OVERVIEW OF BEAM INSTRUMENTATION FOR HIGH-INTENSITY STORAGE RINGS

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Abstract

This paper will present an overview of beam instrumentation with a view towards relevance for future accelerator projects on the basis of experience at KEKB. The KEKB B-Factory shares with other existing and planned electron and positron machines the requirement for precise measurements at high beam intensities.

1 INTRODUCTION

New accelerators and upgrade plans always seek higher beam currents (bunch currents, number of bunches). Beam instrumentation needs to handle the associated heating and dynamic range issues, and provide diagnosis of the increased instabilities that arise. In striving to reach its design goals, KEKB has also encountered many of these issues. This paper will present an overview of beam instrumentation at KEKB, and of our experience of such issues.

KEKB is an electron-positron collider with two rings: the 8 GeV High Energy Ring (HER) for electrons, and the 3.5 GeV Low Energy Ring (LER) for positrons. The rings have circumference of approximately 3 km, and intersect with a crossing angle of 22 mrad at the interaction point. The total number of rf buckets in each ring is 5120, with about 1150 being used at present for physics running. The maximum stored currents have been gradually raised to 1100 mA for the LER, and 873 mA for the HER.

2 BPMS

For closed orbit distortion (COD) measurement, there are 454 4-button pickups installed in the LER, and 443 4-button pickups installed in the HER.[1] To avoid picking up RF leakage from the high-power RF system they are read out at a detection frequency of 1018 MHZ, or $2 \times f_{rf}$. The pickups are small button electrodes of 12 mm diameter. In the HER arc sections the button stems have a non-axially-symmetric structure in order to avoid the growth of coupled-bunch instabilities from coupling impedance. The buttons are mounted in BPM blocks made of copper to match the rest of the beam pipe, reinforced with stainless steel frames and mounted rigidly to the nearest quadrupole magnet for stability.

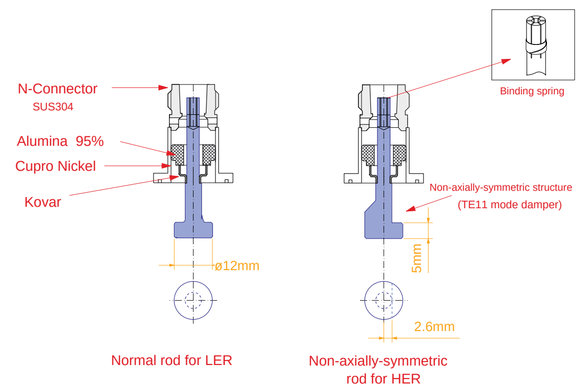

Figure 1: BPM button electrode structure.

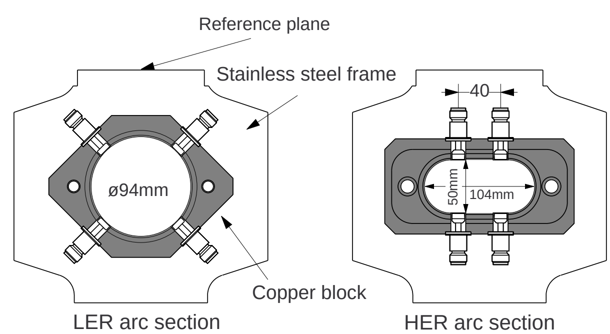

Figure 2: BPM block structure.

The 4 BPM signals from one BPM block are read out in a multiplexed fashion, and after filtering are converted to a 20 kHz intermediate frequency and then directly digitized at a 100kHz sampling rate by an 18-bit ADC. This digitized signal is then FFT analyzed inside a DSP. The number of FFT data points and the number of averages taken of the spectrum can be varied to make different tradeoffs between resolution and measurement time. The system is typically operated at a resolution of 1.5 μm, using a 4-fold average, with a readout cycle time of 2 seconds. The BPMs are divided into 20 sub-control stations, which were initially operated asynchronously. However, in order to diagnose orbit drifts with periodicities of a few seconds (such as one due to leakage fields from a proton synchrotron magnet) it was found to be necessary to synchronize the stations to digitize simultaneously. With this capability, the phase advance around the ring can be measured and the source of the disturbance located.

Another type of orbit drift encountered was a current-dependent shift of the beam near the interaction region. Measurements with capacitative position sensors of the BPM block position in this region revealed that the beam pipe to which the BPM was mounted was moving due to heating of the chamber from SR radiation. (Due to its location, this particular BPM block could not be mounted rigidly as others were.) The solution employed for this beam-dependent BPM offset problem is to correct the BPM offsets using the mechanical position sensor readings, thus incorporating what would normally be considered a "slow control" monitor into the beam-position monitoring system.

