FIRST MEASUREMENTS OF HIGHER ORDER OPTICS PARAMETERS IN THE LHC

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Abstract

Higher order effects can play an important role in the performance of the LHC. Lack of knowledge of these parameters can increase the tune footprint and compromise the beam lifetime. First measurements of these parameters at injection and flattop have been conducted. Detailed simulations are compared to the measurements together with discussions on the measurement limitations.

INTRODUCTION

During the first two years of LHC operation excellent results were achieved regarding the measurement and correction of linear optics [1, 2]. Improvement of the resolution on the optics measurement becomes increasingly important and detailed knowledge of higher order effects are crucial to avoid limitations on the performance of the LHC. Exploratory measurements were conducted using transverse kickers. Turn-by-turn data was acquired and analyzed using an interpolated FFT, such as SUSSIX [3]. Phase and amplitude of the main betatron and secondary lines are used to calculate the presented data.

AMPLITUDE DETUNING

Non-linear magnetic fields are the source for amplitude detuning. Sextupoles (2^{nd} order) and octupoles (1^{st} order) introduce a linear dependence of the tunes in the action [4]:

$$Q_z = Q_z^0 + \frac{\partial Q_z}{\partial \epsilon_x} 2J_x + \frac{\partial Q_z}{\partial \epsilon_y} 2J_y$$

Where $z = x, y$. Q_z being the perturbed tune and Q_z^0 the unperturbed tune. $J_{x,y}$ is the action. $\epsilon_{x,y}$ is the emittance and relates to the action as $\epsilon_{x,y} = 2J_{x,y}$. $\frac{\partial Q_x}{\partial \epsilon_x}$ is the amplitude dependence of the horizontal tune and $\frac{\partial Q_x}{\partial \epsilon_y}$ is the cross term.

During machine studies in 2011 an experiment was conducted to measure and correct the linear and non-linear chromaticity for Beam 2 [5]. Non-linear chromaticity, and amplitude detuning, was corrected using octupolar and decapoles correctors installed around the ring on one side of the dipole magnets. In Fig. 1 and in Table 1 the amplitude detuning is shown. The amplitude dependent terms $\frac{\partial Q}{\partial \epsilon}$ before and after correction are listed, the terms are obtained by a linear fit from the data presented in Figure 1. A significant reduction of the amplitude detuning is achieved. The two main sources for decoherence are chromaticity and amplitude detuning [6]. In Figure 2 turn-by-turn data is shown before and after correction. A clear improvement is shown. More turns could be analyzed, hence improving the measurement resolution.

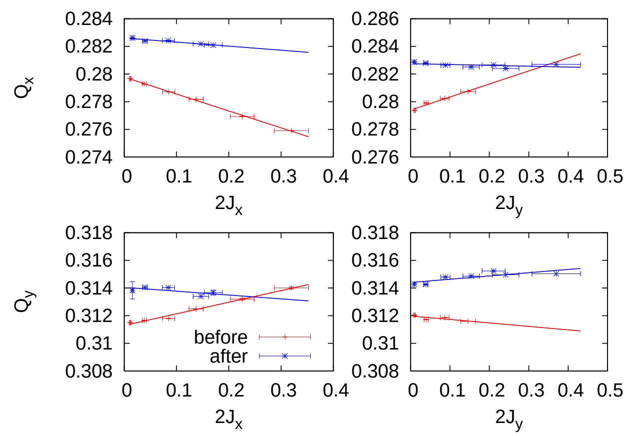

Figure 1: Amplitude detuning before any corrections (red) and after (blue). Horizontal plane (top) and vertical plane (bottom) are shown. A significant reduction is achieved.

Table 1: Amplitude Detuning Before and After Correction, Cross Terms are included. A significant reduction in the amplitude detuning factors is achieved.

function	Before	After
$\frac{\partial q_x}{\partial 2J_x}$	-0.0122 ($\pm$ 0.0002)	-0.0029 ($\pm$ 0.0006)
$\frac{\partial q_x}{\partial 2J_y}$	0.0094 ($\pm$ 0.0013)	0.0006 ($\pm$ 0.0005)
$\frac{\partial q_y}{\partial 2J_x}$	0.0084 ($\pm$ 0.0005)	-0.0027 ($\pm$ 0.0017)
$\frac{\partial q_y}{\partial 2J_y}$	-0.0025 ($\pm$ 0.0015)	0.0023 ($\pm$ 0.0008)

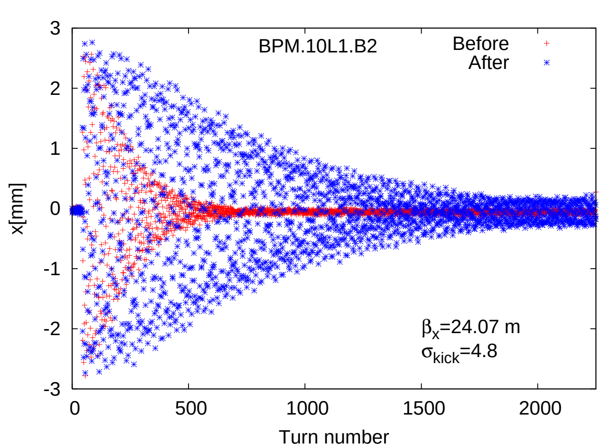

Figure 2: Turn-by-turn data before (red) and after (blue) correction. The decoherence was reduced by a factor of 3.

