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An alternative method to measure amplitude dependence of the closest tune approach

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Summary

In the linear regime, a minimum closest approach of the fractional horizontal and vertical tunes exists, due to linear coupling between the transverse planes. Simulation-, theoretical-, and beam-based studies of the LHC in Run 1 and 2 however, also demonstrated the existance of an amplitude dependence of the closest tune approach. This **A**mpiltude **DE**pendent **C**losest-**T**une-**A**pproach (ADECTA *"Add-Ek-Ta"*) is a topic of interest due to its potential to generate large distortions of the tune footprint in the vaccintity of the $Q_x - Q_y =$ n resonance, which may then impact Landau damping. The measurement technique utilized in previous beam-based studies features a number of significant limitations however, most particularly that it is impractical to apply at top-energy in the LHC. This note presents the result of tests of an alternative measurement technique which can overcome limitations of the previous method.

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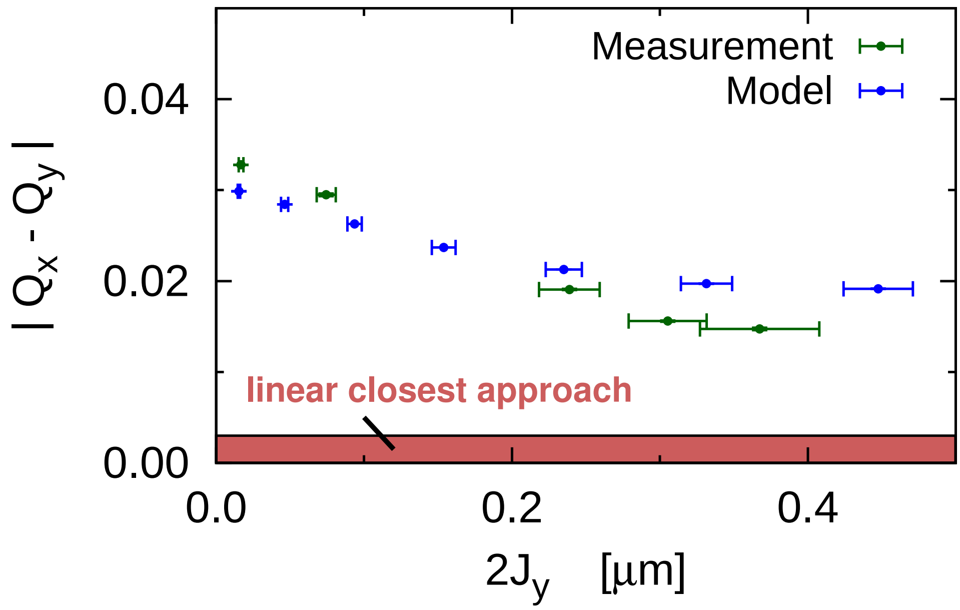

Figure 1: Variation of fractional tune split with action.

1 Motivation and description

Measurement and simulation of amplitude detuning in 2012 [1] demonstrated a highly non-linear (i.e. of order above octupolar) change in $Q_{x,y}$ for the action plane approaching the difference coupling resonance ($Q_x - Q_y$). The nonlinearity of the detuning was observed in simulation to be extrememly sensitive to the initial working point [1]. By examining the change of tune-split with action, $\frac{\partial|Q_x-Q_y|}{\partial 2J}$, as opposed to detuning with action, $\frac{\partial Q_{x,y}}{\partial 2J}$, it was possible to identify these unusual patterns of amplitude detuning with a saturation of the fractional tune-split as a function of action [1]. Of particular interest however, is that this saturation in tune-split occurred for a tune-separation significantly larger than the linear coupling. This is shown in Fig. 1. An interpretation of the observations was proposed in terms of an amplitude-dependence of the closest-tune approach, as described in [1] (*Chap. IV, Sec. B.3*).

Further studies performed in Run 2 have helped improve the understanding of the Amplitude Dependent Closest Tune Approach. Notably, it was identified in simulation that a large ADECTA could be generated through the combination of linear coupling and normal octupole sources [2]. A theoretical description of the mechanism generating ADECTA through these sources was proposed in [3]. This theory predicted that ADECTA generated by linear coupling in conjunction with the Landau octupoles could be suppressed by powering the MOF and MOD with opposite strengths. This was demonstrated in a dedicated MD in 2016 [4, 5]. It was also demonstrated in simulation that skew octupoles in conjunction with normal octupoles could also give rise to ADECTA [6] even in a complete absence of linear coupling (skew octupoles alone do not generate ADECTA in simulation). ADECTA from the combination of a_4 and b_4 sources was then demonstrated at injection in the LHC in 2017 [7]. The observation (with beam and simulation) that skew octupoles can contribute to the ADECTA is a particularly interesting prospect for future operation of the

