CAVITY BEAM POSITION MONITOR SYSTEM FOR ATF2

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Abstract

The Accelerator Test Facility 2 (ATF2) in KEK, Japan, is a prototype scaled demonstrator system for the final focus required for a future high energy lepton linear collider. The ATF2 beam-line is instrumented with a total of 35 C- and 2 S-band resonant cavity beam position monitors (CBPM) with associated mixer electronics and digitizers. The current status of the BPM system is described, including a study of the CBPM performance over a three week period, including systematic effects such as charge, bunch length and beam offset dependence. The BPM system is routinely used for beam based alignment, wakefield kick measurements and dispersion measurements, the operational experience and example measurements are also reported.

INTRODUCTION

The energy frontier machines after the Large Hadron Collider are probably linear lepton colliders between 200 GeV and 1 TeV. There are two main competing technologies for a linear collider, the International Linear Collider (ILC) and the Compact Linear Collider (CLIC). Single pass machines are going to require performant and stable beam diagnostics to realise the luminosity goals. An essential diagnostic system is the beam position monitors (BPMs) which monitor the orbit and whose measurements are used to validate the optical model of the machine, measure dispersion.

The ATF2 [1] is a test accelerator to verify the focusing techniques to be used at ILC and CLIC [2] and a test bed for concepts in beam instrumentation including cavity beam position monitors. The ATF2 studies have mostly been done in a single bunch mode with bunch charges in the range of 0.1 to 2.0×10^{10} electrons per bunch and a 3.12 Hz duty cycle.

There are 35 cavity BPMs operating the dipole mode in C-band at 6.5 GHz and 2 S-band cavities ($f_{\rm d} = 2.9$ GHz) installed at the ATF2. All the cavities are cylindrical with four symmetrically located rectangular waveguides that preferentially couple the position sensitive dipole mode. A cavity output $\tilde{V}$ is an exponentially decaying sine wave, with frequency ω and decay constant τ defined by the coupling strength and internal losses. The amplitude and phase of the dipole signal depend on the bunch charge q, length σ_z, position x, angle θ, tilt α and arrival time:

$$\tilde{V}_{\rm d} = [A_x x + jA_\theta\theta - jA_\alpha\alpha]\, qe^{-t/\tau_d}e^{j(\omega_d t+\phi_d)} . \quad (1)$$

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 used in the position determination:

$$\tilde{V}_r = A_q q e^{-t/\tau_r}e^{j(\omega_r t+\phi_r)} , \quad (2)$$

where sub-scripts d and r denote the dipole and reference cavity signals. 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.

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 low level radio frequency (RF) system, 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 processing system is also 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 digital LO frequency is tuned for each channel by minimising the phase incursion along the down-converted waveform. The resulting complex envelope is sampled at roughly one filter length after the am-

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plitude peak at time t_s and normalised by the reading produced by the reference channel:

$$I + jQ = \tilde{k}\frac{\tilde{V}_{\mathrm{d}}(t = t_{s,d})}{\tilde{V}_{\mathrm{r}}(t = t_{s,r})} \tag{3}$$

where $\tilde{k}$ is a factor containing the gain and phase advance differences between the dipole and reference channels. In order to produce a position reading, the phasor $I + jQ$ is then rotated by an angle θ_{IQ} in such a way that its real (in-phase) component I' is proportional to the position and the imaginary (quadrature) component Q' only contains the angle and tilt information. The required rotation of the IQ plane is measured during the calibration when the position variation dominates over the angular. The position scale S for converting I' into position is measured by relating the introduced beam offset to the corresponding change of I'. The offset is produced 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. Mathematically the rotation and application of scale can be expressed as

$$d = S\,\mathrm{Re}\left[e^{-j\theta_{IQ}}(I + jQ)\right]. \tag{4}$$

ANALYSIS AND RESULTS

The results presented in this paper were taken in a three week period starting on 7th April 2013. In all of the performance, calibration and wakefield measurements a model independent analysis (MIA) technique to remove the orbit variation whilst the measurement is occurring is used, this is based on a singular value decomposition (SVD) inversion of a data matrix of BPM (and related) measurements. Usually we consider BPM measurements for M machine pulses and for N BPMs, denoted m_{ij}. Generally, measurements m can be position, angle, I, Q, beam energy, indeed anything which is linearly related to the position d_i. These measurements (labelled j) can be used to make a prediction of the beam position (or angle) at the BPM of interest for each machine pulse i:

$$d_i = \sum_j m_{ij} c_j\,. \tag{5}$$

There would be M equations of the form of Equation 5 for all the machine pulses considered. So for example in a three BPM system for 5 machine pulses, where the central BPM's vertical y resolution needs to be determined, Equation 5 would read

