CAVITY BPM SYSTEM FOR ATF2*

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Abstract

In this paper we summarise our 2-year experience operating the Cavity Beam Position Monitor (CBPM) system at the Accelerator Test Facility (ATF) in KEK. The system currently consists of 41 C and S-band CBPMs and is the main diagnostic tool for the ATF2 extraction beamline. We concentrate on issues related to the scale of the system and also consider long-term effects, most of which are undetectable or insignificant in smaller experimental prototype systems. We consistently demonstrate sub-micron BPM resolutions and show the route for achieving week-to-week scale drifts of an order of 1%.

INTRODUCTION

The ATF2 [1] is a prototype final focus system for the ILC and other future high energy lepton colliders. The quadrupole and sextupole magnets in this beamline are instrumented with cavity beam position monitors. There are a total of 41 position sensitive dipole cavities: 37 C-band for the extraction, matching and final focus sections, and 4 S-band used in the final focusing doublet, where a larger aperture is required due to high dispersion. The cavities are mounted in the magnets, which in turn are either mounted on a three axis (vertical, horizontal and roll) remotely operated magnet mover system or rigidly fixed. The cavities are based on previous developments with CBPM systems at the ATF [2]. The C and S-band cavity systems are similar enough to be discussed as one system, where differences exist they are highlighted in the relevant section. The BPMs are used for dispersion measurement, beam based alignment, position feedback and steering applications.

CBPM SYSTEM

Details on the components of the BPM system can be found in [3] and papers referenced from there, in this section we give a brief summary.

Cavities

Cylindrical cavities are coupled via rectangular slots into waveguides ending with coaxial adapters. This arrangement allows to extract the position sensitive dipole cavity mode and suppress the strong monopole modes. The BPMs have 4 symmetric couplers, two for each transverse plane. The output is an exponentially decaying sine wave, with the amplitude and phase depending on the charge, length, position, angle, tilt and arrival time of the bunch, and the decay time defined by the coupling strength and internal losses. Additional reference cavities, operating at the same frequencies as the position cavities for C-band and at the image frequency for S-band, provide an independent combined measurement of the bunch charge, length and arrival time, so that these can be excluded. Furthermore, the voltage produced due to angle and tilt is in quadrature phase with respect to the position signal, and can be separated from it using the reference cavity phase, thus only leaving the position dependence in the signal.

Electronics and Digital Signal Processing

The electronics are single-stage image rejection mixers. Most of the C-band CBPM output signals are attenuated by 20 dB to avoid saturation of the digitiser system and simplify the digital processing algorithm. The phase of the local oscillator (LO) signal for the C-band electronics is locked to the accelerator RF, while the S-band LO is free running. The intermediate frequency (IF) is around 20-30 MHz for both C and S-band. Down-converted signals are digitised at 100 MHz by 14-bit digitisers. The VME processor-controller hosting the digitisers publishes the waveform data through EPICS.

The entire system is readout via EPICS and controlled via Python scripting language. The digital signal processing described below is performed in a dedicated data-driven C program, that monitors the arrival of beam, computes the relevant parameters and publishes the resulting output via EPICS. The state of the CBPM system is viewed via a simple EDM application that can view both the raw and processed data.

The digitised IF signals from the electronics are then demodulated digitally using a complex LO signal and filtered to remove the up-converted component and out of band noise. The resulting complex envelope is sampled at roughly one filter length after the amplitude peak and normalised by the reading produced by the reference channel.

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The resulting phasor is then rotated in such a way that its real, or in-phase (I) component is proportional to the position and the imaginary, or quadrature (Q) component only contains the angle and tilt information. The required rotation of the IQ plane is measured during the calibration when the position component of the signal is guaranteed to prevail.

The calibration consists of 2 stages. Firstly, the digital LO frequency is tuned for each channel by minimising the gradient of the phase of the down-converted signal. The position scale for converting the rotated I into position and the IQ rotation are calibrated by either moving the quadrupole which holds the BPM or by performing a 4-magnet closed orbit bump for the cavities which are rigidly fixed.

STABILITY INVESTIGATIONS

In [3] we showed that the resolution varied from BPM to BPM in the C-band system due to variations of the LO power in the electronics. This problem has been rectified by upgrading the LO distribution system and ensuring the same and sufficiently high level of the LO signal supplied to each unit.