LHC and HL-LHC at low-β^*, since large skew octupole errors in the insertion magnets could generate substantial distortion of the tune-footprint, with potentially detrimental effects to Landau damping [8]. Figure 2 (right) shows an example of the tune footprint-distortion which could be expected at $\beta^* = 0.25$ m in the LHC if a_4 errors were left uncompensated, for a typical operational powering of the Landau octupoles (but with no contribution from beam-beam). The skew octupoles introduced in this case are representative of the a_4 errors infered from beam-based measurments of the LHC. This can be contrasted with Fig. 2 (left) which shows the distortion obtained from a $|C^-| = 0.25 \times \Delta Q$ (where ΔQ is the tunesplit at zero amplitude).

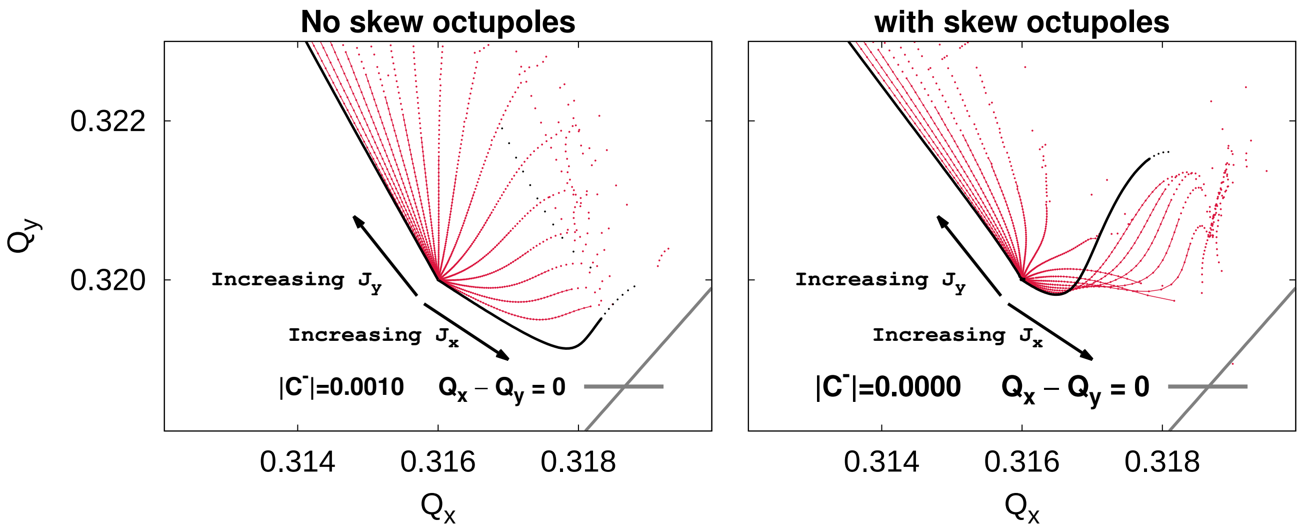

Figure 2: Footprint distortion in the LHC due to typical values of the linear coupling (left), and due to uncompensated skew octupole errors in the triplets (right) at $\beta^* = 0.25$ m. Both cases are considered in conjunction with typical operational powering of the Landau octupoles and for non-colliding beams.

Prior to the MD reported in this note, all beam-based studies of ADECTA had been performed via the saturation of tune-split with action, for the detuning plane approaching the difference coupling resonance, as per Fig. 1. This is clearly a useful measurement, since it directly yields information on the footprint distortion along the action plane which approaches the difference resonance. The method does suffer from several limitations, however:

- It relies on the presence of normal octupole detuning to drive the tunes towards the $Q_x - Q_y$ resonance, in order to observe a saturation of the tune split and departure from the octupole-like detuning which dominates at small amplitude. It is not possible therefore to probe any potential mechanism for ADECTA generation which does not include amplitude detuning (or equivalently to validate with beam the prediction that skew-octupoles on their own cannot generate ADECTA).
- The necessity to detune towards the difference coupling resonance in order to observe ADECTA restricts the parameter space (J_x / J_y / octupole polarity) which can be explored (since for a given polarity of the Landau octupoles the tunes will approach

the difference resonance in one action plane and retreat in the other). This limits the ability to probe the action dependence predicted by theory.

- The method relies upon repeated application of single kicks to a pilot bunch with the aperture kicker (MKA). In the absence of significant damping, the MKA requires a fresh beam for every kick, and for machine protection reasons may only excite a single bunch at a time. It is impractical to employ this method at 6.5 TeV therefore, since every excitation would require a complete LHC cycle. It should be noted that while the AC-dipole can be used to measure amplitude detuning at top-energy, driven oscillations do not display ADECTA as per free-oscillations (as shown in [4, 5]), thus the AC-dipole cannot be used to study ADECTA at top energy.

