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Report from LHC MD 6863: Amplitude Detuning Corrections from Feed-Down

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Summary

Report of the MD6863 performed on the 24th and 25th of June 2022 to establish new corrections for the dodecapole correctors in LHC IP1 and IP5 to mitigate feed-down effects of high-order errors to amplitude detuning. While very tight in timing, the MD was fruitful and not only yield a plethora of amplitude detuning measurement data, but also already a new correction which has been calculated online.

Contents

1 Motivation

During LHC commissioning in 2018, upon changing the crossing scheme from flat-orbit to the operational scheme, an increase in amplitude detuning was measured [1, 2]. Further investigation, e.g. during MD3311 [3] confirmed this finding and revealed the main contribution to be feed-down from high-order errors, i.e. decapole and dodecapole errors and above, to the octupole fields, due to the crossing schemes in IP1 and IP5.

Dodecapole fields are expected to be the main culprit, as they are the first allowed harmonic of quadrupole magnets [4] and also contribute directly to second-order amplitude detuning. The harmful influence of decapole and dodecapole errors on dynamic aperture and beam lifetime in the upcoming HL-LHC has been shown in simulations and dedicated measurements, in which the normal dodecapole errors were artificially increased to replicate the HL-LHC conditions [5, 6, 7, 8, 9, 10].

The possibility to correct the feed-down to amplitude detuning with the normal dodecapole correctors in the nonlinear corrector packages in IP1 and IP5 has been studied in simulations [11], yet the lack of (good quality) amplitude detuning measurement data has prevented the calculation of usable correction values.

During commissioning in 2022 detuning measurements have been taken and yielded a well functional first correction. Due to the limited time during commissioning, the corrections still left room for improvement, e.g. no distinction could be made between the error-sources, neither by IP nor by order (decapole/dodecapole).

This MD was proposed to mitigate this circumstance.

1.1 Proposed Procedure

It was envisioned to get a full overview of the high-order error sources feeding down to amplitude detuning. to achieve this goal, the following detuning measurements were planned:

- at flat-orbit, so we have a base-line without feed-down
- with the full-operational crossing scheme, to see the full influence of feed-down
- with crossing individually turned off in IP1 and IP5 to establish the origin of the errors per IP
- with positive and negative crossing angles (either in both IPs or in one IP and with full-crossing), to analyze the source of the errors by order (decapole or dodecapole) in total and per IP.
- final detuning measurement at full-crossing scheme, with dodecapole corrections in place calculated from the results of the previous measurements.

It was not clear, if the last point would be enough, as it was suggested in [9] that measurements at 5 different crossing angles (instead of the here proposed 3) are required to get reliable results.

To achieve amplitude detuning measurements, the AC-Dipole excitations are performed in the two transverse planes at the same time to be able to measure both tunes. The amplitude of one plane is kept low and constant, while slowly increasing the strength, i.e. action, of the other plane. The $\Delta_Q = |Q_\text{natural} - Q_\text{driven}|$ of the plane with constant amplitude kicks is usually smaller than the other, to increase signal-strength of the tune line even at these low amplitudes due to the decreased adiabaticity of the ramp. In the other plane, the driven tune is kept slightly further apart to avoid exciting diagonal ($\Delta_{Q_x} = \Delta_{Q_y}$) resonances [12, 13]. The amplitude is increased within the amplitude range of the AC-Dipole only in small steps and only until first losses at the collimators can be seen, to not risk a beam dump and to not loose beam intensity, needed to ensure good signals in the subsequent measurements. When the available kick amplitude has been exploited, the procedure is repeated with the roles of the planes switched.

As we have seen a low quality of the cross-term measurements in the past, in preparation for commissioning 2022 and this MD, the possibility of additionally analyzing "diagonal" kicks, with the kick strength increasing in both planes, has been implemented into the `omc3` [14] analysis software package.

The final step, testing the calculated corrections, was left optional, depending on wether or not this would be a two-part MD: with first performing measurements the different suggested scenarios without corrections only, then calculating the corrections offline and then - a few days later - testing the corrections. In case of only a single shift, the procedure including online analysis of the data, was deemed too ambitious.

2 Measurement Summary

2.1 Actual Procedure

The actual MD was not split into the two parts, first gathering data to calculate the corrections and in a second shift, validating the corrections. Instead, any corrections to be tested had to be calculated online. Despite this and the delay due to the AC-Dipole not coming online in Beam 2 in the horizontal plane, which was fixed by the Kicker-Piquet, the MD turned out to be very successful.

