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DELIVERABLE REPORT

[FINAL REPORT GM-BASED FEED-FORWARD]

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Deliverable:

Final report on correlation between GM and orbit measurements and implications for GM-based feed-forward.

Task 2.3 Ground Motion (CERN, CNRS & KEK): Measure ground motion (GM) using 14 installed GM sensors synchronised with beam position measurements to assess novel GM-based feed-forward algorithm.

Executive summary:

We have studied how to mitigate the effect of ground motion on a nanometre-size electron beam for future linear colliders. Vibration source identification and mitigation has been performed on an accelerator test facility (ATF2) in Japan. In addition, the feasibility of a feed-forward system based on ground motion sensors has been validated for the first time.

1. INTRODUCTION

An exchange programme between Europe and KEK for the transfer of experience in instrumentation and beam handling and for hands-on experience with working accelerators like ATF2 at KEK is vital for the R&D for future accelerator projects.

Initial work on ground motion (GM) studies at ATF2 has already been carried out during a fruitful exchange between CNRS and KEK in 2007/08. After a mature understanding of the ATF2 ground motion had been obtained, the idea of using GM for reducing beam jitter (as a method complementary to orbit feedback) has emerged. This topic is the main object of this deliverable report. In addition, a careful identification of vibration sources is also reported to even further mitigate beam jitter.

2. GM MEASUREMENTS

2.1. PERTURBATION EVALUATION

The E-JADE participants contribute to the ATF2 experiment at KEK, Tsukuba, Japan. In this context, we are concentrating on the final-doublet (FD) section, containing the 2 last focusing quadrupoles just before the interaction point (IP) of the electron accelerator. These magnets are called QD0FF and QF1FF. The whole FD system is mounted on a big table made out of a honeycomb structure ensuring vibration stability with the ground. Each magnet is then put on an additional support depending on the magnet model, then on a mover for active beam control. Initially, the two magnets were of the same design. However, QF1FF is in a section where the beam has a large beta function, related to the transverse particle beam size. An evaluation of the beam dynamics showed that the old QF1FF had to be replaced by a new magnet with better multipole properties in order to achieve the smallest possible vertical beam sizes at the IP. In 2012, a new quadrupole has been installed with the desired properties. Having also a larger aperture, it is larger (648×618×461 mm^3) and heavier (1300 kg instead of 400 kg). Figure 1 shows the setup; the new quadrupole is seen in yellow.

Fig. 1: ATF2 final-doublet setup on its support

In our previous report [4], we detected the presence of a detrimental vibration source at 16.5 Hz. This source is not always present, but when it is, the behaviour of the system is such that the relative displacement between the magnet and the instrument with which the beam size is measured is beyond the specifications for a maximum 2% beam size growth. According to the ATF2 proposal (vol. 1) [5], this relative displacement should be below 20 nm, and when the 16.5 Hz appears, we are a little above. Figure 2 shows the power spectral density (PSD) of the top of the QF1FF magnet in the region of interest (10-27 Hz) around the 16.5 Hz perturbation peak. The black curve corresponds to a measurement done on a very hot day in May 2017, the green one to a colder day in May 2017, and the red curve to a cold day in November of that year. As one can see, there is a strong temperature dependence, the amplitude of the 16.5 Hz perturbation peak being highest when it is hot and vanishing when it is cold.

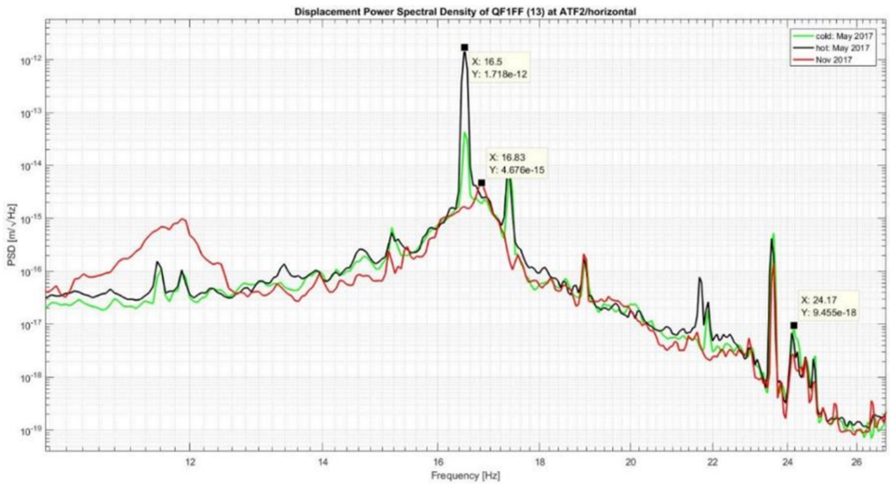

Fig. 2: PSD on QF1FF magnet on different days

Figure 3 shows the amplitude of the 16.5 Hz peak over time during a weekend from Friday May 26 to Monday morning May 29, 2017, this time with the sensor on another magnet QD2X close to the extraction line. The weather conditions are given in the figure. Again, one sees a clear temperature dependence.