These limitations motivate complementary use of an alternative measurement technique which is demonstrated in this note.

A classical measurement of linear difference coupling is performed by forcing the tunes of an otherwise unperturbed beam towards the $Q_x - Q_y$ resonance via quadrupoles trims, and measuring the closest approach of $Q_1 - Q_2$. This is illustrated in Fig. 3.

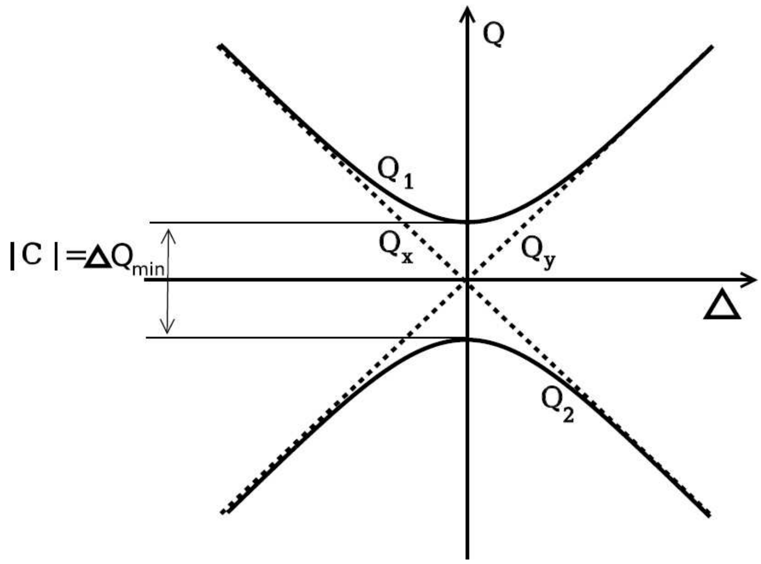

Figure 3: Schematic illustration of a measurement of linear coupling via closest tune approach.

The objective of this MD was to apply this classical closest-tune-approach type study to measurement of ADECTA. At large initial tune separation, single bunches were kicked to large amplitude using the MKA. Following the kick the bunch decoheres on a timescale of several hundred to several thousand turns depending octupole setting and kick amplitude, however the constituent particles persist at the amplitude to which they were kicked. After the bunch has decohered, quadrupole trims can then be applied to try and force the tunes of the decohered beam towards the coupling resonance, with the aim of comparing the closest approach of the kicked bunch compared to that obtained for an unkicked bunch. Since the decohered bunch could not be kicked again without disrupting the charge distribution, this method relies on measurement of the tune of the fully decohered beam via the LHC BBQ. The BBQ is routinely used to measure tune of unkicked beams in the absence of any active excitation. The first aim of the MD was therefore to establish whether it is possible to use the BBQ to measure the tune of a bunch which has previously been kicked and allowed to decohere. Having done so measurement of ADECTA was then attempted via the new closest approach technique. Measurements were performed for linear coupling and octupole configurations which either enhanced or suppressed the ADECTA. Octupole configurations and linear coupling values utilized during the MD were selected to be the same as those used during the 2016 ADECTA suppression MD [4, 5].

2 Measurement Summary

Table 1 summarizes key parameters of the MD. A detailed time-line of the MD is given in Tab. 2. MOF and MOD strengths were manipulated during the MD. In all cases trims were performed on K_{MO} directly in LSA (i.e. not via the Landau damping knob), and all MOF and MOD were trimmed uniformly (though MOF/D were varied independently). Kick strengths are quoted in Tab. 2 according to the applied percentage of the maximum MKA excitation (as set in OP-software).

Table 1: Measurement summary.

Objective:	First attempt at measurement of ADECTA with an alternative method
MD #:	3317
FILL #:	7189
Beam Process:	MD → RAMP_PELP-SQUEEZE-6.5TeV-ATS-1m-2018_V3_V1_MD3@0_[START]
Date:	16/09/2018
Start Time:	16:00
End Time:	22:00
Beam:	LHCB2 (in parallel with ADT MD in beam1)
X'ing config	[170/170/170/-170] μrad in [IP1/IP2/IP5/IP8]
Sep config	[-2.0/3.5/2.0/-3.5] mm in [IP1/IP2/IP5/IP8]

Table 2: MD Time-line. Key measurements are shown in **bold**. Magnet strengths follow LSA conventions.