Due to the tight timing constraints, and as the first kicks showed excellent tune-measurement quality, any diagonal kicks were omitted, and we increased the kick-strength classically only in one plane. Thanks to immediate feed-back from the frequency analysis and thanks to the small Δ_Q high quality measurements could be assured. In the end, a total of 192 AC-Dipole kicks in Beam 1 and 174 kicks in Beam 2 could be performed. This is illustrated in Fig. 1 exemplarily for Beam 2: Shown is the tune as measured from the BBQ-system in the horizontal plane, at at each kick, the excited tune is picked up. So each vertical line corresponds to a single kick in this plane.

We managed to re-measure amplitude detuning with horizontal and vertical action at 30 cm after squeeze at flat-orbit and with crossing angles in (in IP2 and IP8 all nominal; in IP1 and IP5 only in the crossing plane nominal, no separation and no dispersion suppression) and analyse the data: The detuning was mostly similar to the measurements from commissioning (27.05.2022 and 04.06.2022), despite b_4 correction and waist shift knob now in. Only the cross-terms did not agree as well between measurements in horizontal and vertical plane as before.

From the new measurements a b_6 correction knob was calculated. The analysis in general and the calculation of the corrections are discussed in detail in [15]. The correction values were, especially for the `MCTX3.L1`, different from the operational b_6 knob (see Table 4).

Table 1: Key MD parameters.

Objective:	Establishing amplitude detuning corrections of the dodecapole correctors targeting feed-down to b_4.					
MD #:	6863					
Operators:	T. Argyropoulos, M. Hostettler					
Energy:	6.8 TeV					
Fill #:	7860					
Beam Process:	MD → `SQUEEZE-6.8TeV-60cm-30cm_V1_MD1@337`					
Date:	24/25 . 06 . 2022					
Start Time:	21 : 15					
End Time:	06 : 45					
Optics:	`R2022a_A30cmC30cmA10mL200cm`					
Full Crossing Scheme						
CROSSING:		IP-Plane	IP1-Y	IP2-Y	IP5-X	IP8-X
		µrad	-160	200	160	–200
SEPARATION:		IP-Plane	IP1-X	IP2-X	IP5-Y	IP8-Y
		mm	0	1.0	0	1.0
IP5-Only Crossing Scheme						
CROSSING:		IP-Plane	IP1-Y	IP2-Y	IP5-X	IP8-X
		µrad	0	200	±160	–200
SEPARATION:		IP-Plane	IP1-X	IP2-X	IP5-Y	IP8-Y
		mm	0	1.0	0	1.0
New Knob:	`LHCBEAM/ATS_2022_06_25_MD6863_BX_LOCAL_IP15_B6` in `BETA-BEATING-MD` for all R2022a* optics					
Logbook:	2022-06-25					

Figure 1: Horizontal tune as measured from the BBQ system in Beam 2 during the duration of MD6863.

At the same time measurements continued: the crossing in IP1 was trimmed out and detuning measurements performed with IP5 crossing at the nominal value (+160 µrad) and the opposite value (−160 µrad), to be able to determine the source of the high-order errors regarding IP and regarding error order (b_5 or b_6).

Finally, crossing angles were returned to nominal in IP5 and IP1 and the new b_6 correction applied. Detuning with horizontal and vertical action was remeasured under these settings.

As the time was limited, and due to the problems with the AC-Dipole, even more restricted, quite coarse amplitude scans were performed and less kicks per scan gathered as hoped.

In the end, the data had still been enough and of good quality to perform extensive detuning analysis studies offline, which will be published in [15]. In particular, good amplitude (to around 0.014 µm) could be reached for all performed scans, and beam-losses per kick wwere small enough to kick on the same fill for the whole night, thanks to the NLO-collimator sequence, newly prepared by the Collimation-Team.

The online analysis results used to calculate the b_6 correction can be found at 2022-06-25 in the LHC_OMC logbook (link in Table 1) and in Section 2.2. A detailed timeline of the MD procedure is provided by Table 2.

2.2 Results

The measured detuning values for all measured scenarios are summarized in Table 3 and shown in more detail in Figs. 2 and 3. In there and in the following, the four detuning terms are abbreviated: $Q_{a,b} = \partial Q_a / \partial (2J_b)$.

Table 2: MD Time-line. Key measurements are shown in **bold**. At the same time as the kicks were performed, they were also analyzed on the fly.

