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PROBING THE FORCED DYNAMIC APERTURE IN THE LHC AT TOP ENERGY USING AC DIPOLES

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Abstract

Measurements of the dynamic aperture in colliders are a common method to ensure machine performance and offer an insight in the nonlinear content of the machine. Such direct measurements are very challenging for the LHC and High Luminosity LHC. Forced dynamic aperture has been demonstrated for the first time in the LHC at injection energy as a potential new observable to safely probe the nonlinear content of the machine. This paper presents the first measurements of forced dynamic aperture at top energy and discusses the proposed measurement schemes and challenges.

INTRODUCTION

Measurements of forced dynamic aperture have been proposed as an alternative observable to probe machine nonlinearities in particle colliders [1–3]. The availability of forced dynamic aperture measurements has opened up the possibility for fast and reliable characterisation of the nonlinear state of the machine where conventional free dynamic aperture measurements with free kicks are too time consuming [2, 4], and is complementary to the alternative method based on beam heating as presented in [5, 6]

The motion under forced coherent oscillation of an AC dipole is altered compared to the free betatron motion [7–11]. Due to the presence of extra resonances [9], and an increase in amplitude detuning for the direct detuning terms [11] during forced coherent oscillations the forced DA is expected to be smaller than the dynamic aperture under free motion. Nonetheless, measurements of forced DA can provide useful insights in nonlinearities in the LHC and can be used as a valuable figure of merit for nonlinear optics corrections.

The LHC AC dipoles are limited to short excitations of 6600 turns due to hardware heating protections. As such, the presented work in this paper focusses on short term forced DA only. A generalisation to longer time scales is of course possible, but not considered in this paper. Measurements of forced DA are done by probing the beam intensity loss after large coherent oscillations using the LHC AC dipoles. As the excitation amplitude is increased, more particles will cross the forced DA and become lost. By characterising the beam intensity losses with AC dipole excitation amplitude the forced DA can be calculated. Under the assumption that the losses occur dominantly in a single plane the problem can be simplified to a single dimension. Figure 1 shows an AC dipole excited beam traversing the forced DA. In contrast to the free kick case where only particles beyond the free DA are lost, the intrabunch evolution of the particles due to the residual free motion will cause all the tails to be lost. This now greatly simplifies the problem to an integral over the distribution in action space.

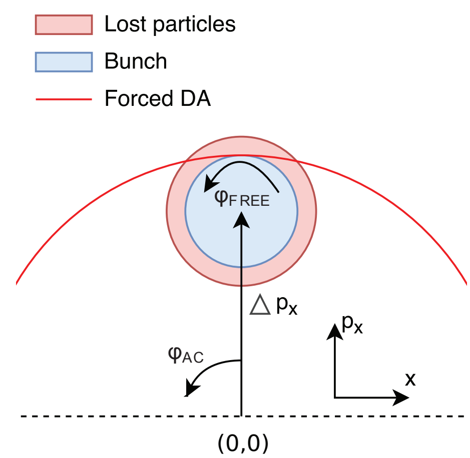

Figure 1: Losses of distribution from AC dipole excitations. The bunch rotates as a whole in phase space with the AC dipole frequency, while the bunch itself revolves with the natural frequency.

$$\frac{\Delta I}{I}(A) = \int_{DA_{\text{forced}}}^{+\infty} \frac{1}{\epsilon_z} e^{-\frac{J_z - A}{\epsilon_z}} \, d\, J_z \quad (1)$$

where $\Delta I/I$ is the normalized measured losses, $2J_z$ are the measured actions, ϵ_z is the measured physical emittance, and $z \in \{x, y\}$ determines the plane of losses. This leads to the following expression for the forced DA

$$DA_{\text{forced}}(J_z, \Delta I/I) = 2J_z - 2\epsilon_z ln\left(\frac{\Delta I}{I}\right) \quad (2)$$

FORCED DA AT TOP-ENERGY

Measurements of forced DA at top energy (6.5 TeV) and end-of-squeeze ($\beta^* = 40$ cm) are presented. Several different magnetic configurations of the Landau octupoles and dodecapolar corrector magnets in the insertion regions are probed. The settings are reported in Tab. 1

The transverse beam size is recorded using the Beam Synchrotron Radiation Telescope (BSRT) [12]. Calibration of the BSRT data is done with wirescanner measurements [12] at the start of the forced DA measurements. The BSRT data is particularly interesting to measure the evolution of the beam size and detect possible beam blow-up. Figure 2 shows

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Table 1: Summary of different magnetic configurations with ϵ_{nom} = 3.75 μm, and measured forced DA.

