The paper describes several topics relating to the beam instrumentation systems at the KEKB B-factory (KEKB) from 2003 to the end of its operation. It covers 1) measurement of the tilt angle of a bunch caused by a crab cavity, 2) a diagnostic system for beam aborts, 3) bunch feedback and related systems, and 4) progress in the beam position monitor system.

1. Introduction
The KEKB B-factory (KEKB) is an electron–positron collider with two rings for studying the B-meson system. One ring is the electron ring (HER), with an energy of 8 GeV, and the other is the positron ring (LER), with an energy of 3.5 GeV. The KEKB operation started in December 1998 and terminated at the end of June 2010 in order to upgrade it to SuperKEKB [1]. During the winter shutdown in fiscal year (FY) 2006, crab cavities were installed at KEKB to realize effective head-on collision by tilting the bunch in order to increase the luminosity [2]. The achieved peak luminosity is $2.11 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. The main parameters of KEKB with the crab cavities are shown in Table 1.

The beam instrumentation systems of KEKB are summarized in a previous paper [3]. They consist of the beam position monitor (BPM), the synchrotron radiation monitor, the bunch-by-bunch feedback system, the betatron tune monitor, the beam loss monitor, and the beam current monitor. Since publication of the paper in Ref. [3], the KEKB instrumentation systems have been improved based on accumulated experience and used for various instances of machine tuning and beam study.

Measurement of the tilt angle of the bunch was an important subject in the beam commissioning with crab cavities, to ensure that the crab cavities worked as expected. Observation of the bunch shape with streak cameras by detecting synchrotron radiation enabled the tilt angle of the bunch to be measured.

The beam abort system was installed to dump the beam as soon as possible when a large beam loss is expected. The system was indispensable for avoiding damage to the accelerator and the Belle detector components. Refining the abort system based on analysis of the cause of beam loss at the beam abort was important for decreasing the number of beam aborts and subsequently increasing the effective integrated luminosity, because it typically took 30 min to refill the two rings.
The transverse bunch feedback system was indispensable for damping the unstable bunch oscillation caused by beam instabilities from the beginning of KEKB operation. The system was also useful for studying beam instabilities such as the electron cloud instability in LER, which severely limited the luminosity in KEKB’s early operation period. It was also used to study the effect of the feedback system on the beam–beam effect, which showed that careful tuning of the feedback gain was necessary for obtaining high luminosity.

In the BPM system, a consistency check of the BPM readings was applied in order to find problems with the BPM system as soon as possible. While four electrode signals were usually used to calculate a beam position, the beam position could also be obtained from the output voltages of any three of the four electrodes. We defined the root-mean-squares of the four beam positions obtained by combinations of the three voltages as consistency. A large consistency suggested malfunctions in some signal channels. The consistency was continuously monitored throughout the KEKB operation to find problems in feedthrough of the BPM, connectors, signal cables, and so on.

The second improvement in the BPM system was beam-based gain calibration. The relationship between the electrode voltages and the beam positions was calibrated at a test bench by a signal source before installation of the BPM blocks in the vacuum chambers. However, the readings of beam positions may drift due to an unpredictable imbalance among output signals after calibration, because they must travel separate paths before being processed by a detector. The beam-based gain calibration measured the gain imbalance among four signals by using the beam to maintain the precision of the orbit measurement throughout the operation.

The third improvement in the BPM system was the installation of displacement sensors at the BPMs near the sextupole magnets. Movement of the BPMs of several hundred microns was observed at beam abort in both rings, although they were fixed to quadrupole magnets. Since the closed orbit was maintained continuously by closed orbit correction to a standard orbit using the BPM readings, the displacement of the BPMs changed the beam position relative to the magnets. Since the optics depends strongly on the orbit, particularly at nonlinear optics elements such as sextupole magnets, the displacement sensors, which measured the relative position between a BPM and a neighboring sextupole magnet, were installed to correct the beam position data.

This paper describes selected topics related to the course of the operation of our instrumentation systems mentioned above, and covers 1) measurement of the tilt angle of a bunch caused by a crab cavity, 2) a diagnostic system for beam aborts, 3) bunch feedback and related systems, and 4) progress in the beam position monitor system.
2. Crabbing angle measurement by streak camera

Two beams collided with a finite horizontal crossing angle of $\pm 11$ mrad at the interaction point (IP) in KEKB. In order to compensate the crossing angle at the IP by tilting the bunch horizontally and thus increasing luminosity, crab cavities were installed in KEKB. Beam operation with crab crossing had continued since February 2007 [2].

A bunch was tilted not only in the interaction region (IR) but also at the emission point of the synchrotron radiation monitor (SRM). Thus, we could measure the tilt of a bunch by observation of the synchrotron light with streak cameras. A schematic view of the crab cavities, SRMs, and the IP is shown in Fig. 1.

We used the synchrotron radiation from individual bunches produced in weak bending magnets. The HER and LER were equipped with their own SRMs. The parameters of the weak bending magnets are given in Table 2. The light paths from the weak bending magnet to the streak camera are 35 m and 38 m in the HER and the LER, respectively. Two-dimensional longitudinal and horizontal beam profiles were taken by the streak cameras (Hamamatsu C5680) [4] to measure the crabbing angle, which is the tilt angle caused by the crab cavities. A schematic view of the streak camera is shown in Fig. 2. We expected to measure the tilt angle with 10% accuracy for a bunch with a length of about 6 mm using this system.

2.1 Optics

The expected tilt angle at the SRM, $\phi_{\text{SRM}}$, is calculated from the crabbing angle at the IP, $\phi_{\text{IP}}$, as:

$$\frac{\phi_{\text{SRM}}}{\phi_{\text{IP}}} = \sqrt{\frac{\beta_{\text{SRM}}}{\beta_{\text{IP}}}} \frac{\cos(\pi v - |\psi_{\text{crab}} - \psi_{\text{SRM}}|)}{\cos(\pi v - |\psi_{\text{crab}} - \psi_{\text{IP}}|)},$$

(1)

where $\psi_{\text{crab}}$, $\psi_{\text{SRM}}$, and $\psi_{\text{IP}}$ are the betatron phases at the crab cavity, SRM, and IP, respectively, $\beta_{\text{SRM}}$ and $\beta_{\text{IP}}$ are the horizontal beta functions at the SRM and IP, and $v$ is the horizontal betatron tune. From the beam parameters given in Table 3, the following tilt angles at the SRM are obtained for $\phi_{\text{IP}}$ of 11 mrad:

$$\phi_{\text{SRM(HER)}} = 40.5 \text{ mrad},$$

(2)

![Fig. 1. Layout of the crab cavities and SRMs in the KEKB rings.](https://academic.oup.com/ptep/article-abstract/2013/3/03A007/1556673)
In order to check that the real optics was consistent with the design optics, readings of the BPMs, which were located both sides of the SR emission point, were compared with the calculated beam positions from the optics parameters when the phase of the crab voltage was changed by 90°. They were consistent within 10%, as shown in Table 4.