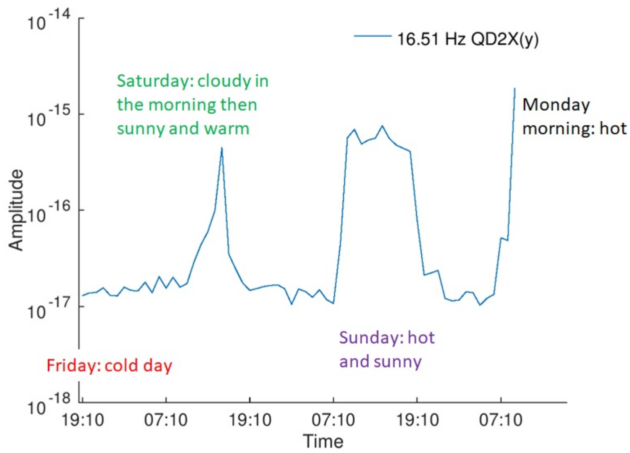

Fig. 3 Amplitude of 16.5 Hz peak over several days with different weather conditions, 26-31 May 2017

2.2. INVESTIGATING THE PERTURBATION

Meticulous investigations were undertaken to identify the source of the 16.5 Hz vibration. The sensors on ATF2 were kept in place, but different conditions were measured, always looking out for the detrimental 16.5Hz peak in the data. Figure 4 shows the ATF2 layout and some points of interest (red dots).

