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DELIVERABLE REPORT

[SYNCHRONISATION OF GM AND ORBIT MEASUREMENTS]

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Deliverable:

Reports on synchronisation of GM and orbit measurements and on new GM sensor performance.

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. Test newly developed GM sensor.

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 evaluated 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 [8]. 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. In parallel, the GM sensors need further evaluation since it has been shown [1] that they are the main limitation for active quadrupole feedback in the development of future linear colliders.

2. GM SENSOR

CNRS has developed a new ground motion (GM) sensor working in the useful frequency range for future linear colliders (0.09-200Hz), measuring nanometres. The sensor has a flat response in this frequency range, a capability that is essential for nanometre active stabilisation applications. The initial idea was to use this sensor for studies at ATF2. However, no work has been done at KEK (Tsukuba, Japan) since the sensor is still under development and can be used more easily at closer locations, like CERN (Geneva, Switzerland) or Virgo (Cascina, Italy).

3. QF1FF SUPPORT AND GM MEASUREMENTS

3.1. SUPPORT 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 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. 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. We thus needed a sturdy and short support while keeping the good vibration properties already obtained with the old support [2].

For evaluation purposes, we first installed an intermediate support that took into account the smaller space available under the magnet. It mainly consisted of two stainless steel plates. Then, we designed a completely new support, which was installed at ATF2 in May 2015.

Fig. 1 ATF2 final-doublet setup on its support

3.2. SUPPORT DESIGN

The aim of the design of a support is to minimise the impact of vibrations like ground motion or cooling systems that can induce detrimental beam jitter. Generally, the vibration level diminishes with frequency [3]. Thus, the design needs to push resonances to higher frequencies. On the other hand, the larger mass of the new magnet pushes the resonance peak to lower frequencies. Thus we concentrated on designing a support with the resonance at the highest possible frequency. The new support was designed to incorporate good vertical and horizontal properties. It is composed of a T-plate, made of stainless steel, 20mm thick, installed just under the magnet mover. Under the T-plate, we have large SS feet 53mm high and 130mm in diameter working as vertical and horizontal stable support. The height adjustment is assured by inserting half-moon shims of the desired thickness. Figure 2 shows the design with the T-plate in green and the feet in Turquoise. Figure 3 shows a photo of the support before installation.

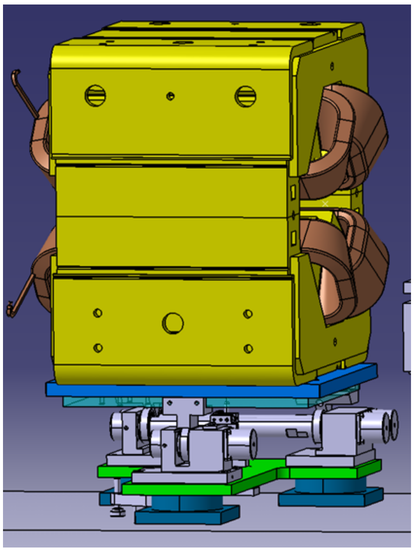


Fig. 2 QF1FF support design

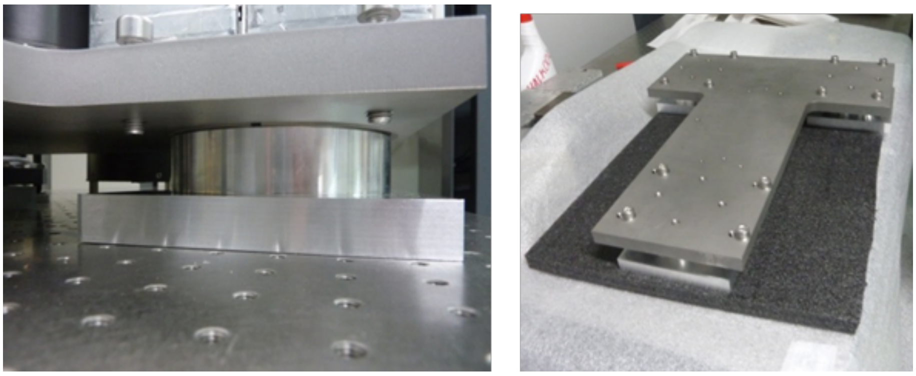


Fig. 3 QF1FF support. Left: a close-up of a foot; right: a view of the T-plate on its feet.