The core length of the HER weak bending magnet is 2.9 m, which is much longer than that of the LER. The position of the SR emission point may deviate from the design value, e.g., by an alignment error of a beam duct due to the large magnet length. The location of the emission point was measured by an orbit bump. The result showed that the correction to the expected crabbing angle due to the position error of the emission point was about 10%.

2.2 Calibration

The accuracy of the measurement was estimated before the crabbing angle measurement. The profile of a bunch was longitudinally divided into several pieces, then the horizontal electric charge center of

\[
\phi_{\text{SRM}(\text{LER})} = 42.9 \text{ mrad}.
\]
gravity of each piece was calculated. The tilt angle \( b \) of a bunch was obtained by fitting the centers of gravity \( H \) to a linear function of \( H = a + b \times L \), where \( L \) is the longitudinal position of a piece. Figure 3 shows an example of a fitting result. The accuracy of the tilt was estimated from the distribution of \( b \) obtained from many samples and a conversion factor between pixel and length. The root-mean-square (rms) width of the \( b \) distribution was 0.022 with no applied voltage on the crab cavity. The width corresponded to \((3.6 \pm 0.68) \times 10^{-3}\) radian, which was about 10% of the expected crabbing angle at the SRM. The calculated tilt was almost the same whether one bunch was divided into 10 pieces or into all longitudinal pixels.

A parallel orbit bump was set at the SR emission point using six steering magnets for the calibration of the horizontal size, as shown in Fig. 4(a). Changing the bump height from \(-2 \text{ mm}\) to \(+2 \text{ mm}\), the intensity center of gravity of the streak image at each point was measured. Figures 4(b) and 4(c) show the movement of the bunch by the bump. The movement in pixels on the CCD of the streak camera was converted to physical distance by fitting the bump height to the movement of the streak image in pixels as shown in Fig. 5. The linearity of the orbit bump with respect to the movement of the streak image was checked by setting a small bump about the beam size. The calibration constants obtained at bumps with large and small step sizes agreed each other within 10%.

A vertical calibration by the orbit bump was done by rotating a light transfer mirror in order to check the systematic error. The result showed a 30% difference of the calibration constant from that of the horizontal calibration. We suppose that the difference was caused by the deformation of the SR extraction mirror, since the mirror deformation in the vertical direction was larger than that in the horizontal direction.

The longitudinal, i.e. time, axis of the streak image was tuned at Hamamatsu Photonics before delivery. The accuracy of the time base was 1.95 ps, according to an inspection report by the company. This corresponds to 10% of the bunch length and was sufficient for our measurement.

| HER | BPM1  | 1.961 | BPM2  | 3.875 | | BPM1  | 1.827 | BPM2  | 3.511 |
|-----|-------|-------|-------|-------| | BPM1  | 0.424 | BPM2  | 0.811 |
| LER | BPM1  | 3.065 | BPM2  | 3.210 |

*Fig. 3.* An example to obtain a crabbing angle at the SRM from the slope of longitudinal bunch axis by fit.
We also calibrated the time axis onsite as a cross check. A quartz plate with 20 mm thickness was inserted in the light path. The refraction index of quartz is 1.462 at 500 nm wavelength of light. The time delay caused by the plate is 3.08 ps. The calibration constants were determined to be 4.24 and 3.16 pixels/mm for the HER and the LER, respectively. The difference between the HER and the LER constants came from the differences in the SR path length, the setup of the optical system.

Fig. 4. (a) A beam orbit at the SR emission point, which is shown by an arrow. The positions of quadrupole and dipole magnets are shown in the lower part. Streak images at bump heights of 0 mm and 2 mm are shown in (b) and (c), respectively.

Fig. 5. Calibration of the horizontal scale on the CCD plane by orbit bumps. The solid line shows the result of a linear fit.

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and the streak camera characteristics. These values were consistent with the calibration constants measured by the company within 1% for the HER and 12% for the LER.

2.3 Measurement of tilt of the bunch

A single bunch of 1 mA was injected into each ring after applying voltage to the crab cavities to measure the crabbing angle. Figure 6 shows the tilted bunch in HER. The bunch tilted oppositely when the phase of the crab voltage changed by 180°.

First, we checked the direction of the tilt and confirmed that both beams were tilted toward the inside of the ring at the SR emission points. Since the direction of the tilt was not changed between the SR emission point and IP according to the machine optics, the above result showed that both beams were tilted toward the inside of the rings at the IP, which meant that the directions of the crabbing angles were correct at the IP.

The crabbing angle of the bunch at the SRM was obtained from the calibration constant. The results of the tilt measurements are shown in Fig. 7. The two peaks correspond to the two sweep phases of the streak camera. While one bunch was on a rising side, another bunch was on a down side of the sinusoidal voltage, depending on the bunch fill pattern, because the sweep frequency of the streak camera was 125 MHz, which was 1/4 of the RF frequency of KEKB. An example is shown in Fig. 8. The crabbing angle is the average of the two peak values. The obtained crabbing angles

![Figure 6](image1.png)

**Fig. 6.** The tilted bunch in the HER. (a) The crab cavity voltage is 0. (b) The crab cavity voltage is ON and the crab phase is 0 degree. (c) The crab cavity voltage is ON and the crab phase is 180°.

![Figure 7](image2.png)

**Fig. 7.** Distribution of crabbing angles among many bunches in the HER (a) and the LER (b).
were 40.1 mrad and 19.8 mrad for the LER and the HER respectively. A comparison between the measured and expected crabbing angles shows that, while the measured crabbing angle in the LER was consistent with the expected value, that in the HER was a factor of two smaller than expected. In order to discover the reason for the inconsistency of the measured and expected crabbing angles in the HER, the following measurements were done.

We checked the bunch current dependence of the measurement. The result is shown in Fig. 9. Though the measurement error at small bunch currents was large, a change in the current did not influence the measurement of the tilt. We noticed that, when the crab voltage was turned off, an offset of the tilt was seen although we expected no tilt without the crab voltage.

We measured the tilt by scanning the phase of the crab voltage by 360°. The tilt should show a maximum at 0 degree and a minimum at 180° of the crab phase. This was confirmed as shown in Fig. 10. In addition, the tilts were the same at 0 and 360°. However, the sinusoidal curve seemed to be shifted by −0.02 rad. The change in the tilt through the whole phase scan was about 80 mrad, i.e. twice the expected crab angle, which indicates that the measurement was consistent with the expected tilt.

