compensated by the MCS. In [13] the decay of the b_3 for different magnets were measured and a standard deviation of around 30% was obtained which did not seem to be correlated with any of the other parameters. If we now introduce a Gaussian spread of 30% of the decay in the main dipoles then we obtained what is shown in Fig. 16a. We observe that the maximum $|C^-|$ created is around 2×10^{-4} which is an order of magnitude smaller than what was observed. In order to have at least 5% of the distribution to be above the measured decay a standard deviation of 250% is needed.

For Beam 2 the situation is slightly different since there is a systematic error from the fact that not all arcs are operational. This in combination with an offset in the orbit manages to explain about 1/3 of the observed decay.

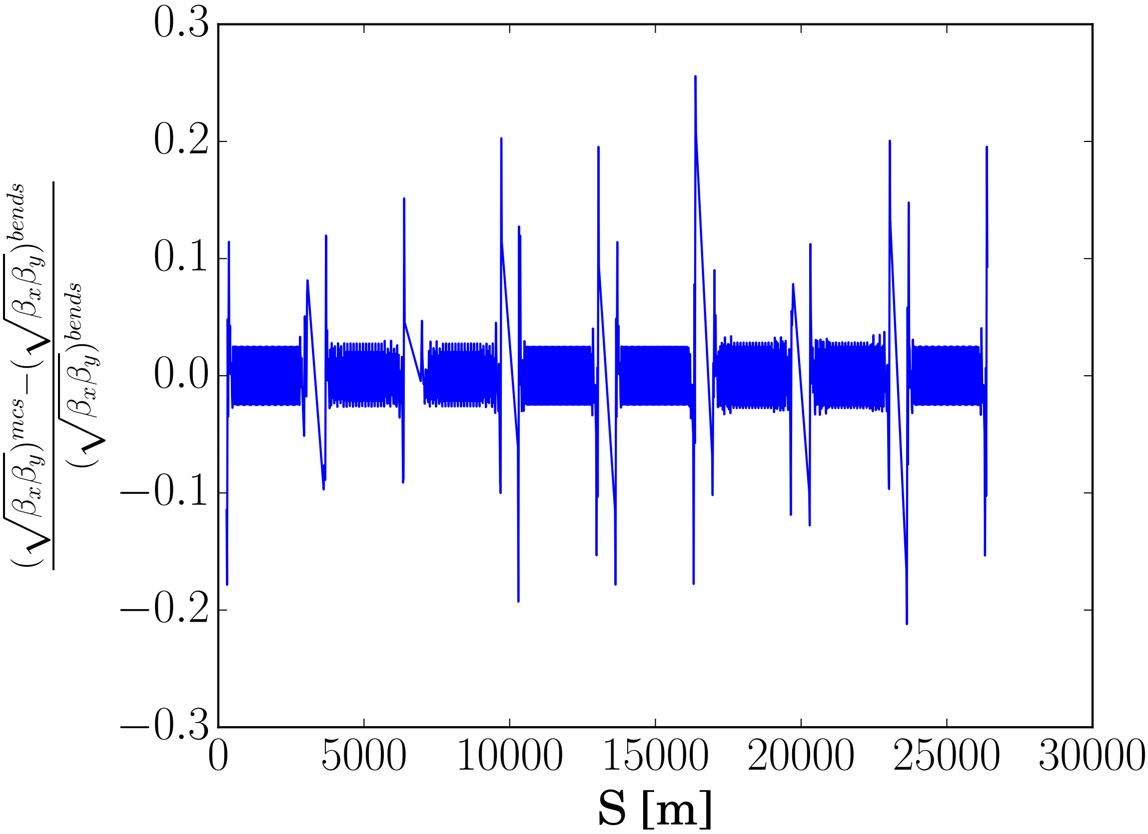


Figure 14: The relative difference between $\sqrt{\beta_x\beta_y}$ at the middle of the bend and at the location of the MCS.

