

HIGH RESOLUTION BPMS WITH INTEGRATED GAIN CORRECTION SYSTEM*

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Abstract

High resolution *beam position monitors* (BPM) are an essential tool to achieve and reproduce a low vertical beam emittance at the KEK *Accelerator Test Facility* (ATF) damping ring. The ATF *damping ring* (DR) BPMS are currently upgraded with new high resolution read-out electronics. Based on analog and digital down-conversion techniques, the upgrade includes an automatic gain calibration system to correct for slow drift effects and ensure high reproducible beam position readings. The concept and its technical realization, as well as preliminary results of beam studies are presented.

INTRODUCTION

The generation and preservation of low emittance beams is mandatory to achieve a high luminosity in the next generation linear acceleration-based lepton collider for *high energy physics* (HEP). Therefore, the damping and extraction of electron beams with ultra-low vertical emittance of < 2 pm is a mission critical goal [1], and has to be demonstrated at the damping ring of the KEK Accelerator Test Facility (ATF) [2]. This requires various optimization methods to steer the beam along an optimum (“golden”) orbit with minimum disturbance of non-linear field effects. A high resolution BPM system is one of the important tools; it needs to meet as initial specifications

- A resolution of ~ 100 - 200 nm in a “narrowband” mode.
- A high resolution (some μm) turn-by-turn measurement option.
- An automatic gain correction system, to compensate slow drift effects in the analog part of the read-out electronics – e.g. due to temperature variations, aging effects of components, etc.

The BPM concept was initiated as KEK/SLAC/Fermilab collaboration [3] in frame of the Global Design Initiative (GDI) of the International Linear Collider (ILC) activities. Today this ATF DR BPM upgrade collaboration is backed by Japan-US funds, with Fermilab as core partner.

As proof of principle prototypes and beam studies are performed on 20-of-96 BPM stations with new read-out hardware:

- 714MHz-to-15MHz downmix / calibration module (located in the ATF accelerator tunnel)

- VME-based digital signal processing and timing electronics, currently based on the commercial *Echotek* digital receiver (will be replaced by in-house digitizers).
- Various FPGA-firmware, control and diagnostics drivers and software (C++, VxWorks, Linux) and an EPICS interface to the ATF controls (V-system).

THE ATF DAMPING RING

The 1.2 GeV ATF damping ring is equipped with 96 button-style BPM pickups, and part of the Accelerator Test Facility (ATF) complex, which includes an S-Band electron linac, and an extraction beam-line (ATF2).

Table 1: ATD DR Machine and Beam Parameters

beam energy E	=	1.28 GeV
beam intensity, single bunch	\approx	~ 1.6 nC $\equiv 10^{10}$ e ⁻ ($\equiv I_{\text{bunch}} \approx 3.46$ mA)
beam intensity, multibunch (20)	\approx	~ 22.4 nC $\equiv 20 \times 0.7 \cdot 10^{10}$ e ⁻ ($\equiv I_{\text{beam}} \approx 48.5$ mA)
f_{RF}	=	714 MHz ($\equiv t_{\text{RF}} \approx 1.4$ ns)
f_{rev}	=	$f_{\text{RF}}/330 \approx 2.16$ MHz ($\equiv t_{\text{rev}} \approx 462$ ns)
bunch spacing t_{bunch}	=	$2/f_{\text{RF}} \approx 2.8$ ns
batch spacing	=	$t_{\text{rev}}/3 = 154$ ns
repetition freq. f_{rep}	=	1.56 Hz ($\equiv t_{\text{rep}} = 640$ ms)
beam time t_{beam}	=	460.41 ms ($\equiv 996170$ turns)
vert. damping time τ	\approx	30 ms
hor. betatron tune (typ.)	\approx	15.204 ($\equiv f_{\text{h}} \approx 441$ kHz)
vert. betatron tune (typ.)	\approx	8.462 ($\equiv f_{\text{v}} \approx 1$ MHz)
synchrotron tune	\approx	0.0045 ($\equiv f_{\text{s}} = 9.7$ kHz)

Table 1 lists some relevant machine and beam parameters of the ATF damping ring. In standard operation a single bunch is injected on axes from the S-Band linac. After ~ 200 ms all injection oscillations are fully damped, and the beam stays for another ~ 400 ms in the ring, before being extracted. Optional multi-batch / multi-bunch operation can be set up on a cycle-by-cycle basis (no extraction), with up to three equally spaced batches, each containing 1...20 bunches, spaced by 2.8 ns.

