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BBQ AND DOUGHNUT BEAMS: A TASTY RECIPE FOR MEASURING AMPLITUDE DEPENDENCE OF THE CLOSEST TUNE APPROACH

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Abstract

Beam-based observations and theoretical studies have demonstrated the existence of a significant amplitude dependence of the closest tune approach (ADECTA) in the LHC. This effect has the potential to generate significant distortion of the tune footprint and thus is of interest in regard to Landau damping. Conventionally ADECTA has been studied through saturation of tune separation with action during amplitude-detuning type measurements. In this paper, an alternative measurement technique is proposed and results of initial tests with beam are presented. The novel technique attempts to measure ADECTA by performing a classical closest approach tune scan, using proton beams in the LHC, which have been kicked and allowed to decohere, effectively giving a large action doughnut beam. It is shown that the tune and closest approach of the doughnut beams can be measured using the existing LHC Base-Band tune (BBQ) measurement system, and an amplitude dependence can be observed.

AMPLITUDE DEPENDENT CLOSEST TUNE APPROACH

Linear coupling creates a closest tune approach (ΔQ_{min}) of the fractional tunes ($Q_{x,y}$), equal to the linear coupling coefficient ($|C^-|$) [1]. During amplitude detuning measurements of the LHC at injection in 2012, a highly non-linear change of $Q_{x,y}$ with action ($J_{x,y}$) was seen for kicks detuning towards $Q_x - Q_y = 0$, with similar effects observed in best-knowledge LHC models [2]. The nonlinearity of detuning was sensitive to initial working point and not explained by expected dodecapole or higher-order errors [2]. By observing the change of tune-split with action ($\frac{\partial |Q_x - Q_y|}{\partial 2J}$) as opposed to detuning with action ($\frac{\partial Q_{x,y}}{\partial 2J}$) this unexpected pattern of detuning was identified with a saturation of the fractional tune-split as a function of kick amplitude. An example of saturation of tune-split versus J_y is shown in Fig. 1. The observed saturation however, occurred for ΔQ far in excess of the measured $|C^-|$. It was therefore proposed that the measurements could be interpreted as an amplitude dependence of the closest tune approach [2]. That is: $\Delta Q_{min} \neq |C^-|$ but instead is a function of the linear coupling and actions $\Delta Q_{min}(J_x, J_y)$.

Simulation studies subsequently identified the main source of amplitude dependent closest tune approach (ADECTA) as the combination of linear coupling with strongly powered Landau octupoles '*MO*' (used for damping of instabilities) [3]. A theory for the mechanism was proposed via the interaction of linear coupling with the h_{1111}

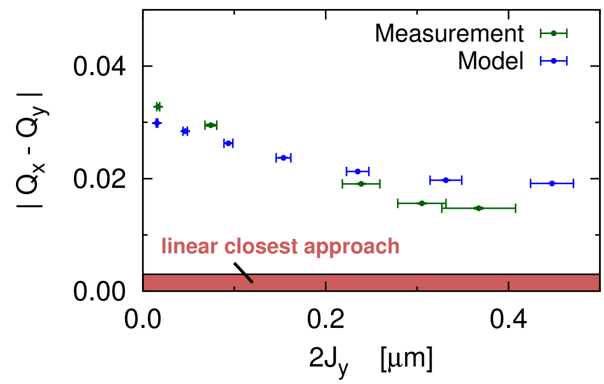

Figure 1: Beam-based observation of amplitude dependent closest tune approach [2].

Hamiltonian coefficient generated by normal octupoles [4]. h_{1111} (related to cross-term detuning, $\partial Q_{x,y}/\partial J_{y,x}$) can be easily compensated in the LHC by powering the focusing ('*MOF*') and defocusing ('*MOD*') MO with opposite polarity. Predictions that compensating h_{1111} would suppress ADECTA were validated by beam-based measurements [5, 6].