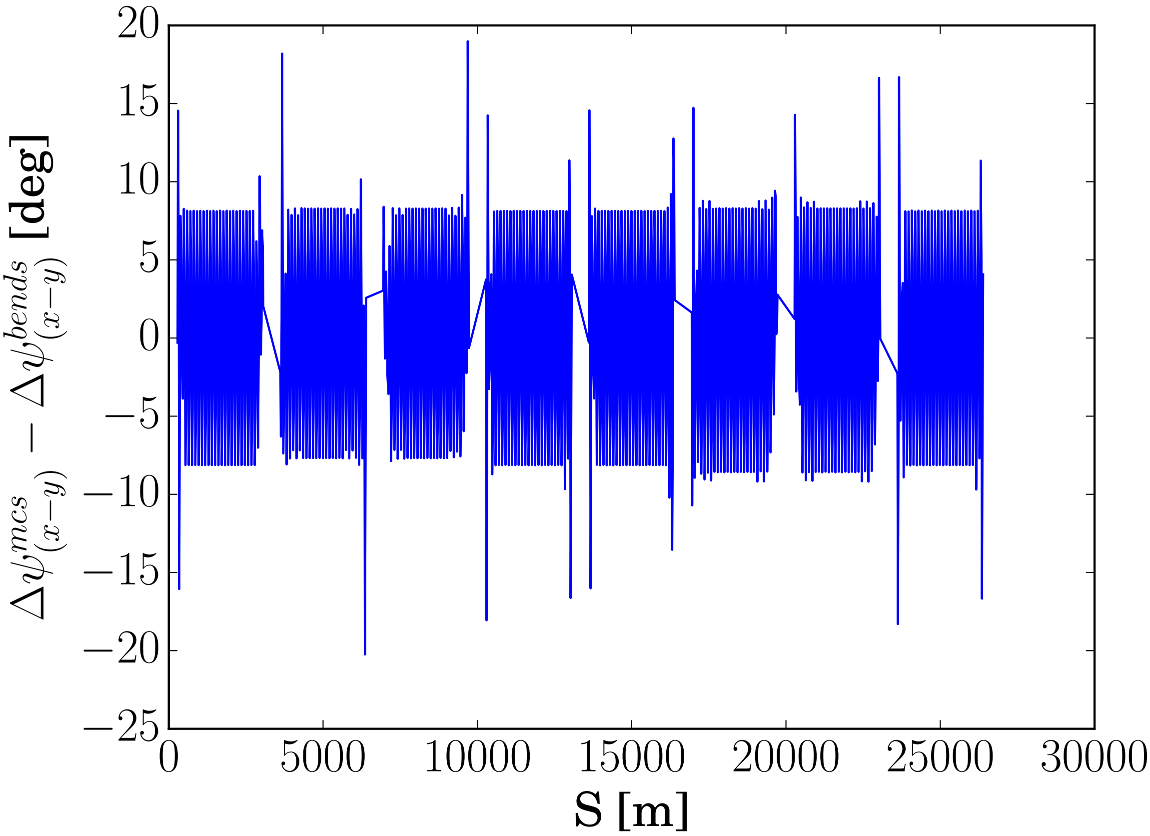
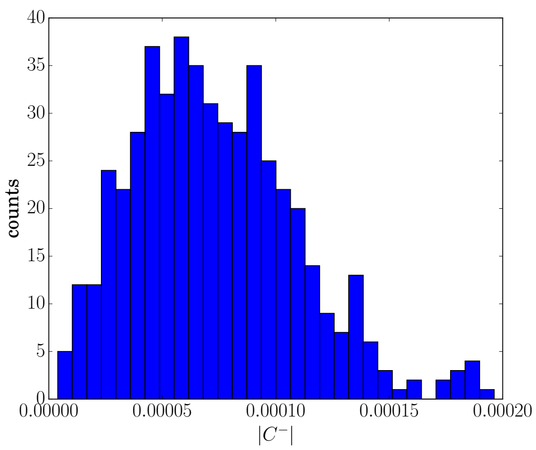
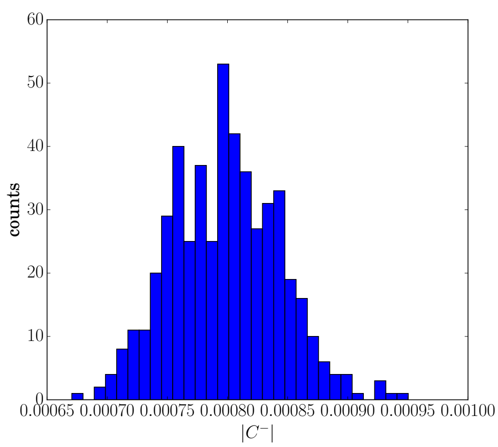


Figure 15: The difference in phase advance between the middle of the bend and the MCS in units of degrees.