16:00:00	Previous MD (coupling decay at injection) ends
17:09:31	MO trimmed to $K_4 = -5.0\,\mathrm{m}^{-4}$ (i.e. same polarity MOF/D)
17:30:00	Setup of MKA and synchro delay
17:40:00 - 18:05:00	Large linear coupling introduced as source of ADECTA applied via ΔLHCBEAM2/CMINUS_RE.IP7 = +0.011
18:22:31	KICK: 25%/25%
18:23:00 - 18:43:00	Closest-approach scan: 25% KICK, same polarity, LQ-data
18:51:55	KICK: 40%/40%
18:52:30 - 19:02:20	**Closest-approach scan: 40%, same polarity, LQ-data**
19:11:26	KICK: 32%/30%
19:12:00 - 19:28:00	**Closest-approach scan: 30%, same polarity**
19:32:40 - 19:42:00	**Closest-approach scan: NO KICK, same polarity**
19:42:58	MOD trimmed to $K_4 = +5.0\,\mathrm{m}^{-4}$ (i.e. opposite polarity MOF/D)
19:44:40	KICK: 25%/25%
19:45:00 - 19:54:30	**Closest-approach scan: 25% KICK, opposite polarity**
19:55:00 - 20:01:00	**Closest-approach scan: NO KICK, opposite polarity**
20:01:01	MOD trimmed to $K_4 = -5.0\,\mathrm{m}^{-4}$ (i.e. same polarity MOF/D)
20:02:03	KICK: 25%/25%
20:02:15 - 20:14:50	**Closest-approach scan: 25% KICK, same polarity, good data**
20:23:17	MOD trimmed to $K_4 = +5.0\,\mathrm{m}^{-4}$ (i.e. opposite polarity MOF/D)
20:25:36	KICK: 32%/30%
20:25:50 - 20:32:05	**Closest-approach scan: 30% KICK, opposite polarity**
20:33:31	MOD trimmed to $K_4 = -5.0\,\mathrm{m}^{-4}$ (i.e. same polarity MOF/D)
20:35:59	attempt kick, but accidentally 2 bunches in machine data no use & bunches lost on BLM
20:54:23	MO trimmed to $K_4 = 0.0\,\mathrm{m}^{-4}$ (i.e. MOF/D off)
22:00:00	MD ends

3 Results

The first objective of the MD was to demonstrate that it was possible to measure the tune of a kicked bunch after it has decohered beam, using the BBQ. Figure 4 demonstrates that this was indeed possible for a pilot bunch. It shows tune data recorded by the BBQ before and after a large amplitude kick was applied to the bunch with the MKA. Note the timescale on the figure is much longer than the time required for the bunch to decohere. The detuning with amplitude is clearly observed, as are tune shifts as a function of quadrupole strength.

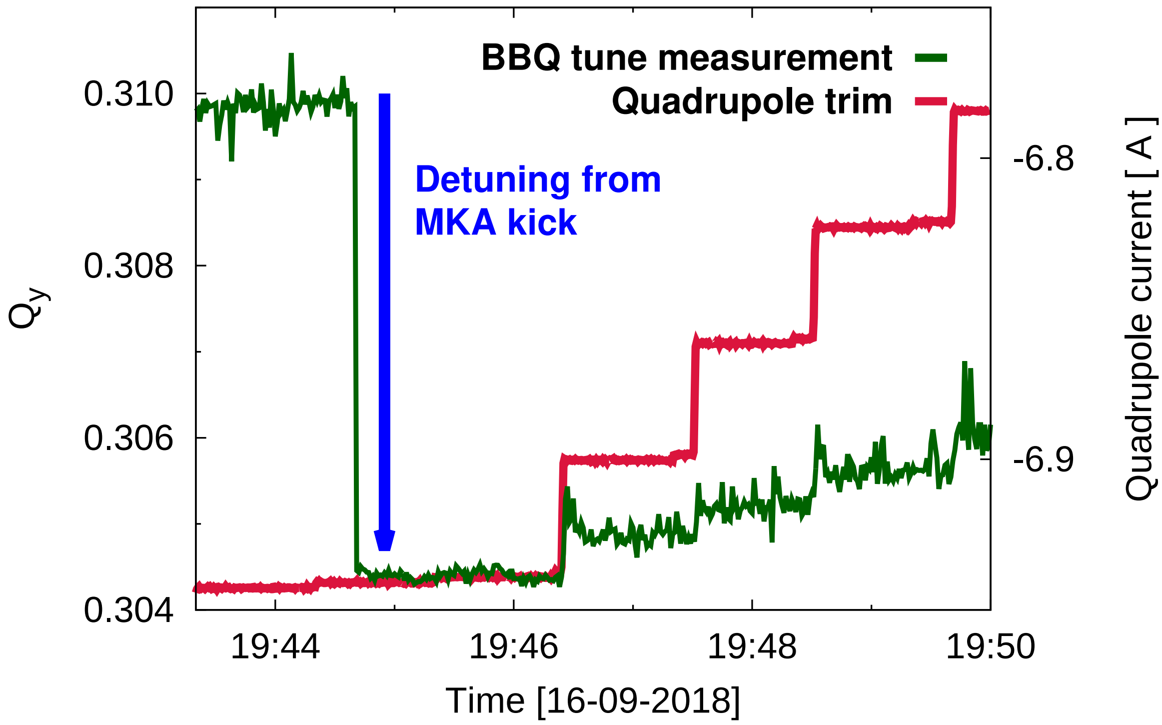

Figure 4: Tune recorded by the LHC BBQ following a large amplitude kick of a single pilot bunch via the MKA.

