IMPROVING THE PERFORMANCE OF AN ORBIT FEED-FORWARD BASED ON QUADRUPOLE MOTION AT THE KEK ATF

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Abstract

The high luminosity requirement for a future linear collider sets a demanding limit on the beam quality at the Interaction Point (IP). Even the natural motion of the ground could misalign the quadrupole magnets to such an extent that the resulting dipole kicks would require compensation. The novel technique described in this paper uses seismometers to measure the positions of the quadrupole magnets in real time and a kicker to counteract the effect of their misalignment. The prototype system deployed at the Accelerator Test Facility (ATF) at KEK in Japan has already demonstrated a reduction in the pulse-to-pulse vertical position jitter of the beam by about 10%. Based on the observed correlation of the beam position to the quadrupole positions the maximum possible jitter reduction from such a system is estimated to be about 25%. This paper details the latest improvements made to the system with the aim of achieving this limit.

INTRODUCTION

In order to achieve the design luminosity for a future linear lepton collider, compensation of the dynamic misalignments of the quadrupole magnets due to the natural motion of the ground will be essential [1]. Several techniques exist for this purpose including passive stabilization of the magnets [2] and intra-train beam position feedback at the interaction point (IP) [3]. Both of these existing techniques have their limitations: passive stabilization systems are bulky and expensive and are thus best suited for use with a few critical components, while intra-train feedback is very effective at removing the beam-beam offset at the IP but as a local system is unable to prevent luminosity loss resulting from the accumulation of misalignment errors along the length of the entire machine.

To address this, the novel technique of ground motion compensation using feed-forward control was proposed [4]. Beam orbit feedback systems use beam position monitors (BPMs) to detect deviations of the beam from the ideal orbit and then one or more kickers to correct for them. Such systems are capable of correcting effects at frequencies much lower than the beam repetition rate (3.12 Hz at ATF). The proposed ground motion feedforward system operates along similar lines, but the BPMs are replaced by seismometers (Fig. 1) so that the deviations in orbit are effectively predicted from the positions of the quadrupoles themselves.

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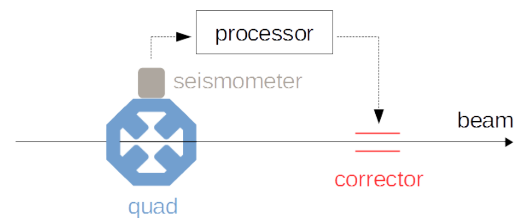

Figure 1: Schematic illustrating the principle of ground motion compensation using feed-forward control.

This allows orbit distortions caused by vibrations of the quadrupoles at frequencies higher than the beam repetition rate to be compensated for.

FEED-FORWARD HARDWARE

Figure 1 shows that the feed-forward system consists of three main components: seismometer, processor and corrector. In addition, the ATF2 beamline contains several cavity BPMs downstream of the corrector that are used to determine the effectiveness of the feed-forward system.

Seismometers

A total of 14 Güralp CMG-6T seismometers are distributed along the ATF2 extraction line. These sensors produce an output proportional to their velocity in both axes perpendicular to the direction of beam travel and respond to frequencies in the range 0.2 Hz up to 100 Hz. Their optimum position along the beam-line was determined by simulation [5] and they are located on top of the quadrupoles in order to measure their actual displacement.

Processor

The outputs of the sensors are digitized and logged using a National Instruments CompactRIO (cRIO) system acting as the feed-forward processor. This FPGA-based solution consists of a cRIO-9064 controller with cRIO-9205 and cRIO-9401 modules for analogue input and digital output respectively.

Corrector

The corrector is a stripline kicker (designated K1) that was installed in the extraction line as part of the FONT intra-train beam position feedback system [6]. A custom FPGA-based digital board, the FONT5 board, allows the

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kicker drive signal to be synchronized to the beam arrival time and an ultra-fast amplifier boosts the drive signal to the level required to change the beam orbit.

DATA ACQUISITION

The cRIO system is essentially a computer with a Real-Time LabVIEW operating system. The feed-forward algorithm is thus implemented using the National Instruments graphical programming language G. The FPGA is configured to digitize the seismometer signals at a sample rate of 1000 Hz and to generate a digital code every 5 ms corresponding to the current calculated value for the feedforward correction. A dedicated cable links the cRIO to the FONT5 board and the FONT5 firmware was modified to interpret the digital code sent by the cRIO and set the amplitude of the kicker drive signal accordingly.