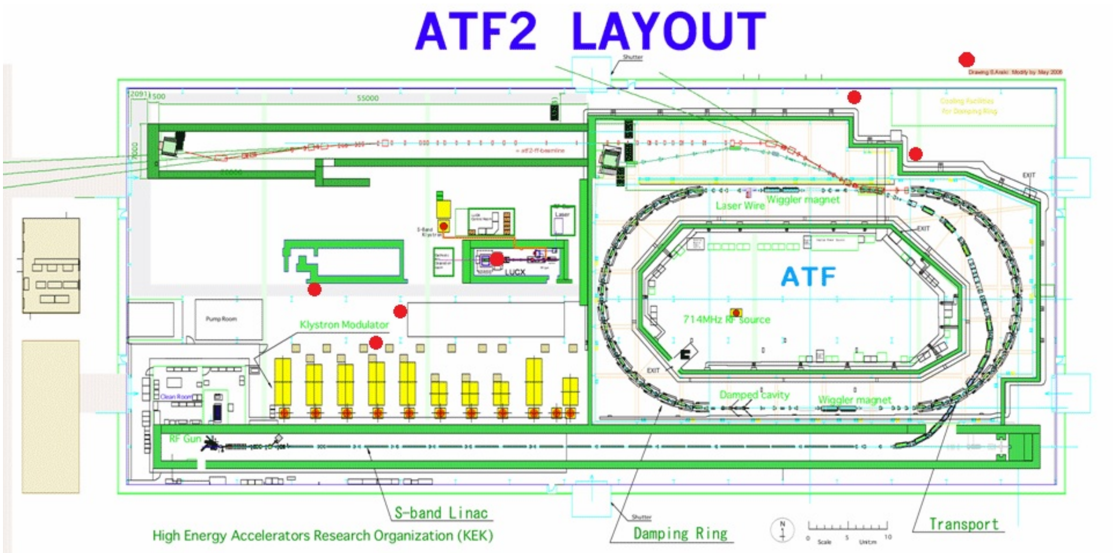

Fig. 4: ATF2 layout

This systematic study has allowed excluding some candidate sources for the 16.5 Hz vibration. On very hot days, some ventilators are turned on near the roof for a better air circulation and cooling. There was no impact with these ventilators on or off. Main cooling water pipes were generally vibrating at a frequency around 24 Hz. The latter are probably not the source; however, as will be seen later, this still needs more investigation. Near QF1FF, there is an air conditioning system to minimize temperature effects on the BSM (beam size monitor) measuring the beam size at IP. This had no effect on the 16.5 Hz peak. Some electronics systems with strong ventilators along the beam line have also been excluded. The FDmMagnets QF1FF and QD0FF right at the end of ATF2 are on supports and movers for active beam control. It was noted that these movers have a characteristic peak at 8.7 Hz. So the latter could also be excluded. Then another path explored was the LUCX (laser undulator compton X-ray) RF power, an X-ray generator sharing the hall with ATF2. It was turned off the whole weekend when the measurements in Fig. 3 were taken. It is thus also not the cause. In addition, different belt fans, klystron power cabinets and other ventilating items were turned on when the 16.5 Hz signal was absent. Some ventilation systems and compressors still need to be investigated. In summary, tt was not yet possible to clearly identify the source of the 16.5Hz peak before this report was due although a lot of possible causes have been excluded. However, a suspect will be the object of our particular attention in the near future: After looking at the vibration measurement data since 2013, it was observed that this peak was absent until May 2014. It first appeared in the data in October 2014. During the summer of 2014, the refrigerator for the ATF2 Extraction line cooling water was replaced. Since all sensors from the extraction line to the FD experience this undesirable vibration (see Fig. 5), finding a cause in a general cooling system looks promising. In addition, the record small beam size of 43 nm was obtained before summer 2014. This value has been reproduced, but often in cold weather periods (e.g. February 2016) tending to indicate that this 16.5 Hz peak is also detrimental for the final beam size at the interaction point. Next measurement campaigns will focus on this refrigerator. All these measurements have been summarized in [6].

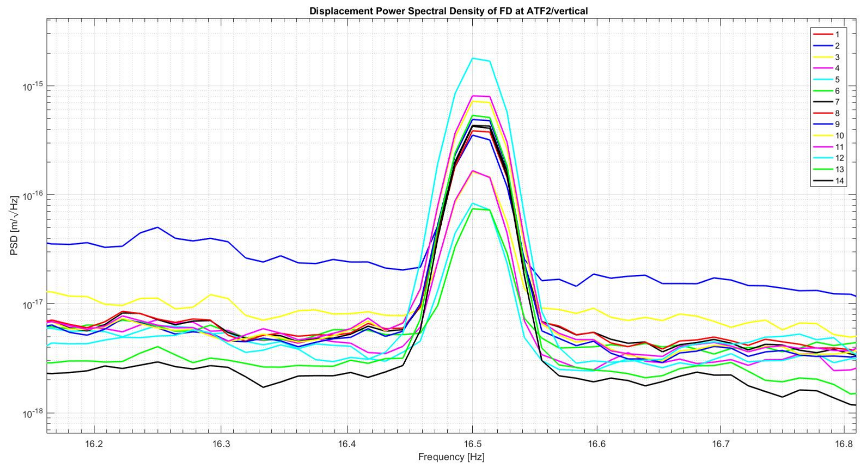

Fig. 5: PSD of all sensors around 16.5 Hz

3. ORBIT SYNCHRONIZATION AND MAGNET MEASUREMENTS

3.1. EVALUATION TOOLS

Ground motion, vibrations and drifts create beam oscillations that harm the beam quality and stability. For future linear colliders, where the beam size is in the nanometre range, high beam quality requirements make mitigation essential.

Different complementary mitigation schemes are being studied:

- First, there is the classical orbit feedback, which can correct frequencies much smaller than the machine repetition rate.
- In addition, intra-train feedback is essential at the IP but cannot correct global orbit distortions.
- Then, for higher frequencies that cannot be corrected by orbit feedback, active and passive stabilization can be used. However, these systems are too bulky and expensive for any but the most critical components.
- As a novel idea, we have investigated a feed-forward system based on ground motion measurements.

In this section, we describe this novel feed-forward system. In order to test the feasibility of a ground motion feed-forward system, we have installed GM sensors on relevant accelerator magnets, and each of these magnets is also equipped with a beam position monitor (BPM).

For the design of a feed-forward system, the beam position needs to be predicted. First, we therefore construct the linear combination of data from the different GM sensors that best matches the position observed at one of the quadrupoles downstream. Then, the correlation between this fit and the actual BPM data determines the performance of the feed-forward system. To evaluate the correlation, we use the following estimator:

$$\frac{\sigma_f}{\sigma_i} = \sqrt{1 - r^2}, \quad (1)$$

where σ_i is the jitter before correction (feed-forward off), σ_f is the jitter after correction (feed-forward on, obtained by subtracting the fit from the initial jitter), and r is the correlation between the fit using the GM sensors and BPM measurements [1].

