KEKB Accelerator

The KEKB injector linac

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The KEKB injector linac has been continuously improved to enhance the stability of many devices and the efficiency of beam operation. These improvements include the development of the new C-band accelerating structure, pulse compressor, klystron, rf window, compact modulator, and the new positron production target using crystalline tungsten. We have also achieved two-bunch beam acceleration, the development of an energy spread monitor, a safety system upgrade, and an event-based timing and control system. These developments and practical applications for advanced linac beam handling result in the success of the simultaneous top-up injection among the three independent storage rings. This result greatly improves the integrated luminosity and the operation stability of the KEKB rings. In this paper, we present the progress of the KEKB injector linac in this decade.

1. Introduction

The KEKB injector linac provides electrons at an energy up to 8 GeV and positrons up to 3.5 GeV [1]. It is utilized as a multi-purpose injector not only for the KEKB B-Factory rings, but also for the Photon Factory (PF), and the Photon Factory Advanced Ring for pulse x-rays (PF-AR). It delivers full-energy beams of 8 GeV electrons to the KEKB high-energy ring (HER) and 3.5 GeV positrons to the low-energy ring (LER). Furthermore, electron beams of 2.5 GeV and 3 GeV are provided for the PF and PF-AR, respectively. The KEK linac was originally constructed as a 2.5 GeV injector for the PF in 1982. A positron source was added later for the TRISTAN project. During 1994–1998, the old injector linac was reconstructed for the KEKB project [2].
Figure 1 and Table 1 show the layout of the KEKB injector linac and the main beam parameters achieved, respectively. Because of the limited site space, the J-shaped linac comprises 125 m-long and 488 m-long straight beam lines. Each line is connected by a 180 degree arc beam line (called the J-arc or sector R), which is tuned for achromatic and isochronous conditions [3]. The two straight beam lines consist of 8 sectors (sectors A–C and 1–5). The bunching section at the beginning of sector A comprises two sub-harmonic bunchers (SHB1 at 114 MHz and SHB2 at 571 MHz), a pre-buncher, and a buncher. Sector A also contains 14 S-band accelerating structures. Other sections in the straight beam lines are utilized as a regular accelerating sector. One regular sector comprises a middle power klystron (called a sub-booster klystron), 8 power klystrons, 8 pulse compressors, and 8 accelerator structures.

In the KEKB injector linac, there are 224 S-band and 8 C-band accelerating structures; the former are driven by an rf of 2856 MHz and the latter by an rf of 5712 MHz. For high power rf generation, 58 S-band and 2 C-band klystrons are utilized for the beam operation up to 8 GeV. A regular accelerator module mounted on an 8.44 m-long girder consists of 4 accelerating structures, which produce an energy gain of 160 MeV at a repetition of 50 Hz.

![Figure 1. Layout of the KEKB electron/positron injector linac.](image)

**Table 1. Main parameters of the KEKB injector linac.**

|   | 8 GeV electron | 3.5 GeV positron |
|---|----------------|-----------------|
| (1) Electron gun | Energy (keV) | 200 | 200 |
|   | Intensity (nC/pulse) | 2 | 14 |
|   | Pulse width (ns) | 1.8 | 2.8 |
| (2) Buncher | Energy (MeV) | 16 | 15 |
|   | Energy spread (σ) (MeV) | 2 | |
|   | Intensity (nC/pulse) | 1.9 | 11 |
|   | Transmission efficiency | 95% | 90% |
|   | Emittance γβe (σ) (mm) | 0.04 | 0.08 |
|   | Bunch width (σ) (ps) | 2.5 | 4.2 |
| (3) Arc | Energy (GeV) | 1.7 | 1.7 |
|   | Energy spread (σ) | 0.29% | 0.38% |
|   | Jitters (p-p) | | 0.1% |
|   | Emittance γβe (σ) (mm) | 0.17 | 1.7 |
|   | Transmission efficiency | 100% | 100% |
| (4) e+ target | Energy (GeV) | 3.7 |  |
|   | Intensity (nC/pulse) | 10 |  |
|   | Transmission efficiency | 96% |  |
| (5) e+ solenoid exit | Intensity (nC/pulse) | 2.4 |  |
|   | Specific yield e+/e− | 6.8% |  |
| (6) Linac end | Energy (GeV) | 8 | 3.5 |
|   | Energy spread (σ) | 0.05% | 0.15% |
|   | Intensity (nC/pulse) | 1.28 | 0.82 |
|   | Specific yield e+/e− | 2.3% |  |
|   | Transmission efficiency | > 80% |  |
|   | Emittance γβe (σ) (mm) | 0.31 | 1.4 |
|   | Pulse repetition (pps) | 50 | 50 |
When the KEKB commissioning started in December 1998, the beam injection time among the 4 independent rings were shared to avoid interference. The many device parameters of the injector linac need to be changed, since the beam injection for each ring requires electron or positron beams with different optimal property and device settings, such as the amount of beam charge, energy, rf phase, timing, magnet settings, and so on. The beam operation performance of the KEKB injector linac has been continuously improved by developing many new devices and applying a new beam operation scheme in this decade.