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{pmatrix} = \begin{pmatrix} x_{11} & x_{13} & y_{11} & y_{13} \\ x_{21} & x_{23} & y_{21} & y_{23} \\ x_{31} & x_{33} & y_{31} & y_{33} \\ x_{41} & x_{43} & y_{41} & y_{43} \\ x_{51} & x_{53} & y_{51} & y_{53} \end{pmatrix} \cdot \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix} \tag{6}$$

where x and y are the vertical and horizontal BPM position measurements. This set of equations can be written in matrix form as

$$\mathbf{D} = \mathbf{MC}, \tag{7}$$

where $\mathbf{M}$ is a matrix of the measured data for correlation, $\mathbf{D}$ is a vector of position data for the BPM of interest and $\mathbf{C}$ is a vector of linear correlation coefficients. These coefficients include all effects (optics, scale variations, mechanical rotations) which relate the selected data to the BPM of interest. The linear correlation coefficients $\mathbf{C}$ can be determined by inverting the matrix $\mathbf{M}$. This inversion is done by decomposing $\mathbf{M}$ using a singular value decomposition $\mathrm{SVD}(\mathbf{M}) = \mathbf{USV^T}$. Where $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices and $\mathbf{S}$ is a diagonal matrix. The matrix is then trivially inverted to calculate the correlation coefficients. The position residuals are computed as

$$\delta\mathbf{d} = \mathbf{D} - \mathbf{MC} = \mathbf{D} - \mathbf{M}\left[\mathrm{SVD}(\mathbf{M})\right]^{-1}\mathbf{D}, \tag{8}$$

and the resolution is just the RMS of the δd_i.

Resolution Performance

Since its commissioning around 2010, the ATF2 cavity BPM system has been consistently delivering at the design resolution in attenuated channels, and better where the attenuation is not necessary (Table 1). The resolution is monitored online using the MIA technique described above for each BPM. Considerable degradation of the resolution in the whole system signals for an adjustment of the overall beam orbit, while in a single BPM it indicates a possible problem. The ATF2 has lately been operated with a lower bunch charge to reduce the wakefield effects, thus making the dependency of the resolution on the bunch charge an important subject. The resolution σ should scale as $\sigma \sim \sqrt{A/q^2 + B}$ as the position signal is charge normalised. This dependency has been observed by changing the bunch charge and repeating the resolution measurement several times, an example is shown in Figure 1.

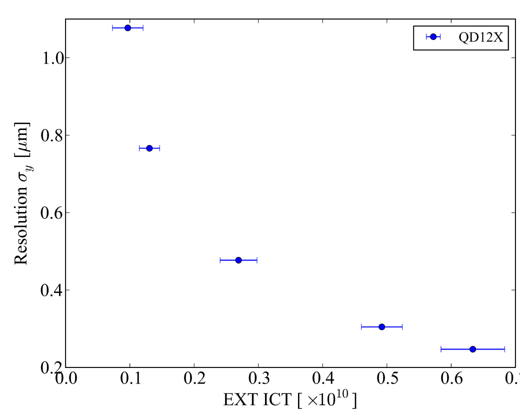

Figure 1: Resolution measured at different bunch charge settings measured by the extraction line current transformer.

System Stability

The most obvious indicator of the overall system stability are the calibration scales and rotation phases. In an attempt to understand the long-term behaviour of the system,

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Table 1: Resolution Summary for the ATF2 Cavity BPM System

C-band resolution (20 dB attn)	$\sim$ 250 nm
Best C-band resolution (no attn)	27 nm
Average S-band resolution	$\sim 1\ \mu$m

the calibration procedure described above was repeated for a representative selection of BPMs in the system many times when machine time was available over the course of a three week period. Histograms of the horizontal scales and rotations for all selected BPMs and all calibrations are shown in Fig. 2 and 3 respectively. The horizontal direction is chosen as the beam position variation is larger compared to the vertical direction, typically in the order of 100 μm. With a typical operational range of the BPMs of ± 1 mm, the calibration step usually does not exceed 250 μm, hence the jitter subtraction substantially improves the measurement of the calibration scale, as can be seen in the middle and bottom plots in Fig. 2. At the same time, large position jitter usually means low angular jitter, hence the jitter subtraction does not affect the measurement of the IQ rotation (Fig. 3).

