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LHC OPTICS MEASUREMENTS FROM TRANSVERSE DAMPER FOR THE HIGH INTENSITY FRONTIER

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Abstract

Current and future accelerator projects are pushing the brightness and intensity frontier, creating new challenges for turn-by-turn based optics measurements. Transverse oscillations are limited in amplitude due to particle losses. The LHC Transverse Damper (ADT) is capable of generating low amplitude ac-dipole like transverse coherent beam oscillations. While the amplitude of such excitations is low, it is compensated by the excitation length of the ADT which, in theory, can last for up to 48h. Using the ADT, it is possible to use the maximum BPM acquisition length and improve the spectral resolution. First optics measurements have been performed using the ADT in the Large Hadron Collider in 2023, and the results are presented in this paper. Furthermore, some observed limitations of this method are presented and their impact on ADT studies are discussed.

INTRODUCTION

Optics measurements from transverse turn-by-turn data are generally carried out with a single low intensity bunch to limit particle losses from the ac-dipole forced betatron oscillations [1]. This is particularly important for high energy accelerators where machine protection constraints are tight. Under such conditions the effects of high bunch intensities and large number of bunches on the optics are not measured. As bunch intensities are pushed further, the resulting optics perturbations become more relevant. Optics measurements under these conditions can yield valuable insights and provide new paths for machine optimisation.

Optics measurements in the Large Hadron Collider (LHC) are mostly performed by exciting coherent transverse oscillations using an ac-dipole [2–8]. These oscillations are measured at Beam Position Monitors (BPMs) around the ring. The spectral analysis of such signals provides amplitude and phase information of the main modes of oscillation from which the optics functions are calculated, as described in Refs. [9–11]. In the LHC, the ac dipole generates large amplitude, 6600 turns flattop excitations. In this paper, the ADT is used in an ac dipole-like mode, as an alternative excitation method to provide low amplitude coherent oscillation with a duration close the maximum recording limit of the BPMs. While lower in amplitude, the increase in number of turns provides an important improvement in the spectral resolution. Most importantly, the ac dipole may not be used with more than 3 low intensity bunches, while the ADT is considered safe for using during nominal operational conditions. It should be mentioned that in operation large chromaticity and Landau octupoles are used to mitigate coherent instabilities. These have an impact in the optics measurement technique that requires further studies [5, 6, 8, 11]. The ADT therefore opens up the possibility to perform optics measurements at the LHC intensity limit.

This paper describes the progress in performing linear and non-linear optics measurements using the LHC ADT in ac dipole mode. The first optics measurements are presented at injection energy with pilot bunches. Lastly, an analysis of the observed sidebands on the ADT excitation resulting from 50 Hz noise is presented.

PHASE RESOLUTION FROM TURN-BY-TURN DATA

The phase error on the main betatronic oscillation has been calculated from the spectral analysis of single BPM turn-by-turn data for different excitation conditions. Figure 1 shows the phase error obtained from turn-by-turn data of ac dipole and ADT excitations as a function of oscillation amplitude. A clear reduction of phase errors is observed for increasing oscillation amplitudes. Figure 1 also shows the measured betatron spectral phase error for ADT excitations with larger number of turns considering a single excitation per point. The phase resolution from ADT driven oscillations matches that from the ac dipole at injection energy.

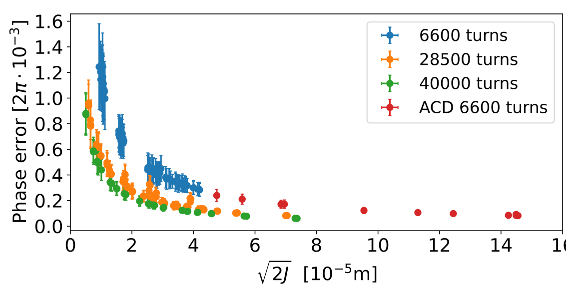

Figure 1: Phase error from ADT and ac dipole (ACD) excitations as a function of oscillation amplitude for different number of turns.

OPTICS MEASUREMENTS WITH THE ADT

Since the end of Run 2 the ADT is used for calculating coupling corrections during the nominal physics cycle in the LHC [12], and they are part of the operational procedure at the start of each fill. The aim of the current studies is to demonstrate the feasibility of performing optics measurements using the ADT, with the future goal of integrating this feature in the operational tools. Optics measurements were performed using the ADT with pilot bunches at injection

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energy with 28500 turns of coherent oscillations. These measurements were obtained during a dedicated Machine Development (MD). Figure 2 shows the measured β-beating for Beam 1 for a section of the machine, compared to the reference ac dipole measurements. A good agreement is observed between the ADT and ac dipole measurements, and is representative for both beams and both planes. Figure 3 shows the difference between the β-beating observed from the two methods compared to the errors from the ac dipole measurements. The observed deviation is generally within the measurement errors of the ac dipole measurements, thus demonstrating that optics measurements can reliably be done with the ADT at injection energy. The operational procedure could therefore be adapted by increasing the number of acquired turns for ADT measurements at the start of each fill to perform routine optics measurements at injection.