Simulation also showed ADECTA was generated by the combination of normal- (b_4) and skew-octupole (a_4) sources (a_4 alone did not generate ADECTA) [7]. ADECTA from $a_4 + b_4$ sources was demonstrated with beam in the LHC [8]. This is of interest to LHC and HL-LHC at top-energy, where large a_4 errors are generated in the low-β^* insertions. Such ADECTA can distort the Q-footprint, which may be detrimental to Landau damping [9]. Figure 2 (bottom) shows the footprint-distortion expected in the LHC ($\beta^* = 0.25$ m) if a_4 errors are uncompensated, at typical MO powering. Distortion is large compared to that from typical $|C^-| \approx 0.001$ (Fig. 2, top). Measurement would thus be of interest at top-energy. The conventional technique (saturation of $Q_{x,y}$-separation with $J_{x,y}$) is impractical however, given the need to dump and re-inject/ramp (taking several hours) after every kick, while methods using AC-dipole kicks do not generate ADECTA [6]. Given the reliance on octupolar detuning to drive $Q_{x,y}$ towards the coupling resonance, the conventional technique is also highly limited in terms of the multipole and J_x, J_y parameter space which can be explored. As such, alternative methods of measurement are of interest.

BBQ WITH DOUGHNUT BEAMS

LHC proton beams suffer minimal radiation damping, especially at injection. Consequently when a single-kick is applied to a bunch, constituent particles remain at the kick

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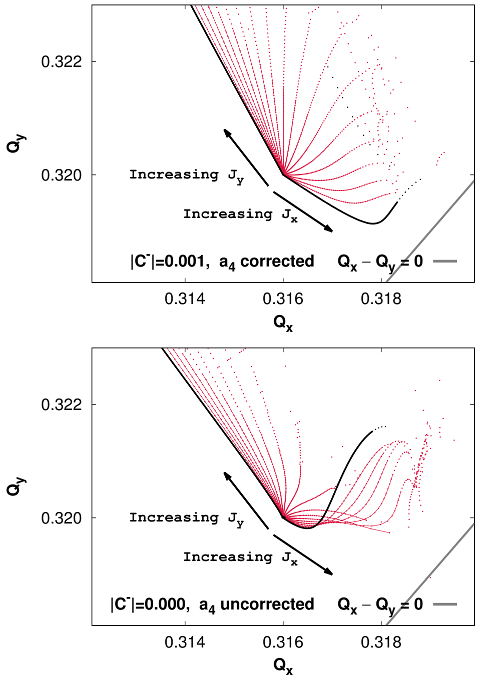

Figure 2: LHC footprint at 6.5 TeV ($\beta^* = 0.25$ m) with $|C^-| = 0.001$ (top), and with $|C^-| = 0.000$ but uncompensated a_4 errors in the low-β IRs (bottom). Typical powering of MO and non-colliding beams are considered.

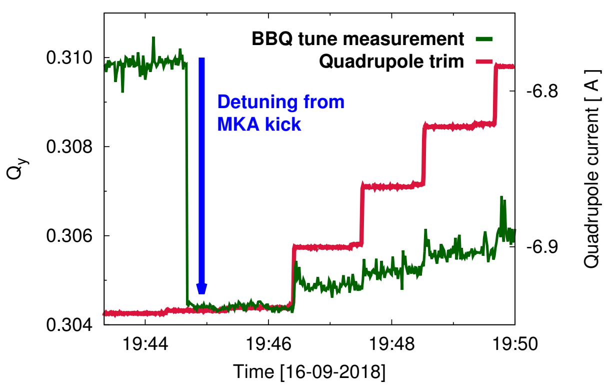

Figure 3: Q_y recorded by the BBQ, a large amplitude kicks performed at 19:44:40.

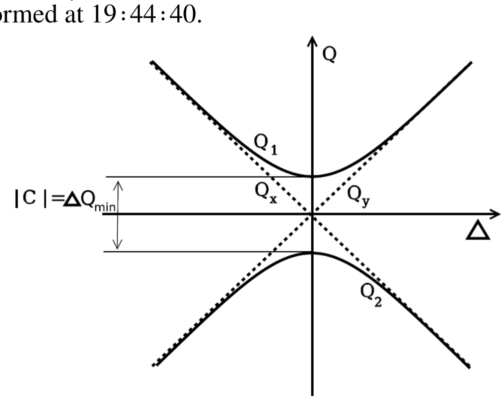

Figure 4: $|C^-|$ measurement via closest tune approach.