We changed the crab voltage from 0 to 1.43 MV and measured the tilt as shown in Fig. 11. The tilt was linear to the crab voltage, as expected. Again, an offset of the tilt of about −0.015 rad was seen at null crab voltage.
We observed the tilts by changing the sweep phase of the streak camera. Figure 12 shows the similar behavior of the tilt at different sweep phases. These measurements indicate that the reason for only half of the expected crabbing angle being observed at the HER was due to the offset of the tilt. The correct crabbing angle was obtained after subtracting the tilt measured by turning off the crab voltage as the offset. The vertical slope of the streak trace at the horizontal and vertical double sweep was measured by a laser diode. The result showed that the slopes in the up-to-down and down-to-up traces were not mirror symmetric with respect to the vertical axis and this slope difference was region-dependent in the screen. The above measurement by the laser explained the offset of 0.013 rad in the worst case. Figure 13 shows a comparison between the measured tilt after the offset correction and the expected tilt. They agree reasonably well with each other.

2.4 Conclusion

The tilt of the bunch caused by the crab cavity was measured with the streak camera in both the HER and LER. We could measure the tilt angle of the bunch after the calibration of the offset angle caused by the characteristics of the streak camera. The measured tilt angles were consistent with the expected angles. The specific luminosity in the crab voltage-on was about 20% larger than that in...
the crab voltage-off. Here the specific luminosity is defined as the luminosity divided by the number of bunches of each beam and also divided by the product of the bunch currents of the two beams. The details of the beam commissioning with crab cavities are presented in Ref. [2].

3. A diagnostic system for beam abort

When large beam loss is expected, the beam should be quickly dumped in order to avoid damage to the accelerator and the Belle detector components [5] due to high current beams.

A controlled beam abort system was installed for this purpose [6]. A circulating beam was kicked horizontally by two horizontal kickers when a beam abort was requested. The kicked beam went out of a vacuum chamber through a 1.4 mm thick Ti window and was bent downward by 75 mrad by a Lambertson DC septum magnet to guide the beam to the beam dump [7]. In order to reduce the power density deposited by the beam at the window, a vertical kicker swept the beam on the window in one revolution period of 10 μs. The bunch train had an abort gap within which the horizontal kicker was excited. The rise-time of the horizontal kicker was reduced to 0.5 μs in 2002 to decrease the length of the abort gap.

![Fig. 12. Crab phase dependence of the crabbing angle. The solid circles and triangles show the results for streak phases of 0 and 180°, respectively.](image1)

![Fig. 13. Crab phase dependence of the crabbing angle after offset correction. The solid circles are the corrected data. Pink and green lines are the expected crabbing angles at the SRM and IP respectively.](image2)
The flow of beam abort trigger signals is shown in Fig. 14. The number of beam abort signal sources was over 130 points. Each hardware group of RF, magnet, vacuum, beam monitor, and beam transport (BT) collected the abort signals and made an OR signal to input it into an interlock module in a local control room (LCR). The output of the interlock module at each LCR was sent to the central control room (CCR). The interlock module in the CCR issued the beam abort trigger using the signals from the LCRs and direct trigger signals from a beam phase signal, an earthquake sensor, and a Belle background sensor. In the Belle detector, the decay vertices were measured by a silicon vertex detector (SVD) located just outside a cylindrical beryllium beam pipe. To avoid radiation damage to the SVD circuit due to the high beam background, the Belle group put PIN photodiodes (PD) inside the SVD as a background sensor and requested the beam abort according to the PD signals.

The system triggered more than 10 000 aborts during the KEKB operation over eleven years. Optimization of the condition to issue the abort trigger was necessary to make a compromise between efficient operation and safety of the hardware. Therefore, we analyzed all of the aborts one by one, and adjusted the abort system throughout the KEKB operation.

3.1 Setup of beam abort monitor

The diagnostic system was based on a high-sampling-rate data logger that recorded beam currents, RF signals, signals from beam loss monitors (LMs), and the Belle detector at the moment of the beam abort. In addition to the data stored in the data loggers, beam oscillation, vacuum pressure, the earthquake sensor, and the dose rate of the Belle detector were also examined to analyze the beam abort.

Loss monitor signals of whole rings were collected at four LCRs, and were sent to the data loggers distributed in five LCRs where both loss monitor signals and RF cavity signals were obtained. The logged time interval and the sampling interval were 600 ms and 5 μs or 300 ms and 1 μs, respectively, depending on the type of data logger.

Fig. 14. The structure of the KEKB beam abort system.
The signal flow of the data loggers is shown in Fig. 15. The logged data were beam currents measured by a direct-current–current transformer (DCCT) [3], some of the loss monitor signals from the PD and ion chambers (ICs), signals from the RF cavities, i.e. cavity voltages and output of klystrons, the beam phase signal showing the deviation of the synchronous phase, the injection trigger timing, and the Belle PD signal. Most PDs were fixed on the movable masks of each ring, and determined the ring in which the beam loss occurred. On the other hand, ICs were installed in the whole tunnel and covered a wide range in space, but could not distinguish the ring where the beam loss occurred. These signals were useful to diagnose the cause of the beam abort since they had a strong correlation with the beam condition. The recorded data were sent to the KEKB CCR via the KEK internal network, and were then monitored by operators. The information was ready for inspection within a few minutes after the abort. The beam oscillation signals were obtained from the bunch oscillation recorder (BOR) [8]. The signals were also ready within a few minutes after the abort. The BOR recorded the bunch-by-bunch beam position over 4000 turns immediately before the beam abort so as to detect vertical and horizontal beam oscillations.

3.2 Typical abort examples

The reasons for beam abort triggers to be issued were beam loss, RF problems, vacuum leaks, magnet problems, the earthquake, failure of the electronics of some pieces of hardware, thunderstorm noise, and so on. Among these, the beam aborts that were caused by beam loss, RF problems, and crab cavity problems are shown in this section as typical examples.

3.2.1 Manual abort. A manual abort is a beam abort triggered manually with switches by operators. An example of the signals at the manual abort in the HER is shown in Fig. 16(a). The DCCT signal shows a delay of 40 μs and decay in 90 μs in spite of the beam being aborted in 10 μs, i.e. one turn. This is normal behavior for the DCCT signal when the beam is aborted in one turn. If the decay...
Fig. 16. Examples of logged signals at the moment of (a) a manual beam abort, (b) a beam phase abort caused by RF voltage down, and (c) a beam loss abort caused by a vacuum problem. The signals in (c) are, from top to bottom, the LER beam current, the beam phase, the loss monitor PD, and the Belle PD.
time and the decay slope differed from this example, the abort was judged to be abnormal and the data logger information was analyzed to determine the cause of the beam abort.