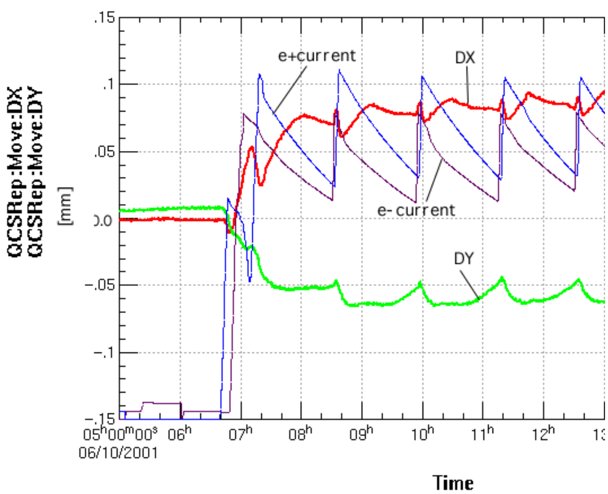

Figure 3: Motion of BPMs near interaction region due to beam-pipe heating.

Another beam-intensity dependent BPM error was found in the "Octpos" BPMs, which are 8-button BPMs near the IP where both beams share a common beampipe. Due to space constraints stripline electrodes (which would be able to separate the two beams by directionality) could not be employed, so button electrodes were used. The analysis of the button electrode signals[2] is very sensitive to error in phase advance from the IP, and it has been found that the Octpos readings suffer from current-dependent offsets.

Finally, turn-by-turn BPMs[3][4] have been set up at one of the BPM pickup locations using a high–speed rf switch (gate width 6 ns) to measure the amplitude and phase of a single bunch turn-by-turn. This has been used for injection tuning to find phase and energy errors, and betatron damping rate measurements to measure the impedance in the ring.[5] It is also used to make bunch-by-bunch phase measurements to measure transient beam loading and loss factors due to resistive impedance at high currents.[6]

3 FEEDBACK-RELATED SYSTEMS

The components of the transverse bunch-by-bunch feedback systems[7][8] (position monitors, stripline kickers and amplifiers, etc.) are located in the straight section in the ring opposite the interaction region. The

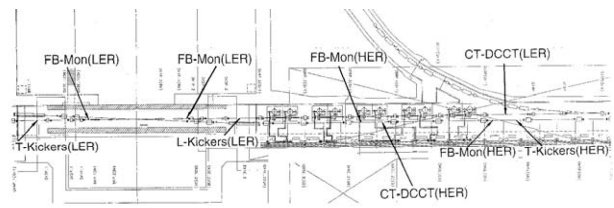

Figure 4: Location of feedback system components in Fuji straight section.

wideband kickers span a range of 10 kHz to 250 MHz, with low-frequency kickers going from 5 kHz to 1 MHz, providing coverage of the full range of betatron modes. The feedback system is based on a 2-tap F.I.R. filter; since KEKB operates with all tunes near the half-integer, the corrective kick applied is proportional to the difference of positions measured 2 turns ago and the positions measured 1 turn ago. The turn-by-turn position readings are recorded in a custom-designed memory buffer, so these parameters can be adjusted as needed.

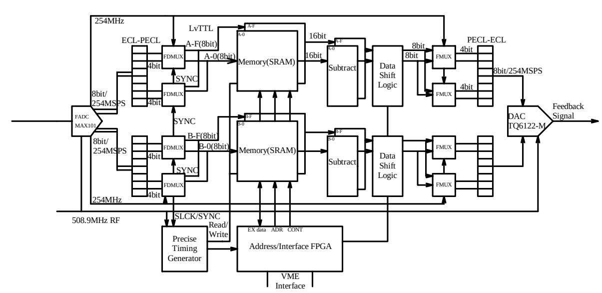

Figure 5: Block diagram of feedback module.

A longitudinal feedback kicker has also been installed, but has not been needed yet.

Based on the components of the feedback system, several important monitors are available: the bunch current monitor, bunch oscillation recorder, and tune and gated-tune meters.

3.1 Bunch Current Monitor

The bunch current monitor is based on the feedback board with a modified front end, and is used to monitor the current of each bunch to ensure even filling (or uneven, shaped filling, if desired) during injection.