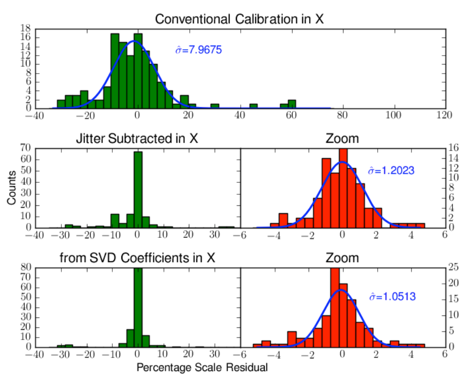

Figure 2: Horizontal CBPM calibration scales S_x.

The level of variation seen in the calibration parameters approaches the level of stability ($<1\%$, $<1°$) measured for the ATF2 BPM electronics over a similar period of time, but does not quite reach it. There are a large number of possible systematic effects which could degrade the BPM performance. These include, but are not limited to bunch charge, length and orbit variation, temperature variation and inherited effects, including timing drifts. It should be possible to eliminate the correlated thermal drifts in the processing electronics by using the built-in pilot tone calibration system. A full scale study of these effects is currently underway and a publication is expected in early 2014. Figure 4 shows an example study in which the extracted bunch length was varied by changing the RF voltage in the ATF damping ring. It is evident that at this level of systematics it is hard to correlate a single small effect to the changes in the system. Possibly, this can be done with help

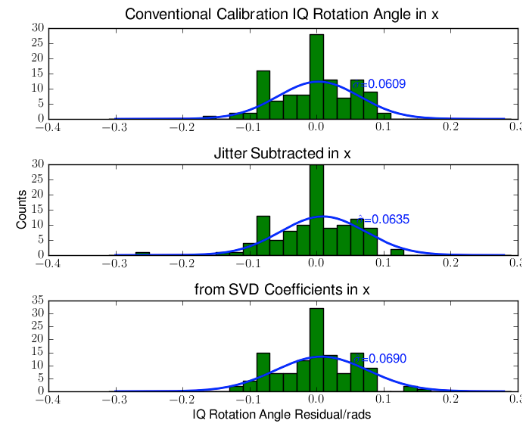

Figure 3: Horizontal CBPM calibration IQ rotations $\theta_{\rm IQ}$.

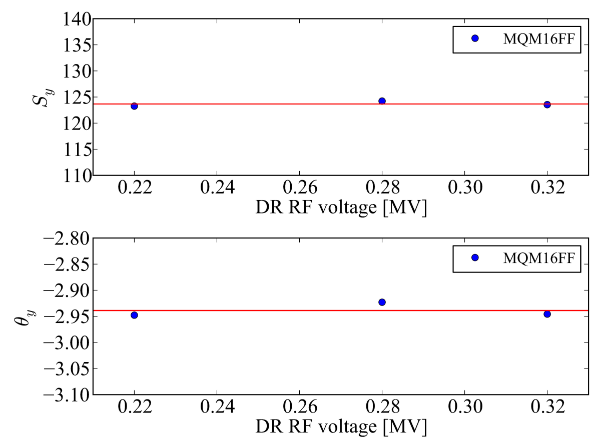

Figure 4: Scale factors as function of damping ring gap voltage.

of minimisation-based MIA.

Wakefield Measurements

Wakefields are an important factor in accelerator design, and a real concern for achieving and preserving low beam emittance. To study the beam distortion and orbit change induced by the wakefields and also to investigate the possibility of compensation of the wakefields generated by other sources, a wakefield test setup including a two axis mover system with a range of ± 4.5 mm in both the vertical and horizontal directions has been installed in the ATF2 beamline. In these measurements, the transverse position of the setup was scanned and the beam orbit recorded for 100-200 beam pulses by the cavity BPM system. In order to remove the effect of the beam jitter, which typically was exceeding the produced offsets, the default orbit was predicted by the upstream BPMs and subtracted from the measurements in downstream locations leaving the wake-induced offsets in the residuals. Various devices, including cavities themselves, have been tested with this system [4]. Fig. 5 shows an example of such a measurement at a relatively sensitive

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(high-β) location after jitter subtraction and averaging.