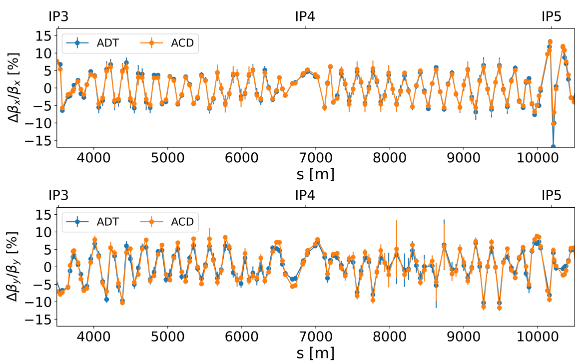

Figure 2: Comparison of horizontal and vertical β-beating of Beam 1 between ADT and ac dipole measurements. The data shown is a representative sample of the whole machine for both beams.

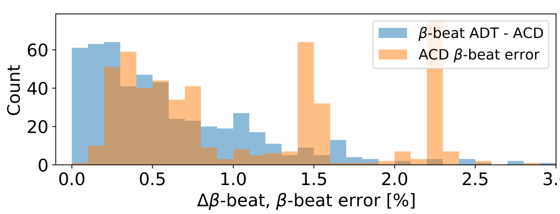

Figure 3: Comparison of difference in β-beating between the ADT and ac dipole measurements and β-beating error for the ac dipole for the horizontal plane of Beam 1.

RESONANCE DRIVING TERMS WITH LOW AMPLITUDE EXCITATIONS

The improved spectral resolution due to the increased number of turns may be of further benefit for measuring resonance driving terms (RDTs) [13–16] using low amplitude excitations. This could allow the measurements of nonlinear optics while reducing the risks of beam losses. If validated for nominal beam intensities this could provide valuable linear and nonlinear optics measurements for machine conditions that are currently restricted, such as with bunch trains.

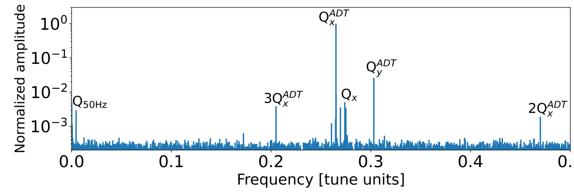

Figure 4: Frequency spectrum of the horizontal plane for Beam 2. Secondary spectral lines are observed at the frequencies $2Q_x^{ADT}$ (normal sextupole) and $3Q_x^{ADT}$ (normal octupole).

Figure 4 shows the spectrum obtained from horizontal turn-by-turn data from an ADT excitation at injection energy in Beam 2. Aside from the main ADT lines, two secondary spectral lines arising from nonlinear sources are clearly observed at frequencies $2Q_x^{ADT}$ and $3Q_x^{ADT}$. Furthermore, several sidebands are observed around the main ADT mode, and will be discussed in the following section.

The line at frequency $2Q_x^{ADT}$ is related to the normal sextupolar RDTs f_{1200} and f_{3000}, while the line at frequency $3Q_x^{ADT}$ is related to the normal octupolar RDTs f_{1300} and f_{4000}. From these measurements, the corresponding driving terms can be calculated. Figure 5 shows the calculated normal sextupolar driving terms f_{1200} and f_{3000} measured with ADT and ac dipole excitations. While the RDT amplitude variations are lost in ADT measurements, possibly due to their small excitation amplitudes, some qualitative agreement is observed between both methods. The results are promising and motivate further studies to improve sextupolar RDT measurements with the ADT.

The normal octupolar RDTs f_{1300} and f_{4000} show a large discrepancy between the ADT and the ac dipole, which could originate from a saturation of the ADT signal. Further investigations are required.

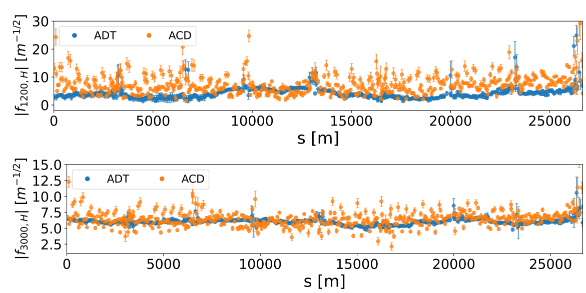

Figure 5: Comparison of normal sextupolar RDTs f_{1200} (top) and f_{3000} (bottom) for Beam 2 between ADT and ac dipole measurements.

OBSERVATION OF 50 Hz SIDEBANDS IN THE ADT

50 Hz sidebands were observed in the frequency spectra around the ADT tune, both at injection energy and at top

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Table 1: Measured relative strengths of the 50 Hz sidebands (B_1/B_0 and B_2/B_0) for both beams and both planes.