The paper is organized as follows. Section 2 presents the achievement of simultaneous top-up injection to three storage rings. Section 3 describes the development of new accelerator components including the accelerating structure, rf system, and positron source. Section 4 presents the development of the beam control and monitor system. Section 5 describes the progress in beam operation, statistics, and the upgrade of the safety system. Section 6 summarizes this work.

2. Simultaneous top-up injection for three independent rings

2.1. Overview

Originally, beam injection to both the KEKB HER and LER was carried out every 90 min. In April 2003, a two-bunch beam with 96 ns separation was successfully accelerated to shorten the beam injection time [4–6]. In February 2005, we achieved continuous beam injection, in which the beam injection interval between the HER and LER has been shortened to several minutes by switching the linac parameters. The continuous injection to KEKB resulted in an increased integrated luminosity. However, further beam current stability was required to tune the collision precisely, especially with crab cavities, and top-up to the PF ring was strongly desired to improve the experimental efficiency. For this reason, we started the linac upgrade, aiming at simultaneous top-up injection among the HER, LER, and PF.

2.2. New beam transport line for PF

2.2.1. Overview. Figure 2 shows the layout of the beam switchyard at the end of the injector linac. The thick black (red) line designates the old (new) line to the PF ring. In the old system, all

Fig. 2. Layout of beam transport lines at the end of the linac.
beams shared the first bending magnet (bend) of the energy compression system (ECS) of the KEKB positron line as a common magnet. For KEKB injection, the electron beam of 8 GeV and the positron beam of 3.5 GeV are designed to be guided to their own beam transport (BT) lines without changing the ECS-bend setting. The beam-mode switching between KEKB and the PF, however, needs to turn off/on at the first bend of the ECS. Since the ECS bends are heavily saturated, about three minutes are required to recover the magnetic fields. In the new BT line, the PF beam is extracted upstream of the ECS bends through a new switch-bend (BM_58_1), which is dedicated to the PF, and guided to the existing line downstream of the beam switchyard. BM_58_1 is able to be set up to the magnetic condition within about half a minute. The new line rejoins the existing line at a bend, BH12.

2.2.2. Construction of the new PF-BT line and optics design. All magnets installed in the new PF-BT line can be available up to a beam energy of 3 GeV. The bending magnets are reused from those of the old TRISTAN-AR BT line [7]. They are H-type conventional block magnets. It takes about half a minute to change the magnetic field up/down from zero to operation field ($\sim$0.92 T). There is, however, a remanent field of 33 Gauss. In KEKB injection mode, the excitation current of BM_58_1 is turned off and the correction coil of this magnet is excited to 0.78 A in order to cancel the remanent field.

The stabilities of the power supplies are less than 100 ppm peak-to-peak (p–p), and their ripples less than 50 ppm (p–p). We estimated the effective emittance growth due to the strength jitter of the power supplies as below:

$$\frac{\varepsilon'}{\varepsilon} \sim \sqrt{1 + \frac{\beta \langle d\theta^2 \rangle}{\varepsilon}},$$

(1)

where $\varepsilon$ and $\varepsilon'$ are the emittances at the entrance and exit of a bend, respectively. $\beta$ is a beta-function at the center of the bend. $\langle d\theta^2 \rangle$ is the mean-squared jitter of deflection angle of a power supply. The estimated values of emittance growths are summarized in Table 2, where jitters of power supplies are assumed to be 100 ppm and $\Delta \varepsilon = \varepsilon' - \varepsilon$. BMAG indicates the emittance growth from beta-mismatch. For the new PF-BT operation, the stabilities of bends with 100 ppm (p–p) are enough for our requirements. As shown in Fig. 2, there are three screen monitors (SC_61_F*), three beam position monitors (BPMs) (SP_61_F*), and one energy-spread monitor (S8_61_F3).