3.2 Bunch Oscillation Recorder

The bunch oscillation recorder (BOR) uses the feedback module memory to record the turn-by-turn positions of all 5120 rf buckets for 4096 turns (41 msec). It is used to measure injection damping time, and also as a transient event recorder for abort post-mortems. At high beam currents, signatures of fast-ion instability have been detected in the High Energy Ring, though so far the feedback system has been able to completely suppress the instability. In the Low Energy Ring, the mode spectrum has been observed to change based on the activation of solenoids placed around the ring to suppress photo-electron cloud build-up, indicating an effect of electron cloud build-up on the LER beam. Studies of the mode spectrum with the BOR are ongoing.

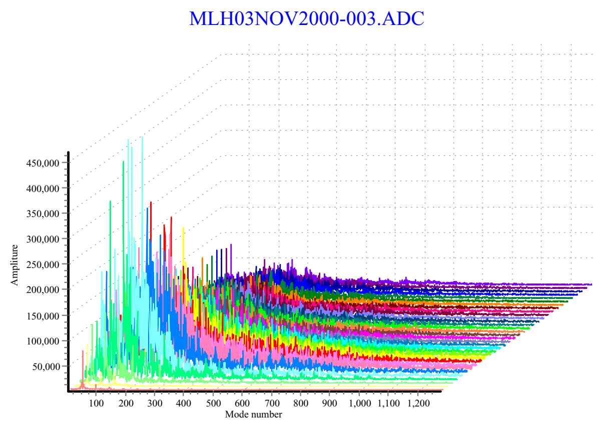

Figure 6: Sample mode spectrum taken with bunch oscillation recorder.

3.3 Tune Meter

The tune meters use the feedback kickers and spectrum analyzers to measure the horizontal and vertical tunes of the LER and HER. The center frequency is at ≈ 2 GHz $(4 \times f_{rf} + n \times f_{rev} + f_{\beta})$. The spectral peaks are found by online fitting. The button electrodes are mounted at 45 degrees, and the system has a 100 Hz bandwidth.

At high current, the tune spread due beam-beam tune shift becomes too large for a peak to be measured. For this reason, a Gated Tune Meter is used, based on a 2 ns gate pulse to measure the tune of a "pilot," non-colliding bunch. The pilot bunch's gated tune is continuously monitored and adjusted throughout a fill to maximize the luminosity during physics running.

The gated tune meter is also used to measure the bunch-by-bunch tune shift along the bunch train, which show the effects of the the electron cloud build-up observed at high beam currents in the LER.[9]

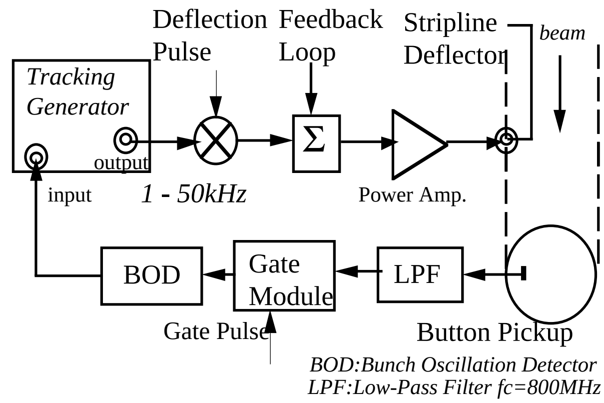

Figure 7: Block diagram of gated-tune meter.

4 SYNCHROTRON RADIATION MONITORS

Synchrotron radiation (SR) extraction mirrors are located in each ring, and several monitors are based on the extracted SR light.[10] The most commonly used monitors are the SR interferometers, which can measure transverse beam sizes down to a few microns. The SR source bends are located at a high-β, low-η section of the ring, and the measurements obtained there are mapped via optics functions to the IP to obtain the beam sizes in collision. By scanning the slit separations, the beam profile can also be measured; this has been done and a Gaussian profile has been verified.

In addition, a streak camera has been used to measure the bunch lengths, yielding natural bunch lengths of 5.5 mm for the HER and 6.0 mm for the LER. A gated camera is also available to measure the bunch-by-bunch beam size based on spot size. The absolute values thus obtained are crude, but useful for measuring relative sizes.

The interferometer and gated camera have been used extensively to study the vertical beam blow-up of the LER at high beam currents due to photo-electron cloud trapping, and to measure the effect of electron-clearing solenoids on the trapping phenomenon.

At high beam currents, several systematic problems have turned up in the operation of the SR interferometers. As the beryllium extraction mirror heats up, it expands and pivots around its mounting point, throwing off the alignment of the optical axis. This is compensated for with an optical axis feedback system based on a remotely movable mirror just downstream of the extraction mirror.