	1st sideband [10^{-3}]	2nd sideband [10^{-3}]
B1 H	2.64 ± 0.10	0.85 ± 0.03
B1 V	3.02 ± 0.05	0.90 ± 0.03
B2 H	1.98 ± 0.11	0.57 ± 0.02
B2 V	2.62 ± 0.08	0.41 ± 0.03

energy. An example frequency spectrum for the horizontal plane of Beam 1 at injection energy, zoomed in around the main mode, is shown in Fig. 6. The spectra exhibit three clear sidebands at frequencies $Q_{x,d} \pm Q_{50Hz}$ and $Q_{x,d} + 2Q_{50Hz}$, with $Q_{50Hz} = 4.45 \times 10^{-3}$. The sidebands are most likely generated by a 50 Hz modulation of the ADT waveform, and function as three weaker ac dipoles on the beam motion. Indeed, the amplitude response of the sidebands is asymmetric and increases as their frequency approaches the natural tune. The spectrum shown in Fig. 6 is representative of all BPMs and for both beams.

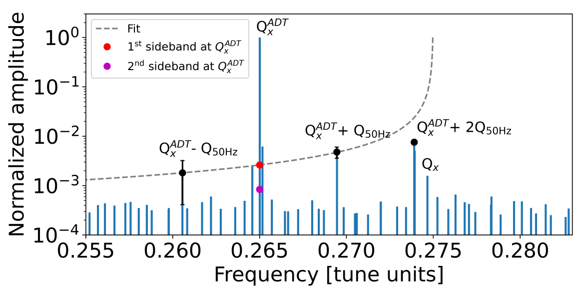

Figure 6: Strength of the 50 Hz sidebands at the frequency of the driven ADT tune.

The relative strength of the sidebands with respect to the ADT kick strength can be estimated by treating the sidebands as ac dipoles. The betatronic amplitude response follows the following relation [5],

$$A_p = \frac{B_p}{\sin\left(\pi(Q_{x,d} + p \cdot Q_{50Hz}) - Q_x\right)}, \quad (1)$$

where $B_p = \sqrt{\beta_{ADT}}\hat{B}_p/(4B_0\rho)$ represents the effective strength of an ac-dipole associated to the p^{th} sideband, $p \in$ {-1, 1, 2}. β_{ADT} is the β function at the ADT, $\hat{B}_p$ is the integrated magnetic field and $B_0\rho$ is the magnetic rigidity. Using this equation, the relative strength of the sideband can be determined. The average amplitude of the sidebands is calculated over all BPMs. Using these averaged amplitudes, the sideband strengths are fit to the measured data using Eq. (1) for the two first order sidebands to interpolate their amplitude at the location of the ADT tune, as shown in Fig. 6. The measured relative strengths of the 50 Hz sidebands are shown in Table 1.

The strength of the 50 Hz sidebands are larger than previously expected, and their presence in the transverse damper may be a source of emittance growth during operational use

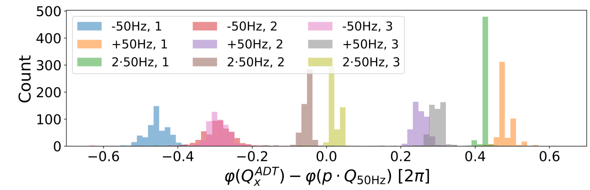

Figure 7: Horizontal phase difference for Beam 1 between ADT and sidebands for three measurements.

of the ADT. Further studies on the effect of such sidebands on operational use are currently ongoing.

Figure 7 shows the phase difference between the main spectral line from the ADT and its sidebands. For the first order sidebands with $p = \pm 1$, the phase difference is of opposite sign. Further analysis is required to fully characterize the the ADT modulation.

CONCLUSIONS

The LHC Transverse Damper (ADT) is considered safe for use in operational conditions. It thus allows for exciting ac dipole-like coherent transverse oscillations at high beam intensities in the LHC, and opens the door for optics measurements at machine conditions that were previously restricted.

Coherent transverse oscillations are successfully excited using the ADT in ac dipole mode, for a duration beyond the BPM limits. Such excitations are lower in amplitude than the LHC ac dipole, but increase the number of acquired turns from 6600 to 40000 turns, yielding similar phase error than the AC dipole at injection energy.

Optics measurements performed using the ADT at injection energy with pilot bunches show a good agreement with reference measurements performed with the ac dipole. Increasing the number of turns to 40000 in the ADT excitations for coupling corrections in operational procedures could yield fill-by-fill optics measurements at injection.

First explorations of the measurements of normal sextupolar and octupolar RDTs with ADT excitations show promising results requiring further developments.

Lastly, significant 50 Hz sidebands are observed around the main ADT tune line in the spectra of turn-by-turn data. This indicates a 50 Hz modulation of the ADT waveform, with a strength of $(0.25 \pm 0.04)\%$ and $(0.069 \pm 0.02)\%$ in the first and second order sidebands, respectively. The phase of the first order sidebands with $p = \pm 1$ have opposite signs, as expected, for example, from amplitude modulation. Further studies are needed to fully characterize the ADT unwanted modulation and estimate its potential detrimental effects.

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