3.2. FEED-FORWARD DESIGN

The feed-forward system is designed following a concept similar to orbit feedback; however, it uses GM sensors instead of BPMs to drive the correction. The main advantages of the system are that it can be cheaper than active stabilization systems, needing less maintenance. It can also correct frequencies out of limits for orbit feedback systems. In addition, it can be designed as a global system instead of many independent systems on all the individual quadrupoles, although a mechanical system could also be designed in a global manner.

A system has been installed in ATF2 using the 14 Güralp Systems CMG-6T seismometers [8], adding National Instruments data acquisition hardware and using synchronization signals for BPM and ground motion data sets [3]. Figure 6 shows the setup.

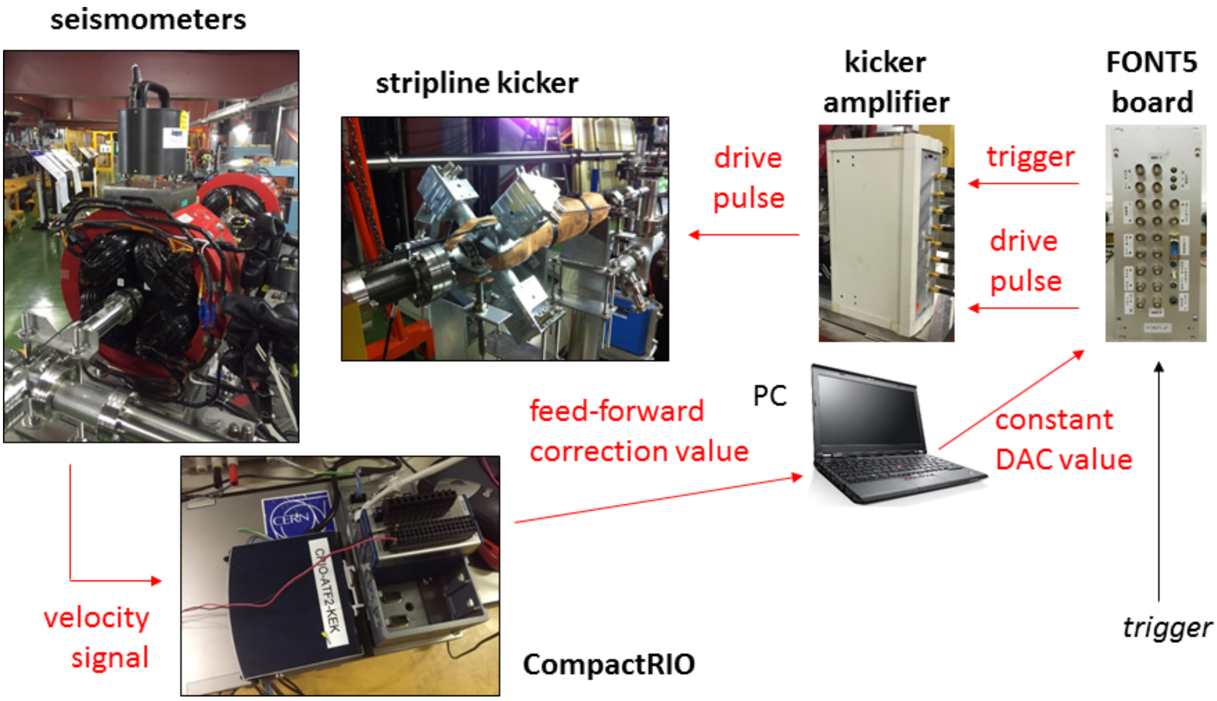

Fig. 6: ATF2 feed-forward system setup

The GM sensors have a limited frequency range in which they give reliable information. Thus we add a filter with a given cut-off frequency. The first step is using the traditional analysis high-pass filter with a cut-off frequency of 0.208 Hz. Below this frequency, the GM sensors show noise, especially when the only signal measurement is very small ground motion. Using a 0.2 Hz high-pass filter doubles the correlation from 0.29 to 0.58.

Figure 7 shows the power spectral density of the full 1024 Hz data set from the seismometer at QD2X. Previous studies carried out with seismometers at ATF identified two pronounced maxima in the QD2X spectrum at 9.94 Hz and 24.25 Hz [1], both of which are clearly visible in Figure 8, which shows the region from 5 Hz to 30 Hz in more detail. These vibration sources were determined at the time to be due to a pair of cooling water pipes in the QD2X region. However, instead of a single maximum at 24.25 Hz, this newer data show in that region a series of four narrow peaks at frequencies of 24.14 Hz, 24.29 Hz, 24.40 Hz and 24.60 Hz. An additional maximum at 11.55 Hz can also be seen.