We also showed that the calibration constants experienced significant changes from calibration to calibration. Further investigations showed that the position scale can vary by as much as 10% in x and 2-3% in y even for consequent calibrations, see Table 1. Phase variations for consequent calibrations are usually small, but on longer timescale can be huge, up to $\pm\pi$. It has been predicted that drifts of the gain and electrical length in the signal processing electronics can cause such effects. For that reason, both the C and S-band electronics were equipped with gain monitoring systems sending a burst of RF oscillations to the input of the electronics following the beam generated signal (Figure 1). This calibration tone is processed in a similar way as the position signal, including the normalisation by the reference, which helps excluding any variations of the calibration tone's amplitude and phase.

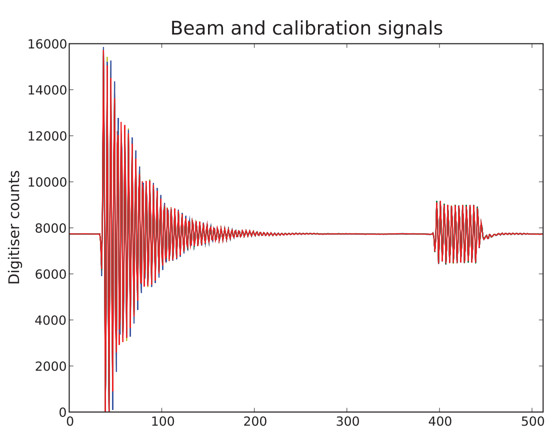

Figure 1: Waveforms containing the beam signal and calibration tone.

Analysing the calibration tone data covering several days, we discovered that the gain variations (Figure 2) are too small to explain the observed variations of the calibration constants. In the following subsections we explain the impact of the two major systematic effects we identified.

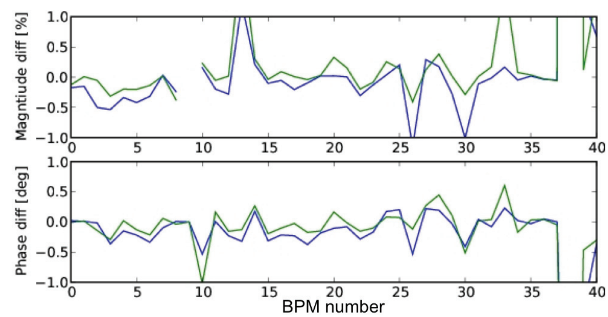

Figure 2: Fluctuations of the amplitude and phase calculated using calibration tone data covering 4 days.

Trigger Variations

Even small variations of the trigger timing with respect to the beam arrival can cause significant leaps of the phase. This is caused by small differences in frequencies between the position and reference cavities. Since the processing is done in the same way for the position and reference signals, we can assume that the ratio of the amplitudes and difference of the phases are preserved throughout. Normalising the position signal (V_p) by the reference (V_r), and assuming for simplicity that both are sampled at a time t_s and start at a time t_0, we get a phasor:

$$\frac{V_p}{V_r} = \frac{A_p}{A_r} e^{-\Delta\Gamma(t_s - t_0)} e^{j\Delta\omega(t_s - t_0)} . \qquad (1)$$

Clearly, any change of the beam arrival time (t_0) relative to the trigger time (defining t_s) will propagate into the measured phase with a coefficient equal to the difference of the frequencies between the position and reference cavities ($\Delta\omega$). Taking $\Delta\omega = 2\pi{\cdot}2$ MHz, and a trigger change of 1 digitiser clock cycle, or 10 ns at 100 MHz, we get a change of 7.2 degrees, while variations exceeding 10 clock cycles have been observed at some points during the operation. Similarly, due to the difference in decay constants the amplitudes can be affected by the trigger changes, but the effect is less pronounced.

In order to correct for the trigger changes, we measure the beam arrival time (analysing the rectified reference signal) at the tuning stage of the calibration as well as during the normal operation. The value obtained during the tuning is then subtracted from the currently measured one, the result multiplied by the difference of the frequencies, also measured during the tuning, and then subtracted from the current measured phase. This correction proved to work very well, but deteriorates with time due to temperature drifts and consequent frequency changes. We are currently working on a more generalised approach to include the temperature drifts and extend the lifetime of the tuning.