(a) Beam 1.



(b) Beam 2.

Figure 16: $|C^-|$ assuming a σ of 30% of the b_3-decay during the third decay measurement.

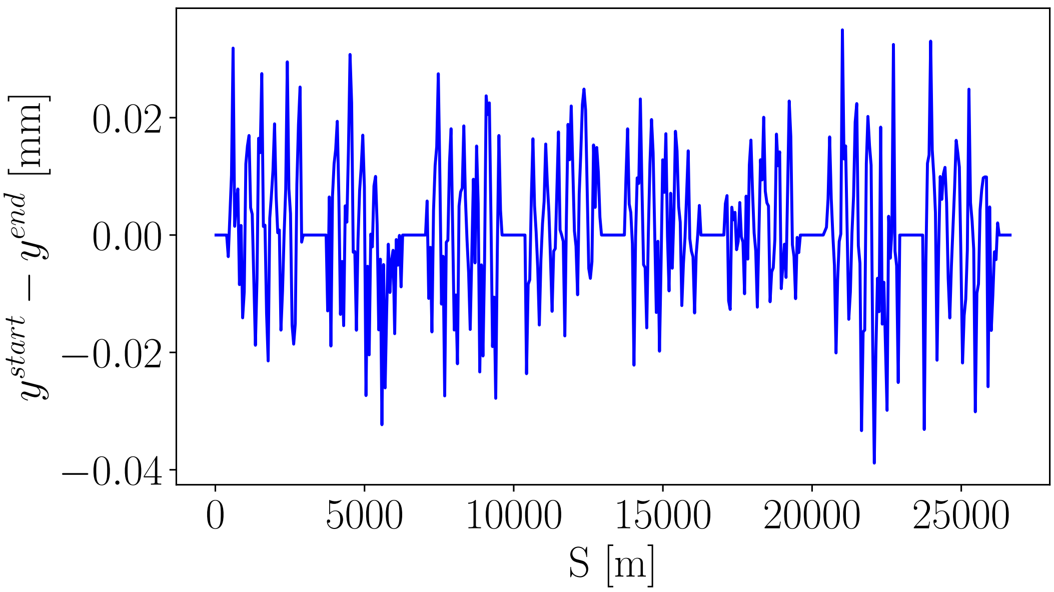


Figure 17: The difference between the vertical orbit for Beam 1 at the end of the decay measurement the start.

4.6 Orbit drifts

One of the most crucial things to rule out is a possible orbit drift, since a change in orbit in conjunction with a non-perfect local correction of the b_3 (static + dynamic) would lead to a change in coupling. In Fig. 17 the difference between the start and end of the measurement is given. We can observe that the orbit drift is less than 0.03 mm which is extremely small, and we do not observe any systematic shift of the orbit in any of the arcs. Assuming no misalignment of the MCS and locally corrected b_3, the change from the the orbit drift is around 10^{-5} for the $|C^{-}|$ in the simulation. In case we also assume an error in the powering of 10% (static + dynamic) the change of the $|C^{-}|$ is still below 10^{-4}. From this, we can conclude that this was not the main reason for the observed coupling shift.