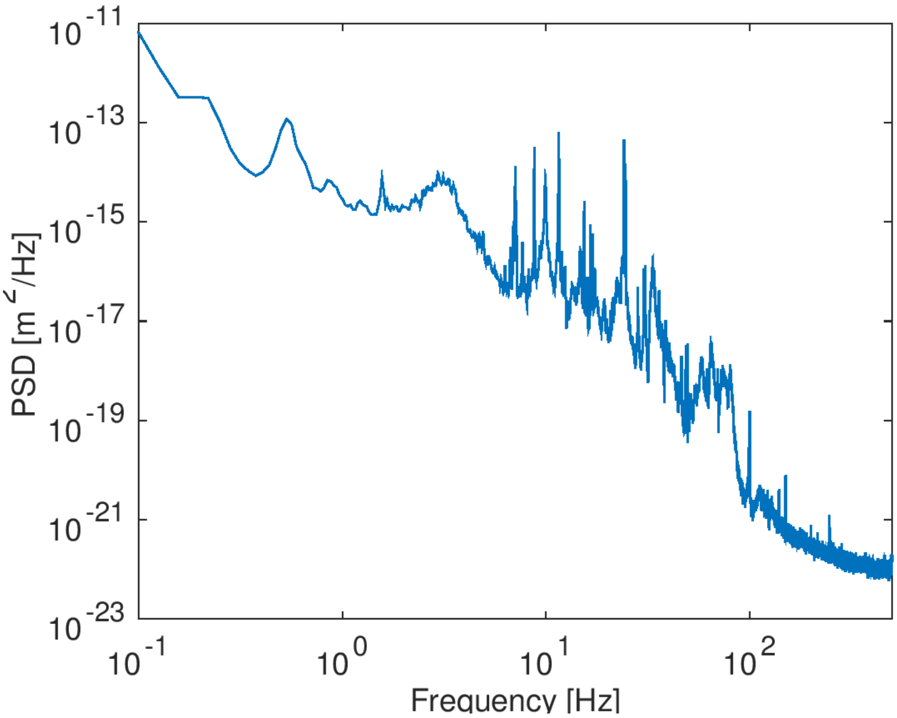

Fig. 7: Power spectral density of the position of the seismometer at QD2X

The known frequency response of the seismometers suggests that a band-pass filter with limits of 0.2 Hz and 100 Hz (also related to coherence) should be applied to the seismometer data at the very least [7].

The maximum correlation that can be achieved in this case is 0.58 for the 14:30 data set. An attempt was made to increase the correlation beyond this limit by modifying the passband of the filter that was applied to the seismometer data. Another solution would be to use a band-pass filter and adding an upper limit in order to take into account the significant frequency range of the BPMs.

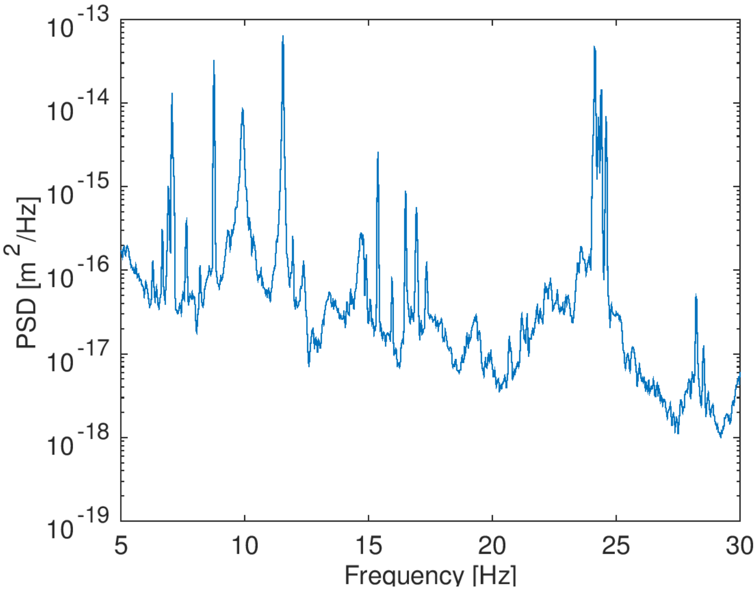

Fig. 8: Power spectral density of the position of the seismometer at QD2X in the 5 Hz to 30 Hz range

Figure 9 shows the correlation coefficient r between the position of the beam at BPM downstream and the position of the seismometer on QD2X as a function of the high and low frequency limits of the band-pass filter applied to the seismometer data. The best result of r = 0.71 is achieved for a passband of 5 Hz to 100 Hz; including data from the other four of the first five seismometers in the fit increases this slightly to r = 0.75.

