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TOWARDS HIGHER STABILITY IN LARGE SCALE CAVITY BPM SYSTEMS*

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Abstract

In this contribution we consider a possible solution to long-term stability issues common in cavity BPM systems. The method will see a wider use active in-situ calibration systems injecting a tone into the measurement channel. We plan to compensate the bulk of the beam generated signal and so potentially extend the dynamic range of the electronics, reduce the amount of wakefield seen by the beam. The signal matching the real beam can then be used for mimicking the beam and calibrating out any drifts of the whole sensing and processing chain. We present the concept, give some simulated results and consider possible hardware solutions.

INTRODUCTION

In a large accelerator such as a Free Electron Laser (FEL) or a Collider, it is critical to ensure a stable and reproducible beam orbit. Therefore, beam position monitors (BPM) need to provide reliable readings during start-up and operation.

Most FELs employ cavity BPMs to achieve sub-µm resolution at low beam charge. Due to overall high stability requirements their machine tunnel is often kept at a very stable temperature, which reduces any drifts in cavity BPMs and allows them to achieve high stability [1]. This is not likely a plausible scenario for a Collider: it may be unreasonable to expect the same level of stability from a 30 km long facility. Therefore, a different solution may be required.

At KEK (Japan), ATF2 is a model of a collider beam delivery system which relies on cavity BPMs [2]. The facility typically operates over the workdays restarting on a Monday. Cavity BPMs are re-calibrated once a stable beam is available. For operational reasons, calibrations may take about 6-8 hours. While within a week cavity BPMs do not experience substantial drifts, calibrations are rarely transferable to the next week due to changing conditions. The cavity BPM system there is equipped with a subsystem generating a test tone, currently injected directly into the processing electronics. While this system demonstrated that the electronics are responsible for a small fraction of the observed drifts, with modifications it can inject a signal directly into the cavities. In this paper we discuss how the injected pulse can be utilised and how such a system could reduce operational and construction costs in a linear collider.

SYSTEM CONSIDERATIONS

Cavity BPM

Most cavity BPMs deployed at ATF2 use selective waveguide coupling and operate at 6424 MHz (C-band), Fig. 1. Two types of cavities are in use: position sensitive cavities operating the first dipole mode and smaller reference cavities with the first monopole mode tuned to the same frequency $f_{ref} = f_{pos}$ for phase and charge normalisation (Fig. 2). Using the pillbox approximation, the radii of the two types of cavities are then locked by the equality of their frequencies:

$$\frac{j_{01}}{R_{ref}} = \frac{j_{11}}{R_{pos}}, \tag{1}$$

where j_{nm} are Bessel function zeros. This would also mean that in the same environment for both cavities for a change of temperature ΔT the change in diameter is $\Delta R = \alpha \Delta T R$ and the two cavities experience the same frequency offset for a given change in temperature:

$$\frac{\Delta f_{ref}}{\Delta f_{pos}} = \frac{j_{01}}{R_{ref}(1-\alpha\Delta T)} \frac{R_{pos}(1-\alpha\Delta T)}{j_{11}} = 1. \tag{2}$$

However, this closed-cavity model does not take into account the effect of the beampipe, which usually has the same or a very similar diameter in both cavities. Moreover, the cavities always have a small frequency mismatch in the order of 2-3 MHz, varying from cavity to cavity. Together with changes in beam trigger timing these can result in significant phase drifts.

Let us estimate the frequency drifts numerically, again, using a simple model consisting of a cylindrical cavity with only a beampipe attached using the dimensions of ATF2 C-band cavities. The thermal expansion coefficient $\alpha = 17 \cdot 10^{-6}$ for copper. A one degree temperature change would result in the radii of the cavity and beam pipe to expand by 0.91 and 0.34 µm in the position cavity and by 0.65 and 0.27 µm in the reference cavity respectively. In terms of frequency, these changes would result in $39 + 17 = 56$ kHz for the position and $251 - 36 = 215$ kHz for the reference. Note that for the reference cavity the change in beampipe diameter even has the opposite sign as the perturbation introduced by the beampipe depends on the mode structure. While this actually helps reducing the reference's higher temperature sensitivity, it is still four times that of the position cavity. The temperature sensitivity does not appear so dramatic until it is expressed in terms of the phase advance it produces. These numbers result in about 19 and 72 degree

