BEAM INSTRUMENTATION IN SUPERKEKB

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Abstract

SuperKEKB is the upgraded collider of the KEK B-factory (KEKB). Beam instrumentation of KEKB has been commissioned in phase 1 operation which has just finished in this June. A beam position monitor system consists of super heterodyne detectors, turn by turn log-ratio detectors with fast gates and detectors for the orbit feedback to maintain stable collision. New x-ray beam profile monitors with the coded aperture method are installed. A bunch-by-bunch feedback system is upgraded using low noise frontend electronics and new 12 bits iGp digital filters. An introduction of instrumentation of SuperKEKB and its performance in phase 1 operation will be given here briefly.

INTRODUCTION

SuperKEKB is the upgraded electron-positron collider of the KEKB B-factory [1]. The design luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ will be achieved using so-called nano-beam scheme. Main machine upgrades include the replacement of cylindrical copper chambers in LER to those with aluminum TiN coated ante-chambers so as to withstand large beam current and also mitigate the electron cloud effect, a new final focus system in order to adopt the nano-beam scheme and the construction of a positron damping ring. Phase 1 operation has just finished in June 2016 [1].

This paper introduces the beam instrumentation in SuperKEKB and shortly comments on its performance in phase 1 operation. Detailed reports to which this paper often refers are appeared in [2, 3, 4, 5] and their references.

BEAM POSITION MONITOR SYSTEM [2,3]

The number of beam position monitors (BPMs) in SuperKEKB is 445 in the low energy ring (LER) and 466 in the high energy ring (HER). The BPM chambers and button electrodes in HER are reused from KEKB. New button electrodes whose diameter is 6mm are installed on new LER vacuum chambers. The electrode is a flange type for easy replacement. A pin-type inner conductor is adopted for tight electrical connection.

A narrowband detector system which follows that in KEKB is a main detection system. A new narrowband detector with a detection frequency of 509 MHz has been developed and used in LER since the cutoff frequency of the new LER ante-chamber is below the detection frequency of the KEKB detector of 1 GHz. Analogue

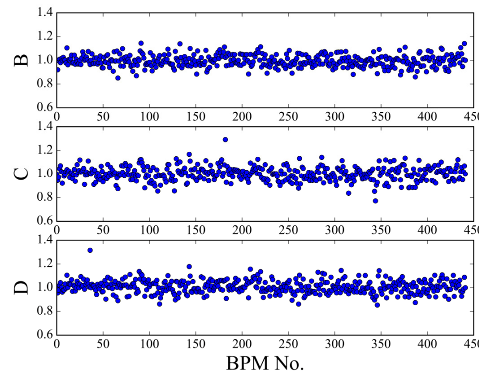

Figure 1: BPM gain mapping of LER relative to electrode A [3].

circuits are housed in an aluminum shield case. An isolator is put in front of a variable attenuator to reduce change of signal level upon switching of the attenuator. Discrete PIN diodes with DC coupling are used in a multiplexer and the attenuator to improve transient characteristics such as spike and ringing. S/N ratio larger than 90 dB is achieved by 2048 points FFT and averaging of 8 points data with CW signal, which corresponds to position resolution better than 0.5μm.

Gain calibration [6] has been applied by the narrowband detection system. Imbalance of signal level of four channels was measured by beam and then corrected in position calculation. Figure 1 shows measured relative signal levels with respect to that of the electrode A. Dispersion of the LER gain is slightly larger than that of HER, which probably reflects the difference of flange-type connection (LER) and brazing (HER) to fix the BPM to the chamber.

Beam based alignment [7] has been applied to measure the BPM position offset against the center of an adjacent quadrupole. The rms values of the measured offset (x/y) were 0.570 mm/0.222 mm in LER and 0.505 mm/0.392 mm in HER [8]. Rotation angle of BPMs was measured prior to the operation to correct the position data of the beam. The rms values of rotation were 0.62 mrad and 0.78 mrad in HER and LER respectively.

