

# EXPERIMENTAL VERIFICATION TOWARDS FEED-FORWARD GROUND MOTION MITIGATION AT ATF2

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## Abstract

Without counter measures, ground motion effects would deteriorate the performance of future linear colliders to an unacceptable level. An envisioned new ground motion mitigation method (based on feed-forward control) has the potential to improve the performance and to reduce the system cost compared to other proposed methods. For the experimental verification of this feed-forward scheme, a dedicated measurement setup has been installed at ATF2 at KEK. In this paper, the progress on this experimental verification is described. An important part of the feed-forward scheme could already be demonstrated, namely the prediction of the orbit jitter due to ground motion measurements.

## INTRODUCTION

Ground motion is a severe problem for future linear colliders. The continuously misaligned quadrupole magnets induce beam oscillations, which result in emittance increase and beam-beam offset at the interaction point. If uncorrected, these effects reduce the luminosity to an unacceptable level. Different mitigation methods have been studied to reduce the deteriorating ground motion influence. Orbit feedback systems can suppress beam oscillations efficiently, if their frequencies are about a factor 20 lower than the beam repetition rate  $f_R$  (oversampling necessary for digital control to be efficient). For the remaining components at higher frequencies, additional mitigation methods have to be foreseen. Two systems have been designed and tested in the past: intra-pulse feedback systems [1] and stabilisation systems [2, 3]. Intra-train feedback systems measure the positions of the first few bunches of each beam train, in order to correct the following bunches via the utilisation of ultra-fast feedback electronics. Even though they work very efficient for the ILC, they are not sufficient for CLIC where the bunch spacing is too short to react quickly enough. Additionally, intra-train feedback systems can only be utilised at a few dedicated locations and no spatially distributed corrections can be applied. Therefore, stabilisation systems are the baseline solution for CLIC. These systems compensate mechanical motion of quadrupole magnets by stabilising each of them with a dedicated positioning structure. Stabilisation systems have shown to meet their stringent specifications, but they are

costly and the individual quadrupole magnets are stabilised independent of each other.

To overcome these disadvantages a third mitigation method is presented in this paper. It is based on feed-forward control utilising vibration sensors that are positioned along the beamline. The sensor measurements are used to predict the beam orbit change due to the misalignments of the quadrupole magnets. For this prediction, a linear system model is used, which is represented by the orbit response matrix  $R_q$ . As a last step, actuations of corrector magnets are computed to compensate the predicted beam motion.

The described feed-forward system has the potential of cost reduction and performance improvements compared to other systems. An analytic model and simulation studies of the feed-forward scheme has been already presented in [4] and [5], respectively. In this paper, results from an experiment at ATF2 [6] at KEK are presented. The experiment aims to demonstrate the practical feasibility of the prediction part of the overall system. Also updated simulation studies for this experiment are shown. The important demonstration of the full mitigation system is subject to future work.

## SIMULATION RESULTS

Simulations have been presented in [5], in which the feasibility of the prediction of orbit jitter from vibration measurements with seismometers is evaluated. The focus was laid on the predictions of orbit changes (orbit jitter)  $\Delta \mathbf{b}_k = \mathbf{b}_k - \mathbf{b}_{k-1}$  in all beam position monitors (BPMs), where  $k$  is the beam pulse index. Using the orbit jitter corresponds to a high-pass filtering of the orbit data  $\mathbf{b}_k$ , which suppresses low frequencies that would be corrected in a real application by an orbit feedback system. The simulations have been performed with the tracking code PLACET [7]. Realistic ground motion has been created with a ground motion generator using a model developed especially for ATF2 in [8]. Also other dynamic and static imperfections have been included, most importantly orbit jitter at the beginning of the beamline with an RMS value of 10% and 25% of the beam size in the horizontal and vertical direction, respectively.