3.2.2 Beam loss abort. The beam aborts were categorized as beam loss aborts when loss of the beam current was observed before trips in the RF cavity. About half of the beam aborts were beam loss aborts. In most cases, a PD signal at the movable masks was also detected. The PD signal was useful for identifying the location of the beam loss when the beam loss happened at the movable masks. The PD information was analyzed together with the BOR data to identify the cause of the beam loss. The analyzed result was used to improve the operation parameters of KEKB.

Some beam loss aborts were caused by the beam oscillation. For example, when the LER beam was aborted, the HER beam sometimes remained alone in the ring. Then an instability in the HER beam accompanied by horizontal oscillation occurred, probably because the damping effect by the beam collision was lost. As a result, the HER beam was also aborted. This depended on the beam condition and the parameters of the bunch feedback system. The typical oscillation amplitude was about 5 mm for lower oscillation modes, where all bunches move together in nearly the same betatron phase. Figures 17(a) and 17(b) show the statistics of the aborts caused by beam loss. The ratio of beam loss aborts without oscillations to total beam loss aborts increased in the latter period of KEKB operation. When no oscillation was found in spite of a large beam loss, we often found that the tune was shifted. Sometimes the LER beam loss triggered the HER abort and vice versa. We call this event a wrong abort. The PIN PD could identify the ring where the beam loss occurred, thus did not generate the wrong abort. RF signals did not generate the wrong abort either. On the other hand, the ICs and the Belle PDs could not identify the ring where the beam loss occurred because the sensors reacted in both HER and LER beam loss. They could generate the wrong abort. To improve this situation, the Belle group introduced a logic that checked which ring was being injected when the beam loss at Belle happened, then judged which ring should be aborted. Another improvement came from RF arc sensors, which were PIN PDs located at the RF cavities. Figures 17(c) and 17(d) show the status of the beam and the beam loss when the beam loss abort was requested in the HER and LER respectively. “HER abort” in Fig. 17(d) means the LER beam was lost after the HER abort, probably because the LER beam became unstable. “HER Loss”, “LER Loss”, and “Both Ring Loss” mean that the beam loss was observed by DCCT in the HER, LER, and both rings, respectively. The wrong abort corresponds to “HER Loss” because the LER beam was aborted although the beam loss was observed in the HER. Figure 17(e) shows which sensors requested the HER abort. The “other” in Fig. 17(e) was almost issued by the RF arc sensors. The number of wrong aborts in the LER decreased as the “other” abort requests in 17(e) increased. This correlation appeared after the installation of the crab cavities. We suppose that the wrong aborts in the LER decreased because the RF arc sensors near the crab cavities could identify the ring where the beam loss occurred. It is probable that the extensive beam loss that caused the IC abort was avoided, since the loss was first detected by the arc sensors and then the right ring was aborted.

Figure 16(c) shows another example of the beam loss abort in which no beam oscillation was observed. The tunes were stable. The beam phase (BP) started to swing before the beam loss happened and also before the loss monitor PD signals and the Belle PD signal appeared. This type of abort was found in February 2005. It was found that there were problems with some bellows. The pressure and temperature near the bellows were higher than usual. For example, the temperature of a bellows, which was usually 60°, suddenly rose to 70° and finally reached 95°. The abort ceased after fixing the vacuum problem. This type of abort happened again in 2006 as shown in Fig. 18. Vacuum problems were also found in this case.
The number of beam loss aborts decreased in 2004 after continuous injection started to keep the beam current at a fixed level.

3.2.3 RF abort. The cavities tripped easily whenever the beam was lost because of the strong interaction between an accelerated beam and the RF cavities. On the other hand, when one of the cavities tripped, coherent synchrotron motion of the beam occurred and gave strong radiation to the Belle detector. Figure 16(b) shows an example of logged signals at the beam phase abort caused by an RF trip. The BP signal starts to rise in response to the RF trip. On the other hand, when the beam loss happens earlier than the RF trip, the BP starts to swing downward because the RF cannot compensate the loss of the beam-induced field immediately. In both cases, the

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**Fig. 17.** Cause of beam loss in the HER (a) and the LER (b), status of beam loss and the abort when the HER (c) or the LER (d) was aborted, signals that requested the abort of the HER (e), and aborts triggered by the RF of the HER (f) and the LER (g). In (a) and (b), HV-, H- and V-oscillation mean that the oscillation was observed in the horizontal and vertical planes, the horizontal plane and the vertical plane, respectively.
induced synchrotron oscillation caused a large beam loss, which could lead to damage to hardware components. In order to avoid this situation, the BP was used as an abort trigger [9]. The trigger level of the BP abort was set to one degree in the HER and five degrees in the LER. We also installed a fast cavity voltage monitor in each RF station. Figures 17(f) and 17(g) show the rate of RF aborts. While the HER was equipped with both superconducting cavities (SC) and normal conducting cavities (NC) [10], the LER was equipped with only NCs. The abort rate was similar in both types of cavities.

3.2.4 Crab abort. Two crab cavities were installed in 2007 to improve the luminosity [2]. Since the beam current was limited during the first several months after starting the crab operation in order to tune the crab cavities, the breakdown of the crab cavities did not affect the beam. However, the beam was manually aborted to recover the cavity voltage after the breakdown. In the early period of operation, breakdown of the LER crab cavity occurred frequently. The breakdown caused beam loss at a few hundred mA of the beam current. The luminosity was improved after the operation of the crab cavities became stable and the number of aborts caused by the crab cavities decreased.

3.3 Statistics

The statistics of the beam abort in the HER and LER, which are categorized by analysis of the information from the data loggers and other monitors, are shown in Figs. 19(a) and 19(b), respectively. It shows the number of aborts per day averaged over one month during eight years of operation of KEKB with high beam current. The manual aborts issued by operators are not included. From the figure, we see that there are two major origins of the beam abort: RF problems and beam loss. Since the coupling between the beam and RF cavities is strong, it was important to clearly classify the cause of the abort in order to improve machine performance. The fractions of RF and beam loss aborts in all aborts were 30% and 60%, respectively, before the crab cavity installation. The ratio of crab cavity abort to all RF aborts was higher than the other RF cavity aborts, but the sum of all aborts was not changed after the installation of the crab cavities, since the beam current during crab operation was lower than that before crab operation. There were many other aborts due to earthquakes, problems with the vacuum system and the magnet power supplies, and so on, though the fraction of these aborts was small. The number of aborts did not strongly depend on the beam current, as shown in Fig. 19(c), and was reduced by optimization of the abort condition and refinement of the abort system.
There were several optimization and refinement procedures. Firstly, the delay of the abort timing was checked. An unnecessary filter in the interlock circuit was removed to reduce the delay of the signal through it. Secondly, the introduction of the PD monitors enabled the fast response of the beam abort and the identification of the location where beam loss occurred. The PD interlock level was checked extensively. As the result, the interlock signal was masked at injection timing to reject unnecessary abort by injection noises. Even a little beam loss in the movable masks aborted the beam to protect the masks. Thirdly, cavity trips caused by problems in the RF system

Fig. 19. Statistics of the beam abort for the last eight years of KEKB operation in the HER (a) and the LER (b). (c) History of the beam current and the luminosity in KEKB.
were distinguished from trips caused by sudden changes in the RF voltage due to beam loss. This contributed to adjusting and repairing the cavities. Finally, the operators always checked the signal of each abort sent to the CCR to diagnose the accelerator situation and adjust the operation parameters, such as the tunes and the feedback parameters.