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THE ATF DR BPM UPGRADE

The currently installed read-out system for the 96 button style BPMs does not meet the requirements in terms of resolution, reproducibility, intensity independence and turn-by-turn measurement capabilities to tune the ATF damping ring to the ultimate low vertical emittance goal of < 2 pm. In the past (2006–2008) several upgrade efforts have been made, testing new read-out electronics on 20 button-style BPMs. Recently (2009) an improved analog downmix unit with integrated calibration system has been investigated at six BPM locations.

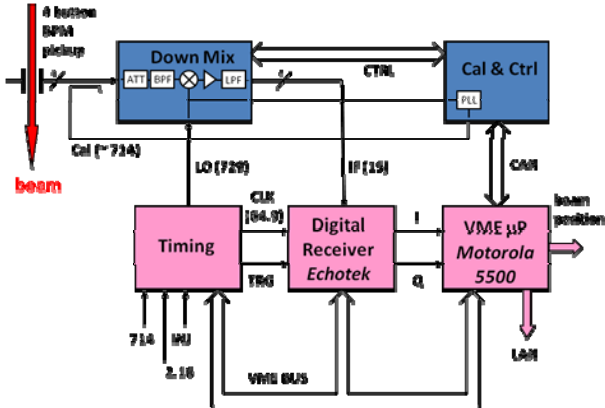


Figure 1: ATF Damping Ring BPM upgrade system.

Figure 1 shows an overview of the upgraded read-out system for a single BPM location. The downmix and calibration units are located inside the accelerator tunnel, converting 714 MHz beam signals from the four button-style BPM electrodes to an IF of 15.145 MHz. The digital receiver (commercial *Echotek* VME-board) and most of the auxiliary hardware (timing, VME processor, CAN-bus controller, power supplies, etc.) are located outside the tunnel.

Button-style BPM Signal Processing

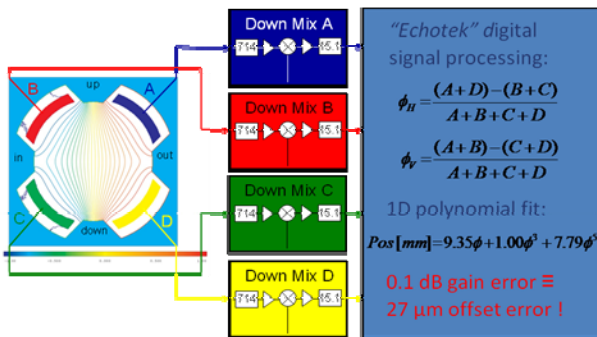


Figure 2: BPM signal processing schema.

The button-style BPM pickup, which is the only unchanged component of the upgrade project, utilizes four “button” electrodes, arranged symmetrically under 45° into the vacuum chamber of 24.4 mm diameter. Figure 2 shows the signal processing schema, which is based on a two-step down converting process:

1. Analog: 714 MHz to 15.1 MHz
2. Digital: 15.1 MHz to DC (baseband, I/Q)

The filtered (CIC & FIR) I/Q signals of each electrode are summed in quadrature, and the magnitude results of the A, B, C and D pickup signals are arranged as normalized horizontal or vertical displacement information (Fig. 2). Some of the pickup non-linearities are taken into account by applying a 5th order polynomial to fit the calculated equipotentials.