The simulations showed that the orbit jitter due to ground motion is a factor 20 to 100 smaller than the orbit jitter from other sources. Therefore, the detection of ground motion effects seems to be very challenging. To overcome this problem a technique was developed that removes incoming, parasitic orbit jitter from other sources than ground motion. The initial technique was based on a singular value decomposition (SVD) of the BPM data, but turned out to be not

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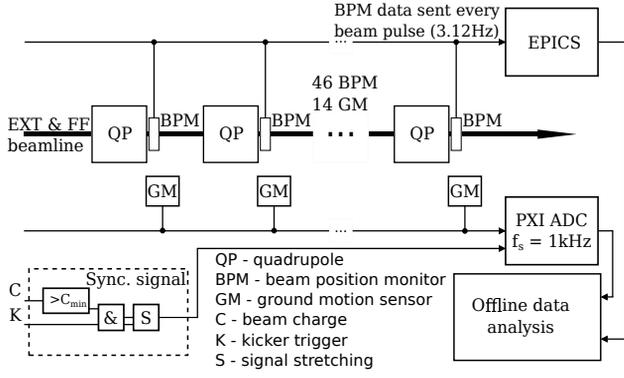


Figure 1: Overview of the experimental setup at ATF2, with the beam passing from left to right.

robust enough for a practical application. Another technique is presented in this paper, which shows improved robustness properties. Three upstream high-resolution cavity BPMs (number 10, 11 and 12 out of 46 BPMs) are used to estimate the incoming orbit jitter and to remove it from the downstream BPM measurements via a decorrelation technique. This is done due to simulation results that predict that the ground motion effect is very small at these three BPMs, and the measured orbit jitter is fully parasitic. To describe the decorrelation procedure, it is convenient to combine the BPM measurements of all time steps (1 to  $N_p$ ) to

$$\Delta \mathbf{B} = \begin{bmatrix} \Delta \mathbf{b}_1^T \\ \vdots \\ \Delta \mathbf{b}_{N_p}^T \end{bmatrix}. \quad (1)$$

The  $i^{\text{th}}$  column of  $\Delta \mathbf{B}$  corresponds to all measurements of the  $i^{\text{th}}$  BPM and is in the following referred to as  $\Delta \mathbf{B}_i$ . Using this abbreviation, the mentioned decorrelation of the measurements  $\Delta \mathbf{B}_i$  can be achieved according to [9] by

$$\Delta \mathbf{B}_i^{(r)} = \Delta \mathbf{B}_i - \mathbf{K}_{up} \Delta \mathbf{B}_i \quad (2)$$

$$\mathbf{K}_{up} = \Delta \mathbf{B}_{up} \Delta \mathbf{B}_{up}^\dagger \quad (3)$$

$$\Delta \mathbf{B}_{up} = [\Delta \mathbf{B}_{10}, \Delta \mathbf{B}_{11}, \Delta \mathbf{B}_{12}]. \quad (4)$$

After applying the procedure in Eqs. (2-4) to the measurement data, the sensitivity of the experiment is increased to a level, where a practical implementation seems to be possible.

## EXPERIMENTAL SETUP AND DATA PROCESSING

The experimental setup for the prediction of orbit jitter due to vibration measurement is depicted in Fig. 1. The overall setup consists of three parts: BPM system, vibration measurement system and a synchronisation signal. The available BPM system consists of two different types of devices: stripline BPMs at the beginning of the beamline with a resolution of  $5 \mu\text{m}$ , and cavity BPMs further downstream with  $0.1 \mu\text{m}$  resolution. The simulation studies have shown that only the cavity BPMs are sensitive enough to

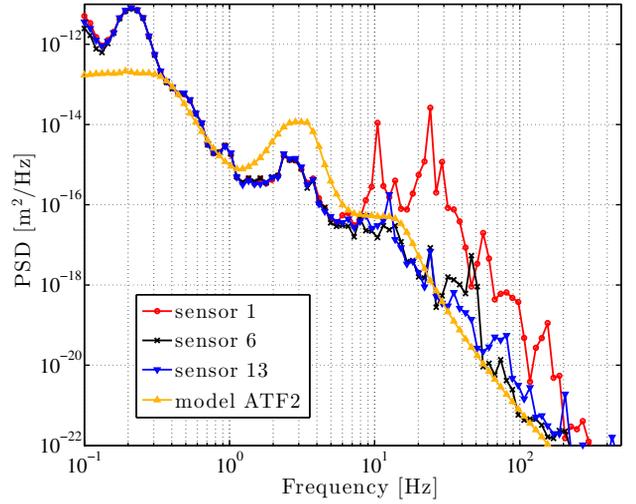


Figure 2: Power spectral densities (PSDs) of the vibration sensor measurements and model data in vertical direction.