The number of HER and LER aborts was 3.7/day and 2.3/day, respectively. The total number of aborts was about 6000 and 4000 in the HER and LER, respectively. Figure 20 shows that the integrated luminosity per 8 hours increased steadily, though the increase was due not only to the refinement of the abort system but also to improvements in various pieces of hardware and progress in beam tuning.

3.4 Conclusion
A controlled beam abort system was installed in KEKB to protect the hardware components from the loss of high current beams. In order to clarify the reason for each abort, various signals, such as PIN photo-diode beam loss monitors and status signals of the RF system, were collected by the data logger system and analyzed to identify the cause of the beam loss and the beam abort. The results showed the actual state of the accelerator hardware and gave us a lot of hints, not only to protect the hardware but also to optimize the operation parameters. As a result, we could suppress the unnecessary beam aborts and improve the luminosity.

4. Bunch feedback systems and related systems
From the early stage of the commissioning of KEKB, we found that the actual transverse coupled-bunch instabilities were much stronger than predicted. The operation of the transverse bunch feedback systems in both the HER and LER rings were indispensable for accumulating a beam more than 100 mA. In contrast, no serious longitudinal instability was found till the end of operation of KEKB. We have not operated the longitudinal systems other than for the study of the system itself. Several feedback-related systems have been used for the operation. The betatron tune measurement systems, both on the global tune measurement, where entire bunches in the ring were excited, and on the tune measurement of a specific bunch, where only a selected bunch without collision, which was mainly the pilot bunch, was excited, played an important role in keeping the betatron tune very near to the resonance lines, especially to the half integer line [11]. The bunch current monitors and the bucket selection system were also very important to equalize the bunch filling pattern to maintain the

Fig. 20. Trend of integrated luminosity per 8 h of KEKB.
optimized filling pattern for higher luminosity. Data from the bunch oscillation recorders were useful not only for the post-mortem analysis of the beam abort but also for the study of the beam dynamics, such as electron-cloud instability [12,13].

4.1 Transverse bunch feedback system

The bunch feedback system consists of mainly three parts: a bunch position detector (detector) to detect the individual bunch position, a signal processing part (digital filter) to cut out unnecessary components and to adjust the timing, and high power amplifiers and transverse kickers to kick the bunches. A block diagram of the transverse bunch feedback system is shown in Fig. 21 [8]. All the feedback equipment was installed in the Fuji straight section. There are two BPM sections designed for the bunch feedback in each ring, to allow a suitable betatron phase-rotation from the monitor to the kicker by vectorially combining the two signals from the upstream and downstream beam position pickups. The 2 GHz component of the beam signal is filtered using a cable-type band-pass filter then down-converted to a DC signal by mixing it with a signal of 4 times the frequency of the RF signal. The residuals of the closed orbit distortion at the BPMs are cancelled by a local offset canceller circuit. The signal is processed with the hardware two-tap FIR filter board described in Ref. [8]. A differentiator setting meaning kick \( \propto \) (position data two turns before) – (position data one turn before) has been employed on both the horizontal and vertical planes. Stripline-type kickers with a length of 40 cm for transverse deflection are installed upstream of the feedback BPM. Four 250 W amplifiers (Amplifier Research AR250A250 with a bandwidth of 10 kHz–250 MHz) to drive the kicker are used for each ring. The measured smallest damping time with a single beam in a special filling pattern was around 100 \( \mu \)s (10 turns). Normally, we set a rather moderate damping time around 500 \( \mu \)s.

After maintenance of the low level circuits of the feedback detector in the winter of 2005, we unexpectedly introduced a larger feedback gain due to the much larger LO level of the phase shifter connected to the double balanced mixer. During this period, we had struggled with the problem of lower luminosity and a larger vertical beam size than before. When the feedback gain was accidentally dropped down to 3/4 due to a hardware problem in the transverse kicker, we found that the luminosity had jumped up and the vertical beam size dropped. After recovery of the feedback kicker, we

![Fig. 21. Block diagram of the KEKB transverse bunch feedback systems. AR250A250 250W amp.: 250W power amplifier with a bandwidth of 10 kHz–250 MHz; 40 cm kicker: transverse stripline kicker with a length of 40 cm.](https://academic.oup.com/ptep/article-abstract/2013/3/03A007/1556673)
examined the effect of the feedback gain on the luminosity and the vertical beam size, then found a clear relationship between the specific luminosity or the vertical beam size and the LER vertical feedback gain during collision, as shown in Fig. 22. Here, the specific luminosity is defined as the luminosity ratio (%) to the reference luminosity normalized by the beam current product. Under the single beam condition, the LER vertical feedback gain showed a fairly weak relationship with the vertical beam size, as shown in Fig. 23. We therefore reduced the vertical feedback gain of the LER to as low a level as was necessary to maintain the beam’s single beam condition. By a simulation study, it was pointed out that the low noise level in the feedback system might be enhanced due to the beam–beam effect [14].

In the crab operation, the LER vertical feedback gain had no effect on the luminosity. We have examined the effect of the feedback noise on the collided beam by artificially introducing the noise to the feedback systems. The results showed good agreement with a simulation study though the noise level required to change the vertical beam size was much larger than the signal level of the feedback detector. Before the crab collision, we used a collision position feedback using the vertical beam size information [15]. A small change in the vertical beam size due to the feedback noise might be enhanced with this collision feedback by changing the collision condition to a worse direction.