Position resolution of the narrowband system was measured by the three BPM method. The obtained resolution is better than 3μm and 5μm in LER and HER, respectively, for most of the BPMs. The result represents upper bound of the resolution because the measurement could be affected by beam movement between switching interval of a multiplexer. The beam current dependence of BPM resolution was small because signal voltage was adjusted by the variable attenuator as a function of the beam current. Anti-correlation between resolution and signal level was seen.

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ISBN 978-3-95450-187-8

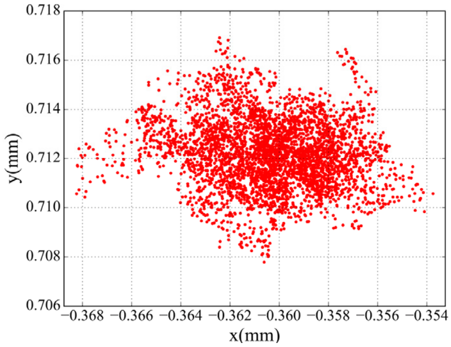

Figure 2: Transverse beam positions measured by a prototype detector for the orbit feedback at IP (preliminary).

One hundred seventeen gated turn by turn detectors (GTBT) are installed at selected BPMs to measure the optics during collision. A non-colliding pilot bunch is kicked by the bunch-by-bunch feedback system and then the GTBT measures turn by turn position of the pilot bunch using a fast gate to select the signal of the pilot bunch. The gated signal is processed by a log-amp then sent to an ADC. Signals of remaining bunches are sent to the output port of the detector which is connected to the narrowband detector in order to allow the simultaneous measurement of the narrowband detector and the GTBT. Optics parameters such as beta functions and coupling parameters can be obtained from the bunch oscillation data. The GTBT is also available for injection tuning.

FFT spectrum of orbit vibration in HER was measured by the GTBT from 1.3s, i.e. 131k turns data in phase 1. The peaks at 9.1 Hz and 16.68 Hz were found with amplitude of around 5 µm. The oscillation could affect the resolution of the narrow band measurement.

A special wideband detector is to be installed at four BPMs closest to the collision point (IP) for orbit feedback to maintain stable collision. Tentative specifications for the detector are resolution less than 1 µm, repetition from 5k to 32kHz, bandwidth of 1kHz. It down-coverts 508.8MHz component of the beam signal to intermediate frequency (IF) of 16.9 MHz with an analog mixer. IF signal is supplied to a low pass digital filter with a cut off frequency of 2kHz which consists of two CICs and one FIR. The digital part is implemented in a µTCA board developed for the SuerKEKB LLRF system. EPICS is embedded in the board.

A prototype model was tested by the beam in phase 1 operation. Figure 2 shows preliminary data of the beam position measurement in LER.

A displacement sensor monitors the change of the distance between a BPM and an adjacent sextupole because orbit change at the sextupoles causes vertical emittance growth and tune change. The displacement sensors used in KEKB are re-installed at BPMs near every sextupoles in SuperKEKB. Special sensor supports made of Metal Matrix Composites with low thermal expansion coefficient of 3 10^{-6} K^{-1} are used in the sensors near rotatable sextupoles in LER. The support has a long pillar fixed to a base of the sextupole because the sensor can't be mounted on the movable sextupole.

BUNCH-BY-BUNCH FEEDBACK SYSTEM

A transverse feedback system [3, 9] consists of BPMs, frontend electronics, a digital filter, backend electronics, power amplifiers and stripline kickers. To ensure a fast response of the feedback two sets of short stripline kickers which cover two feedback loops with 90 degrees phase difference between monitor chambers are installed in each ring.

The button electrode has a glass-type sealing with low relative dielectric constant (~4) which has good time and frequency response. The detection frequency is 2 GHz. A difference signal is mixed with LO with frequency of 4 x RF frequency, amplified to increase gain, fed to a 600 MHz Bessel LPF then amplified by a DC amp.

The design of the kicker is similar to that of the KEKB kicker. Eight power amps with power of 500W or 250W are used to drive the kickers in each ring.