The rest of the signal processing is performed on the real-time controller of the cRIO. This includes the integration of the velocity signal from the seismometers and filtering of the resulting position data, calculation of the feed-forward correction based on the user-provided gain, and logging the digitized data to file.

Beam position data from the witness BPMs and beam charge data is generated at the machine rate of 3.12 Hz and is made available in real time using the Experimental Physics and Industrial Control System (EPICS) to publish the data over the local network. In order to determine the correlation between the seismometer data recorded by the cRIO and the beam position data (and hence the ability of the feed-forward system to reduce this correlation), the seismometer data must be down-sampled from 1000 Hz to 3.12 Hz and the two data sets must be in phase. For this reason an additional synchronization signal is logged by the cRIO.

This signal functions as a beam arrival time indicator. The width of the pulse generated when the beam is detected is sufficiently narrow to justify the 1000 Hz sample rate used by the cRIO. The pulses of the synchronization signal are used to identify which samples from the seismometer data set correspond to the arrival of the beam and hence perform the down-sampling. Furthermore, by starting data acquisition for both the seismometers and the BPMs while the beam is turned off and turning the beam on almost immediately, and then turning the beam off just before the acquisition ends, a pair of reference points in time are created in both data sets that can be used to ensure the two are in phase.

FEED-FORWARD RESULTS

The simplest example of a feed-forward system is the one illustrated conceptually in Fig. 1 where the position measured by a single seismometer is used to drive a single kick. Previous studies have shown that the dominant contribution to the beam jitter at ATF is due to motion of the quadrupole QD2X [7], making that seismometer the obvious choice. The position at BPM MQD4BFF has been used to determine the performance of the system as it is both located in a region of high β (so that the jitter is naturally large) and with a betatron phase difference of 90° with respect to the stripline kicker (so that the effect of the kick is clearly evident).

Table 1: Correlation between Filtered QD2X Seismometer Data and MQD4BFF Beam Position

Filter limits [Hz]	Correlation
No filter	0.13
0.2-100	0.11
9.5-10.5	0.16
15-16	0.19
23-26	0.60

Figure 3 shows the power spectral density of the position reported by the seismometer on QD2X. It can be seen that, excluding the zero region, the largest peak in the spectrum occurs at a frequency of about 24.25 Hz. It was empirically observed that the correlation between the seismometer data and the beam position data was maximized by applying a 2nd order Butterworth filter with a passband of 23-26 Hz to the seismometer data. A matching filter was thus used for this feed-forward study. Table 1 shows the correlation measured for a variety of different limits for the band-pass filter.

The feed-forward algorithm assumes that the beam position is linearly dependent on the seismometer position, in which case the gain parameter is simply the fit coefficient, scaled to account for the kicker calibration constant. Figure 4 shows the jitter observed at BPM MQD4BFF as a function of this gain parameter. The data shows that the jitter at MQD4BFF is reduced from 51.6 ± 8.8 μm when the feed-forward is not operating to 42.3 ± 7.3 μm when the gain parameter is set to the presumed optimal value of 125. This is about a 20% reduction. The correlation is also reduced from 0.65 to 0.41.

Figure 5 shows the effect of the feed-forward system on the power spectral density of the position at the BPM. Aliasing results in the 24.25 Hz oscillation of QD2X appearing at a frequency of 0.70 Hz. It is clear that the feed-forward system dramatically reduced the amplitude of this peak. On the other hand, the two peaks at 0.20 Hz and 0.54 Hz correspond to oscillations of QD2X at frequencies of 15.4 Hz and 9.9 Hz respectively. As these frequencies are not within the passband of 23-26 Hz, their amplitude was not affected.

CONCLUSION

A reduction in the beam jitter induced by vibration of a quadrupole at a frequency much higher than the beam repetition rate of 3.12 Hz has been demonstrated at ATF2. The feed-forward system consisted of a single seismometer and a single kicker. Previous studies [7] demonstrated a 15% reduction in beam jitter when only low frequencies (<0.1 Hz) were considered. By specifically targeting the dominant vibration mode of the quadrupole at 24.25 Hz, the beam position jitter was reduced by 20% and the spectral