![Fig. 22. Degradation of the specific luminosity due to vertical feedback gain at the LER.](image)

![Fig. 23. Vertical beam size of the LER vs. vertical feedback gain of the LER.](image)
4.2 Hardware problems with the feedback systems

During the operation of the KEKB bunch feedback system, we encountered several hardware problems, mainly due to the huge beam power. Though there exists almost no trapped mode in the transverse kicker, the wall current passing through the stripline plates easily heats up the plates due to the thermally isolated structure. The most serious problems were the breakdown of the transverse stripline kicker. Downstream feedthroughs and kicker plates made of stainless steel coated with copper were designed to release the expansion of the plates due to heating by the beam. The original design employed a flexible structure made of Kovar (Fe-Ni-Co alloy) with an RF shield in the

![Diagram](https://academic.oup.com/ptep/article-abstract/2013/3/03A007/1556673)

**Fig. 24.** Connection scheme of the feedthrough (FT) and the stripline plate. (a) Original structure with bending mechanism on the FT. (b) Modified structure with a sliding slot on the stripline plate. (c) Final structure with a flexible structure made of BeCu on the FT. SUS; stainless steel.
feedthrough, as shown in Fig. 24(a). After many mechanical cycles, they broke and some RF shields touched the ground. After these breakdowns, we tried to use copper for the stripline plates and employed a slide structure between the feedthrough and the plate to avoid a flexible structure on the feedthrough, as shown in Fig. 24(b). The results were even worse; the copper plate was completely annealed and pushed the feedthroughs, then finally broke the connection screw between the plate and the feedthrough. The upper plate fell down during operation and disturbed the beam (March 2002), as shown in Fig. 25. The feedthroughs were pushed and twisted to touch the wall. The third trial was to use copper-coated stainless steel as the plate again, and to employ a flexible structure in the feedthrough by changing the material of the flexible part to BeCu, as shown in Fig. 24(c). Since this bending structure was not soft enough at the first trial, we also encountered deformation of the feedthrough. However, after changing the feedthrough to a sufficiently flexible structure (August 2005), no more trouble was encountered over several years of operation. We also checked the internal structure with time domain reflectometry (TDR) during the long maintenance shutdown time. No obvious deformation of the plates was found.

Even though the feedthrough was twisted due to the large expansion in the stripline plate, no vacuum leak was found. One unfortunate exception was the feedthrough used for the longitudinal kicker. Due to the bad structure at the anchor contact in the 20D flange connector, it heated up due to RF power, initiated contact failure, and then burned out (October 2007). A large standing wave struck the feedthrough to crack the ceramic seal.

We also encountered breakdown of the high power attenuators, which melted the cables connected to the attenuators several times. After changing the attenuators to those with a higher power rating—from 500 W to 1 kW—and introducing a beam interlock system to abort the beam when excess reflection power to the amplifiers was seen, the situation improved. Even in the case of catastrophic breakdown of the high power attenuator, we successfully aborted the beam before melting of the cables.

Sometimes we encountered the failure of the hardware two-tap FIR filters or memory boards included in the bunch current monitors. Most of these were caused by contact failures in some soldered part. Failures also occurred on parts of the analog-to-digital converter (ADC, MAX101), the digital-to-analog converter (DAC, TQ6122M) and the custom LSIs (Large Scale Integrated-circuits), mainly the fast data demultiplexer (FDMUX, OKI GHDK4211) [8], which demultiplexes the 4-bit

![Fig. 25. Damaged transverse stripline. The screw connecting the upper left stripline plate and the feedthrough had broken due to stress of thermal expansion of the stripline plate, and then the plate dropped and blocked the circulating beam. Other stripline plates showed similar deformation to the dropped one.](image-url)
508 MHz signal down to a 16-ch 4-bit signal. Since we had enough spares on the system, the repair was not so difficult.

4.3 Instability study using bunch feedback systems

The bunch feedback systems contributed to several beam studies. The beam behavior at growing transients, which occur just after opening the feedback loop, gives clear information on the strongest unstable mode and its growth rate, which is useful for comparing with the theoretical models. The wideband response of the detector and the kicker enabled us to measure bunch by bunch differences in the betatron tunes. The study of the electron cloud instability is a good example. We measured the change of the oscillation mode with or without the solenoid field, compared the unstable mode with simulation, and estimated the secondary emission yield [13]. The synchrotron sideband coming from intra-bunch oscillation by the electron cloud instability was observed using the BOR [12]. The shift of the betatron tune along the bunch train due to the electron cloud was observed using a gated bunch measurement [16].

4.4 R&D for general-purpose bunch feedback systems

We have been collaborating with SLAC and INFN-LNF to develop next-generation general-purpose bunch feedback systems, supported by a US–Japan collaboration on high energy physics since FY2003. One of the important outcomes of the collaboration is the design and fabrication of an integrated general-purpose feedback processor (iGp) [17,18,19]. This consists of a fast 8-bit ADC (MAX108), a Virtex-II FPGA (XC2V6000) with 8 Mbytes of external SRAM, a fast 12-bit DAC (MAX5889), a slow 8-channel ADC (MAX1202) and DAC (AD8842), and a 32-bit general-purpose I/O (GP-IO), and is controlled by a built-in EPICS-IOC through a USB bus. As the FPGA is completely programmable, it supports almost any harmonic number \( h \), including odd numbers. The largest one is for KEKB (\( h = 5120 \)) with a maximum 8-tap FIR filter available. It is now widely used at many accelerators, such as KEK-PF (\( h = 312 \), 16-tap FIR, \( f_{RF} = 500 \text{ MHz} \)), DAΦNE, CesrTA, ALS, and so on. We have also installed the iGp in KEKB and examined the functions. They showed excellent performance both on a single beam run and on a collision run.

5. Progress in beam position monitor system

The BPM system was a fundamental tool of KEKB. It was used for the correction of beam optics, the slow orbit feedback to keep the orbit to a standard orbit where the machine was operated under the best conditions, various machine studies, injection tuning, and so on. Therefore, keeping the high-accuracy orbit measurement system throughout the beam operation was very important for the machine operation. Improvements to the BPM system for this purpose, i.e. a consistency check of the BPM readings, beam-based gain calibration, and measurement of the mechanical movement of the BPM heads by the displacement sensor are described below.