3.3. GM MEASUREMENTS AROUND QF1FF

3.3.1. Comparison between intermediate and new support

We made a comparison between the intermediate and the new support. Figure 4 shows the integrated rms of (left) the intermediate support and (right) the new support. To compute the integrated rms, we first determine the transfer functions as a function of frequency between the top of the FD table and the top of QF1FF. This way of presenting the data shows the behaviour of the measured system free of ground or outside perturbations. Each peak corresponds to a resonance or a vibrational feature of the system between the two sensors (magnet support, magnet mover and magnet) [4]. From this we determine the integrated rms: going from right to left, each step corresponds to a peak in the transfer function and adds up to the relative displacement between the two sensors. To compare the different configurations, we look at the relative integrated displacement at 1 Hz.

The main resonance peak of the system is at 8 Hz and at 16 Hz in horizontal direction and at 30 Hz and 45 Hz in vertical direction for the intermediate and the new (LAPP) support, respectively. The resonance peak is thus pushed to higher frequencies with a damped peak as planned.

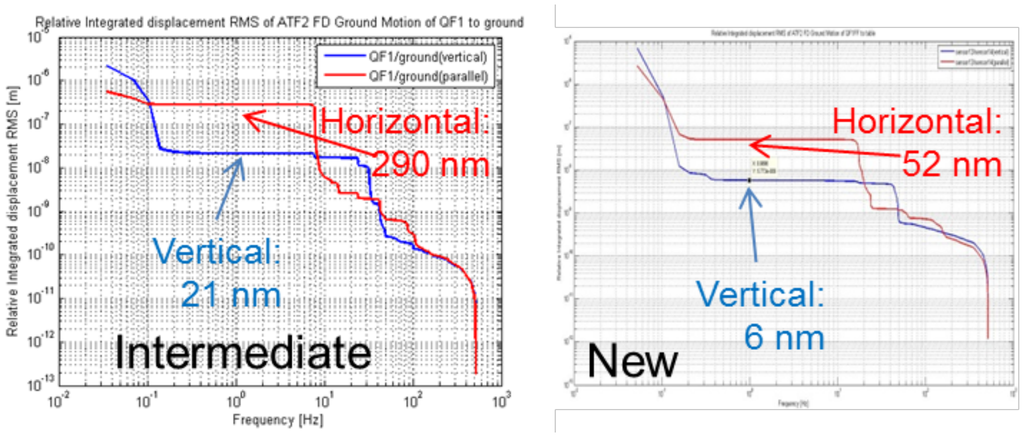
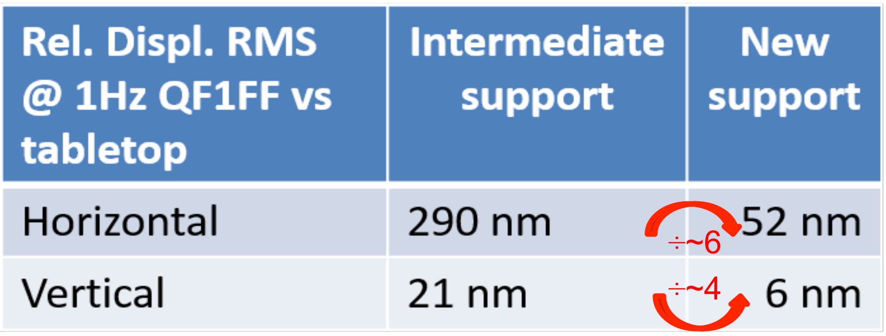


Fig. 4: Integrated rms at 1 Hz of (left) the intermediate support and (right) the new support. Measurements with Intermediate support were done in May 2013, and with the new support in February 2016, in similar conditions

The integrated rms values at 1 Hz of the two supports are given in table 1. The intermediate support showed an rms of 290 nm and 21 nm in horizontal and vertical direction, respectively; these values could be lowered to 52 nm and 6nm with the new support. We have reduced the level of vibration by a factor 6 and 4 in the horizontal and in the vertical direction, respectively. The initial values were in a range where we could not reach the desired beam size. Now, we are in a better position to reach it from the QF1FF vibration point of view.