In attempting to measure ADECTA it is necessary to precisely know the value of the linear closest approach, and to ensure it remains stable to allow comparison of the measurements at different amplitudes. This MD was therefore deliberately scheduled to follow an MD on linear coupling decay at injection. The previous MD remained at injection from **04:00** until the start of the ADECTA study, allowing coupling, tune and chromaticity decay to saturate prior to any attempt to measure ADECTA. The linear closest approach was also measured with unkicked beams to provide a reference to which measurements of the kicked and decohered beams could be compared. Figure 5 shows two measurements of the linear closest approach performed with the two Landau octupole configurations utilized during the MD. The linear closest approach is observed to be extremely stable.

Several ADECTA measurements were performed with equal strength powering of the MOF and MOD (a similar configuration to nominal LHC operation), with a large linear coupling introduced. In this configuration the linear coupling and Landau octupoles are expected to generate a sizable amplitude dependent closest tune approach. RQTF and RQTD

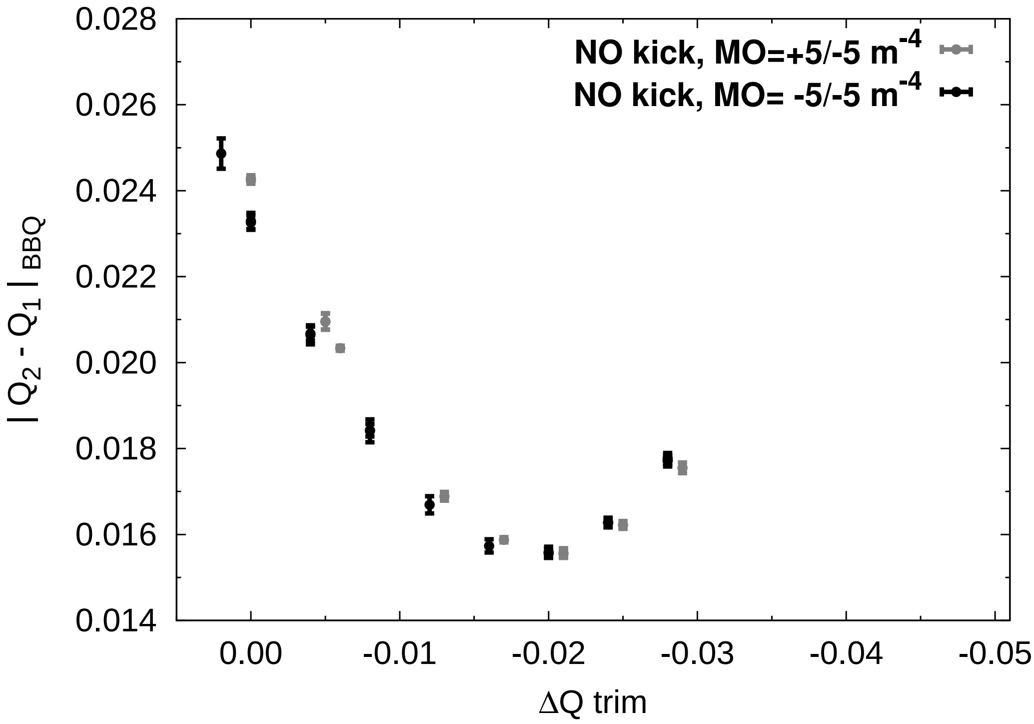

Figure 5: Comparison of stability of closest approach of unkicked beams

were trimmed in a series of plateaus to try and force the tunes towards the linear coupling ($Q_x - Q_y$) resonance. Histograms of BBQ data within each tune trim plateau were cleaned to remove any obvious noise lines and the mean and standard-deviation of the remaining BBQ data taken as the value and error on $Q_{x,y}$. Figure 6 shows tune separation inferred from the BBQ data (vertical axis), together with the total applied ΔQ-trim (horizontal axis). Three closest-approach scans were performed for different strengths of MKA kicks, at $\sim 25\,\%$, $\sim 30\,\%$, and $\sim 40\,\%$ of the maximum possible MKA excitation. The same kick excitation was applied to both the horizontal and vertical planes. Figure 6 compares the linear closest approach of the unkicked beam (black) to that obtained following decoherence of the $\sim 25\,\%$ MKA kick (red). It should be emphasised that all ADECTA data (red) is obtained from a single kick, with the distinct datapoints corresponding to the individual tune trim platteaus that have been applied after decoherence of the bunch). It is observed that following the kick, the beam has detuned slightly towards the coupling resonance (red data at $\Delta Q_{trim} = 0.0$ shows a smaller $|Q_2 - Q_1|_{BBQ}$). As quadrupole trims are applied to the kicked beam, the tune separation evolves in a similar manner to the linear unkicked cases, initially approaching the coupling resonance, saturating at a non-zero ΔQ_{min}, then retreating away to larger ΔQ. However, the ΔQ_{min} which could be achieved with the kicked beam is significantly larger than that obtained in the unkicked case, as expected due to the amplitude dependent closest tune approach.