be useful for the experiment. In parallel to the BPM data, also vibration data are recorded with 14 seismometers of the type CMG-6T from Guralp, which are positioned along the beamline. These instruments are sensitive in a frequency range from 0.03 Hz to 100 Hz. Their analogue signals are digitised by a National Instruments PXI 8109 RT controller equipped with the digitiser card 6289. The BPM system and the vibration data acquisition system sample at different frequencies: 3.12 Hz (BPMs) and 1024 Hz (National Instruments digitiser). To correlate the two signals, the vibration data sets have been selected, which are closest in time to the BPM measurements. For that reason, the PXI controller also records a synchronisation signal. This signal indicates the beam arrival, which triggers the BPM data acquisition. The thereby selected vibration data are used to predict the resulting orbit jitter  $\Delta \hat{\mathbf{b}}_k$  with the relation

$$\Delta \hat{\mathbf{b}}_k = \mathbf{R}_q \Delta \hat{\mathbf{x}}_k, \quad (5)$$

where  $\Delta \hat{\mathbf{x}}_k$  are the estimated changes of the quadrupole magnet positions, and  $\mathbf{R}_q$  is the orbit response matrix. The quadrupole magnet position changes  $\Delta \hat{\mathbf{x}}_k$  are created via linear interpolation from the vibration measurement.

After the computation of  $\Delta \hat{\mathbf{b}}_k$ , these predictions of the ground motion effect can be compared with the real BPM measurements. As a measure the correlation coefficient  $r$  is used, which is given for the  $i^{\text{th}}$  BPM by

$$r_i = \frac{\text{cov}(\Delta \mathbf{B}_i, \Delta \hat{\mathbf{B}}_i)}{\sigma(\Delta \mathbf{B}_i) \sigma(\Delta \hat{\mathbf{B}}_i)}, \quad (6)$$

where  $\sigma$  and  $\text{cov}$  symbolise the standard deviation and the covariance, respectively.

## EXPERIMENTAL RESULTS

The power spectral densities (PSDs), calculated with Welch's method [4], of measurements of three different seismometers are depicted in Fig. 2. The data are compared

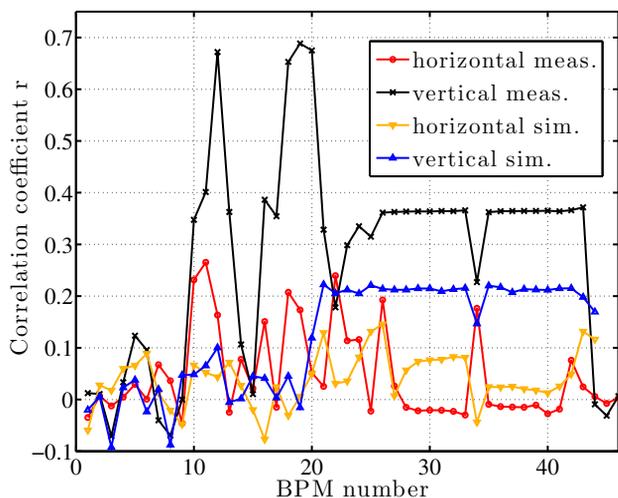


Figure 3: Correlation coefficients calculated from the predicted and the measured orbit jitter. The results are compared with data produced by the simulations described earlier.

with a ground motion model [8] created especially for ATF2. Some model deviations in the frequency range from 1 Hz to 6 Hz can be observed, which are normal, since these vibrations are created by the changing crustal motion (crustal resonance). Also below 0.3 Hz the model does not fit the measurement data well, but the corresponding frequency components are only of small importance for the experiment. Apart from these deviations, all sensor measurements (including not depicted ones) are well described by the model with the exception of sensor 1. The latter shows strongly increased vibrations in the frequency range from 10 Hz to 100 Hz. This observation suggests that the orbit jitter due to ground motion  $\Delta\hat{B}$  might be significantly stronger than predicted in simulations. Especially, ground motion contributions from the beginning of the beamline will be more important than forecasted. As a result, the foreseen removal technique, given by Eqs. (2-4), will not work as expected.