21:15→00:20	MD setup. Waiting for previous MD to finish. AC-Dipole fixing.
00:20	Flat Orbit, with previous b_6 Corrections
	Knob: `LHCBEAM/ATS_2022_05_29_BX_LOCAL_IP15_B6`
00:20→00:55	*Horizontal Kicks*
00:30	*Coupling Correction:* Beam 1: $(-1+2.5\mathrm{i})\times10^{-3}$, Beam 2: None
00:58	Trim out b_6 correction.
01:00	**Flat Orbit, no b_6 Corrections**
01:00→01:30	*Horizontal Kicks*
01:30→02:00	*Vertical Kicks*
02:00	Enabeling full crossing scheme.
02:00	**Full Crossing, no b_6 Corrections**
02:00→02:30	*Kicks for Coupling Correction*
02:30	*Coupling Correction:* Beam 1: $(2.6+2\mathrm{i})\times10^{-3}$, Beam 2: $(0+2\mathrm{i})\times10^{-3}$
02:38→03:06	*Vertical Kicks*
03:09→03:35	*Horizontal Kicks*
03:20	Removing crossing in IP1.
03:30	**IP5@+160 µrad, no b_6 Corrections**
03:40→03:50	*Kicks for Coupling Correction*
03:45	*Coupling Correction:* Beam 1: $(-5-3\mathrm{i})\times10^{-3}$, Beam 2: $(0-1\mathrm{i})\times10^{-3}$
03:50	*Coupling Correction:* Beam 1: $(1.4+0\mathrm{i})\times10^{-3}$, Beam 2: $(-1.4+0\mathrm{i})\times10^{-3}$
03:55→04:21	*Horizontal Kicks*
04:23→04:40	*Vertical Kicks*
04:40	Switching crossing angle in IP5.
04:45	**IP5@−160 µrad, no b_6 Corrections**
04:45→04:47	*Kicks for Coupling Correction*
04:47	*Coupling Correction:* Beam 1: None, Beam 2: $(-4+0\mathrm{i})\times10^{-3}$
04:45→05:07	*Vertical Kicks*
05:07→05:25	*Horizontal Kicks*
05:30	**Trim in new correction,**
	based on measurements from 01:00 - 03:30 with flat-orbit and full-crossing
	Knob: `LHCBEAM/ATS_2022_06_25_MD6863_BX_LOCAL_IP15_B6`
05:30	Enabeling full crossing again.
05:33	**Full Crossing, with b_6 Corrections**
05:33→05:35	*Kicks for Coupling Correction*
05:35	*Coupling Correction:* Beam 1: $(1.6+0\mathrm{i})\times10^{-3}$, Beam 2: $(5.4+1.2\mathrm{i})\times10^{-3}$
05:37→05:58	*Horizontal Kicks*
05:58→06:30	*Vertical Kicks*

As also already established during commissioning, we see, that the feed-down from the high-order errors to amplitude detuning is still present in the current state of the machine.

From the measured values, corrections for the dodecapole errors have been calculated, as presented in Table 4. In this table, also the correction strengths calculated offline after the MD are shown, which take also the measurements into account in which only crossing in IP5 is activated. This is discussed in detail in [15], in which it is also shown, that both IP1 and IP5 contribute in equal amounts to the measured detuning and that indeed, the majority stems from normal dodecapole field errors.

In Fig. 4 the detuning change between full-crossing and flat-orbit is presented, with and without the during the MD calculated corrections: it can bee seen, that in total the detuning was reduced, but that there are trade-offs between the terms. Yet especially Beam 1 direct horizontal ($Q_{x,x}$) and Beam 2 direct horizontal and cross-terms ($Q_{x,x}$, $Q_{x,y}$), which were the terms with the largest detuning coefficients, have been reduced.

Table 3: Summary of amplitude detuning measurements from the MD. Detailed orbit setups are described in Table 1 while here the measurements are identified by either "flat-orbit" (i.e. crossing bumps deactivated) or which of IP1 and IP5 are activated and at ("@") which half-angle. If both IPs are mentioned with different signs, the top sign refers to IP1 and the bottom sign to IP5. Measurements for Beam 1 are shown in blue (top) and for Beam 2 in red (bottom). The results have been corrected for the effect of forced oscillations [16].