Due to their high impedance cavity BPMs also became a suspect as a possible source of wakefield kicks. While it is true that the system can potentially produce considerable wakefields, the cavities are typically much better aligned with the beam than other sources (on average, 200 μm vs. 1 mm or more). A recommendation has been made to reduce the contribution of such so far uncontrolled sources as vacuum bellows by shielding and improve the overall alignment of the beamline.

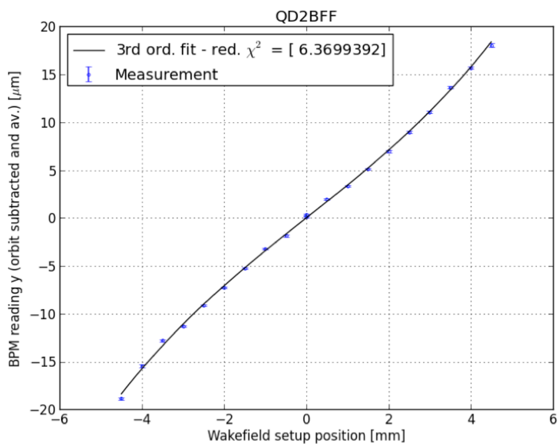

Figure 5: Example of a wakefield kick measurement.

Orbit and Dispersion Measurements

The ATF2 cavity BPM system should eventually be considered in the context of the whole system, where its major application is aiding the beam optics tuning. Examples in Fig. 6 and 7 show the orbit response measurements in x and y respectively. In these measurements the orbit is perturbed by changing the strength of one of the corrector magnets, which manifests itself as varying offsets downstream of the corrector. Precision measurement of the sensitivity to this perturbation at multiple locations along the beamline allows for accurate reverse-engineering of the beamline's optical system and comparisons to the model, including higher-order terms crucial for achieving the sub-100 nm beam size. Achieving small beam size also requires good control of the dispersion in the beamline, which is another application of the BPM system. For these measurements, the energy of the extracted beam is varied via small changes of the damping ring RF frequency. This variation produces small orbit changes proportional to the dispersion at a given beamline location. An example is shown in Fig. 8.

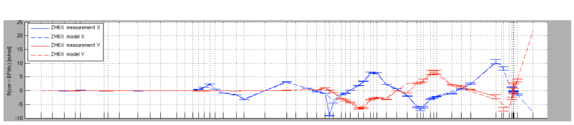

Figure 6: Example of a horizontal orbit response measurement.

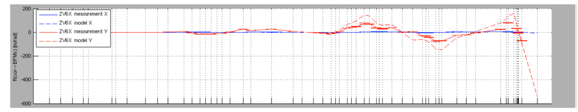

Figure 7: Example of a vertical orbit response measurement.

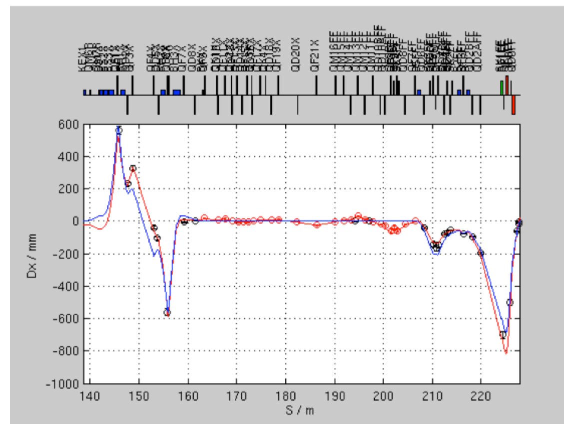

Figure 8: Example of horizontal dispersion measurement.

CONCLUSIONS

The cavity BPM system at ATF2 has been operating at the design resolution (or better) for about 3 years and has become a reliable tool for precision beam optics studies. The effects of the beam jitter on the quality of the BPM calibrations have been studied and eliminated and a study is underway to understand and, where possible, reduce the systematic effects and improve the long-term stability of the system. A clear beam intensity dependency of the resolution has been observed and sub-μm resolution confirmed in lower bunch charge regime currently in use at ATF2. Recent investigations also include wakefield kick measurements, in which the system featured as both precision diagnostic tool and one of the possible high impedance suspects. It has been concluded though, that due to naturally better alignment of the system to the beam, it is currently not the major contributor to the total wakefield budget.

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