# CALIBRATION ERRORS IN THE CAVITY BEAM POSITION MONITOR SYSTEM AT THE ATF2*

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*Abstract*

It has been shown at the Accelerator Test Facility at KEK, that it is possible to run a system of 37 cavity beam position monitors (BPMs) and achieve high working resolution. However, stability of the calibration constants (position scale and radio frequency (RF) phase) over a three/four week running period is yet to be demonstrated. During the calibration procedure, random beam jitter gives rise to a statistical error in the position scale and slow orbit drift in position and tilt causes systematic errors in both the position scale and RF phase. These errors are dominant and have been evaluated for each BPM. The results are compared with the errors expected after a tested method of beam jitter subtraction has been applied.

## INTRODUCTION

The Accelerator Test Facility 2 (ATF2) is equipped with 37 cavity beam position monitors that consistently perform at high resolution. It takes 8 hours to calibrate them all individually and so stability of the calibration constants is required to prevent large amounts of time being lost to recalibration. The problem will be magnified in future linear lepton colliders that will have 1000s of similar BPMs.

The amplitude of the first resonant dipole mode ($TM_{110}$) excited by the beam in the BPM cavities is, within the range of a few millimetres, linearly dependent on the beam offset. In addition, it has beam angle and bunch tilt components that are in quadrature phase with the offset component. The $TM_{110}$ mode is extracted via waveguides and then downmixed and digitised. The signal is then demodulated and at a specific time after the signal maximum, its amplitude and phase are measured. The same processing is applied to the same frequency first monopole mode from a reference cavity in order to remove bunch length and charge dependence. The amplitude and phase of the referenced signal are then represented by the in-phase $I$ and quadrature-phase $Q$ components given by

$$I = \frac{A_p}{A_r}\cos(\phi_p - \phi_r) \tag{1}$$

$$Q = \frac{A_p}{A_r}\sin(\phi_p - \phi_r), \tag{2}$$

where $A_p$ and $A_r$ are the measured amplitudes and $\phi_p$ and $\phi_r$ are the measured phases of the signals from the position and reference cavities respectively. The BPM signal can then be represented as a phasor in the $IQ$ plane with amplitude $\frac{A_p}{A_r}$ and phase $\phi_p - \phi_r$. Beam-based calibration is required to determine the phase that corresponds to pure position information (the $IQ$ rotation angle $\theta_{IQ}$) and factors ($s$, $s'$) that scale to physical units. This gives the final values for the offset $d$ and the combined angle and tilt $d'$ as

$$d = sI' = s(I\cos(\theta_{IQ}) + Q\sin(\theta_{IQ})) \tag{3}$$

$$d' = s'Q' = s'(-I\sin(\theta_{IQ}) + Q\cos(\theta_{IQ})), \tag{4}$$

where $I'$ and $Q'$ are unscaled values for the position and combined angle and tilt respectively.

The calibration procedure depends on the BPM. Most of the BPMs are fixed to magnets which are on movers and the position of the beam within the cavity is varied using the mover. For the rest, a closed orbit bump is used. The position is varied in steps and at each step, the average $I$ and $Q$ of about ten pulses are recorded. A fit is made to the results to determine the phase $\theta_{IQ}$ in the $IQ$ plane that corresponds to pure changes in position. The results are then rotated to $I'$ and $Q'$ and a fit of $I'$ against the known positions in the position scan is then used to determine the position scale $s$. The tilt scale $s'$ is not determined.

