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LOCALISATION OF BEAM OFFSET JITTER SOURCES AT ATF2

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Abstract

For the commissioning and operation of modern particle accelerators, automated error detection and diagnostics methods are becoming increasingly important. In this paper, we present two such methods, which are capable of localising sources of beam offset jitter with a combination of correlation studies and so called degree of freedom plots. The methods were applied to the ATF2 beam line at KEK, where one of the major goals is the reduction of the beam offset jitter. Results of this localisation are shown in this paper. A big advantage of the presented method is its high robustness especially to varying optics parameters. Therefore, we believe that the developed beam offset jitter localisation methods can be easily applied to other accelerators.

INTRODUCTION

At the Accelerator Test Facility (ATF) at KEK, an international collaboration aims to demonstrate several key concepts of future linear colliders. Significant achievements have been already reached, e.g. the feasibility verification of the ILC damping ring specifications [1], and the verification of an ILC/CLIC like final focus system [2]. However, an important open issue that is currently studied is to reach the high beam stability specifications of the ATF2 beam line (goal 2). The transverse pulse-to-pulse beam offset (in the following simply called beam offset jitter), currently between 15% and 28% of the nominal beam size, has to be reduced to below 5%.

In this paper we contribute to the achievement of goal two, by applying two complementary methods to localise the sources of beam offset jitter along the ATF2 beam line. The first method is based on the well-known Model Independent Analysis (MIA) [3], but uses instead of the full beam position monitor (BPM) measurements the correlation matrix of the BPM measurements. This improves the robustness of the method. Since this first method is well suited to determine the location of the jitter source, but it is hardly possible to extract detailed properties of the beam offset jitter (shape of the trajectory and signal power) a second method is used as well. This second method is based on the de-correlation of different BPMs from each other. Both methods will be presented in this paper.

The two mentioned methods have been applied to the ATF2 beam line. The results of this localisation have been used as a basis for a series of experiments to identify the beam jitter source. In this paper, the progress on both the jitter localisation and its identification will be discussed.

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METHODS

Modified Degree of Freedom Plot

Degree of Freedom (DoF) plots (see [3]) are very well suited to determine the location of beam offset jitter sources. Such plots can be created from BPM measurements with the following procedure. The measurement data are combined to a matrix $\boldsymbol{B} = [\boldsymbol{b}_1, \boldsymbol{b}_2, ..., \boldsymbol{b}_n]$, where $\boldsymbol{b}_j$ is the vector of measurement data from the jth BPM and n is the total number of BPMs. Usually, i is defined to be 3 or 4. The first few columns of this matrix $\boldsymbol{B}_i = [\boldsymbol{b}_1, \boldsymbol{b}_2, ..., \boldsymbol{b}_i]$, $i < n$ are then used for a singular value decomposition (SVD) to compute the vector of singular values $\boldsymbol{s}_i$. Then one more BPM is considered and the matrix $\boldsymbol{B}_{i+1} = [\boldsymbol{b}_1, \boldsymbol{b}_2, ..., \boldsymbol{b}_{i+1}]$ is used to calculate $\boldsymbol{s}_{i+1}$. This procedure is repeated until all singular value sets $\boldsymbol{s}_i$, $\boldsymbol{s}_{i+1}$, ... $\boldsymbol{s}_n$ are known. The first line in the DoF plot consists then of the largest singular values of each sets $\boldsymbol{s}_i$, $\boldsymbol{s}_{i+1}$, ... $\boldsymbol{s}_n$. The second line consists of the second larges singular value of these sets and so on. Note that the different lines have a different number of points.

In the paper [3] it is shown that a change in slope of these singular value lines indicates new jitter sources. This can be understood in the way that at a certain BPM the beam motion cannot be decomposed in the same number of modes as before anymore, but new modes have to be added which correspond to independent sources. In our analysis we have used instead of the BPM data $\boldsymbol{B}$, the matrix $\boldsymbol{R}$ consisting of the Person correlation coefficients r_{ij} of $\boldsymbol{b}_i$ with $\boldsymbol{b}_j$ (modified DoF plots). The Person correlation coefficient is defined as