FIRST LHC MEASUREMENT OF F_{3000}

First attempt to measure non-linearities has been conducted. For this experiment the aperture kicker was limited to 5σ, due to operational and hardware reasons. Only measurements for Beam 2 were conducted. In Fig. 3 the absolute value of the f_{3000} resonance driving term [7] is shown. f_{3000} is the resonance driving term coming from normal sextupolar terms and is identified in the frequency spectrum by the $-2Q_x$ line. The effect of decoherence is taken into account for the measured data. Using the decoherence factors as presented in [4]. Measurement and model [8], in the arcs, are in relative good agreement. However, around the IP a large discrepancy is observed. Measurement is significantly larger. This discrepancy between measurement and model could be explained by several factors [9], such as noise, phase advance between the BPMs in the IP or by the non-linearity of the BPMs.

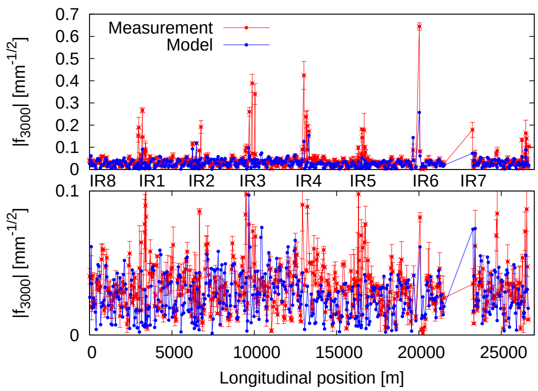

Figure 3: The absolute value of the f_{3000} resonance driving term is shown. Top plot including large values around the IPs and bottom zoom on the arcs. The gap in the data is due to some missing BPMs. Measurement (red) and model (blue), in the arcs, are in relative good agreement. Decoherence factor of 2 is included in the measurement data.

CHROMATIC ABERRATIONS

When reaching lower β^* the control of the chromatic aberrations for the β function is important to avoid aperture limitations. Algorithms were developed to measure these aberration. Dedicated simulations were conducted to test the implemented algorithms. The observable used is the Montague function [10]. The chromatic amplitude, $W_{x,y}$, and phase, $\phi_{x,y}$, function are defined as:

$$a_{x,y} = \left(\frac{1}{\beta_{x,y}}\frac{\partial\beta_{x,y}}{\partial\delta_p}\right)$$

$$b_{x,y} = \left(\frac{\partial\alpha_{x,y}}{\partial\delta_p} - \frac{\alpha_{x,y}}{\beta_{x,y}}\frac{\partial\beta_{x,y}}{\partial\delta_p}\right)$$

$$W_{x,y} = \sqrt{a_{x,y}^2 + b_{x,y}^2}$$

$$\phi_{x,y} = \arctan\left(\frac{a_{x,y}}{b_{x,y}}\right)$$

The slopes $\frac{\partial\beta_{x,y}}{\partial\delta_p}$ and $\frac{\partial\alpha_{x,y}}{\partial\delta_p}$ are calculated using a linear fit for every beam position monitor at different δp settings.

Simulations

First simulation was conducted to find possible limitations on the existing algorithms with respect to the δp range. A histogram of the relative measurement error is shown in Fig. 4. Two different simulations are shown. In red, a small frequency trim was applied, $\delta p = \pm 0.5\times 10^{-3}$. For blue a medium radial frequency trims was applied, $\delta p = \pm 10^{-3}$. The error of the chromatic amplitude function is increasing when higher radial frequency trims are applied. This is explained as β is not longer linear for larger δp. Second simulation was conducted to identify the systematic difference between model and tracking. Two different models were used. One model was constructed using Twiss parameters at different δp settings, from here on defined as external model. The other is using the chromatic function calculated in MAD-X, from here on defined as internal model. Figure 5 shows a histogram of the normalized difference between measurement and model, for both models. Small δp setting for external model (red). Medium δp

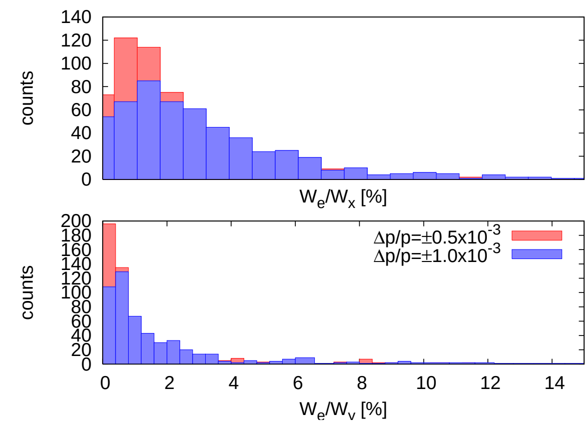

Figure 4: Histogram of the relative systematic measurement error is shown. Horizontal plane, above and vertical plane, below. Two different simulations are shown.