Figure 7 shows the unkicked and $25\,\%$ MKA kick cases, together with the two additional scans performed at successively higher amplitude ($30\,\%$ and $40\,\%$ of maximum MKA excitation shown in blue and purple respectively). Tune measurement quality from the BBQ has deteriorated significantly as MKA kick strength has increased. For the large amplitude kicks, even though substantial tune trims were applied it was not possible to force the tunes closer than their initial separation. This suggests the ADECTA has increased with amplitude, such that the amplitude dependent ΔQ_{min} was already equal to the initial separation.

ADECTA can be suppressed by powering the MOF and MOD with opposite polarities (in terms of magnet strength). Closest-approach scans at the 25 % and 30 % excitation strengths were also performed for this octupole configuration. Figure 8 compares closest approach measured in the 25 % case for the two octupole arrangements. The closest approach with opposite MO polarity (ADECTA suppression) is significantly closer to the linear ΔQ_{min} than the equal strength configuration, as expected from theory and previous experience. It is worth noting that since arc-octupole errors were uncompensated in 2018 a perfect suppression of the closest approach was not expected. Similarly in the 30 % case, powering Landau octupole to suppress ADECTA (as far as possible) allowed a closest approach to be observed, which was significantly smaller than in the original octupole configuration. No data was obtained for the 40 % excitation strength in the second octupole configuration.

Table 3 details the $J_{x,y}$ values for the kicks obtained from the OMC GUI. Due to the decoherence of the kicks with strong octupoles the actions quoted are inferred from the peak-to-peak betatron oscillations rather than from spectral analysis, however since the coupling (linear and nonlinear) can also affect the peak-to-peak via beating of the motion between the horizontal and vertical planes further analysis will be required to obtain better estimates of the true actions in order to compare to theory. The values quoted should be taken as indicative only.

Table 3: Actions of kicks applied during the MD (as inferred from P2P TbT data and analyses with OMC tools - the effect of beating due to coupling is not accounted for in these estimates).

Time	Kick [%]	KOF/KOD [m^{-4}]	$2J_x$ [μm]	$2J_y$ [μm]
20:02:03	25	-5/-5	0.11 ± 0.01	0.17 ± 0.01
19:11:26	30	-5/-5	0.22 ± 0.02	0.34 ± 0.02
18:51:55	40	-5/-5	0.27 ± 0.03	0.40 ± 0.03
19:44:40	25	-5/+5	0.12 ± 0.01	0.17 ± 0.01
20:25:36	30	-5/+5	0.20 ± 0.02	0.25 ± 0.02

4 Conclusions

The MD appears very successful, with all key aims completed. It was shown that closest-approach tune-scans of kicked and decohered beams could be performed utilizing the LHC BBQ data. The closest approach of kicked beams was observed to increase relative to that of the unkicked (linear) closest-approach. An explicit amplitude dependence of the closest approach was also seen for the first time. It was observed that powering the Landau octupoles to try and suppress ADECTA yielded a closest approach which was significantly reduced when compared that obtained with the original octupole configuration. Application of the traditional closest tune approach scan to kicked beams does therefore appear to be a