$$r_{ij} = \frac{\mathrm{cov}(\boldsymbol{b}_i, \boldsymbol{b}_j)}{\sigma(\boldsymbol{b}_i)\sigma(\boldsymbol{b}_i)} = \frac{\mathbb{E}\left\{[\boldsymbol{b}_i - \mu(\boldsymbol{b}_i)][\boldsymbol{b}_j - \mu(\boldsymbol{b}_j)]\right\}}{\sigma(\boldsymbol{b}_i)\sigma(\boldsymbol{b}_i)}, \quad (1)$$

where $\mu(\boldsymbol{b}_i)$ and $\sigma(\boldsymbol{b}_i)$ correspond to the mean value and the standard deviation of the BPM data, respectively, and $\mathrm{cov}(\boldsymbol{b}_i, \boldsymbol{b}_j)$ corresponds to the covariance of two BPM measurements. The use of $\boldsymbol{R}$ instead of $\boldsymbol{B}$ reduces the data by neglecting temporal patterns, but makes the analysis more robust against influences from changing beam line properties, e.g. the beta function.

Beam Offset Jitter Extraction

Modified DoF plots are well suited to detect the location of beam offset jitter sources. For the identification of the corresponding source it is often necessary to have additional information about the created beam offset jitter, e.g. oscillation shape and signal power. Hence, it is shown in the following, how beam offset jitter from a specific source can be extracted from the overall beam motion. The intention is to remove all beam jitter that is created upstream the beam jitter source located at BPM $m \le n$. Therefore, we

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de-correlate the data $\boldsymbol{b}_j, \forall j \geq m$ one after the other, from all BPM data sets $\boldsymbol{b}_i$, $i < m$. First, we only focus on the de-correlation of two BPMs. Formulating this intention mathematically, we search for a signal

$$\hat{\boldsymbol{b}}_j = \boldsymbol{b}_j + k_{ij}\boldsymbol{b}_i, \tag{2}$$

with k_{ij} such that $\hat{\boldsymbol{b}}_j$ is linearly de-correlated from $\boldsymbol{b}_i$, which is

$$\mathrm{cov}(\hat{\boldsymbol{b}}_j, \boldsymbol{b}_i) = 0. \tag{3}$$

Using the definition of the covariance from Eq. (1) in Eq. (3) and solving for k_{ij} gives

$$k_{ij} = -\frac{\mathrm{cov}(\boldsymbol{b}_i, \boldsymbol{b}_j)}{\sigma(\boldsymbol{b}_j)^2} = -r_{ij}\frac{\sigma(\boldsymbol{b}_i)}{\sigma(\boldsymbol{b}_j)}, \tag{4}$$

were r_{ij} is the already mentioned Person correlation coefficient. Usually, the beam motion originating from upstream of BPM $\boldsymbol{b}_m$ cannot fully be observed in only one upstream BPM $\boldsymbol{b}_i$. In this case it is advantageous to de-correlate several or all upstream BPMs in a combined way. Therefore, the above derivation can be generalised for several BPMs, which can be shown to be (see e.g. [3])

$$\begin{aligned} \hat{\boldsymbol{b}}_j &= \boldsymbol{b}_j - \boldsymbol{K}_{up}\boldsymbol{b}_j \quad \text{with} \\ K_{up} &= \boldsymbol{B}_{up}\boldsymbol{B}_{up}^{\dagger} \quad \text{and} \\ B_{up} &= [\boldsymbol{b}_1, \boldsymbol{b}_2, \ldots, \boldsymbol{b}_{m-1}]. \end{aligned} \tag{5}$$

JITTER SOURCE LOCALISATION

To apply the above described methods to the ATF2 beam line, the according BPM data had to be acquired via the distributed control system EPICS [4]. Figure 1 shows the modified DoF plot computed from data taken on the 10th of April 2013. For completeness it should be mentioned that not the full BPM data, but the difference between two time steps $\Delta\boldsymbol{b}_i = \boldsymbol{b}_i[2,\ldots,n] - \boldsymbol{b}_i[1,\ldots,n-1]$ was used to focus on jitter-like motion instead to the beam orbit. In the experiment the bunch charged was varied in steps from N equal to 3×10^9 to 6×10^9 particles per bunch. It can be observed, that the first mode of the beam offset jitter (solid line) is much stronger than the sum of all other modes (dashed line). This first mode, which will be named in the following source 1, is observed early in the beam line around BPM MQD10X. Unfortunately, it cannot be located precisely, since the BPMs before BPM MQD10X don't have sufficient resolution to allow a bunch-to-bunch analysis. For the experiment illustrated in Fig. 1, source 1 creates a beam offset jitter of about 20% compared to the overall beam jitter of 21%. It is therefore the main jitter source in the ATF2 beam line.

