

# 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 38 C and S band resonant cavity beam position monitors (CBPM) with associated mixer electronics and digitizers. The current status of the BPM system is described, with a focus on operational techniques and performance.

## INTRODUCTION AND ATF2

The ATF2 [1] is a prototype final focus system for the ILC and other high energy future lepton colliders. The ATF2 quadrupole and sextupole magnets are instrumented with cavity beam position monitors (CBPM). There are a total of 38 position sensitive dipole cavities, 34 C-band (for the extraction, matching and final focus section) and 4 S-band (used in the final focusing doublet, where a larger aperture is required). The cavities are located inside quadrupole 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 and beam feedback and steering applications.

## CAVITY BEAM POSITION MONITOR SYSTEMS

The cavities are cylindrical with monopole suppressing waveguides that extract the position sensitive dipole cavity mode. The main parameters of the cavities are shown in Figure 1. The BPMs have 4 symmetric rectangular waveguide couplers, two for each transverse plane. The signal

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Table 1: Cavity Parameters

Parameter	C-Band	S-Band
Frequency (GHz)	6.422	2.888
$Q_L$	~ 6000	~ 1800
x-y isolation (dB)	45	16

output for a polarisation is given by  $V(t) = A \sin(\omega t + \phi) \exp(-t/\tau)$ . The signal amplitude  $A$  is proportional to the product of bunch charge ( $q$ ) and beam displacement ( $d$ ) and tilt angle ( $d'$ ) within the cavity. The induced voltage due to tilt is  $90^\circ$  out of phase with respect to the position signal. The dipole mode cavities are augmented with 5 reference cavities (4 C-band and 1 S-band) which operate with their monopole mode at the same frequency as the dipole frequency of the position sensitive cavities. The reference cavities are insensitive to position and detect beam arrival phase and bunch charge.

## Electronics and Data Acquisition

The signals from the two output ports for a given direction are combined using a hybrid to increase signal amplitude. The electronics for the C and S band CBPMs consist of an amplification stage, single image rejection mixer downconverters and filtering with gains of 25 dB and 12 dB respectively [3, 4]. 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 local oscillator (LO) signals for the C-band RF electronics are generated by dedicated phase locked electronics in the case of the C-band system and a low noise (but not phase locked) synthesiser for the S-band system. The intermediate frequency (IF) signals are digitised by 100 MHz Struck 8 channel, 14-bit waveform VME digitisers. The VME processor-controller publishes the waveform data through EPICS.

The entire system is readout via EPICS and controlled via Python scripting language which enables data acquisition via (cothread; Python EPICS interface) and off-line data analysis via (scipy; scientific Python libraries). The signal processing described below is performed in a dedicated C program, that monitors arrival of beam and computes relevant parameters. Then publishes the resulting

output via EPICS for consumption by the ATF control system and other interested users. The ATF2 (magnet strengths, beam charge, etc) and the magnet mover system are also controlled via a similar EPICS interface and where required integrated with the python/cothread/scipy environment. The state of the CBPM system is viewed via a simple EDM application that can view both the raw data and the processed information generated via the C processing code.

### Signal Processing

The signal processing is a digital downconversion algorithm used extensively for cavity BPM signals [2]. The IF signal from the electronics are digitised and then mixed digitally using a complex local oscillator of frequency  $\omega_{DDC}$  to baseband and filtered using a Gaussian time domain filter ( $g(t)$ ), with a bandwidth of approximately 3 MHz to remove the  $2\omega$  signal.

$$y_{DDC}(t_i) = \sum_{j=0}^{n \text{ samples}} g(t_j - t_i) \exp(i\omega_{DDC}t_j) \cdot y_{dig}(t_j) \quad (1)$$

An example of the digital signal processing is shown in Figure 1.