A digital filter adjusts a gain so as to maximize it at betatron frequency and also adjusts a phase shift between the kicker and the pickup to 90 drgrees. The iGp12 processor [10] is a baseline system of the digital filter. It was developed under US-Japan collaboration (KEK-SLAC). Main features of the iGp12 are 12 bit ADC and DAC, FPGA of Vertex-5 (VSX95T, VSX50T), 10 to 20 tap FIR filter, 12MB memory to analyze instabilities and availability for single bunch excitation by PLL.

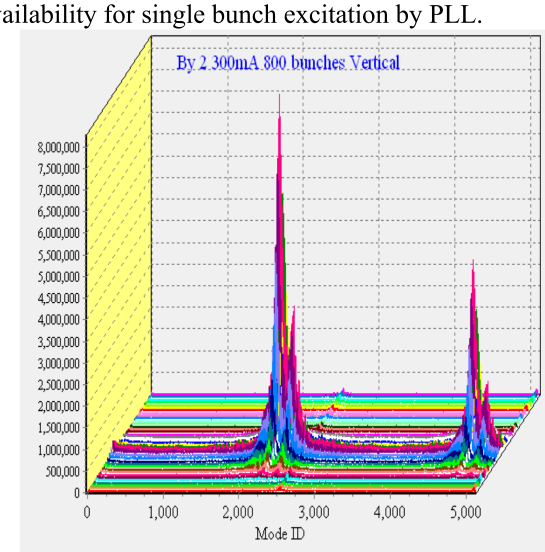

Figure 3: Evolution of vertical unstable modes with by- 2 fill pattern in LER at a current of 300 mA [3].

Strong transverse coupled-bunch instability was observed in both horizontal and vertical planes in both rings at very early stage of the phase 1 commissioning as shown in Fig. 3 [3]. The instability was successfully suppressed by the feedback up to maximum beam current (1A in LER, 0.87A in HER) with minimum bunch spacing of 4 ns. Transverse feedback damping time around maximum beam current was about 0.5 ms (i.e. 50 turns).

ISBN 978-3-95450-187-8

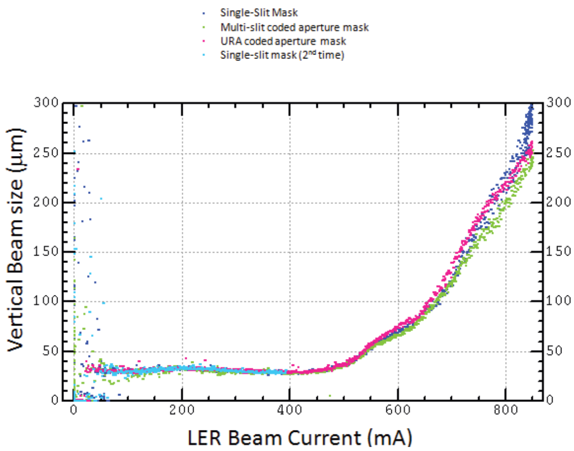

Figure 4: LER Vertical beam size as a function of beam current. Different colors represent data taken with different x-ray optical elements [3].

A growth rate of the longitudinal coupled bunch instability due to the impedance of ARES cavities in LER is estimated to be 15 ms which is shorter than the longitudinal radiation damping time of 22 ms. Thus the longitudinal feedback system is prepared in LER. Four DAFNE type kickers, with 2-input and 2-output ports are used to get larger capture range. A calculated shunt impedance and a quality factor are ~1.6kΩ and ~5 respectively. Two 500W power amps per kicker are used. The frontend electronics and the digital filters are same as those of the transverse system.

Unexpected longitudinal instability starting at beam current larger than 660mA in a by-3 fill pattern was found in phase 1. Growth time was about 15ms. It was successfully suppressed up to 1A by the feedback.

PHOTON MONITORS

Three kinds of photon monitors, x-ray beam size monitors (XRM), visible synchrotron radiation monitors (SRM) and large angle beamstrahlung monitors (LABM) are installed in SuperKEKB [2].

The XRM uses coded aperture imaging to measure the vertical beam size. Light from an object is modulated by a mask. The resulting image is calculated through mask response including diffraction and spectral width by Kirchhoff integral over mask for various beam sizes to make a template assuming a Gaussian profile. The beam size is determined by a template fit to a measured image. Large open aperture of 50 % gives high flux throughput for bunch-by-bunch measurements. Three masks (a single slit mask, a multi-slit mask and a URA mask) are installed.