Analog Downmix and Calibration Unit

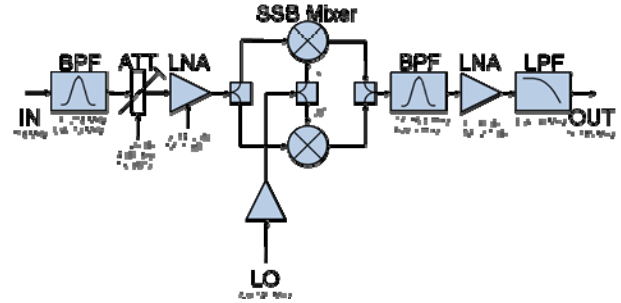


Figure 3: Analog downmixer (1-of-4 channels).

An analog downconverter is required to match the high-pass transfer impedance of the button electrode ($0.74 \Omega @ 714$ MHz) to the pass-band (~ 40 MHz) of the *Echotek* digital receiver (105 MSPS). Figure 3 shows the simplified block schema of one downmix channel; bandpass filters, gain-stages and attenuators are used for signals conditioning. The 15.1 ± 1.5 MHz IF band-pass defines the signal waveform at the output, which decays within ~ 400 ns to allow time resolved turn-by-turn measurements (Fig. 4, left). The circuit offers a >90 dB dynamic range, plus 40 dB by gain switching element (Fig. 4, right).

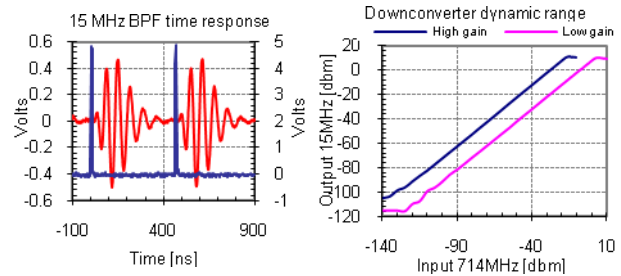


Figure 4: Measured performance of the downmix unit.

A 10 dB directional coupler at the input is used to apply an internally generated calibration signal (Fig. 1), which is used to compensate slow drift effects in the analog signal path, e.g. due to temperature changes or component aging effects. The calibration signal is generated by a fractional PLL from the 729 MHz LO-signal, the frequency is ~ 400 kHz above/below the 714 MHz beam signal, within the pass-band of the analog processing chain. The simultaneous detection of reflected and transmitted (through the button BPM) calibration signals is performed only in narrowband mode, by utilizing separate down-converters in the digital receiver. For each channel (X: A, B, C or D) a correction term:

$$X_{corr} = \frac{A_{Cal} + B_{Cal} + C_{Cal} + D_{Cal}}{4 X_{Cal}}$$

is derived from the detected calibration signals, and multiplied to each of the beam signals.

Digital Signal Processing

A commercial 8 channel digital receiver (*Echotek* ECDR-GC814) VME-board, based on 14-bit 105 MSPS *Analog Devices* AD6645 A/D converters, is currently used for the digital signal processing. Each channel is equipped with a 4-channel direct downconverter (DDC) ASIC (GC-4016 *Graychip*), which holds the I/Q mixer, NCO, digital filters (CIC & FIR), and other signals processing elements. Two fundamental operating modes are programmed for the ATF DR BPM signal processing:

- **Wideband (turn-by-turn, TBT) mode**
 - 5-stage CIC: decimate by 4
 - CFIR: 7-tap boxcar, decimate by 2
 - PFIR: 1-tap, no decimation
- **Narrowband mode**
 - 5-stage CIC: decimate by 2746
 - CFIR: 21-tap raised cosine, decimate by 2
 - PFIR: 64-tap raised cosine, decimate by 2

In case of the narrowband mode, two additional *Graychip* channels, for the detection of reflected and transmitted calibration signals, have to be activated. Their NCO frequencies are tuned to the corresponding calibration frequencies ($15.14545 \text{ MHz} \pm 400 \text{ kHz}$). In the final ATF BPM system configuration the *Echotek* digital receiver will be replaced by an equivalent, in-house designed VME digitizer board.