Random jitter during the calibration introduces statistical errors to the fits. Furthermore, slow orbit drift adds to the position variation expected from the position scan and introduces systematic errors. An effective solution to both random jitter and slow orbit drift, which has been tested for the BPMs on movers, is beam jitter subtraction. For each pulse, the upstream BPMs are used to predict how the $I$ and $Q$ signals in the BPM being calibrated will differ from their mean values. The predictions are then subtracted from the recorded values to remove the unwanted beam motion. Only the upstream BPMs are used because the change in position of the magnet on the mover during the calibration alters the dynamics downstream. Before the calibration of BPM $i$, 100 pulses are recorded and a matrix of the $I$ and $Q$ signals of the upstream BPMs ($1 \leq j < i$) in both horizontal, $x$, and vertical, $y$, polarisations is constructed. Both polarisations are included because the BPM axes are not perfectly aligned. Singular Value Decomposition (SVD) is then used to invert this matrix to find the coefficients ($\alpha^I_{jk}$, $\beta^I_{jk}$, $\alpha^Q_{jk}$, $\beta^Q_{jk}$, $\delta^I$ and $\delta^Q$) that give $\Delta I_i$ and $\Delta Q_i$ ($\Delta I_i = I_i - \bar{I}_i$, $\Delta Q_i = Q_i - \bar{Q}_i$) as a linear combination of the upstream BPM signals [1].

$$\Delta I_i = \sum_{j=1}^{i-1}\sum_{k=x,y}(\alpha^I_{jk}I_{jk} + \beta^I_{jk}Q_{jk}) + \delta^I \tag{5}$$

$$\Delta Q_i = \sum_{j=1}^{i-1}\sum_{k=x,y}(\alpha^Q_{jk}I_{jk} + \beta^Q_{jk}Q_{jk}) + \delta^Q. \tag{6}$$

* The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no.227579, DITANET under EU contract PITN-GA-2008-215080 and by STFC

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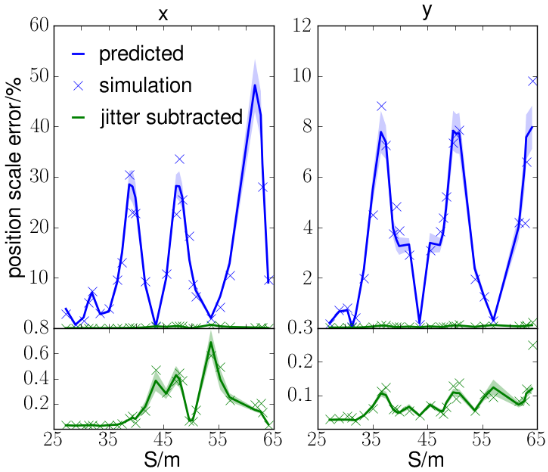


Figure 1: Position scale error determined using Serpentine simulations with predictions based on the mean jitter. The results for the jitter subtracted calibrations is enlarged in the lower plot. The shadow on each line indicates the error from the variation in jitter between calibrations.

## RANDOM ERRORS

The general formula for the standard error on the slope $m$ of a least squares fit to $n$ points of $q$ against $p$ is

$$\delta m = \sqrt{\frac{\sum_i^n (q_i - \hat{q}_i)^2}{n-2}} \sqrt{\frac{1}{\sum_i^n (p_i - \bar{p})^2}}, \quad (7)$$

where $\hat{q}$ is the value predicted by the fit [2]. Since the position scale $s$ is determined from a least squares fit, if there are $n$ equally spaced positions in the calibration position scan and no error on the IQ rotation angle, the error on the position scale will be given by

$$\delta s = \sqrt{\frac{\sigma_x^2}{N(n-2)}} \sqrt{\frac{3(n-1)}{(n+1)\Delta I'^2}}, \quad (8)$$

where $N$ is the number of beam pulses recorded in each step, $\Delta I$ is half the total range of the $I'$ signal over all the steps and $\sigma_x$ is the root mean square (RMS) position jitter. The standard error on the mean beam position in each step has been used as an approximation of the mean difference, $q - \hat{q}$, between the beam position and the prediction of the fit. $\Delta I'$ can be written in terms of the range of the position scan as

$$\Delta I' = \frac{\Delta x}{s}, \quad (9)$$

giving the predicted fractional error on the position scale as

$$\frac{\delta s}{s} = \sqrt{\frac{3(n-1)\sigma_x^2}{N(n+1)(n-2)\Delta x^2}}. \quad (10)$$

This means that with 100 $\mu$m of random beam jitter, seen in some parts of the ATF2, an error of 10% would be expected on a position scale as measured during a calibration with 5 steps of 10 pulses each in a position scan of $\pm 250$ $\mu$m.