The vertical size measurement by the XRM in LER in phase 1 shows good fill-to-fill repeatability and good agreement between different masks, especially below 150 µm as shown in Fig. 4. On the other hand large difference between the measured HER vertical beam size via the XRM and the estimated beam size from optics correction was found [4]. Systematic study to clarify this discrepancy is under way.

We developed a diamond mirror [11] in the SRM that would not deform as much under the heat load by synchrotron light, since the heat deformation was a problem at KEKB. Good heat conductance and low thermal expansion coefficient of diamond make apparent change in magnification smaller than that of Be mirrors used at KEKB.

The SRM was used mainly to measure the bunch length by streak cameras in phase 1. An unsolved problem is that the measured magnification factor is more than twice as large as that of the design in both rings. The check of the alignment of a light transport and deformation of optical elements are underway.

The LABM measures relative offset and size ratio of the beams at the IP. Beamstrahlung is the radiation of the particles of one beam due to the bending force by the electromagnetic field of the other beam. Beamstrahlung polarization at specific azimuthal points provides information about the beam-beam geometry.

The LABM in SuperKEKB is being built in US, mostly at Wayne State University. The monitor consists of four viewports. Light is transported through an optical channel to an optics box where light is separated into two transverse polarizations and four different wavelength bands before sent to photomultipliers.

LABM beam lines and optics boxes were installed at interaction region in phase 1 even without beam collision. Measurements were made with the beam using synchrotron light from far side of the IP to refine models of the beam line.

LOSS MONITOR

The loss monitor system [5] provides a trigger to the beam abort system. Abort request signals from each hardware component are collected at twelve local control rooms, and then sent to the abort kicker within 20 msec. The sensors of the loss monitors are coaxial ion chambers and PIN photo-diodes. Several selected signals are logged by four data loggers to analyze abort events.

The total number of beam aborts was about 1500 in phase 1, among them about 95% were recorded. Main causes of the aborts were manual aborts (53% in the total), beam loss aborts (27%) and RF Aborts (10%). Manual aborts were triggered for optimization of kicker timing, beam study of beam instability, beam size measurement, detector background study and so on. Beam loss aborts were caused by a trouble of software of injection trigger system and a vacuum spike occurred at higher current operation. RF Aborts were caused by troubles of a frequency tuner and beam instability by HOM.

OTHERS

A bunch current monitor measures the bunch current of all bunches with a fast ADC. The recording stops by the injection trigger. The ADC data are sent to the bucket selection system via a reflective memory [3].

ISBN 978-3-95450-187-8

The global tune meter uses a tracking method in which all bunches are excited by the feedback kicker by the signal from a tracking generator of a spectrum analyzer.

In the single bunch tune measurement, the iGp12 is used to close the PLL excitation of a selected bunch without feedback damping. The betatron frequency is directly measured by the excitation frequency of the loop [3].

DCCTs for beam current measurement are reused from KEKB.

SUMMARY

The electron-positron collider KEKB B-factory is being upgraded to SuperKEKB. The BPM system in SuperKEKB is equipped with the super-heterodyne detectors, the gated turn-by-turn log ratio detectors and the IP orbit feedback detectors. New x-ray beam profile monitors based on the coded aperture imaging method are installed. The large angle beamstrahlung monitor detecting polarization of the synchrotron radiation generated by beam-beam interaction is installed near the IP. The diamond mirror has been developed for the visible light monitors. The bunch-by-bunch feedback system is upgraded using low noise frontend electronics and new 12 bits iGp2 digital filters. The loss monitor system provides a trigger to the beam abort system and is used to analyze the performance of the machine.

Phase 1 operation without Belle II and final-focus quads continued from this February to June. Most of the beam instrumentations prepared for phase 1 are working well.

ACKNOWLEDGMENTS

The author would like to thank all the members of the KEKB beam monitor group for their help to prepare this paper. He also would like to thank Prof. M. Tobiyama for careful reading of the manuscript.

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ISBN 978-3-95450-187-8