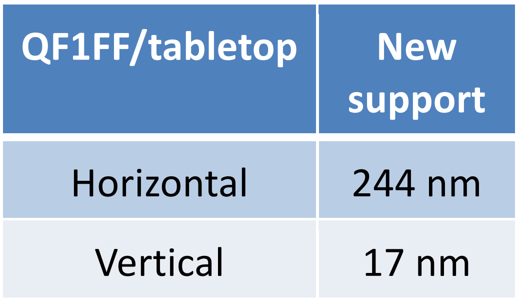


Rel. Displ. RMS @ 1Hz QF1FF vs tabletop	Intermediate support	New support
Horizontal	290 nm	÷~6 52 nm
Vertical	21 nm	÷~4 6 nm

Table 1: Integrated rms values at 1 Hz. Measurements with Intermediate support were done in May 2013, and with the new support in February 2016, in similar conditions

3.3.2. Outside perturbations

There were, however, in some cases, measurements that surprisingly showed that the new support was detrimental to the vibration behavior. Table 2 below summarizes the relative displacements at 1 Hz in a case where the new support surprisingly shows a worse horizontal rms than the intermediate support.



QF1FF/tabletop	New support
Horizontal	244 nm
Vertical	17 nm

Table 2: Relative displacements at 1Hz for the new support for a measurement done in June 2015.

In order to understand these results, Figs. 5 and 6 show the displacement power spectral densities (PSD) of the sensor on top of QF1FF (sensor 13, in green) and of the sensor on the FD table (sensor 14, in black) for the intermediate and the new support, respectively.

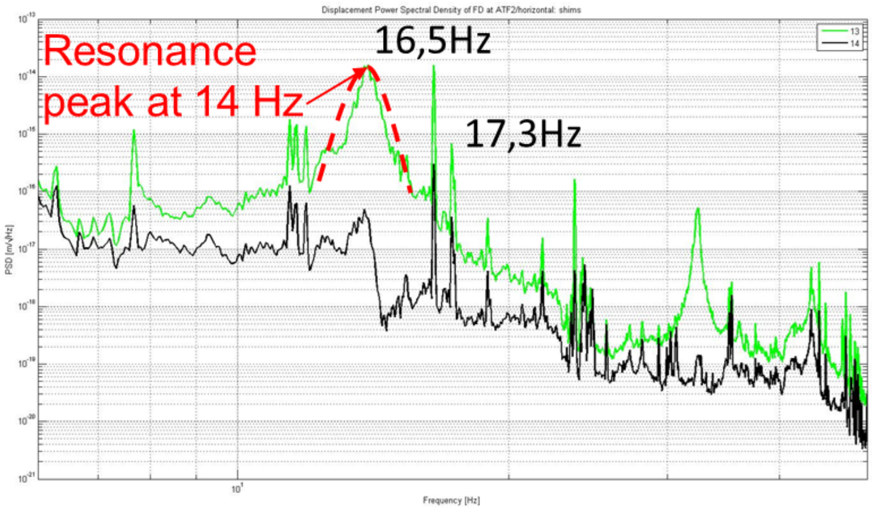


Fig. 5 PSD in horizontal direction for the intermediate support (6-50Hz) The red dashed curve enhances the main resonance peak. Measurements were done in October 2014.

Figure 5 shows the PSD in horizontal direction for the intermediate support. There is the main resonance peak at 14 Hz with a characteristically broad damped shape (enhanced by the red dashed curve). One also sees some external perturbations on the table and on top of QF1FF characterized by very thin peaks most notably the ones at 16.5 and 17.3 Hz and visible both on the FD table and on top of QF1FF.