In addition, as the shape of the mirror changes, the light balance between the interferometer slits change, reducing the apparent fringe depth (visibility) and thus increasing the apparent beam size. This effect can be measured by the use of remote-controllable shutters in front of the slits, and compensated for.

Most seriously, as the mirror surface deforms, the apparent beam size changes by up to 30% as the beam current goes from 200 mA to 900 mA. By measuring the resulting distortion of the interference pattern, this effect can be measured and compensated for. Using this method we are freed from the problem of mirror distortion. (See [11] for further discussion of these issues.)

5 BUNCH LENGTH MONITORS

Besides the streak camera mentioned above, other bunch length monitors based on the bunch spectrum have been developed. One, using a BPM pickup,[12] measures the spectrum at two frequencies ω_1 and ω_2, to yield the bunch length $\sigma_t = \sqrt{\frac{2}{\omega_2^2-\omega_1^2} \ln \frac{F_1(\omega_1)}{F_2(\omega_2)}}$. Bunch lengths measured in this way agree with the measurements obtained by streak camera, and the measurements are much easier to make since the equipment is always available. In addition, another bunch spectrum monitor using a pickup on a high-power RF waveguide has been developed,[13] and can also provide freely available bunch length measurements once calibrated.

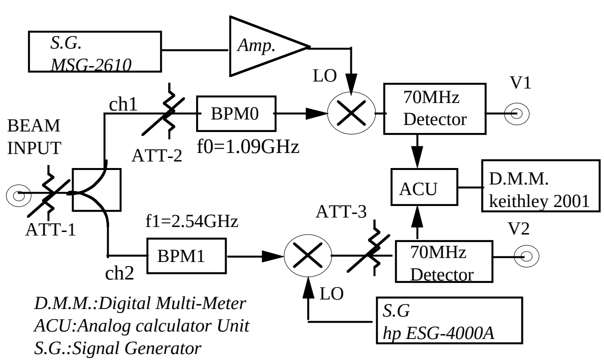

Figure 9: Block diagram of BPM-pickup bunch length monitor.

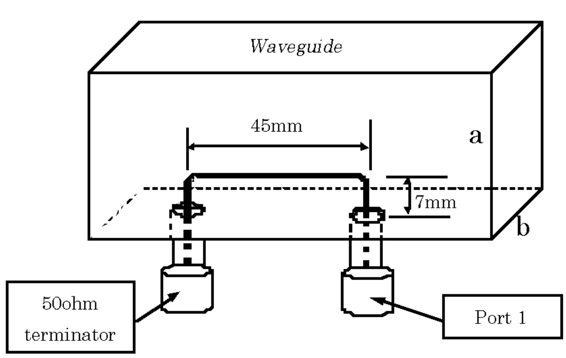

Figure 10: Pickup of RF-waveguide-based bunch length monitor.

6 LOSS MONITORS

Two types of loss monitor systems have been installed at KEKB. The first type, based on air ionization chambers, has a slow response time (≈ 1 msec drift time), but is low-maintenance and nearly indestructible. Ion chambers are arrayed to give wide coverage around the rings and beam transport line and are connected to the beam abort system for machine protection.

As beam currents have been raised over the course of operation, problems with damage to beam masks have occurred, leading to loss of vacuum in some instances, necessitating the use of fast response loss monitors around the mask regions. For this purpose the ion chambers near the masks have been replaced with PIN diodes, which give ≈ 60μsec response (from cable plus amplifier input impedance). These detectors will require regular replacement, but can issue an abort signal within a few turns and so are dedicated to mask protection.

7 DCCT AND CT

Traditional DCCT designs require the use of carefully matched core pairs, or else suffer from ripple. Custom DCCTs developed for KEKB use a parallel-feedback design to minimize ripple suppression problems when using unmatched cores.[14] These DCCTs achieve a ripple on the order of $1\mu A$ with a wideband frequency response (cutoff = 24 kHz). They are read out once per second for beam current and lifetime measurements.