The second beam offset jitter source (source 2), appears around BPM MQF21X, which corresponds to BPM 111 in Fig. 1. Contrary to source 1, the location of source 2 can be well determined. Also, the beam offset jitter created by source 2 has been reconstructed by removing the

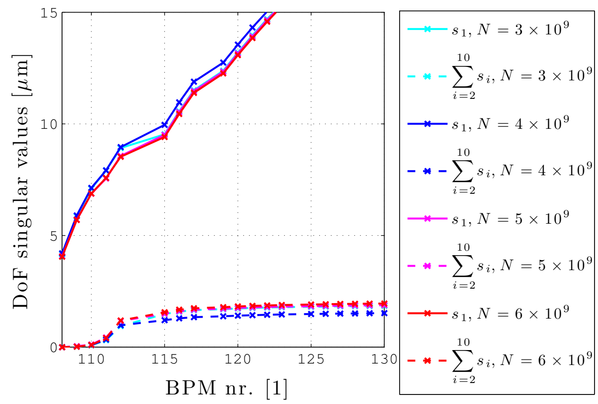

Figure 1: Modified degree of freedom plot of the beam offset jitter. The different colours correspond to different beam charges N. The solid lines correspond to the largest singular values s_1, while the dashed lines are the sum of all other singular values s_i.

components that correspond to source 1 using the method to extract beam jitter described in the last section. It was found that the standard deviation of the beam offset jitter of source 2 was about 5% of the nominal beam size. Note that the amplitudes of source 1 and source 2 have to be added in quadrature, since the two signals are independent stochastic processes. From Fig. 1, it also clear that there is no charge dependence on the created beam offset jitter.

JITTER SOURCE IDENTIFICATION

After localising the existing beam offset jitter sources, studies to identify the causing device were performed (source identification). Since no charge dependence of the beam offset jitter was observed in the identification experiment (see Fig. 1), wake fields in combination with charge variations can be excluded as an explanation for the observed beam offset jitter. Also varying electric fields cannot be the cause of the beam offset jitter, since its strength would have to be about 1 kV over the typical length of a quadrupole, which is unreasonable high. Hence the reason for the observed beam offset jitter is very likely to be a varying magnetic field.

To find these magnetic fields, the focus was laid firstly on source 2, since it lies within the area equipped with high resolution BPMs, contrary to source 1. The extracted beam offset jitter was used to determine its typical shape. This was done by taking the first mode of the SVD of the already extracted data. A simple average of the oscillation data would have been not sufficient, since the sign of the jitter oscillations varies. Since the modes computed by an SVD are orthonormal (l_2-norm of 1), the first mode has been scaled, such that its amplitude corresponds to the standard deviation of the beam offset jitter of source 2. The so extracted typical motion is depicted in Fig. 2 (red line).

As a next step, tracking studies have been performed with LUCRETIA [5] to identify kick locations, at which the cre-

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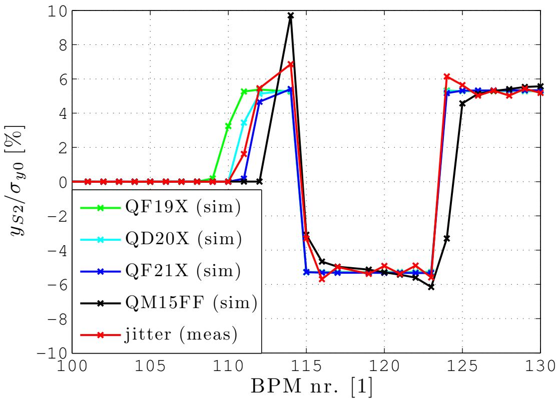

Figure 2: Comparison of the shape of the extracted beam offset jitter from measurements in red (with its amplitude set to its standard deviation), with the beam trajectory due to offsets of different quadrupoles in simulations.

ated beam motion corresponds to the typical jitter created by source 2. The simulations reveal (see Fig. 2) that a kick from quadrupole QD20X (cyan) explains the measured beam offset jitter very well. Kicks from quadrupoles before and after QD20X fit less well. A vertical misalignment of QD20X by only 400 nm was used in simulation to create the depicted motion. Equally, a relative field jitter of 2×10^{-4} in combination with 1 mm beam orbit at QD20X could explain the observed beam jitter as well.