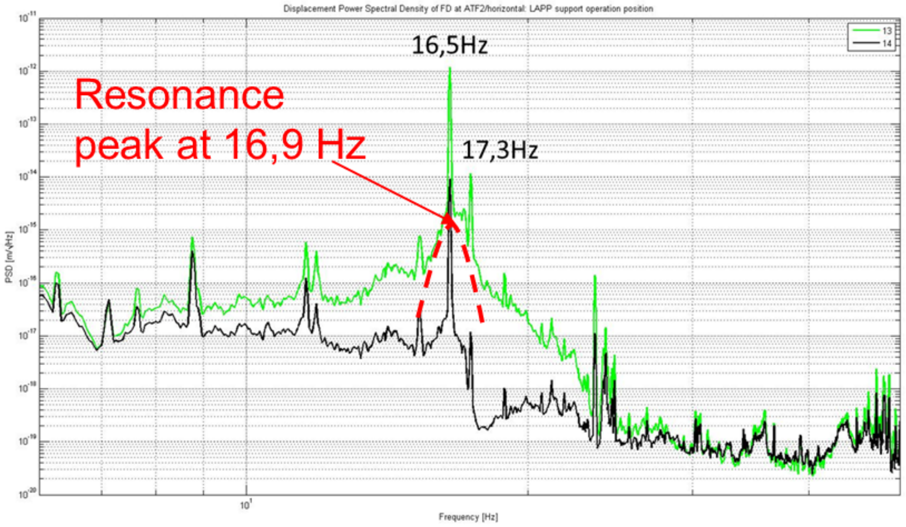


Fig. 6: PSD in horizontal direction for the new support (6-50Hz). The red dashed curve enhances the resonance peak). Measurements were done in June 2015.

Figure 6 shows the PSD in horizontal direction for the new LAPP support. Again, one sees the external perturbations with very thin peaks at 16.5 and 17.3 Hz. The main resonance peak has now moved to higher frequency at 16.9 Hz (enhanced by the red dashed curve), very close to the external perturbation peaks. All these peaks result in a combined large and high peak contributing negatively to the relative displacement. The external perturbations are visible in both configurations. The new support, although having a better vibration behavior, has a resonance peak at higher frequencies that falls exactly on the peaks of the external perturbations. These perturbations have shown a detrimental effect on the relative displacement. When looking in detail at the level of perturbation, one can see from the PSDs that the vibration source was at an amplitude of an order of magnitude higher for the measurements done with the new support, thus contributing even stronger to the relative displacement. To get a better horizontal behavior of QF1FF, this external perturbation needs to be mitigated.

In order to enhance ATF2 performance, it is very important to identify the source of the perturbation at 16.5 Hz. Probably, this vibration has a mechanical source like a motor turning at about 1000 tpm, or maybe a pipe vibrating. The mover motors or the cooling pipes are suspects to be examined, but other sources should be explored [5].

3.3.3. Conclusion

By replacing the original support under QF1FF by a new support designed at LAPP, the aim of building a support with better vibration behavior has been achieved. However, the improvement was in some cases overshadowed by the detrimental effect of external perturbations at frequencies at 16.5Hz. It is thus very important to identify the source of these perturbations – this needs to become a priority for ATF2. The vibration measurements will be monitored in a more systematic way to identify and mitigate this source of vibration.

4. SYNCHRONIZATION OF ORBIT AND GM MEASUREMENTS

4.1. 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 unreachable for the 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 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:

$$\frac{\sigma_f}{\sigma_i} = \sqrt{1-\rho^2},$$

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 ρ is the correlation between the fit using the GM sensors and BPM measurements [6].

4.2. 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, that it can correct frequencies out of limits for orbit feedback systems, and that it can be designed as a global system instead of many independent systems on all the individual quadrupoles.

A system has been installed in ATF2 using the 14 Güralp Systems CMG-6T seismometers, adding National Instruments data acquisition hardware and using synchronization signals for BPM and ground motion data sets [7]. Figure 7 shows the setup.