	$Q_{x,x}$ [10^3 m^{-1}]	$Q_{y,x}$ [10^3 m^{-1}]	$Q_{x,y}$ [10^3 m^{-1}]	$Q_{y,y}$ [10^3 m^{-1}]
w/o b_6 flat-orbit	-18 ± 2 -19.2 ± 1.7	32 ± 2 13.1 ± 1.7	22 ± 4 12 ± 2	0.0 ± 0.9 3.4 ± 0.8
w/o b_6 IP1&5 xing @ $\mp$160 µrad	9 ± 2 20.9 ± 1.1	36.8 ± 2.0 -39 ± 2	27 ± 2 -42.7 ± 1.6	2.1 ± 1.0 19.7 ± 1.3
w/o b_6 IP5 xing @ +160 µrad	23 ± 2 10.6 ± 1.2	1 ± 2 -8 ± 3	-3.7 ± 1.2 -15.8 ± 1.6	3.0 ± 1.4 5.3 ± 1.2
w/o b_6 IP5 xing @ −160 µrad	8.9 ± 1.4 20.3 ± 1.7	4 ± 3 -15 ± 4	-0.9 ± 0.5 -23.3 ± 1.7	0.3 ± 0.5 -1.5 ± 1.6
w/ b_6 IP1&5 xing @ $\mp$160 µrad	-12.7 ± 1.0 -46 ± 4	33 ± 2 31 ± 2	30.1 ± 1.0 34.5 ± 1.4	17.5 ± 1.4 -17.9 ± 1.0

Table 4: Dodecapole-corrector strength values (K_6). In parenthesis the percentage (rounded to integers) of the maximum powering at 6.8 TeV is given. The "w/ IP5" and "w/o IP5" labels on refer to whether the additional measurements of crossing-bumps only around IP5 were taken into account or not.

	IP1			
	`MCTX.3L1` $[10^3\,\mathrm{m}^{-6}]$		`MCTX.3R1` $[10^3\,\mathrm{m}^{-6}]$	
Commissioning 2022	-0.606 ± 0.715	(2%)	-2.696 ± 1.179	(7%)
MD6863 w/o IP5	1.269 ± 0.731	(3%)	-3.288 ± 0.577	(9%)
MD6863 w/ IP5	0.493 ± 0.192	(1%)	-3.982 ± 0.188	(11%)
	IP5			
	`MCTX.3L5` $[10^3\,\mathrm{m}^{-6}]$		`MCTX.3R5` $[10^3\,\mathrm{m}^{-6}]$	
Commissioning 2022	5.004 ± 0.752	(14%)	-5.053 ± 0.907	(14%)
MD6863 w/o IP5	6.367 ± 0.563	(18%)	-4.087 ± 0.782	(11%)
MD6863 w/ IP5	5.003 ± 0.132	(14%)	-5.032 ± 0.162	(14%)