In Fig. 3 the correlation coefficient, defined in Eq. (6), is depicted for measured and simulated data. The measured data show a strong correlation especially in the vertical direction. Values of 0.69 are reached at some BPMs. No removal of the incoming jitter, according to Eqs. (2-4), has been applied. If it is applied, the correlation drops strongly, which shows that most of the orbit jitter that is created by ground motion originating upstream of the high-resolution BPMs used for the decorrelation procedure. All of these observations are in contrast to the expectation from simulations. This discrepancy comes from the unexpected, strong vibrations around sensor 1.

A careful inspection of the beamline around the location of sensor 1 has been performed. Two difficult to find vibration sources have been identified. A metal pipe and a plastic tube, both transporting cooling water, were touching the girder of the quadrupole magnet QFIX. Vibrations generated by the cooling water flow were transmitted from the pipe and the tube to the girder. The two vibrating objects could be

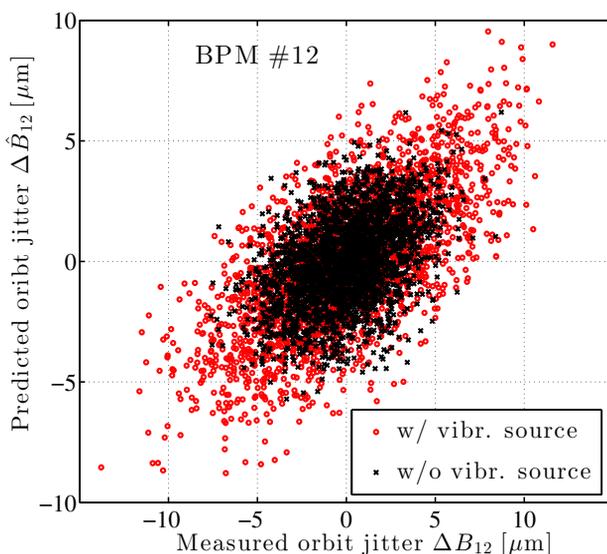


Figure 4: Predicted and measured orbit jitter at BPM 12, before (red) and after (black) removal of the vibration sources.

separated from the girder, and as a result the beam jitter was reduced by a factor of 1.4. This amplitude reduction corresponds to halving the excitation power. Also the correlation calculated from the predicted and measured orbit jitter was reduced drastically, as can be seen in the correlation plot in Fig. 4. A week after the described measurement, a second set of measurements was performed, which confirmed the reduction of the RMS orbit jitter by the mentioned factor.

## CONCLUSIONS

The efficient mitigation of ground motion effects is inevitable for the operation of future linear colliders. For this reason, a novel mitigation method has been introduced. The focus of this method is the correction of ground motion effects with frequencies that are too high to be suppressed by orbit feedback systems. It is based on feed-forward control, where motion sensors are used to measure the deteriorating vibrations of high frequency directly. The feed-forward scheme has several advantages compared to other methods. To prove the feasibility of the scheme an important part of the system has been implemented and tested at ATF2, namely the prediction of orbit jitter from vibration measurements. Correlations up to 0.69 between the predicted and measured orbit changes have been found. This is in contrast to simulation studies that predicted only very small correlation values. Strong additional magnet vibrations in the beginning of the beamline are the reason for this discrepancy. The according vibration sources have been identified. Water cooling pipes were touching the girder of a quadrupole magnet, which transmitted vibration from the pipes to the magnet. By removing these vibration sources, the orbit jitter power could be halved. The implementation of the full feed-forward scheme is planned in the near future at ATF2. This important study will also include the correction of the already successfully predicted orbit jitter.

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