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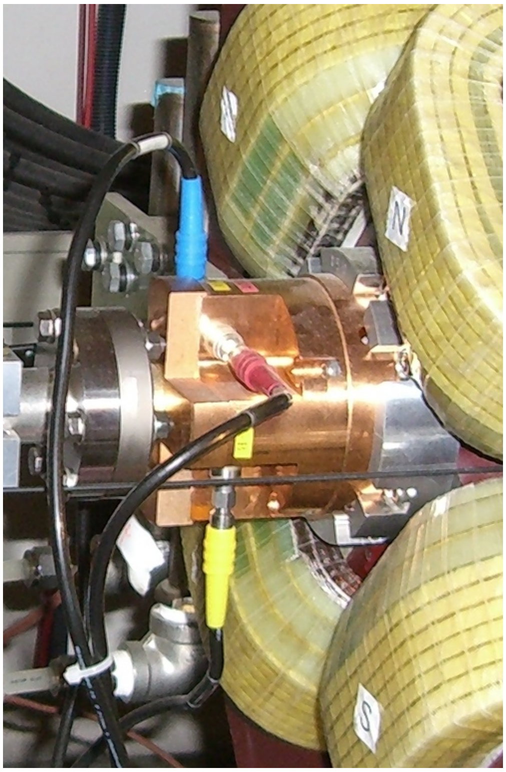

Figure 1: A C-band cavity BPM mounted in a quadrupole magnet in the ATF2 beamline at KEK.

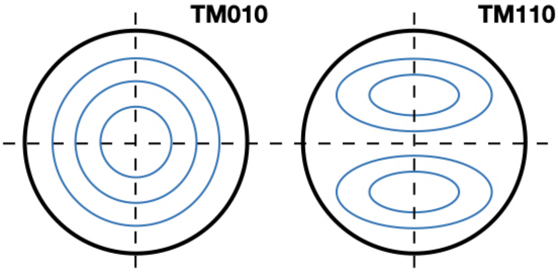

Figure 2: Magnetic field lines in a cylindrical cavity for the monopole (left) and dipole (right) modes.

changes for a quality factor of 6000! The difference is then 53 degrees, which results in a complete mix of the position and angle signals, with the measured position jitter contribution reduced to around 60%. Due to the operational cycle, the temperature in the ATF2 tunnel can change by several degrees, which completely demystifies week-to-week phase jumps observed throughout the operation [3].

Test Pulse

Ideally the test pulse would be equivalent to the electromagnetic pulse produced by the beam, several ps in duration and some 10's of kV in amplitude. This would then be filtered out by the different modes of oscillation possible in the resonating cavity and produce a beam-like signal. In practice, it is not efficient to try generating such a pulse using expensive specialised equipment and just waste most of its energy as it is distributed in a wide spectrum. Furthermore, feeding such a broadband pulse into a cavity presents a problem: most cavity BPMs use waveguide adapters with a bandwidth of 100's of MHz, so a (possibly dangerous) fraction of the pulse would have been reflected even before reaching the cavity.

There are two other possibilities: a continuous wave (CW) tone or a burst of radio-frequency (RF) oscillations. CW is the easiest option, but it does not satisfy the requirement that the system be calibrated with no beam present, it is preferable to have a time-evolving signal so that no assumptions have to be made. A short burst of RF, about a ns in duration, is still about 3 orders of magnitude longer than a beam pulse, but even for a state-or-the-art data acquisition (DAQ) system it is likely to be much shorter or comparable with the sampling time. Thus, the initial transient it may cause will not be noticeable for the system, hence this option appears to be the best one.

Following this discussion, we can summarise the approximate requirements for a test tone source: nanosecond level RF pulse duration, µW power. The shortest pulse duration available with standard laboratory pulse generators does not normally go below 5-10 ns. However, suitable off-the-shelf high speed pulse generators that can provide up to 5 V with 0.2-4 ns pulse duration are available [4].

MODELLING

A very simple model has been used to test the interaction of the beam pulses and RF bursts in a cavity. The cavity is represented by a single-pole filter with a centre frequency of 6424 MHz and a quality factor of 6000. As the beam excitation is instantaneous compared to the RF burst, a single sample in the simulated waveform is set in that case. The RF burst is a Gaussian-modulated sinewave with the same frequency and a $\sigma = 1$ ns. The results of the simulation are presented in Fig. 3.

Even this primitive simulation made us realise that the optimum timing for the test pulse is to reach half of its amplitude when the beam arrives. This way, the maximum amplitude the signal can reach is halved, and only for a short transient lasting for only half of the duration of the test pulse. With the correct timing, any static offsets can be significantly reduced and the dynamic range of the system used more efficiently.