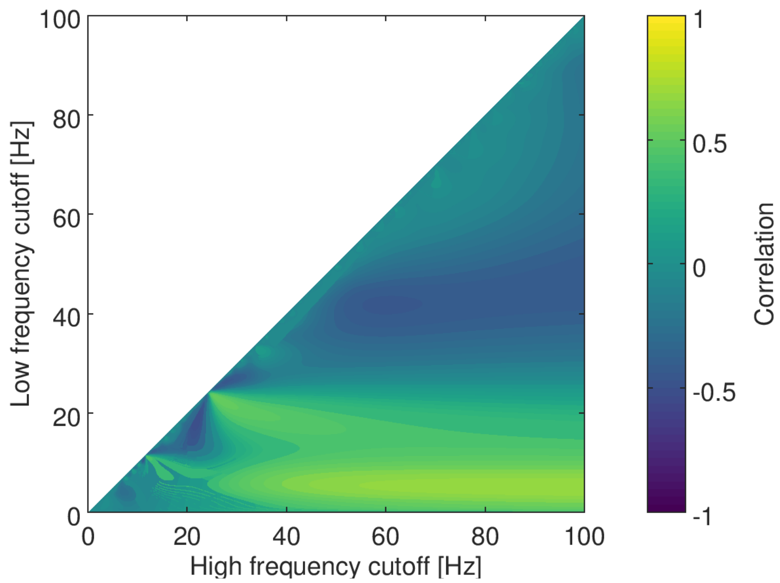

Fig. 9: The correlation coefficient r between the position of the beam at MSD4FF and the down-sampled to 3.12 Hz position of the seismometer at QD2X as a function of the frequency limits of the band-pass filter applied to the seismometer data before down-sampling

3.3. IMPLEMENTATION OF A COMPENSATION SYSTEM FOR ORBIT DISTORTIONS DUE TO QUADRUPOLE MOTION

The feed-forward system at ATF consists of three components [2].

The seismometers that measure the quadrupole displacements should be placed directly on top of the quadrupoles as has previously has been established. A study is ongoing to optimize the feed-forward behaviour with respect to the transfer function (TF) between ground and magnet. In future linear colliders, the sensors will not have the required space to be placed on top. Implementing such a TF directly into the feed-forward control parameters will be essential, although modelling such a magnet behaviour is non-trivial, especially when the TF is very noisy as it is in ATF2. This section deals with the remaining two elements of the feed-forward system: the processor that calculates the compensatory kick and the kicker that applies the calculated correction to the beam.

3.3.1. Feed-forward processor

The role of the feed-forward processor is filled by a National Instruments CompactRIO (cRIO) system. This FPGA-based unit consists of a cRIO-9064 controller chassis with a cRIO-9205 module for analogue input and a cRIO-9401 module for digital output. The control software is depicted schematically in Fig. 10.

The firmware on the FPGA was written in LabVIEW and performs the low-level input and output tasks. The analogue inputs are sampled at a frequency of 1000 Hz and then transferred to the real-time LabVIEW operating system on the cRIO, where they are integrated to give the current position of each seismometer. The vector of seismometer positions is then filtered and multiplied by the matrix of gain coefficients to yield the value for the corrective kick. These gain coefficients are determined from a fit of the position at the BPM of interest as a function of the seismometer positions. In the simplest case, the beam position at a single BPM is fitted as a function of the position of a single quadrupole so that there is only one non-zero gain coefficient. The calculated value for the kick is then sent back to the FPGA where it is transmitted as a digital code at a rate of 200 Hz so that the correction is never more than 5 ms out of date. The real-time LabVIEW data acquisition software is also able to store data locally for later transfer to a personal computer for analysis.