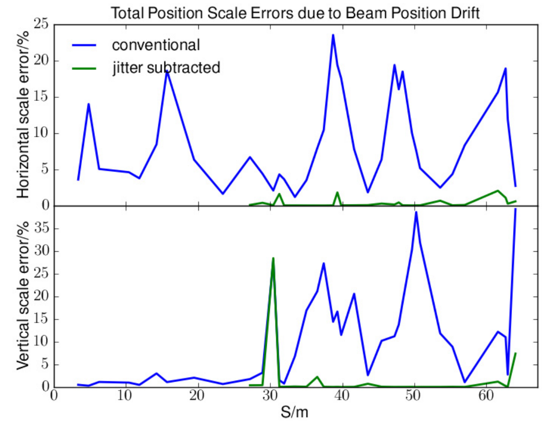


Figure 2: Errors on the BPM position scales estimated from 1000 pulses of beam jitter. The BPM at $S = 30$m was producing large, uncorrelated signals in y.

The tracking code Serpentine [3] was used to simulate the calibration procedure for all the BPMs on movers in the ATF2, both with and without jitter subtraction. Using simulated data instead of real data allowed many more calibrations to be analysed than can be done in a practical amount of time. The random incoming position jitter was taken to be 20% of the beam size $\sigma$ both horizontally and vertically. The calibration steps were 10 pulses each and five steps were taken over a mover range of $\pm 250$ $\mu$m. The same Python code that is used to analyse the real calibration data was used on the simulated data. 20 calibrations of each BPM were simulated so that the RMS error on the position scale could be estimated. The results are shown in Fig. 1 along with the predicted result calculated using Eq. 10 and the average jitter over the 20 calibrations. The results mostly agree with the predictions, except for in the BPMs with the highest jitter where the estimated errors are heavily affected by single outliers.

## ONLINE MEASUREMENTS

The same fits that would be made during a calibration can be applied to pure jitter in order to estimate the fractional position scale error due to slow orbit drift in position and tilt. Using the position readings of the BPM and Eq. 9, the fractional error on the position scale is given by

$$\frac{\delta s}{s} = \frac{\delta x}{\Delta x}, \quad (11)$$

where $\delta x$ is the drift of the beam position over the time period of a calibration and $\Delta x$ is the half-range of the calibration position scan. Position measurements of 1000 consecutive beam pulses by all BPMs were used to get a sample of the beam jitter. For each BPM, the sample was then smoothed using a moving average with a flat window of length equal to the number of pulses per step in the calibration. Pulses separated by the window length plus 3 to allow for mover tuning were fitted against the steps of the

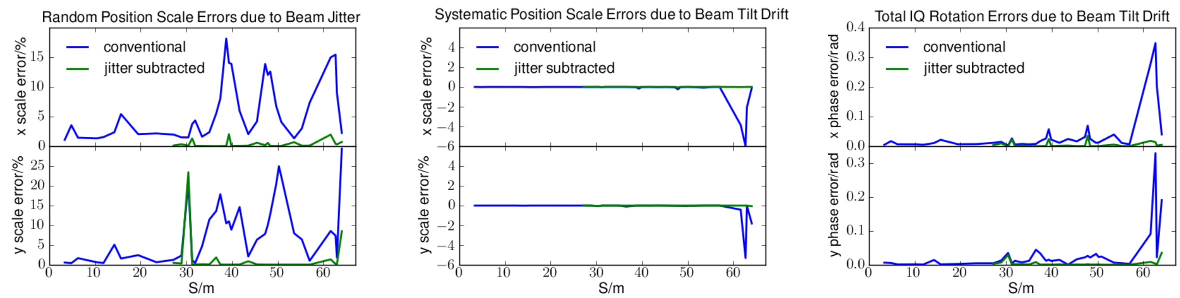


Figure 3: Estimated random error on the position scales (left) and the error on the position scales (middle) that results from the total error on the $IQ$ rotation angles (right).