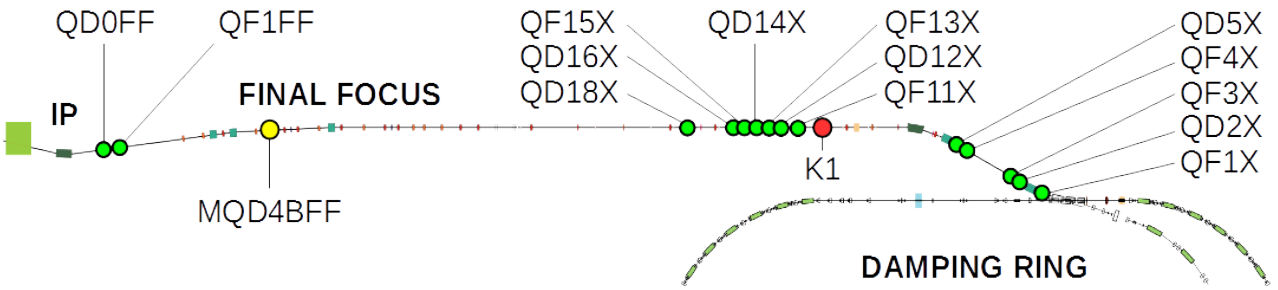

Figure 2: Schematic of the ATF. Green dots indicate the location of the seismometers, which are labelled with the name of the associated quadrupole. The kicker K1 is located at the red dot and the cavity BPM MQD4BFF at the yellow dot.

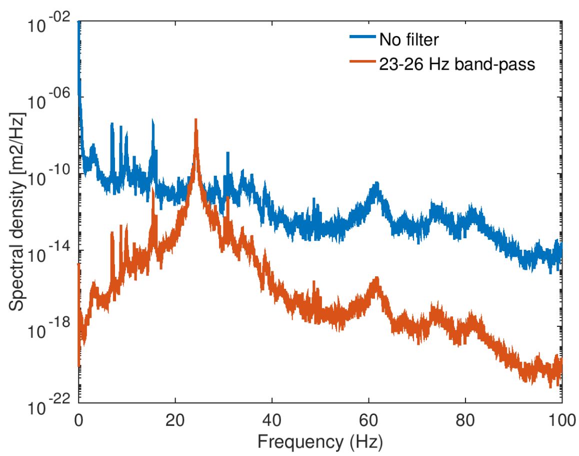

Figure 3: Power spectral density of the seismometer on QD2X. The unfiltered data is shown in blue and the result of applying a 23-26 Hz band-pass filter is shown in red.

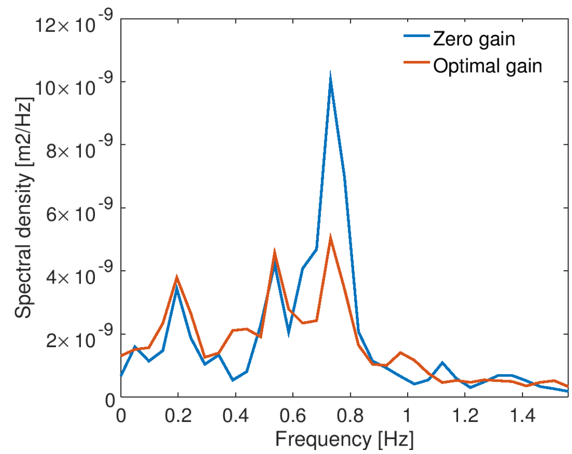

Figure 5: Power spectral density of the beam position at MQD4BFF. The blue line corresponds to a data run with feed-forward off and the red line to a run with the feedforward gain parameter set to the optimal value of 125 and a 23-26 Hz band-pass filter applied to the QD2X data.

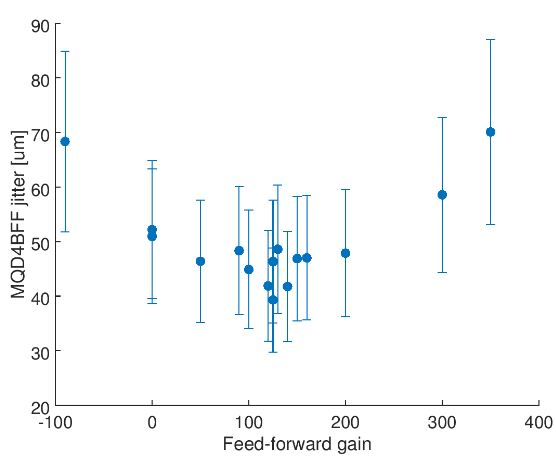

Figure 4: Beam position jitter as a function of the gain parameter. The position of the seismometer on QD2X with a 23-26 Hz band-pass filter applied is used as the input of the feed-forward calculation.

density of the vibration at 24.25 Hz was halved. Future work will look to add other seismometers and kickers to the feed-forward system to achieve a more distributed correction.

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