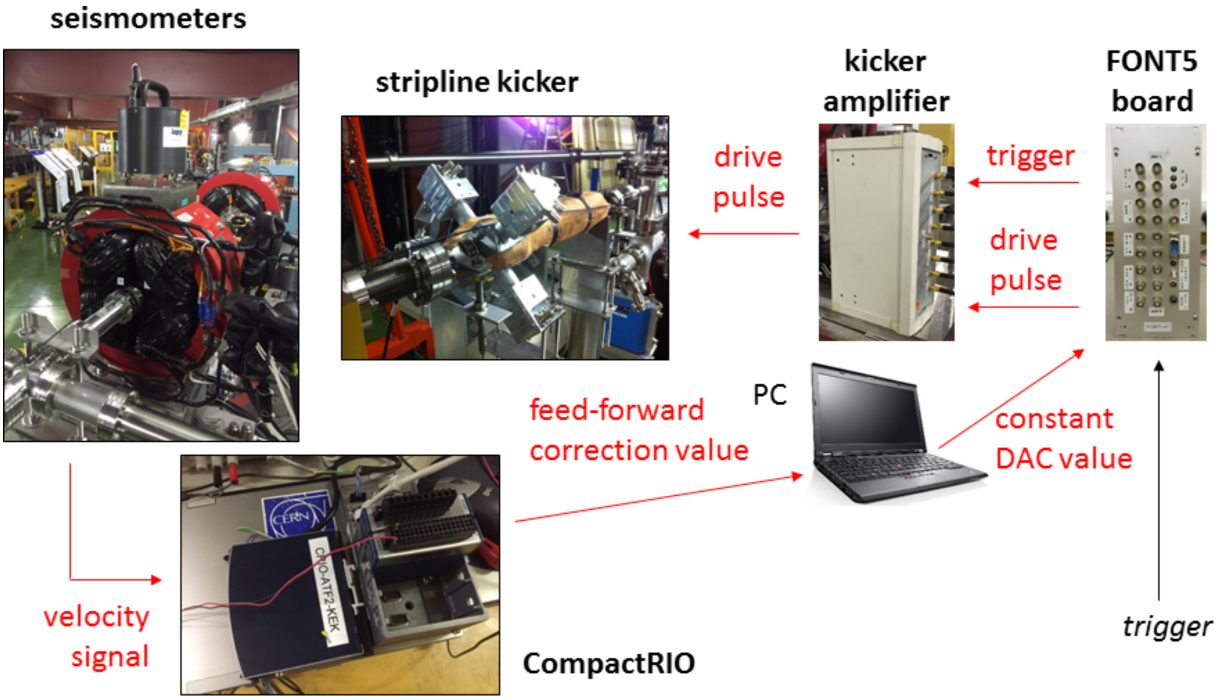


Fig. 7: ATF2 feed-forward system setup

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.

Another solution would be to use a band-pass filter, adding an upper limit in order to take into account the significant frequency range of the BPMs. Figure 8 shows an analysis for the choice of the best low and high frequency limits determined by a fit using 1-5 sensors and looking at the effect on a final-focus magnet. A frequency range between 0.32 Hz and 1.26 Hz has been chosen in order to stay in the blue region of Fig, 8.