These important quantitative findings about source 2 can also be extrapolated to source 1, if one assumes that the beam offset jitter of source 1 is created by a vertical quadrupole motion of the same size as necessary to explain source 2. Furthermore, we assume a random phase advance between the kick location i and a BPM at location s, at which the beam offset jitter $y_i(s)$ is measured. Then $y_i(s)$ due to a vertical quadrupole displacement Δy_i scales as

$$y_i(s) \propto \sqrt{\beta_i} y_i' = \sqrt{\beta_i} \Delta y_i K_i, \quad (6)$$

where β_i is the beta function at the kick location, y_i' the applied kick, and K_i is the integrated strength of the according quadrupole. Using Eq. (6), one can predict the beam offset jitter $y_j(s)$ created at another position j with the same quadruple offset jitter by

$$y_j(s) = f_{ij} y_i(s) \quad \text{with} \quad (7)$$
$$f_{ij} = \frac{\sqrt{\beta_j} K_j}{\sqrt{\beta_i} K_i}.$$

Applying the scaling law Eq. (7) to quadrupoles upstream in the possible area of source 1 to predict the potentially created beam offset jitter, results in the estimates given in Tab. 1. From these results it is clear that some of the quadrupoles in the possible area for source 1 are more sensitive then the ones at the location of source 2. Therefore, a similar error as at source 2 could well explain source 1.

Further experiments were performed to investigate the possibility of field fluctuations of the quadrupoles (due to ripple from the power supplies) being the source of the created beam offset jitter. In this case the beam offset jitter would be dependent on the beam orbit through the quadrupoles. Therefore, beam orbit bumps were created at possible locations for source 1 and 2. No change of the beam offset jitter could be observed however. Hence, field fluctuations of the quadrupoles can be ruled out as a possible beam offset jitter source. Further experiments are planned to finally identify the sources and resolve the beam offset jitter problem at ATF2.

Table 1: Predicted standard deviation of the created beam offset jitter relative to the nominal beam size, if the according quadrupole is misaligned in the same way as QD20X to explain the beam offset jitter of source 2

QF1X	QD2X	QF3X	QF4X	QD5X	QF6X
16%	51%	19%	18%	50%	21%

CONCLUSIONS

In this paper, two complementary methods that can be used to localise beam offset jitter sources are discussed. Both methods are based on correlation techniques. They have been successfully applied to the ATF2 beam line, where a major goal is to reduce the beam offset jitter from the present range between 15% and 28% to below 5% of the nominal beam size. Two sources could be localised. Source 1 is the stronger one and creates nearly all of the observed beam offset jitter. This source is located far upstream in the beam line or even the damping ring, where unfortunately no sensitive enough BPMs are available to localise the source more precisely. Source 2, which creates much less beam motion (about 5%), could be well located around quadrupole QD20X. First experiments to identify the localised sources have been performed, and quadrupole field fluctuations can be ruled out as the cause of beam offset jitter. Further studies are ongoing to finally remove the sources. The presented methods have been proven to be very robust, allowing to localising beam offset jitter source at each accelerator that is equipped with BPMs with sufficiently high resolution.

REFERENCES

[1] K. Kubo et al., Phys. Rev. Lett. 88, 194801, 2002.

[2] G.R. White et al., Phys. Rev. Lett. 112, 034802, 2014.

[3] J. Irwin et al., Phys. Rev. Lett. 82, p.1684-1687, 1999.

[4] EPICS documentation, http://www.aps.anl.gov/epics/, ANL.

[5] The LUCRETIA project, http://www.slac.stanford.edu/accel/ilc/codes/Lucretia/, SLAC.