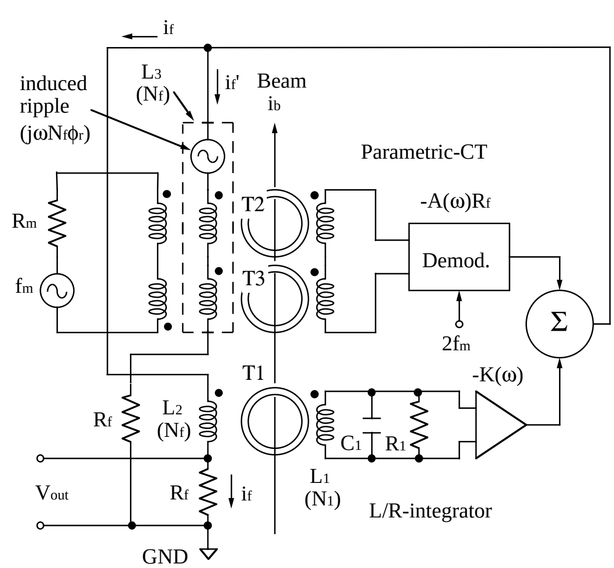

Figure 11: Block diagram of parallel-feedback DCCT.

A simple CT is also used for visual monitoring during initial injection tuning.

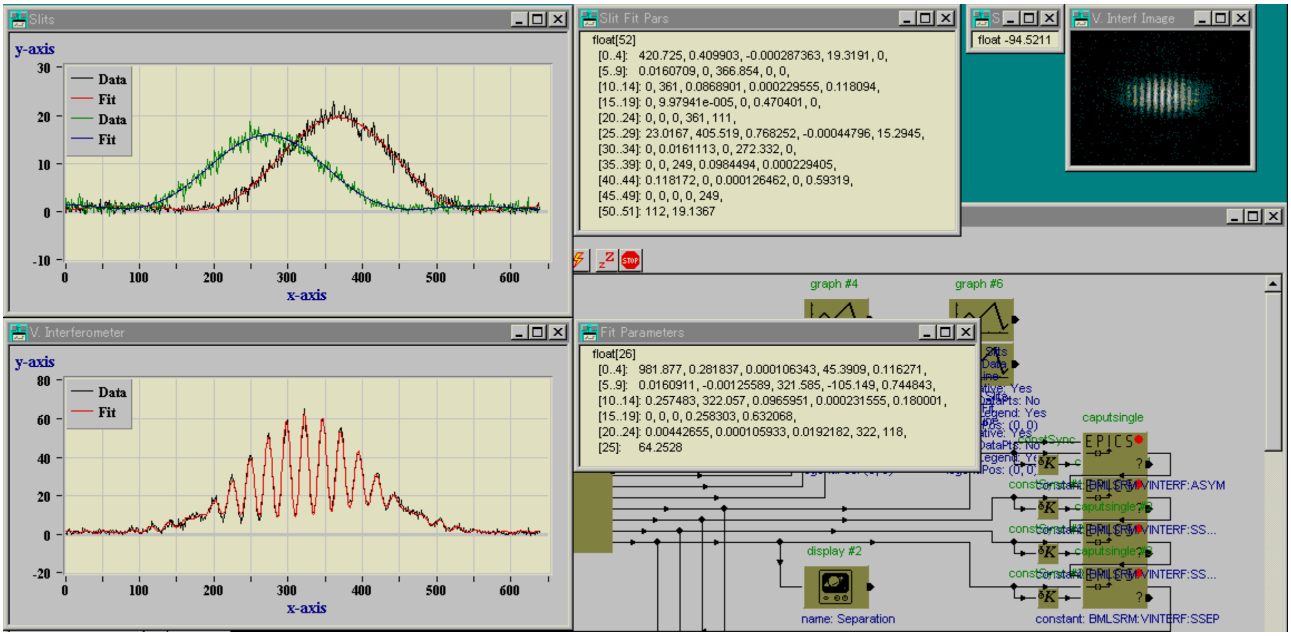

Figure 8: SR monitor data acquisition and analysis system. The curves in the upper left are the single-slit components of the interferogram measured with a shutter, and the lower curve is the resulting 2-slit interferogram. The separation and unequal heights of the single-slit peaks are the result of mirror distortions due to heating, and have to be corrected for to measure the beam size accurately.

8 SUMMARY

High intensity beams lead to problems of heating (SR, HOM), dynamic range, and instabilities which create the need for more diagnostics: BOR, SR monitor, turn-by-turn BPM, gated camera, gated tune, and gated phase. Also, using 2 rings to get many bunches with 1 interaction region introduces additional complexities into the range of COD motions that can occur. To diagnose these, it has been necessary to be able to adjust the timing, synchronization, and precision of the BPMs, and even to incorporate what would usually be considered slow/environmental monitors into the BPM system. As beam currents rise, additional diagnostics will be needed, as well as an open mind as to what constitutes beam instrumentation.

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