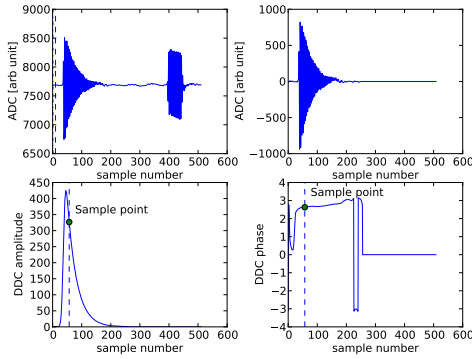


Figure 1: Example of raw and digitally downconverted signals for a dipole C-band cavity.

The DDC LO frequency  $\omega_{DDC}$  is determined by minimising the gradient of the phase of the down converted signal. For both the dipole and reference cavities the amplitude and phase are sampled at a single point yielding  $A$  and  $\phi$ .

The beam position in the CBPM is calculated from the in-phase ( $I$ ) and quadrature-phase ( $Q$ ) signal of the baseband BPM signal compared with the appropriate (nearest spatially and correct frequency) reference cavity, so

$$I = \frac{A_d}{A_r} \cos(\phi_d - \phi_r) \quad (2)$$

$$Q = \frac{A_d}{A_r} \sin(\phi_d - \phi_r) \quad (3)$$

where the subscript  $d$  represents dipole cavity and  $r$  a reference cavity quantity. The amplitude and phase are determined from the digitally mixed signal at a certain sample time  $t_{DDC}$ , so

$$A = |y_{DDC}(t_{DDC})| \quad (4)$$

$$\phi = \arg[y_{DDC}(t_{DDC})] \quad (5)$$

Saturation of the ADC is handled by neglecting data until the digitiser leaves saturation ( $t_{unsat}$ ) and using the measured exponential decay of the downmixed amplitude ( $\tau_{DDC}$ ) to extrapolate the amplitude back to the fixed sample point  $t_{DDC}$ . This allows the BPM to have a large ( $\sim 10$  mm) dynamic range at the expense of resolution, which is degraded due to uncertainties in the measurement of  $\tau_{DDC}$ .

### Calibration

The CBPMs are calibrated by either moving the quadrupole which holds the BPM or by performing a 4-magnet closed orbit bump for those cavities not located inside quadrupoles on movers. The calibration constants for a CBPM polarisation takes the form of the scale and rotation of the measured phasor to position and tilt so

$$d = S(I \cos \theta_{IQ} + Q \sin \theta_{IQ}) \quad (6)$$

$$d' = S'(-I \sin \theta_{IQ} + Q \cos \theta_{IQ}) \quad (7)$$

where  $\theta_{IQ}$  represents a phase and  $S$  and  $S'$  are scaling factor to position ( $d$ ) and angle ( $d'$ ) respectively. An example calibration is shown in Figure 2. The CBPM or beam is typically moved between  $\pm 500 \mu\text{m}$  to  $\pm 250 \mu\text{m}$  in both directions and the  $I$  and  $Q$  response recorded as function of beam position within the cavity.

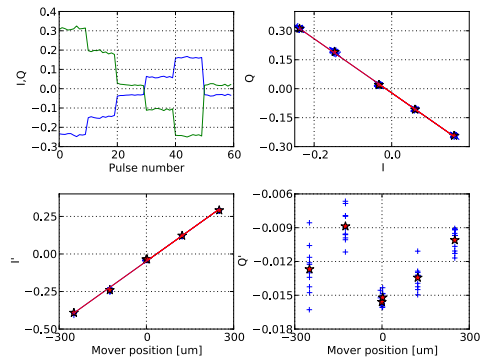


Figure 2: Example of C-band calibration using the magnet movers

## SYSTEM PERFORMANCE

The data presented in this paper are from a three week period during April 2010 and is typical for the system performance. Early in each week a single shift period of 8

hours was used to calibrate and test the system performance. The beam charge was typically of order  $0.2 \times 10^{10}$  electrons per bunch. Although the S and C band CBPMs are treated in exactly the same manner, the cross-coupling indicated in table 1 for the S-band BPMs was bad enough to prevent analysis of the 4 S-band BPMs. The following sections mainly describe the C-band system.