5.1 Consistency check method for beam position

The configuration of four electrodes of a BPM in KEKB is shown in Fig. 26. The beam position \((x, y)\) is usually calculated from the output of four electrodes of a BPM \((V_1, V_2, V_3, \text{ and } V_4)\) as

\[
x = F_x(h, v), \quad y = F_y(h, v),
\]

where \(F_x\) and \(F_y\) are third-order polynomials, and \(h\) and \(v\) are horizontal and vertical normalized
The four beam positions can also be obtained from the output voltage of any three electrodes chosen out of four electrodes as

\[
\begin{align*}
\frac{h}{v} &= \frac{(V_1 - V_2 - V_3 + V_4)(V_1 + V_2 + V_3 + V_4)}{(V_1 + V_2 - V_3 - V_4)(V_1 + V_2 + V_3 + V_4)}.
\end{align*}
\]  
(5)

The four beam positions can also be obtained from the output voltage of any three electrodes chosen out of four electrodes as

\[
\begin{align*}
x_1 &= F_{1x}(h_1,v_1), \\
x_2 &= F_{2x}(h_2,v_1), \\
x_3 &= F_{3x}(h_2,v_2), \\
x_4 &= F_{4x}(h_1,v_2), \\
y_1 &= F_{1y}(h_1,v_1), \\
y_2 &= F_{2y}(h_2,v_1), \\
y_3 &= F_{3y}(h_2,v_2), \\
y_4 &= F_{4y}(h_1,v_2),
\end{align*}
\]  
(6)

where \(h_1, h_2, v_1\), and \(v_2\) are given by

\[
\begin{align*}
h_1 &= \frac{V_1 - V_2}{V_1 + V_2}, \\
h_2 &= \frac{-V_3 + V_4}{V_3 + V_4}, \\
v_1 &= \frac{V_2 - V_3}{V_2 + V_3}, \\
v_2 &= \frac{V_1 - V_4}{V_1 + V_4}.
\end{align*}
\]  
(7)

If the four outputs have ideal correlation, these four beam positions \((x_1, x_2, x_3, x_4)\) and \((y_1, y_2, y_3, y_4)\) should coincide with each other. We defined a consistency \(x\) and \(y\) as a standard deviation of \((x_1, x_2, x_3, x_4)\) and \((y_1, y_2, y_3, y_4)\) respectively, then monitored continuously during operation. A large consistency suggests problems in the BPM system. This monitor was very useful for detecting problems in the BPM system, such as damage to connectors, abnormal contact between a connector and a feedthrough, and so on.

### 5.2 Beam-based gain calibration

The relation between a beam position and the output voltages of the BPM was calibrated at a test bench using a signal source. However, the relative gain of the four output data may drift due to an unpredictable imbalance between the output signals from the pickup electrodes, because each output signal travels through separate paths, such as cables, connectors, attenuators, and switches.

In KEKB, we found noticeable errors larger than 0.1 mm in almost all the BPM readings using the consistency check method. Supposing that these errors came from the imbalance between the four output voltages of the BPM, the gains of every BPM were calibrated by the nonlinear chi-square method using the beam [20].
5.2.1 Modeling of output data. The output signal $V_i$ from each electrode is given by:

$$V_i = g_i \cdot q \cdot F_i(x, y), \quad i = 1-4,$$

where $q$ denotes the beam charge and $x$ and $y$ denote horizontal and vertical displacement of the beam against a geometrical center respectively. Function $F_i(x, y)$ is an ideal response function normalized by $F_i(0,0) = 1$. The factors $g_i$ represent the signal imbalance between the electrodes normalized by $g_1 = 1$. The response function $F_i(x, y)$ depends only on the geometrical structure of the pick-up head.

5.2.2 Gain calibration. Assume that the beam positions are measured $m$ times by changing the orbit at the monitor. The signal from the $i$th electrode at the $j$th measurement is given by:

$$V_{i,j} = g_i \cdot q_j \cdot F_i(x_j, y_j), \quad i = 1-4, \quad j = 1, 2, 3, \ldots, m.$$

Then we have data with a total number of $4m$. Assuming that $g_i$ do not change at each measurement, $g_2, g_3, g_4, q_j, x_j,$ and $y_j$ are unknown parameters. After the $m$th measurement, the number of unknown parameters is $3 + 3m$. If $m$ is larger than 4, the number of the data $4m$ is larger than that of the unknown parameters $3 + 3m$, and we can then estimate the unknown parameters by minimizing the following chi-square:

$$\chi^2(a) = \sum_{i} \sum_{j} \frac{(V_{i,j} - g_i q_j F_i(x_j, y_j))^2}{\sigma_{i,j}^2}, \quad a = (g_2, g_3, g_4, q_1, x_1, y_1, \ldots, q_m, x_m, y_m),$$

where $a$ denotes the array of fitting parameters. $\sigma_{i,j}$ is the data error of the $i$th electrode at the $j$th measurement. This pick-up model has such symmetry that all of the response functions can be expressed with only one function:

$$F_2(x, y) = F_1(-x, y), \quad F_3(x, y) = F_1(-x, -y), \quad F_4(x, y) = F_1(x, -y).$$

The ultrarelativistic charge couples only to TEM fields, whose potential is governed by a two-dimensional Laplace’s equation. Therefore, $F_i(r, \theta)$ can always be expanded into a series of harmonic function in the polar coordinate system as

$$F_i(r, \theta) = 1 + \sum_{n=1}^{\infty} r^n (a_{i,n} \cos n\theta + b_{i,n} \sin n\theta), \quad i = 1-4.$$

$F_1(x, y)$ is given up to the fourth order as

$$F_1(x, y) = 1 + a_{1,1} x + b_{1,1} y + a_{1,2} (x^2 - y^2) + b_{1,2} (2xy)
+ a_{1,3} (x^3 - 3xy^2) + b_{1,3} (3x^2y - y^3) + a_{1,4} (x^4 - 6x^2y^2 + y^4) + b_{1,4} (x^3y - xy^3).$$

Coefficients $a_{1,n}$ and $b_{1,n}$ are determined by the cross section of the BPM head and the geometry of the electrodes, and can be obtained by fitting the results of a numerical calculation for a BPM model to the polynomials. The beam-based gain calibration was carried out for the first time in May 2003. The mapping data were taken at 25 different positions of each BPM. The result is shown in Fig. 27. Figures 28 and 29 depict the consistency in a single measurement before and after the gain calibration, respectively. The figures clearly show a marked improvement of the consistency.

We suppose that the most probable source of the gain drift is the change in the electrical characteristics of the signal cables by temperature drift, because we found seasonal variation in the gain.
error and positive correlation between the length of the cable and the gain error, and also found that covering a part of the cables, which was exposed in the outdoors, by thermal insulation sheets was effective in reducing the consistency.

The gains of every BPM have been calibrated by the beam-based calibration method approximately every month. By monitoring the consistency error and applying the beam-based gain calibration, we have realized a high-accuracy BPM system.