All required reference signals (LO, clock, trigger, etc.) are locked to the 714 MHz damping ring RF, generated by an in-house developed VME timing board (Fig. 1). The 69.24 MSPS clock frequency defines 32 data samples per turn, which are decimated by 8 in wideband, turn-by-turn mode. The given 5-stage CIC filter limits the bandwidth to $\sim 1 \text{ MHz}$. In narrowband mode the decimation is set to 10984, which results in samples spaced by $158 \mu\text{sec}$, and a bandwidth of $\sim 500 \text{ Hz}$. All data post-processing and control activities are handled in a VME *Motorola* 5500 processor board, which also controls the local CAN-bus.

PRELIMINARY RESULTS

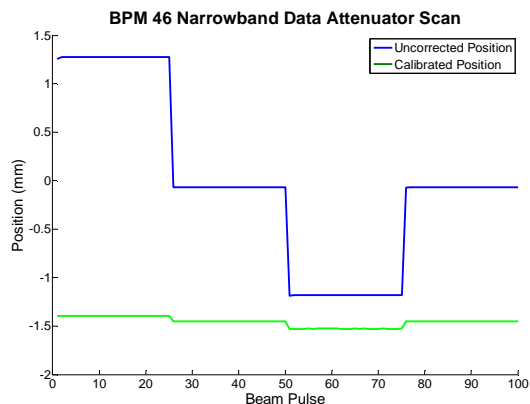


Figure 5: Calibration system test at BPM # 46.

Figure 5 shows a proof-of-principle beam test of the automatic gain correction system. Gain errors in the analog signal processing stages may occur due to temperature drifts or component aging effects, a typical 0.1 dB gain error in one channel corresponds to a $27 \mu\text{m}$ displacement error (position offset). Introducing an extreme gain error of 4 dB in a single channel, results in a $\sim 1.3 \text{ mm}$ offset error in the uncorrected case, which is corrected to $< 50 \mu\text{m}$ using the reflected calibration signal.

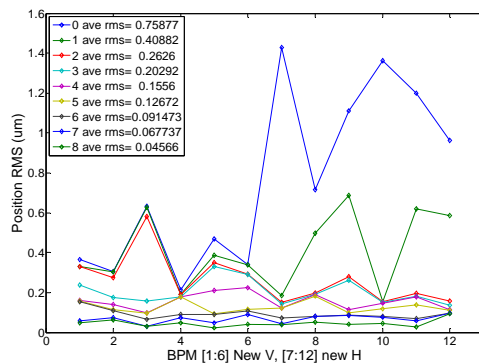


Figure 6: BPM resolution in narrowband mode.

The narrowband mode resolution of the upgraded BPM read-out electronics has been analyzed by taking 1280 consecutive data samples ($\sim 200 \text{ msec}$), starting at turn # 400,000, i.e. the beam is fully damped. A 126 tap box-car filter is applied on the data to reject the 50 Hz power ripple, followed by an SVD analysis to decompose the beam motion from the systematic noise of the BPM hardware. As Figure 6 indicates, the resolution seems to be $< 200 \text{ nm}$, after applying a reasonable cut of the first three modes..

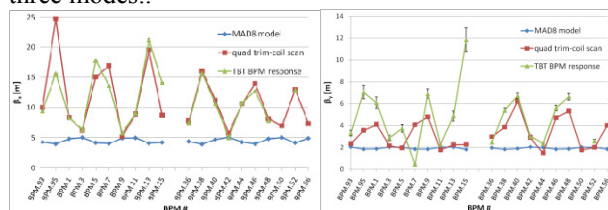


Figure 7: Comparison of measured and theoretical β -functions.

The TBT mode was tested by Fourier analyzing the BPM response (2048 turns) to coherent beam oscillations [4], excited by a kicker. The single pass resolution is found to be $< 10 \mu\text{m}$ RMS. Figure 7 compares theoretical and measured (TBT kicked beam and quad scan methods) β -functions at the 20 BPM locations.

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