	MO [m^{-4}]	MCTX [m^{-6}]	forced DA [σ_{nom}]
Settings 1	10.8	-	4 ± 2
Settings 2	14.3	-	3.3 ± 1.6
Settings 3	14.3	38000	2.7 ± 1.3

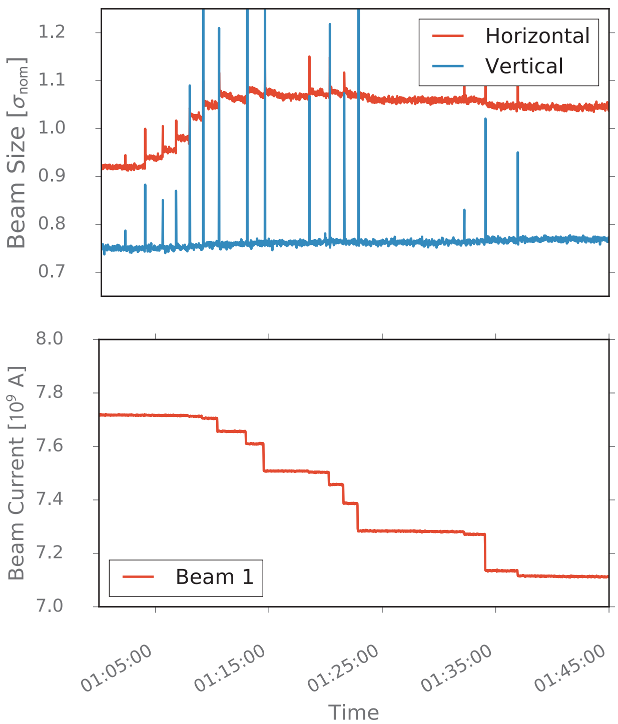

Figure 2: Measured beam size for horizontal and vertical planes of Beam 1 at top energy (6.5 TeV) and β^* = 40 cm, using the LHC BSRT system (top figure). Measured beam current of Beam 1 at top energy (6.5 TeV) and β^* = 40 cm, using the LHC BCT system (bottom figure).

the measured beam size for the vertical and horizontal plane of Beam 1 in units of nominal emittance. Where the nominal normalized emittance is defined as σ_{nom} = 3.75 μm. The large vertical spikes in the data correspond to the AC dipole excitations.

Some beam blow-up is observed in the horizontal plane for the first 4 vertical excitations with low octupole currents (Settings 1). The beam size later stabilizes and no further blow-up is observed. Fortunately the blow-up occurs in the plane opposite to the excitation and the effect on measured losses for the first view excitations is negligible as will be presented later. All further measurements are performed with stable beam size and can thus be directly compared.

Figure 2 shows the measured beam intensity from the Beam Current Transformers System (BCT) [13] for Beam 1.

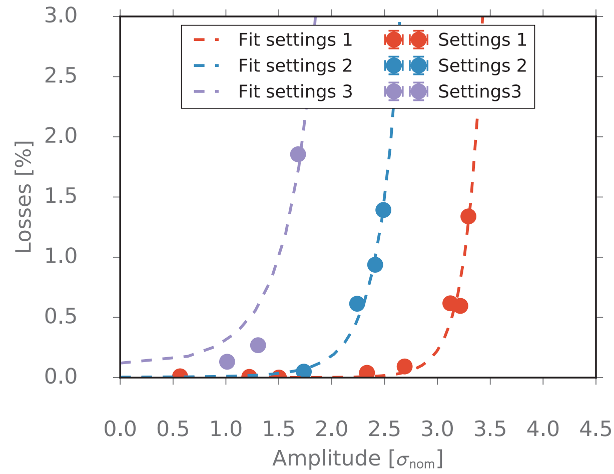

Figure 3: Measured beam intensity losses with vertical AC dipole excitation amplitude for Beam 1 at top energy (6.5 TeV) and β^* = 40 cm. Measured forced DA from fits is summarised in Tab. 1.

At each excitation a reduction of beam intensity is observed. By characterising the losses over the measured actions an estimate on forced DA may be obtained.

The measured losses in percentages of beam intensity before the excitation are presented in Fig. 3 as a function of the measured excitation amplitudes for the different magnetic configurations. By fitting Eq. (2) to the measured data, using the physical emittances measured from the wirescanners, an estimate of forced DA is acquired for the three settings. The results are presented in Tab. 1. The configuration with the lowest octupole strengths shows the largest forced DA at (4 ± 2) σ_{nom}. The forced DA decreases to (3.3 ± 1.6) σ_{nom} when increasing the MO strengths and further down to (2.7 ± 1.3) σ_{nom} when also including the dodecapoles. Unfortunately the fit errors are large due to the limited number of measurements and the limited allowed beam intensity losses due to machine protection thresholds on the Beam Loss Monitors. Furthermore, a closer look at the beam profiles from the wirescanners may improve the modeling of the beam distribution and thus improve the fit quality.

A significant decrease in forced DA is observed as the nonlinear magnetic sources are increased. Secondly, a direct effect of the dodecapolar sources on the forced DA is measured. Forced DA may form a valuable figure of merit to correct dodecapolar sources in the insertion regions of the High Luminosity LHC, along side the method of beam heating [2].