Beam Jitter

The beam jitter is averaged at each step of a calibration. However, slow components of the transverse beam motion can not be averaged and can contribute drifts affecting the outcome of a calibration, most noticeably the scale, as shown in Table 1. At ATF, the cooling water cycle period is around 5 minutes, which is likely to affect calibrations taking about 2 minutes. The beam jitter can be subtracted using the BPMs upstream of the one in question in a mover calibration (the BPMs downstream will be affected by the kicks produced by a quadrupole moved off-centre), or BPMs upstream of the corrector magnet used for calibration. The correlation between the I and Q values of the current BPM and the BPMs upstream is usually computed using singular value decomposition (SVD). Using the correlation coefficients it is possible to make a prediction of the beam position in the BPM being calibrated and subtract it from the measured I and Q for each beam pass. The right two columns of Table 1 show the calibration constants calculated using jitter subtraction. There is a clear improvement of the scale variation from calibration to calibration, from 10% in x and 2-3% in y down to about 1%. A less obvious improvement is also observed for the IQ rotation.

Table 1: Calibration Constants Calculated from Consequent Calibrations in x with and without Jitter Subtraction

Try	With jitter		Jitter subtracted	
	Scale	IQ rotation	Scale	IQ rotation
1	-89.44	-0.0108	-100.15	-0.0130
2	-108.79	-0.0138	-99.44	-0.0151
3	-99.80	-0.0203	-100.83	-0.0189
4	-90.16	-0.0233	-101.09	-0.0249
5	-103.30	-0.0378	-101.26	-0.0243

SYSTEM PERFORMANCE

With the LO levels fixed and the above corrections implemented, the residuals for all the BPMs in the ATF2 beamline were monitored for several days in February 2011. The residuals are the difference of the position measured by the BPM and the position predicted for this BPM by other monitors in the beamline. Figure 3 shows the residuals for all the BPMs in the beamine calculated for 500 beam triggers. Most CBPMs are well below the required resolution of 500 nm (2 μm for S-band), with the majority residing at around 200 nm. A few BPMs show a residual of less than 100 nm, in those the attenuators have been removed for a maximum sensitivity. In cases were the residual is above the 500 nm threshold, the offset measured by beam based alignment (BBA) is usually large, meaning that the position signals saturate the digitisers, and extrapolation is applied. However, even in this case the residual is in the order of a few μm and offsets of up to several mm can still be measured.

It is important to note here that over around 3 days of monitoring we did not see any significant degradation of the residuals, which proves that the major sources of systematics have been rectified. A logical continuation of this investigation would be a stability measurement for the residuals and calibration constants ranging over several weeks, which was our plan for Spring 2011. However, due to the earthquake in Japan in March 2011, these measurements will probably take place in late 2011.

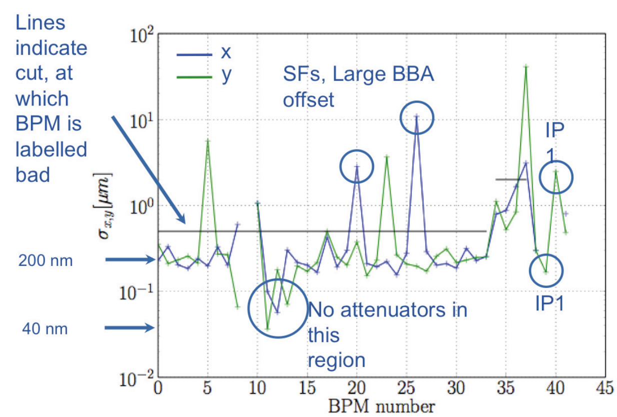

Figure 3: CBPM residuals measured along the ATF2 extraction beamline.

The plot in Figure 3 proved to be an extremely useful tool for monitoring the condition of the system and has been included in the online code. Every 500 triggers the code updates the residuals so that they are never older than around 5 minutes at 1.56 Hz beam rate. High residuals in all BPMs indicate that the beam is far off the centre and some steering may be required, while residuals growing for individual BPMs signal a need of a re-calibration or a hardware problem.

SUMMARY

The CBPM system at ATF2 has been in operation for over 2 years and achieved its resolution goals in 2010, after the LO distribution system had been upgraded. Stability issues calling for frequent re-calibrations were tackled by correcting for the beam trigger variations and subtracting the beam jitter. A stable operation has been observed since the corrections had been implemented. Further measurements covering several weeks of operation will be taken as soon as the facility resumes its research programme.

REFERENCES

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