### General Performance

The resolution of a BPM was investigated using a model independent analysis (MIA) as the beam motion is typically two or three orders of magnitude larger than the CBPM resolution. After the calibration procedure is performed for all the CBPM the  $x$  and  $y$  CBPM positions are recorded for approximately 250 machine pulses. The data is used to construct a linear system of equations of the form

$$d_{ik} = \sum_{j \neq k} d_{ij} v_j \quad (8)$$

Where  $d_{ki}$  is the measured displacement in CBPM  $k$  for machine pulse  $i$ . The vector  $v_j$  is the correlation coefficients between the all the CBPMs and the one of interest. The matrix  $d_{ij}$  is typically inverted using a singular value decomposition (SVD) to give  $v_j$ . The output of this procedure, for an indicative run, is shown in Figure 3. For the

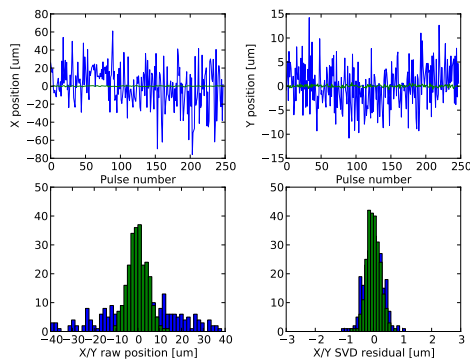


Figure 3: Example of resolution determination using a SVD based MIA

C-band CBPMs root mean square variation ( $\sigma$ ) in the SVD position for the example shown in Figure 3 is  $\sigma_x = 329$  nm and  $\sigma_y = 229$  nm for the horizontal and vertical directions respectively. Typically for the CBPMs with 20 dB attenuators the resolution is between 200 nm and  $\sim 1.2$   $\mu$ m. The variation in the resolution is consistent with variation of the LO power provided to each set of mixer electronics. This LO power variation will be removed by upgrading (in the near future) the amplifier which provides RF power to the entire C-band system.

Four CBPMs had the 20 dB attenuators removed to test the high resolution performance. The four BPMs selected were MQM16FF, MQM15FF, MQM14FF and MFB2FF. The same MIA was performed (only using these BPMs)

and the best resolution was 27 nm. This is consistent with the  $\sim 200$  nm measured resolution for the CBPMs with attenuators.

The system stability was investigated by examining the BPM calibration constants ( $S$  and  $\theta_{IQ}$ ) during the three week run period. Tables 2 and 3 show the vertical calibration scale and IQ rotation respectively from the repeated calibration measurements. MQD10X is located in a quadrupole without a mover system so is calibrated using a bump. MQD16FF and MQD10BFF are mover calibrated, although MQD16FF had the 20 dB attenuator removed.

Table 2: Vertical Calibration Scale ( $S_y$ ) Stability over 3 Weeks

BPM name	Week 1	Week 2	Week 3
MQD10X	1800.35	-	1883.3
MQD16FF	138.3	111.9	111.1
MQD10BFF	929.9	906.4	1254

Table 3: Vertical Calibration Phase Rotation ( $\theta_{y,IQ}$ ) in Radians Stability over 3 Weeks

BPM name	Week 1	Week 2	Week 3
MQD10X	-0.565	-	-0.676
MQD16FF	-0.814	-0.749	-0.801
MQD10BFF	-0.503	-0.427	-0.610

## CONCLUSIONS

The ATF2 C-band system is performing well, with individual CBPM resolution approaching or at the design resolution of 50 nm. The changes in the CBPM calibration observed over three weeks can probably be attributed to thermal effects on the mixer electronics systems. The CW calibration tone power will be upgraded to monitor changes in the electronics gain and phase.

The four S-band CBPMs are still to be investigated, the main problem associated with these cavities is a large cross coupling between the  $x$  and  $y$  ports. This combined with the large design dispersion in that region makes the digital signal processing difficult, although various techniques exist to determine the cavity parameters [5] and use these coupled signals for beam position determination [6].

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