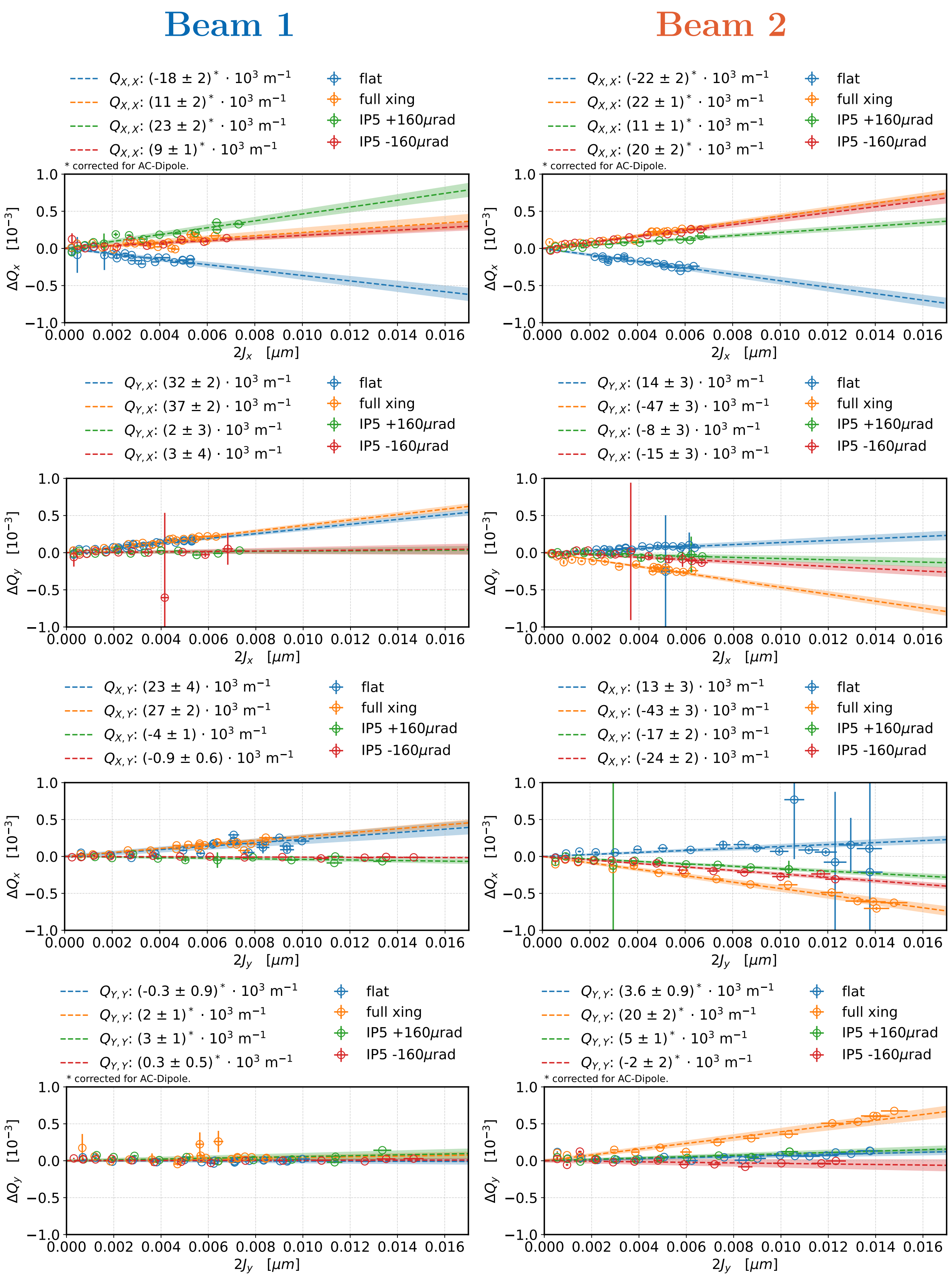

Figure 2: Amplitude Detuning measurements results for detuning measurements with flat-orbit, full-crossing and only IP5 crossing (both sides) **without** b_6 corrections.