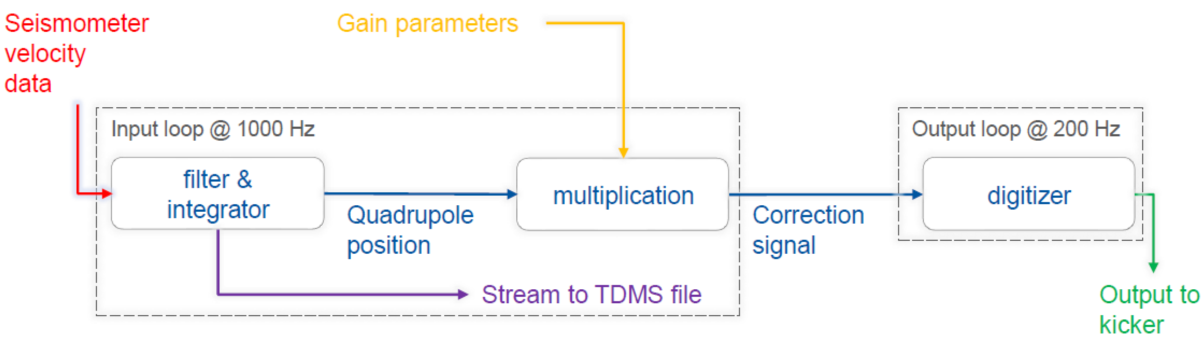

Fig. 10: Schematic of the software running on the feed-forward processor

3.3.2. Kicker

The actuator selected for use with the feed-forward system is a simple stripline kicker originating from the SLAC National Accelerator Laboratory [9]. It was originally installed as part of the intra-train beam position feedback system developed by the Feedback On Nanosecond Timescales (FONT) group at the University of Oxford. This kicker deflects the beam using the electric field generated when a potential difference is applied across the vertical axis. An ultra-fast, high-power amplifier developed by TMD Technologies generates the voltage signals required for this purpose. This amplifier is well beyond the requirements of the feed-forward system but was retained in order to avoid disturbing the existing arrangement of hardware inside the accelerator area.

A custom-made FPGA-based control unit (FONT5) uses signals from the ATF timing system to produce a trigger for the amplifier that is synchronized with the beam arrival time. When used for its original purpose, the FONT5 board also provides a kicker drive signal based on BPM signals. A more detailed description of the FONT kicker and associated electronics can be found in Ref. [9]. Here it is noted that the FONT5 board was already capable of generating constant kicker drive signals for calibration purposes. The only extra functionality required was thus a means of updating this constant value with the current value of the correction calculated by the feed-forward processor. This was achieved by modifying the firmware of the FONT5 board to update the amplitude of the kicker drive signal according to the digital code received over the direct connection to the cRIO system.

3.4. PERFORMANCE OF THE FEED-FORWARD SYSTEM

The feed-forward system was most recently tested in June 2017. Each feed-forward data run consisted of a 90 second record of the beam position data (generated at the machine rate of 3.12 Hz) and a slightly longer measurement of the seismometer data (generated at 1000 Hz). The synchronization signal is then used to obtain a set of approximately 250 simultaneous measurements of the position of the beam at BPM and the position of the quadrupole QD2X.

In order to maximize the performance of the feed-forward system, several control runs were taken in an attempt to accurately assess the correlation between the quadrupole position and the beam position. During this analysis, it was found that reducing the lower frequency cut-off of the band-pass filter applied to the quadrupole position data significantly increased the correlation. The feed-forward algorithm was therefore set to use a 2-100 Hz band-pass filter.

Ultimately, many control runs were taken and the feed-forward system was operated with a number of different gain settings.

Figure 11 shows the beam jitter measured as a function of the feed-forward gain parameter g. The average beam jitter is smaller for every gain value from 70 to 200 but is increased for a gain as large as 300. The correlation decreases as the gain increases and is approximately zero for the “optimal" gain values of 125, 135 and 150; beyond this, the feed-forward system begins to introduce a negative correlation. The performance of the feed-forward system is summarized in Tab. 1.

Tab. 1: Feed-forward results from the shift on 23 June 2017. σ_b is the average of the vertical jitter of the beam, r is the average of the Pearson correlation coefficient between the beam position and the linear reconstruction from the filtered position of quadrupole QD2X, and n is the number of runs taken for the given gain setting. "Optimal" (gain) refers to the ensemble of runs which had a gain of 125, 135 or 150.

Gain	σ_b	r	n
zero	91.3± 1.0	0.56± 0.01	36
optimal	78.6 ±1.5	0.05 ±0.02	18

The mean correlation of the zero-gain runs of 0.56 was high compared to previous studies, and inserting this value into Eq. (1) suggests that 17% of the beam jitter measured is due to the motion of QD2X. The ratio of the two jitters in Tab. 1 shows that the feed-forward system achieved a 14% reduction in the beam jitter and, although this represents a modest reduction in absolute terms, an equivalent statement is that the feed-forward system was able to remove over 80% of the correlated component of the jitter.