FORCED DA WITH SKEW OCTUPOLAR CORRECTIONS

Correction of nonlinear magnetic errors in the insertion regions of the LHC have been a priority in 2017, and successful correction of b_3, a_3 and b_4 sources have been achieved [14].

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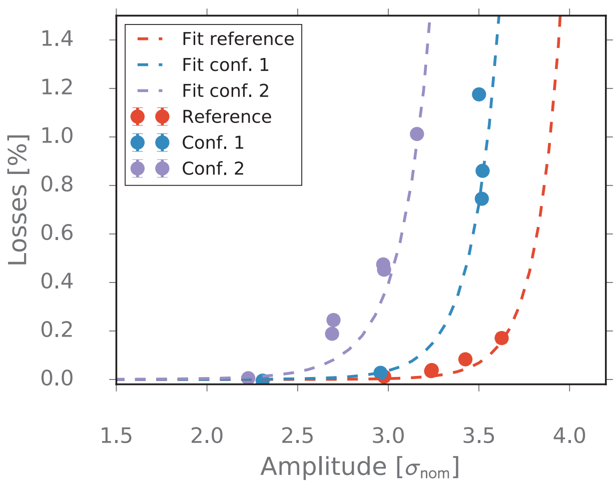

Figure 4: Measured beam intensity losses with vertical AC dipole excitation amplitude for 3 different corrector settings in Beam 2 at top energy (6.5 TeV) and $\beta*$ = 30 cm.

Local corrections for skew octupolar sources (a_4) have been calculated from feed down measurements to tune as a function of crossing angles. While corrections of IR1 have been validated with crossing angle scans and implemented operationally in 2017, IR5 corrections proved more challenging. Part of the challenge comes from confusion about the polarity of the a_4 correctors in IR5 due to differences in conventions between simulation codes and the magnet powering architecture in the LHC. There are two a_4 correctors in IR5, one left of the IP and one right of the IP. The corrector strengths were calculated as potential local corrections from feed down measurements. The two configurations of correctors have the same strengths but opposite polarity, as specified in Tab. 2.

Forced DA measurements taken parasitically at top energy (6.5 TeV) and β^* = 30 cm are shown for three different configurations of the a_4 correctors in IR5 in Fig. 4. The forced DA is again calculated by fitting the measurements with Eq. (2) and using the physical emittance measured with the wirescanners. The reference measurement with no powering of the correctors shows the largest forced DA of $(4.5 \pm 2)\,\sigma_{\text{nom}}$, while the forced DA decreases to $(4 \pm 2)\,\sigma_{\text{nom}}$ and $(3.8 \pm 1.9)\,\sigma_{\text{nom}}$ for the configurations with respectively the positive and negative polarity. The measurement errors are very large and prevent these studies from being conclusive. It is critical for future studies to increase the number of measurements to reduce the fitting errors. The forced DA is observed to deteriorate for both configurations, which suggests a mismatch between a_4 errors and the attempted local correction. These findings are in line with resonance driving terms measurements presented in [15].

Furthermore, it is interesting to see that a small change in the a_4 correctors in the insertion regions, at β^* = 30 cm, produces a reduction in forced DA of the same order of magnitude as an increase of the MOs to 14.3 m^{-4}. This underlines the importance of a_4 errors in the insertions regions as significant sources of forced DA and motivates further studies for successful corrections in view of the High Luminosity LHC.

Table 2: Summary of Different Magnetic Configurations

	a_4 left [m^{-4}]	a_4 right [m^{-4}]	forced DA [σ_{nom}]
No correction	-	-	4.5 ± 2
Configuration 1	-0.36	-0.53	4 ± 2
Configuration 2	0.36	0.53	3.8 ± 1.9

CONCLUSIONS

Measurements of forced DA have been successfully performed at top energy in the LHC. Changes in forced DA resulting from increased Landau octupole strengths as well as dodecapolar corrector magnets are shown to be measurable. Forced DA has demonstrated to be a promising observable to measure nonlinear sources, and may at some point be used for validation of dodecapolar corrections in the High Luminosity LHC. Furthermore, attempted local skew octupolar corrections in IR5 are studied. The implementation of both corrections independently result in a decrease in forced DA. The second correction (assuming negative polarity of the corrector magnets) shows the largest degradation. The results presented in this paper reject the proposed local a_4 corrections in IR5. The successfull correction of a_4 in the insertion regions of the LHC is considered as one of the main objectives of the 2018 commissioning campaign.

In general the fit quality is poor, but as a first demonstration the results are promising. Great care should be taken to take more measurements and improve statistics. To conclude, the method of forced DA has been demonstrated to be a valuable observable to probe machine nonlinearities as well as the validity of nonlinear optics corrections.

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