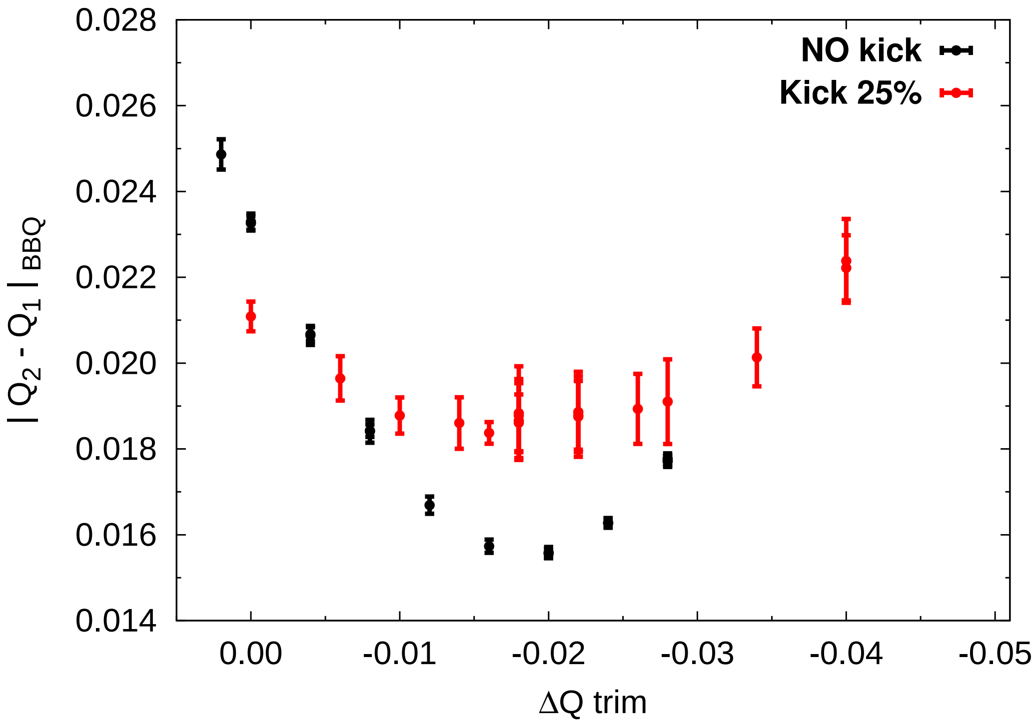

Figure 6: Tune separation vs quadrupole trim with uniform MO powering (enhanced ADECTA).

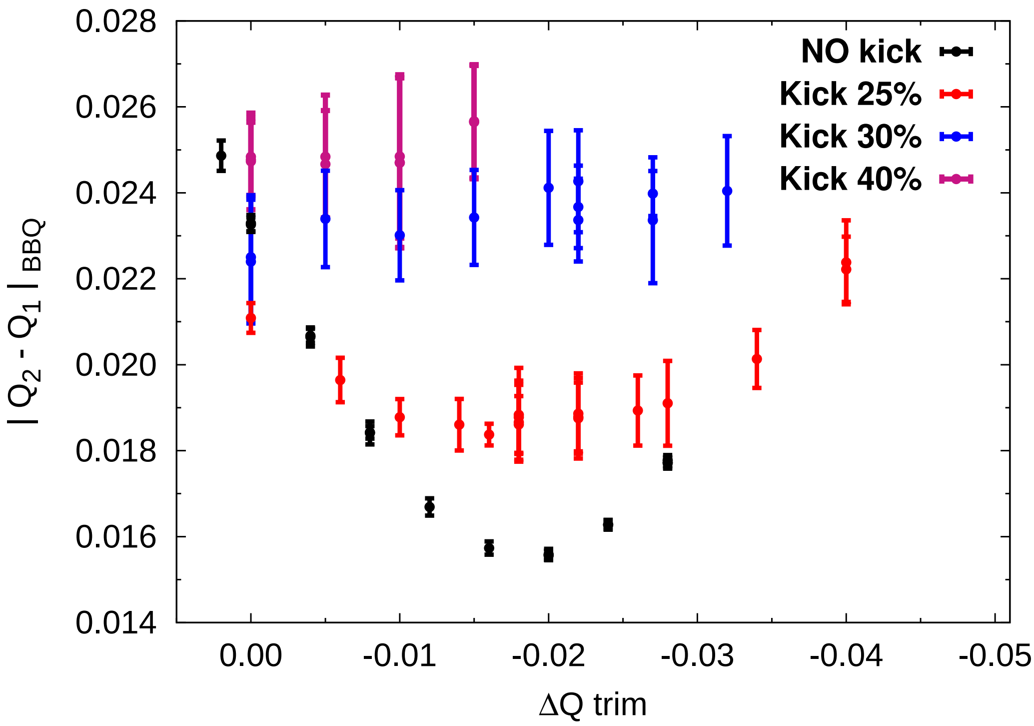

Figure 7: Tune separation vs quadrupole trim with uniform MO powering (enhanced ADECTA), including 2 additional very large amplitude kicks.