amplitude for an extended period. The bunch rapidly decoheres however, leaving a persistent *'donought'* beam of particles at non-zero action. Large-amplitude single-kicks can be applied using the LHC aperture kicker ('*MKA*'). Typically, for detuning type measurements, $Q_{x,y}$ of kicked beams are obtained from spectral analysis of the initial $10^2 - 10^3$ turns following the kick, before the turn-by-turn signal fully decoheres. Examples of typical LHC measurements are found in [2, 10, 11]. The LHC however, is also equipped with a Base-Band-Tune ('*BBQ*') measurement system [12–14], capable of providing continuous passive tune measurement from residual oscillations. Figure 3 shows Q_y vs time measured by the BBQ for a single low-intensity (10^{10} p) bunch. At 19:44:40 during the time window shown, a $\sim 4_{\text{nom}}$ kick was performed with the MKA (where σ_{nom} corresponds to nominal LHC normalized emittance $\epsilon_\gamma = 3.75$ m). An amplitude dependent Q change upon kicking is clearly seen in the BBQ data. Significantly, the tune remains measurable via BBQ long after the kick has decohered (on a timescale of 10^3 turns ≈ 0.1 s). The doughnut-beam's response of Q_y to quadrupole trims could also be measured. Figure 3 shows that the BBQ can measure the tune of kicked/decohered beams.

MEASUREMENT OF ADECTA

A classical measurement of linear difference coupling is performed by forcing the tune towards the $Q_x - Q_y$ resonance via quadrupoles trims, and measuring the closest approach. This is illustrated in Fig. 4.

Having shown that continuous Q-measurement of a kicked doughnut beam was possible using the BBQ, the classical closest-tune-approach type measurement was applied to study of ADECTA by performing quadrupole scans to force the tunes of kicked doughnut beams towards the $(Q_x - Q_y)$ resonance. The closest tune approach could then be measured for different kick amplitudes.

For the proof-of-principle studies presented here, measurements were performed in the LHC at 450 GeV, and ADECTA artificially generated by introduction of large $|C^-| = 0.014$ plus strong MO powering. Two octupole configurations were tested. The first, with equal MOF and MOD strength $K_{4,MOF} = K_{4,MOD} = -5\,[\text{m}^{-4}]$, was designed to generate ADECTA. The second, with opposite MOF/MOD polarity $K_{4,MOF} = -K_{4,MOD} = -5\,[\text{m}^{-4}]$, was designed to suppress ADECTA (as in [6]). Due to residual b_4 and several broken MO circuits perfect compensation was not possible. Octupole strength ($n = 4$) at magnetic rigidity $B\rho$ is defined by $K_n = \frac{1}{B\rho}\left.\frac{\partial^{n-1}B_x}{\partial x^{n-1}}\right|_{x=0,y=0,s}$. Studies were made with kicks at 25 % and 30 % of the maximum MKA strength, Table 1 summarizes the measured kick actions. BBQ measurements deteriorated at higher kicks, where attempts to measure were unsuccessful. Studies were performed ≥ 4 hours after the previous LHC pre-cycle, to minimize $Q_{x,y}$ and $|C^-|$ decay during the study.

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Table 1: Measured Kick Action and MO Configurations

MKA	K_{MOF}/K_{MOD}	$2J_x$ [μm]	$2J_y$ [μm]
25%	-5/-5 [m^{-4}]	0.11 ± 0.01	0.17 ± 0.01
30%	-5/-5 [m^{-4}]	0.22 ± 0.02	0.34 ± 0.02
25%	-5/+5 [m^{-4}]	0.12 ± 0.01	0.17 ± 0.01
30%	-5/+5 [m^{-4}]	0.20 ± 0.02	0.25 ± 0.02

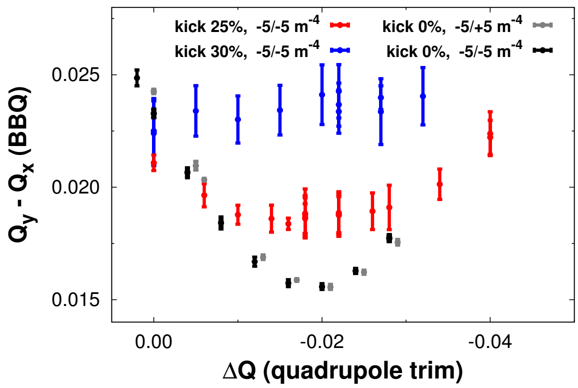

Table 2: Tune split measured by the BBQ as quadrupole trims attempt to force $Q_{x,y}$ towards the linear coupling resonance. MOF and MOD are powered with the same polarity to enhance ADECTA.