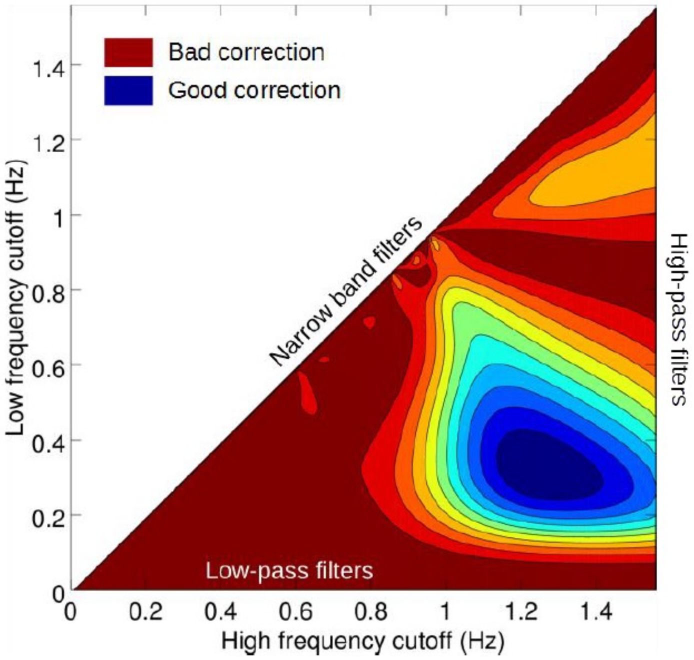


Fig. 8: Band pass estimation

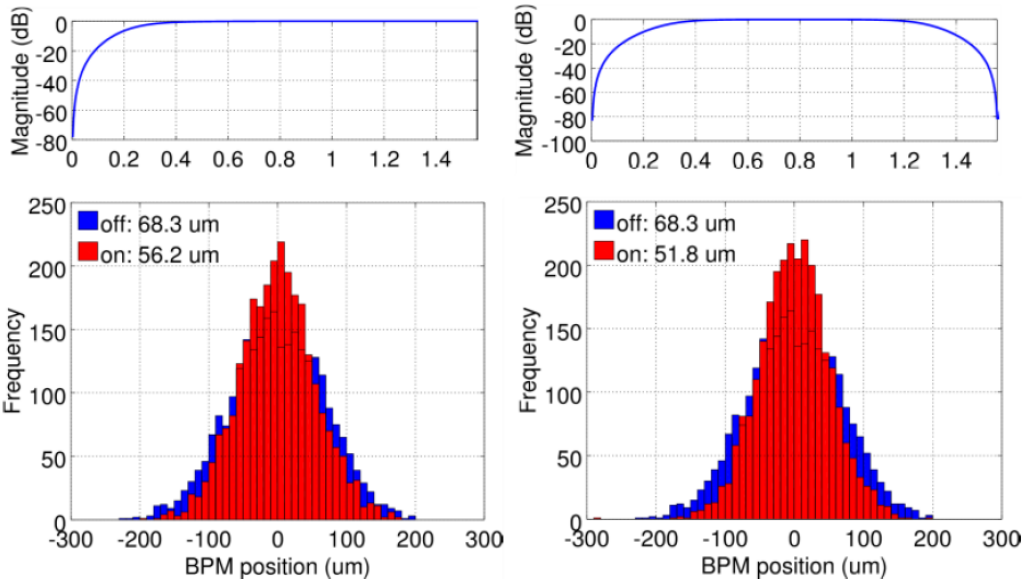


Fig. 9: Comparison between high-pass and band-pass filter

The results for the jitter reduction have been compared between a high-pass filter with a cut-off frequency at 0,27 Hz, and the band-pass filter chosen using Fig. 8. The results are shown in Fig. 9. With the high-pass filter (> 0.27 Hz), the jitter reduction is 18%. With the band-pass filter (0.32 Hz – 1.26 Hz) the jitter reduction is 24%. We conclude that with an optimized band-pass filter on the feed-forward system, a significant jitter reduction can be obtained.

4.3. FIRST RESULTS

Experimental tests have been performed on the ATF2 test facility. The beam characteristics were an energy of 1.3 GeV for single bunches with a repetition rate of 3.12 Hz and a charge of 1.6 nC. A two-stage programme has been adopted in order to demonstrate ground motion feed-forward:

- First, demonstrate that the beam position can be predicted from seismometer data.
- Second, demonstrate that beam jitter can be reduced using a correction based on seismometer data.

As a first test, using a 0.2 Hz high-pass filter shows that the correlation doubles from 0.29 to 0.58, see Fig. 10. This increases the expected reduction in beam jitter from ~5% to ~20%. At the levels of typical beam jitter of the final-focus BPMs, 20% reduction corresponds to ~15 µm and thus should be easily measurable.