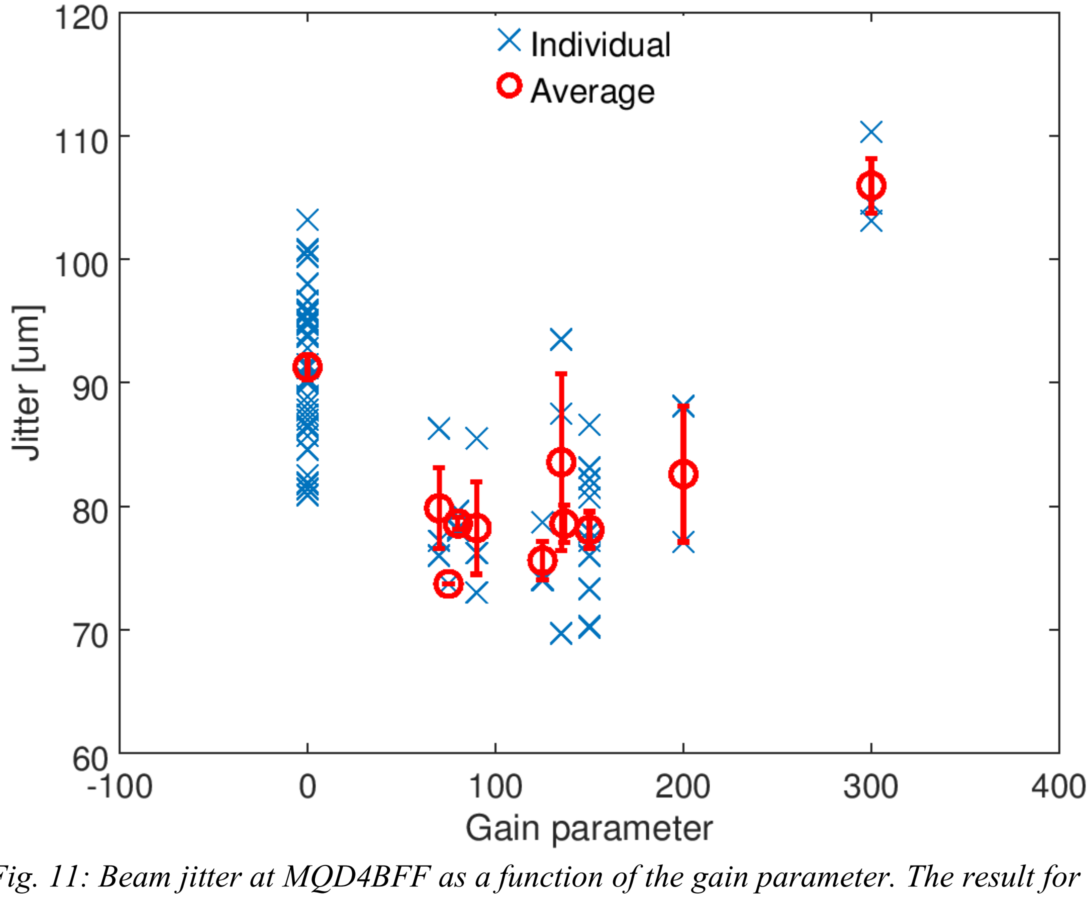

Fig. 11: Beam jitter at MQD4BFF as a function of the gain parameter. The result for each individual run is shown as a blue cross and the calculated mean and standard error of the mean for each gain setting is shown in red.

3.4.1. Summary

Dynamic misalignment of the quadrupole magnets presents a real challenge to the maintenance of a beam of the required luminosity for a future linear collider. The novel technique of compensation of orbit distortion due to quadrupole motion using feed-forward control would be able to compensate for higher frequency oscillations than conventional beam orbit feedback, with lower cost and less of the integration issues than are associated with quadrupole stabilization systems.

The technique was demonstrated for the first time at the KEK ATF where it was able to eliminate 80% of the component of the final focus beam jitter that was due to the motion of the upstream quadrupole. Future work will examine the possibility of introducing additional sensors and actuators to the feed-forward system.

Future plans, conclusions and relation to other work

We will study the best way to monitor vibrations more systematically to help identify the source of the 16.5 Hz resonance. A continuous measurement or automatic measurements at given intervals are being considered.

For the feed-forward system, feasibility has been demonstrated. However, some additional studies need to be performed to bring it even closer to future accelerator needs.

4. REFERENCES

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ANNEX: GLOSSARY

Acronym	**Definition**
CERN	European Organisation for Nuclear Research, Geneva, Switzerland
CNRS	Centre national de Recherche Scientifique, France
KEK	High Energy Accelerator Research Organization, Tsukuba, Japan
GM	ground motion
BPM	beam position monitor
ATF2	accelerator test facility at KEK
LAPP	Laboratoire d'Annecy-le-Vieux de Physique des Particules, France
QD0FF and QF1FF	final-focus quadrupoles
FD	final doublet containing the final-focus magnets
SS	stainless steel
PSD	power spectral densities
IP	Interaction point
TF	Transfer Function