5.3 Displacement sensor

Movement of the BPMs was observed in beam operation in both the LER and the HER, although the BPMs were fixed to quadrupoles. The movement was supposed to be caused mainly by the deformation of vacuum chambers due to heating by synchrotron radiation generated by large beam
currents of 1.2 A for the HER and 1.6 A for the LER. A measurement showed that the typical movement relative to nearby sextupoles was 0.4 mm horizontally and 0.1 mm vertically at a beam abort in the HER arc sections, as shown in Fig. 30. It took 30 to 40 min for the position of the BPMs to reach a steady state at re-injection after the abort. The amount of movement depended on the beam current. Since the closed orbit was maintained by a continuous closed orbit correction at a predetermined level using the BPM readings, the displacement of the BPMs changed the beam position relative to the magnets. The orbit shift at the magnets affects the beam optics. In particular, the orbit error at the sextupoles produces quadrupole and skew-quadrupole components that depend on the beam orbit. Actually, the change in the vertical tune of 0.02 observed at the LER was explained by a simulation based on the measured horizontal orbit change of about 50 µm at four sextupoles for the local chromaticity correction, where the vertical beta function was as large as 460 m.

Since fixing the BPMs firmly to the quadrupoles would be difficult due to large thermal stress, a decision was made to measure the movement of a BPM relative to an adjacent sextupole, then apply a correction to beam position data.
A displacement sensor that is cheap but has sufficient performance for our purpose was developed at KEK. Table 5 and Fig. 31 show the specification and a schematic diagram of the displacement sensor, respectively. The sensor is an electrostatic capacitive sensor. The capacitance $C_x$ between a sensor head and an aluminum target is proportional to a gap $x$ between them. Applying a sinusoidal signal at the output of an amplifier with unit gain results in the output voltage $V$, which is proportional to gap $x$ as

$$V = \left(\frac{C_0}{C_x}\right)E = \left(\frac{C_0 E}{\varepsilon_0 S}\right)x,$$  \hspace{1cm} (14)

where $S$ is an area of the sensor head of $50.3 \text{ mm}^2$ and $C_0$ is a capacitance of $47 \text{ pF}$. The typical value of $C_x$ is $0.89 \text{ pF}$ for $x$ of $0.5 \text{ mm}$. The sensor head as shown in Fig. 32 is a pipe made of stainless steel that accommodates an electrode with a guard ring to reduce stray capacitance. A sensor cable between the sensor head and the amplifier is a tri-axial cable with a guard shield where the output of the amplifier is connected to reduce the capacitance to the ground. The cable is a radiation-resistant poly-ether-ether-ketone (PEEK) cable. A bootstrap circuit is applied to obtain a very low effective input capacitance of $6.5 \times 10^{-5} \text{ pF}$ for the operational amplifier, which is estimated by a circuit analysis.

The output signal of the amplifier is fed to a detector followed by a low-pass filter with a cutoff frequency of $100 \text{ Hz}$ to remove the ripple component and an isolation amplifier to avoid a ground loop forming between the sensor ground and the accelerator ground. The output signals from the displacement sensors were A/D-converted, then transferred to an IOC (input output controller) of the EPICS control system through twelve network loggers in the tunnel.

A laboratory measurement showed that the temperature coefficient of the sensor was less than $0.15 \text{ m/degree}$ in the temperature range of $15$ to $35^\circ\text{C}$ and reproducibility in a temperature cycle from $15$ to $35^\circ\text{C}$ was less than $1 \text{ m}$m. In order to measure the linearity, the gap data were taken at several set points using a movable target. The relative deviation of the position data with respect to a linearly fitted line of data was within $\pm 0.3\%$.

<table>
<thead>
<tr>
<th>Channels</th>
<th>2</th>
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<tr>
<td>Range (mm)</td>
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</tr>
<tr>
<td>Output voltage ($V$)</td>
<td>$-10$ to $10$</td>
</tr>
<tr>
<td>Resolution ($\mu$m)</td>
<td>$&lt; 0.2$</td>
</tr>
<tr>
<td>Nonlinearity (%)</td>
<td>$&lt; \pm 0.3$</td>
</tr>
<tr>
<td>Frequency response (Hz)</td>
<td>0 to $100$</td>
</tr>
<tr>
<td>Temperature coefficient ($\mu$m/deg.)</td>
<td>$&lt; 0.2$</td>
</tr>
</tbody>
</table>

Table 5. Specifications of the displacement sensor.

Fig. 31. A schematic diagram of the displacement sensor. LPF: low pass filter.
An arm where the sensor head is attached is fixed to an adjacent sextupole, as shown in Fig. 33. It is made of aluminum for reasons of easy fabrication. The temperature dependence of the gap data was measured immediately after the end of beam operation. No beams were in the rings at the measurement. The vertical data changed by 4 μm/degree for a change in the tunnel temperature of 0.7◦. No clear change in the horizontal data was observed.

A total of 232 displacement sensors (118 in the LER and 114 in the HER) were installed by autumn of 2007 to measure the BPM movement near the sextupoles. Figure 34 shows the frequency distribution of the largest displacement of the BPMs, which are located immediately downstream of the dipole magnets, over two and a half months. The horizontal movement at the HER amounts to 1 mm. The largest displacement of the BPMs about 10 m away from the dipoles was less than 0.3 mm and 0.06 mm at the HER and LER respectively. These data suggest that the movement of the BPMs was caused by the synchrotron radiation emitted by the dipole magnets.

6. Summary

The tilt angle of the bunch caused by the crab cavity was measured by a streak camera in both the HER and LER in order to confirm the performance of the crab cavities. The measurement showed that the tilt angles were consistent with the expected values.
Refinement of the abort system based on a detailed analysis of the beam aborts enabled the number of beam aborts to be decreased, and also allowed a reduction in unnecessary injection time to increase the integrated luminosity.

The bunch feedback system worked well to suppress the unwanted transverse bunch oscillation caused by collective beam instabilities. The system was also useful for studying the beam dynamics, such as the electron cloud instability and the beam–beam effect. The experience from the hardware problems due to the large beam power provided valuable information for the design of the bunch-by-bunch feedback system of SuperKEKB. The development of the iGp processors by the international collaboration also contributed to this.

Several improvements were made in the KEKB BPM system to maintain the high-accuracy orbit measurement system throughout the beam operation. The consistency check was useful for finding problems in the BPM system as soon as possible and estimating the gain drift of the BPM signals. The beam-based gain calibration allowed the correction of the drift of the gains between four BPM output voltages during the operation. The mechanical movement of the BPM heads was measured by the displacement sensor. The data were used to correct the BPM readings.

Fig. 34. Frequency distribution of displacement of several BPMs immediately downstream of the dipole magnets.

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The rate of increase of the integrated luminosity rose steadily throughout KEKB’s operation. We believe that the improvement of the KEKB instrumentation systems contributed to this increase, though it is difficult to evaluate how much the improvement of the instrumentation systems contributed to the increase of the integrated luminosity because various improvements in hardware and beam tuning progressed simultaneously.

Acknowledgements

The authors would like to thank all of the KEKB accelerator staff members, especially the KEKB commissioning staff, for their strong support for the operation of the beam instrumentation.

References