Why is this important? Many cavity BPMs at ATF2 operate with static offsets between 0.5 and 1 mm. Due to mechanical limitations, it is not plausible to solve this problem by re-alignment. In the context of a linear collider, one would similarly want to minimise the requirements for re-alignment. The resolution typically degrades with increasing amplitudes due to non-linearities. The range for ATF2 cavities typically does not exceed 1 mm. Keeping the signals low improves the position resolution and allows for the full dynamic range of the electronics to be used for measuring the dynamic changes rather than static offsets. Another possible consequence of injecting a test pulse for compensation of static offsets is a significant reduction of

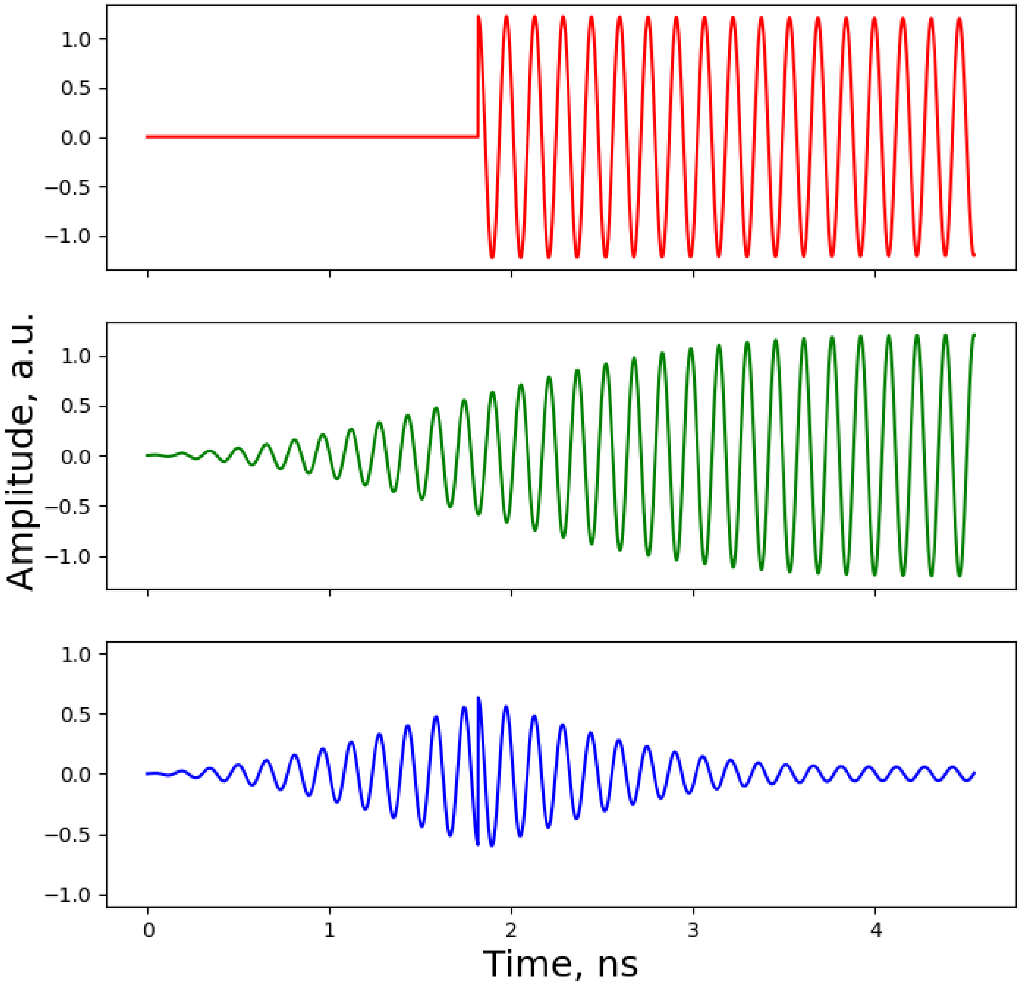

Figure 3: A set of simulated waveforms demonstrating the compensation scheme: beam signal (top), test tone (middle) and the resulting sum signal (bottom).

the wakefields acting back on the bunch. While unlikely to be a huge problem for short bunches in linear colliders, for ATF2 with its typical bunch length of about 7 mm, wakefields result in "banana" shaped bunches, which produce abnormally large projections in transverse directions. This effect complicates the transverse beam size measurements. Reducing the wakefields for cavity BPMs has been a hot discussion topic since they became a suspect in affecting the beam size measurements.

CONCLUSION

This paper lays ground to prototyping an active calibration and compensation system injecting a pulse of RF oscillations into cavity BPM sensors instead or together with the beam signal respectively. Using a very simplistic representation of a microwave cavity we have demonstrated how such a system may operate. However, its practical application will require some carefully judged design decisions to minimise any effect of the drifts in the test tone system itself on the calibration and measurements.

Further work will focus on testing this approach on a single cavity BPM using laboratory test equipment with and without beam. Once a suitable configuration is found, a dedicated set of hardware will be designed and tested.

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