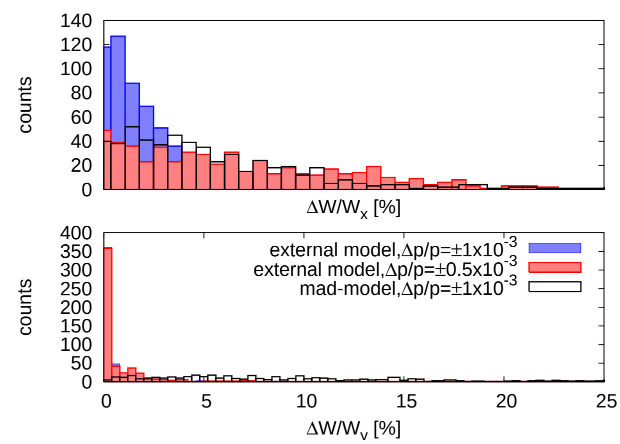

Figure 5: Histogram of the normalized difference between measurement and model. Small δp setting for external model (red) and model (pink). Medium δp setting for external model (blue) and model (green). Large discrepancy between the two models is observed, mainly in the vertical plane.

setting for the external (blue) and internal model (black). Small δp setting for the internal model is not shown, as the result is similar as for medium δp setting. Large discrepancy between the two models is observed, mainly in the vertical plane. This discrepancy is $\sim 5\%, 15\%$, respectively for the external and internal model. Tracking for difference δp setting shows almost no influence in the vertical plane. However, in the horizontal plane, tracking for smaller δp shows larger error.

The outcome of the simulations is that δp settings in the range of $0.5-1\times10^{-3}$ should be applied. External model is the preferred model. As a large discrepancy was observed between the internal model and tracking.

Measurements

Measurements for the chromatic amplitude function have been conducted at several instance during the commissioning. Measurement conducted at $\beta^* = 1.0$ m is shown in Fig. 6. Horizontal plane, top and Vertical plane, bottom. Model and measurement are in relative good agreement. Histogram of the relative error on the chromatic amplitude function for measurement at $\beta^* = 3.5$ is shown in Figure 7. The error on the measurement is significant. Slightly better result if only large trims are considered.

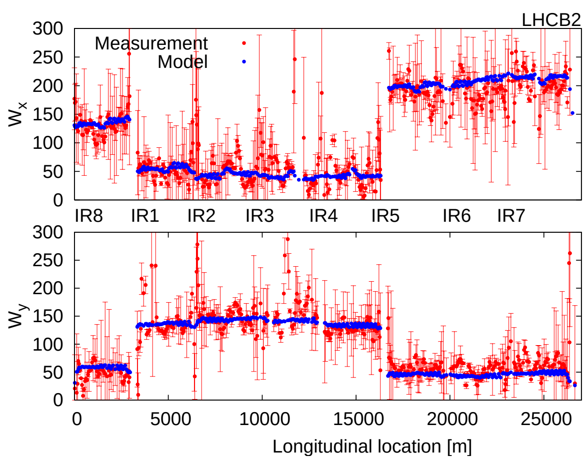

Figure 6: Measurement for the chromatic amplitude function at $\beta^* = 1.0$ m. Measurement, red and model, blue. Measurement and model are in relative good agreement.

CONCLUSIONS AND OUTLOOK

First measurements of the f_{3000} are shown. A reasonable agreement in the arcs is shown between model and measurements. Around the IPs a large discrepancy between measurement and model was observed. It will be investigated if this discrepancy could be explained by noise, phase advance between the BPMs at the IPs or by the non-linearity of the BPMs. For the chromatic aberrations, large discrepancy between MAD-X model and model constructed from the Twiss parameters at different δp settings is observed. This discrepancy is larger in the vertical plane. Model constructed from the Twiss parameters should be used. Furthermore, for measuring the chromatic

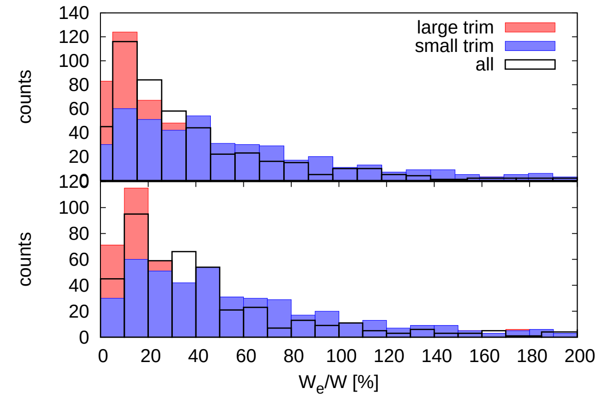

Figure 7: Histogram of the relative error on the chromatic amplitude function for measurement at $\beta^* = 3.5$ is shown . The error on the measurement is significant. Slightly better result for large trims.

abbreviation δp settings should be applied in the range $0.5 - 1 \times 10^{-3}$. Measurements of the chromatic amplitude function show a relatively good agreement between measurement and model.

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