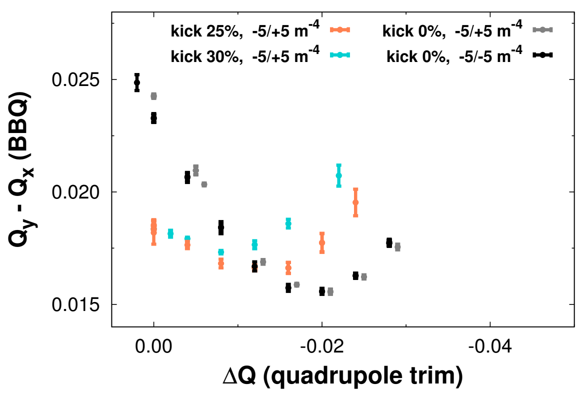

Table 3: Tune split measured by the BBQ as quadrupole trims attempt to force $Q_{x,y}$ towards the linear coupling resonance. MOF and MOD are powered with opposite polarity to partly suppress ADECTA.

After application of MKA kicks, quadrupole trims were applied in steps to move the tunes towards the $Q_x - Q_y$ resonance. BBQ data from the quadrupole plateaus were analyzed to obtain ΔQ at each step. Measurements were also performed with unkicked beams to obtain the linear $|C^-|$, and confirm it did not drift during the measurements, and was not altered by the MO configuration. The linear $|C^-| = \Delta Q_{min}$ was extremely stable over the course of the studies. Figures 2 and 3 show results of the closest approach measurements with same and opposite MOF/D polarities respectively (measurements with unkicked beams are indicated in black/gray).

Upon applying kicks at 25 % MKA strength with the same MOF/D polarity, the tunes detuned towards $(Q_x - Q_y) = 0$. On applying quadrupole trims the tunes then moved even closer to the coupling resonance, a minimum approach was then reached before the tunes further separated. An increase to the closest approach for the kicked beam was observed compared to that of the unkicked beam. When kicking to higher amplitude (30 % MKA strength) the bunch did not detune closer to the coupling resonance, and quadrupole trims could not force $Q_{x,y}$ closer together. Trims applied only to Q_x led to equal Q_y shifts maintaining the separation, as expected for a bunch already at $\Delta Q = \Delta Q_{min}$. It was concluded therefore that an amplitude dependence of the closest approach could be observed.

When kicking with opposite MO polarity, closest approach of the kicked bunches once again showed some amplitude dependence. However this was significantly reduced compared to same polarity measurements, as expected since operating with opposite MOF and MOD settings should significantly reduce h_{1111} in the accelerator, generating less ADECTA for these measurements. Differences in precise evolution of $Q_{x,y}$-separation with quadrupole trims for the different kicks were expected given the different initial detuning.

CONCLUSIONS

The LHC BBQ can be used to measure amplitude detuning, and in particular measure the tune of kicked and decohered '*doughnut*' beams, long after the turn-by-turn signal in regular BPMs has decohered. This has been employed to perform classical-style closest-tune-approach measurements on kicked/decohered beams in the LHC at injection. Where octupole configurations designed to enhance ADECTA were utilized, a dependence of the closest tune approach on applied kick amplitude could be observed. Use of octupole configurations designed to reduce ADECTA showed significantly less amplitude dependence of the closest tune approach (consistent with earlier studies of tune-split saturation with kick amplitude [6]). Application of the traditional closest-approach measurement to kicked doughnut beams does appear therefore to present a viable option for beam-based study of this behaviour.

Use of the BBQ to perform classical closest-tune-approach measurements on doughnut beams represents an interesting possibility for the study of amplitude-dependence of the closest-tune-approach. Since it relies on far fewer kicks than conventional detuning-type measurements, it represents a more viable option for study at top energy in the LHC and HL-LHC. Further, since the method does not rely on a specific octupolar detuning to drive the tunes towards the linear coupling resonance, it can expand the possibilities for beam-based study of ADECTA generated by different error sources and action configurations.