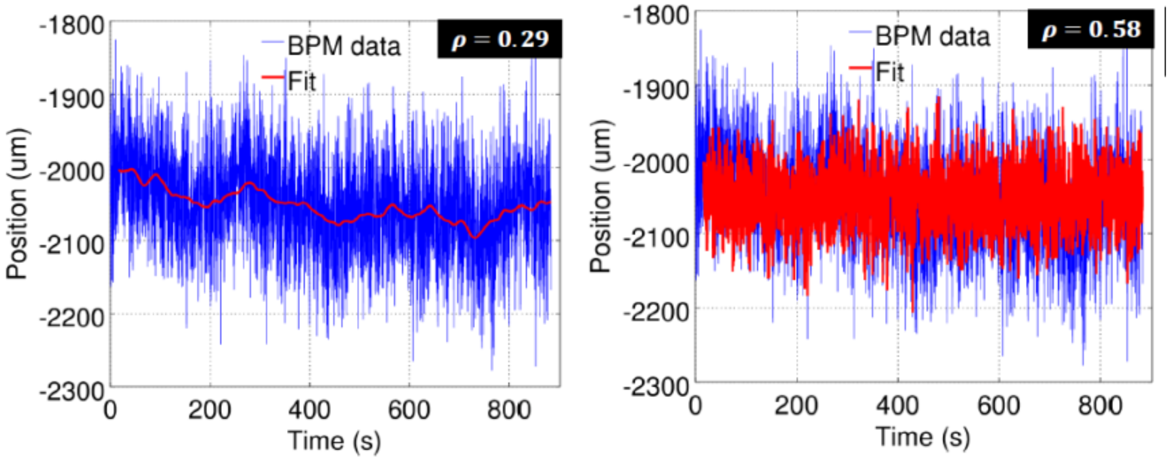


Fig. 10: Left: Correlation between fit from GM data and BPM data determined without high-pass filter; right: correlation between fit from GM data and BPM data determined with a 0,2Hz high-pass filter

Now that the feasibility of predicting the beam position using GM sensors instead of BPMs has been demonstrated, the actual test of the feed-forward system can be done. Figure 11 shows the first demonstration of ground motion feed-forward system. The achieved reduction is about 15% in beam jitter when comparing the jitter with feedback off (blue) to jitter with the feedback on (green).

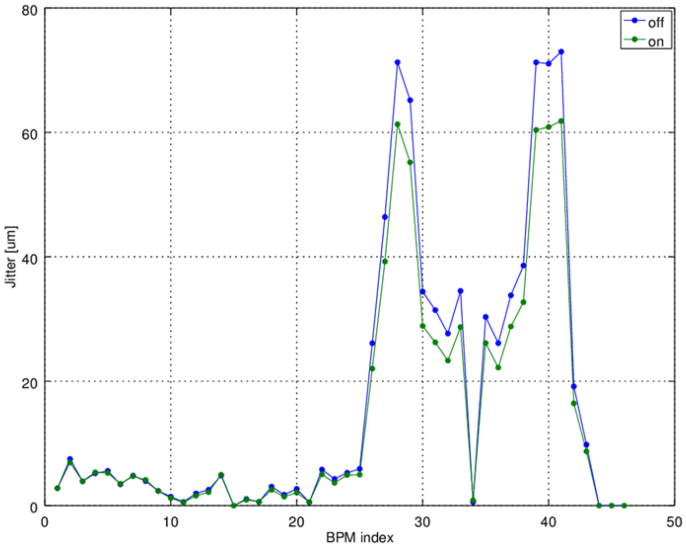


Fig. 11: Jitter at different BPM locations with feedforward off (blue) and on (green)

4.3.1. Summary

We have designed and demonstrated the feasibility of a GM feed-forward system suppressing the effect of quadrupole vibrations at frequencies higher than those covered by orbit feedbacks. Additional beam-based alignment methods can be envisaged to improve orbit stability (e.g. DFS removes energy dependence from orbit, WFS removes charge dependence).

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, new hardware will be installed in the National Instruments compact cRIO-9064 chassis to upgrade the system to a more robust version.

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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
FONT	feedback on nano-second timescales