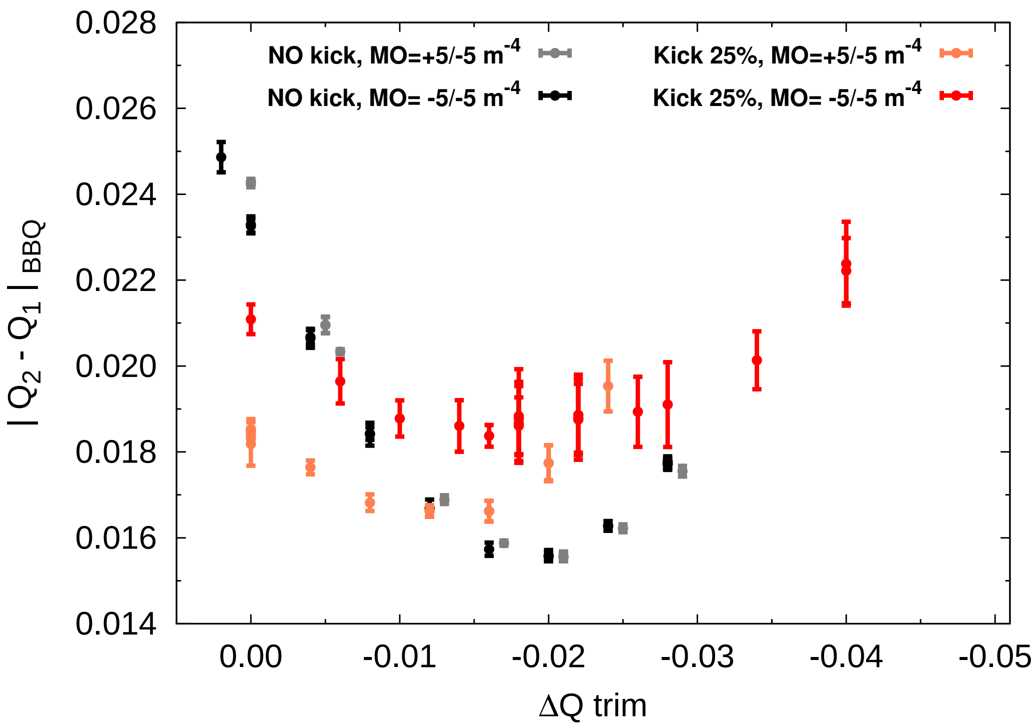

Figure 8: Comparison of closest approach of kicked beams for MO powering which enhances and suppresses the ADECTA.

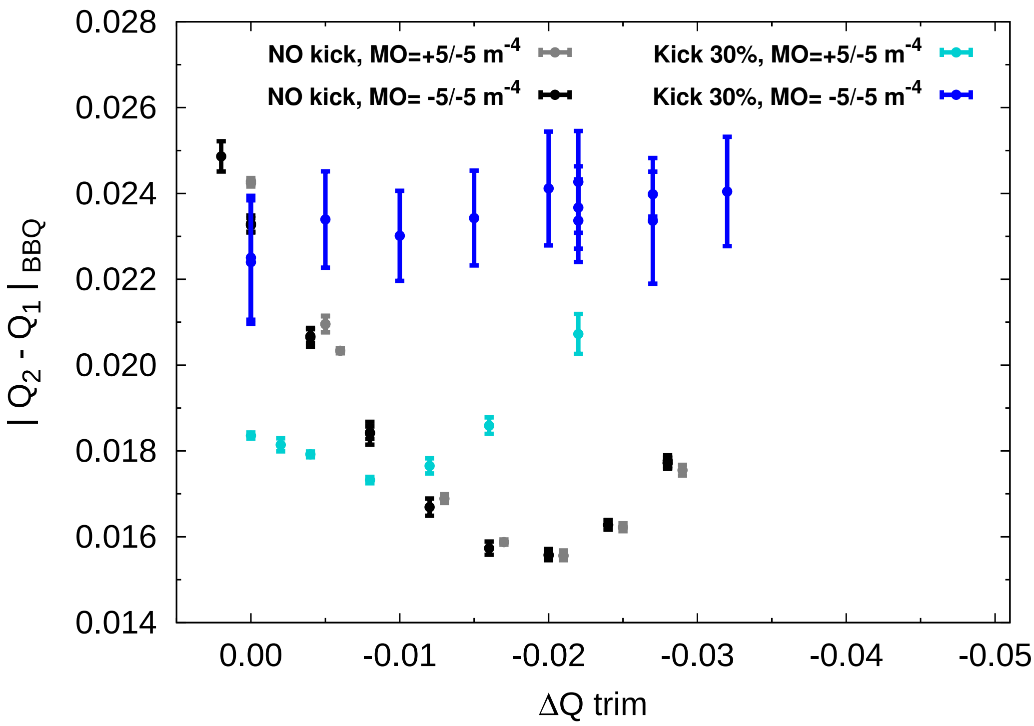

Figure 9: Comparison of closest approach of kicked beams for MO powering which enhances and suppresses the ADECTA.

viable method to study ADECTA in the future, and the data collected in this MD will be useful to test theoretical predictions of the amplitude dependent closest tune approach.

5 Acknowledgments

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