5 Conclusion and Outlook

The potential missalignments of the MCS have been studied in detail. There is compelling evidence that there are systematic vertical misalignments of the MCS. The measurement of the coupling when changing the powering of the MCS gives a direct answer to how much the orbit on average is offset with respect to the MCS. However, to answer the question if the dipoles are misaligned as well, other studies presented within this report were needed. The clearest evidence that the MCS are significantly more misaligned than the dipole and the main sextupoles is perhaps that the coupling did not change nearly as much when the compensation was done with the main sextupoles instead of the MCS. A second convincing result is how well the measured coupling pattern is matching the simulated one when assuming a misalignment of the MCS. The third one is that a very large spread in the error of the b_3-decay errors in the dipole would be needed to explain the observed coupling decay. Additionally, we have ruled out the possibility that the change is driven by difference in orbit, β-function and phase advance. In comparison, a simple model assuming a vertical misalignment of the MCS fits well with the different observations.

A way to mitigate the coupling decay has also been demonstrated during MD. This would reduce the coupling decay and possibly save time when setting up the machine. The impact on dynamic aperture, Q'' as well as the Montague functions, is minimal in the simulations. It is therefore a very attractive option to mitigate the coupling decay when the LHC is to be switched back on for Run 3.

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A Sign validation

MAD-X and LSA uses different definitions of the sign for skew components. However, in this case we are changing the MCS which have the same convention and we will be following the MAD-X convention in this part. The purpose of this appendix is to be able to go back in and cross check in case a sign error is discovered later.

The following part is copy pasted from the automatic logging. These values correct the machine in MAD-X (needs to be swapped to correct the machine):

```
RCS.A34B2/K2    -0.01
2018-09-16 04:27:31.252 - qx=0.2754 qy=0.295 qdx=0.2634 qdy=0.31 -
3.0\% 3.0\% - 1.4484mm 1.5036mm - dpp: 2.279E-5 -
Coup re: 0.0 im: -7.0E-4

RCS.A34B2/K2    +0.01
2018-09-16 04:29:37.917 - qx=0.2754 qy=0.295 qdx=0.2634 qdy=0.31 -
3.0\% 3.0\% - 1.3825mm 1.4446mm - dpp: 2.261E-5 -
Coup re: 0.0018 im: -1.0E-4
```

The difference in real is: 0.0018-0 $=$ 0.0018, imag $=$ (1E-4)-(-7E-4) $=$6.0E-4. This is the difference for a change of K2 of $+$0.02. To convert from $1b_3$=$1k_2$/(-30.35). The real part per b_3 is then equal to 0.0018/(-30.35 * 0.02) $=$ -0.003 (same calculation for the imaginary part) which is also what is given in Tab. 3a.

In MAD-X what is done is that a misalignment is introduced and the setting of the MCS is introduced. A correction of the coupling is then calculated. The script is included for completeness.

```
call, file = "main.seq";
call, file = "ats_11m_fixQ8L4.madx";

beam, particle = proton, sequence=LHCB1, energy = 450.0;
beam, sequence=LHCB2,particle=proton,
energy=450,kbunch=1,npart=1.15E11,bv=-1;

use, period=LHCB2;
SELECT, FLAG = ERROR, PATTERN = "MCS.*";
EALIGN, DY =-0.55E-3 ;
```

Date	Beam	Measurements description
29/10/2018	2	π vertical orbit bumps
16/9/2018	2	Uneven b_3 compensation + MCS change
04/04/2018	1,2	Coupling Decay
15/05/2017	2	Removed dynamic MCS
31/10/2016	2	Coupling Decay [3]

Table 4: The dates where the different measurements were performed.

```
SELECT, column=name, dy;
kcs.a34b2 = 0.02;

match;
vary, name=Cmrs.b2;
vary, name=Cmis.b2;
constraint, range=#E, r11=0, r12=0,r21=0, r12=0;
lmdif;
endmatch;

value, Cmrs.b2;
value, Cmis.b2;
```

The relevant output from MAD-X is:

```
value, Cmrs.b2;

cmrs.b2              =      0.001822546667 ;
value, Cmis.b2;

cmis.b2              =     0.0005885522116 ;
```

The signs are now the same as what we got from the measurement meaning that there should be a negative vertical misalignment of the MCS compared to the reference orbit.

B Measurements

In Tab. 4 the dates for the different measurements are shown. They were all carried out with a single pilot bunch at injection. The first of the two MDs was carried out on the 16/9/2018 during a 4 h slot with only Beam 2 available. The second MD was carried out on the 29/10/2018 during a 2 h slot.