position scan to estimate the orbit drift during a calibration. This was done for several different starting pulses in order to estimate the RMS position scale error. This error includes the systematic component from the slow orbit drift and the random component from the random beam jitter. The calibration parameters were chosen to be the same as for beam tests presented in [1] (5 steps of 10 pulses each over a mover range of $\pm 75\,\mu$m). The results are shown in Fig. 2 which predicts, in some cases, more than 30% variation in position scale between calibrations with these parameters. For each BPM, the smoothed jitter was also subtracted to leave the random component and the random errors were calculated from Eq. 10 and are shown in Fig. 3. Jitter subtraction was then applied and the analysis, repeated. The small peaks seen in the jitter subtracted predictions can be attributed to the larger resolutions of the S-band BPMs in the final doublet ($S > 57$ m) and of saturated BPMs operating at large offsets. The large peaks in the horizontal position scale error at $S < 25$ m in Fig. 2 are at the BPMs where the slow orbit drift is the most coherent. More investigation is needed to determine why this is.

Slow orbit drift of the beam angle produces a systematic error in the IQ rotation angle and this also propagates to the position scale. Since the position and tilt signals combine in quadrature, the change in magnitude of the $I'$ signal during a calibration will always be increased and so the position scale will be underestimated. Using data from the same beam pulses, a sample of the unscaled tilt signals $Q'$ from each BPM was smoothed in the same way as for the position measurements before. The tilt signal was then fitted to the unscaled position signal expected from a calibration and the slope was used to determine $\delta\theta_{IQ}$ - how much the measured $IQ$ rotation angle would differ from its true value. The $I'$ signal for each pulse will no longer be given by pure positional information but instead by

$$I' = \frac{x}{s\cos(\delta\theta_{IQ})}. \quad (12)$$

The fractional change in the measured position scale is then

$$\frac{\delta s}{s} = \cos(\delta\theta_{IQ}) - 1. \quad (13)$$

Again, this procedure was repeated to get the RMS errors that are shown in Fig. 3. They are only likely to be noticeable near the final doublet where they are well suppressed by jitter subtraction.

Table 1: Comparison with Repeat Calibration of MQM15FF

| | **conventional** | | **jitter subtracted** | |
|---|---|---|---|---|
| **error** | predicted | measured | predicted | measured |
| x scale/% | 4 | 8 | 0.4 | 0.6 |
| y scale/% | 3 | 3 | 0.4 | 0.9 |
| x phase/rad | 0.014 | 0.008 | 0.010 | 0.004 |
| y phase/rad | 0.013 | 0.002 | 0.007 | 0.003 |

Repeated calibrations of MQM15FF (at $S = 28$ m) were used to measure the position scale and $IQ$ rotation angle errors with and without jitter subtraction within twelve hours of the jitter sample [1]. A comparison with the predictions from the method described above are shown in Table 1. Although the agreement is not perfect, it is within the variation seen over time between jitter samples.

## SUMMARY

The calibration errors on the BPMs at the ATF2 have been estimated and compared with simulated and real data. It is possible to estimate these errors without spending an impractical amount of time on repeat calibrations. For most of the BPMs on movers, jitter subtraction is able to reduce the position scale error to below 0.5%. This corresponds to 100 nm stability over a dynamic range of $\pm 20\,\mu$m. The technique must be extended to all BPMs and refined in order to reach the targeted stable dynamic range of $\pm 100\,\mu$m.

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