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REFERENCES

[1] G. Guignard, "Betatron coupling and related impact of radiation", *Phys. Rev. E*, vol. 51, p. 6104, 1995. doi:10.1103/PhysRevE.51.6104

[2] E.H. Maclean, R. Tomás, F. Schmidt, and T.H.B. Persson, "Measurement of nonlinear observables in the Large Hadron Collider using kicked beams", *Phys. Rev. ST. Accel. Beams*, vol. 17, p. 081002, 2014. doi:10.1103/PhysRevSTAB.17.081002

[3] T. Persson, Y. I. Levinsen, E. H. Maclean, and R. Tomas, "Non-linear Coupling Studies in the LHC", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 2105–2107. doi:10.18429/JACoW-IPAC2015-TUPTY042

[4] R. Tomás, T.H.B. Persson, and E.H. Maclean, "Amplitude dependent closest tune approach", *Phys. Rev. Accel. Beams*, vol. 19, p. 071003, 2016. doi:10.1103/PhysRevAccelBeams.19.071003

[5] T.H.B. Persson *et al.*, "Suppression of Amplitude dependent closest tune approach and first tests of the ADT as an AC-dipole (MD 1412)", CERN, Geneva, Switzerland, Tech. Rep. CERN-ACC-Note-2016-0057, 2016. https://cds.cern.ch/record/2220704?ln

[6] T.H.B. Persson, T. Tomás, and E.H. Maclean, "Suppression of amplitude dependent closest tune approach and its behavior under forced oscillations", *Phys. Rev. Accel. Beams*, vol. 22, p. 051001, 2019. doi:10.1103/PhysRevAccelBeams.22.051001

[7] E. H. Maclean, T. Persson, and R. Tomas, "Amplitude Dependent Closest Tune Approach Generated by Normal and Skew Octupoles", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3147–3150. doi:10.18429/JACoW-IPAC2017-WEPIK091

[8] E.H. Maclean, R. Tomás, T.H.B. Persson, and F.S. Carlier, "Report from LHC MD 2171: Amplitude dependent closest tune approach from normal and skew octupoles", CERN, Geneva, Switzerland, Tech. Rep. CERN-ACC-Note-2018-0027, 2018. http://cds.cern.ch/record/2310163

[9] X. Buffat, "Our understanding of transverse instabilities and mitigation tools/strategy", in *8th Evian Workshop*, Evian, Dec. 2017. https://indico.cern.ch/event/663598/contributions/2782391/attachments/1574451/2485684/2017-12-13_instabilities-expanded.pdf

[10] E. H. Maclean, F. S. Carlier, M. Giovannozzi, T. Persson, and R. Tomas, "Effect of Linear Coupling on Nonlinear Observables at the LHC", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3151–3154. doi:10.18429/JACoW-IPAC2017-WEPIK092

[11] E.H. Maclean, *et al.*, "Commissioning of the nonlinear chromaticity at injection for LHC Run II", CERN, Geneva, Switzerland, Tech. Rep. CERN-ACC-Note-2016-0013, 2016. https://cds.cern.ch/record/2121333?ln

[12] M. Gasior and R. Jones, "The principle and first results of betatron tune measurement by direct diode detection", CERN, Geneva, Switzerland, Tech. Rep. lHC-Project-Report 853, 2005. http://cds.cern.ch/record/883298?ln

[13] A. Boccardi, M. Gasior, O. Jones, P. Karlsson, and R.J. Steinhagen, "First Results from the LHC BBQ Tune and Chromaticity Systems", CERN, Geneva, Switzerland, Tech. Rep. CERN-LHC-Performance-Note-007, 2009. http://cds.cern.ch/record/1156349?ln

[14] A. Boccardi, M. Gasior, R. Jones, and R.J. Steinhagen, "An overview of the LHC Transverse Diagnostics Systems", CERN, Geneva, Switzerland, Tech. Rep. lHC Project Report 1166, 2009. http://cds.cern.ch/record/1156346?ln