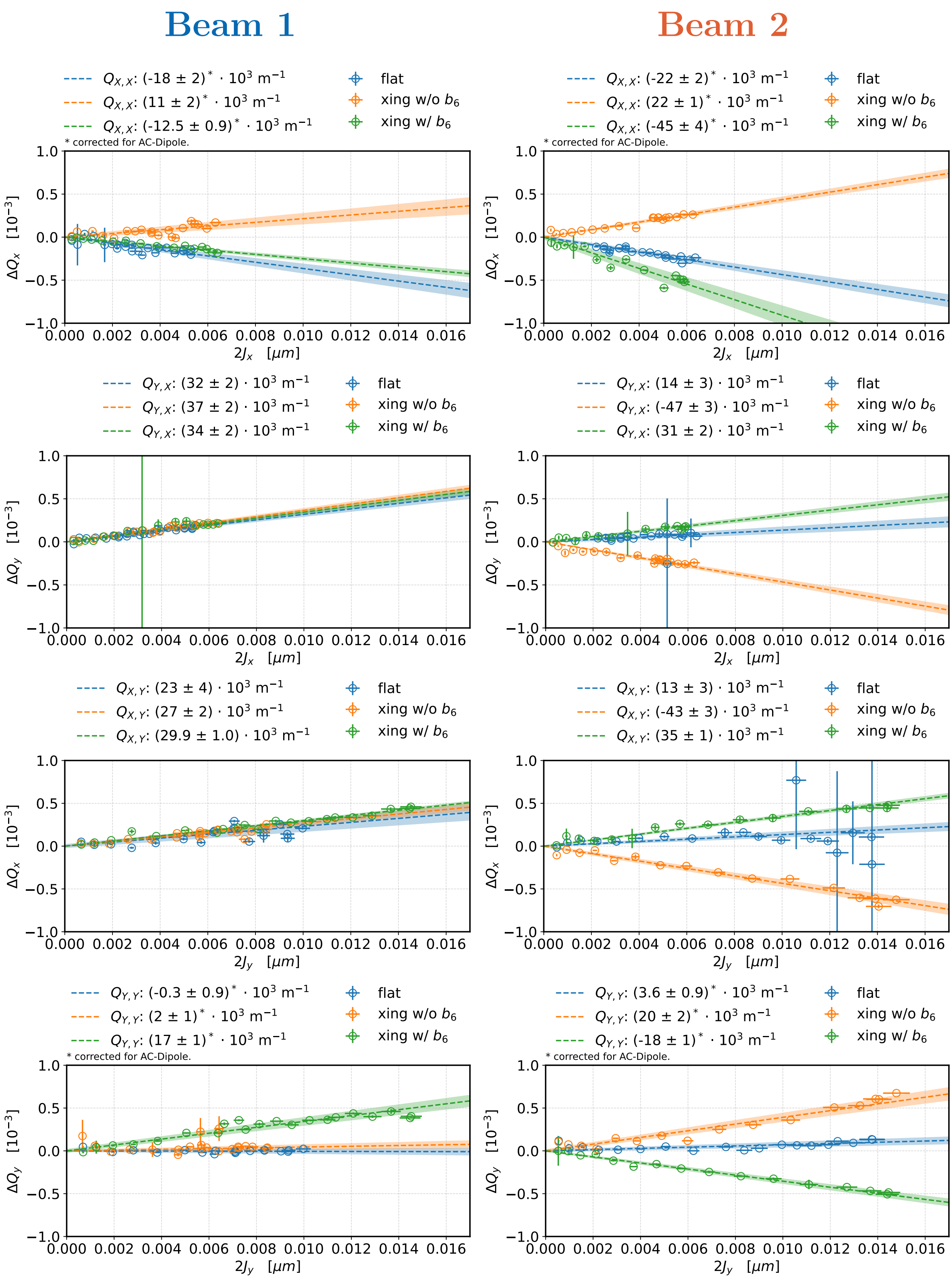

Figure 3: Amplitude Detuning measurements results for detuning measurements without and with b_6 corrections at full crossing.

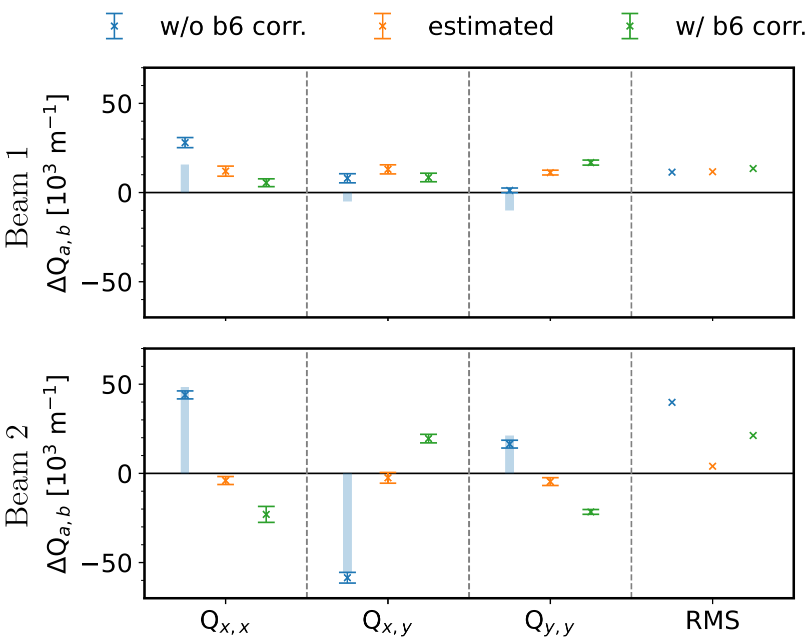

Figure 4: Detuning shifts between detuning with full crossing and at flat-orbit for all detuning terms and the error-weighted root-mean-square (RMS) over all terms. Measured values for the cross-terms $Q_{x,y}$ and $Q_{y,x}$ have been averaged. Shown in blue is the measurement without dodecaple correction applied as circle with error bars, and the detuning to be compensated by the correction as simulated via the bar. In orange the estimated value after correction is shown. The data in green is the actual measured detuning shift with crossing angle after dodecapole correction.

3 Conclusion

Despite early hick-ups at the beginning of the MD, MD6863 has been extraordinarily successful and produced very good amplitude detuning measurements and a well working second iteration of the correction settings for the IR dodecapole corrector package. The settings have since then been further refined [15], taking all of there here performed measurements into account, which are as of commissioning 2023 used operationally.

Only, measurements for the detuning solely stemming from IP1 could not be performed, due to the lack of time.

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