All magnets newly installed in the new PF-BT line were aligned by using a laser tracker that can measure the magnet position with a precision of 1 $\mu$m. All calculations for the optics were done with the SAD code [8]. The design optics of the beta-functions, dispersion functions, and beam sizes with an energy spread of 0.125% are shown in Fig. 3. The blue and red lines mean the horizontal and vertical planes, respectively. The dispersion function at a profile monitor (SC61F2) is zero in the design optics. In practical operation, however, with a different beam energy, a beam orbit

| Bend   | $\theta$ (rad) | $\delta\theta/\theta$ | $\Delta\varepsilon/\varepsilon$ | BMAG       |
|--------|----------------|------------------------|-------------------------------|------------|
| BM_58_1| 0.114          | $10 \times 10^{-4}$    | $4 \times 10^{-3}$            | $1 + 8 \times 10^{-6}$ |
| BM_61_F1| -0.114         | $10 \times 10^{-4}$    | $2.2 \times 10^{-2}$          | $1 + 2 \times 10^{-4}$ |
| BM_61_F4| 0.0874         | $10 \times 10^{-4}$    | $3 \times 10^{-3}$            | $1 + 6 \times 10^{-6}$ |
| BH11   | 0.131          | $10 \times 10^{-4}$    | $8 \times 10^{-3}$            | $1 + 3 \times 10^{-5}$ |
| BH12   | 0.131          | $10 \times 10^{-4}$    | $1.0 \times 10^{-2}$          | $1 + 5 \times 10^{-5}$ |
displacement of a few mm was observed on SC61F2. The observed dispersion error could be attributed to a strength error of the quadrupole magnets in the region where the horizontal dispersion functions are not zero. We measured the correction factors of the quadrupole magnets using the beam [9]. Applying these correction factors to the quadrupole magnet settings, we confirmed that the measured horizontal dispersion function is in good agreement with the designed one [10].

2.2.3. Beam operation with the new PF-BT line. The new PF-BT line has been successfully commissioned without major difficulties. The round-trip mode switching time between KEKB and the PF is 2.6 min, while it was 5.3 min in the old PF-BT line. The orbit deviations are 4 mm and 2 mm at maximum for the horizontal and vertical planes, respectively. This is small enough in comparison with the vacuum chamber aperture of 57.2 mm, since the horizontal and vertical beam sizes of 1σ are 3 mm and 1 mm, respectively. The beam injection rate for the PF ring surpassed 2 mA/s at a repetition rate of 25 Hz, which is a very good value compared to that in the old PF-BT line.

During commissioning, we found that the leakage field from the ECS magnets affects the beam orbit in the PF-BT line. After the vacuum chambers were shielded by mu-metal, the orbit fluctuation caused by the leakage field was drastically suppressed from 12 mm to 1 mm. The beam injection to the PF by using the new PF-BT line was successfully completed in September 2005.

2.3. Pulsed bending magnet system

2.3.1. Overview. BM_58_1, described in the previous section, has been replaced by a pulsed bending magnet for fast beam-mode switching between the PF ring and KEKB ring injection. The electron beam of 2.5 GeV can be selectively extracted to the PF-BT line with a magnetic field of 1.22 T and a maximum repetition rate of 25 Hz. The deflection angle of the magnet is 0.114 radians. The magnet system has been designed for beam operation up to 3 GeV. Table 3 shows the specification of the pulsed bending magnet system.

2.3.2. Magnet. The magnet is a wind frame magnet made of 0.35 mm thickness laminated steel welded to the 25 mm stainless end-plates [11]. A photograph of the pulsed bending magnet is shown...
Table 3. The specification of the pulsed bending magnet system.

| Parameter name                          | Value                          |
|-----------------------------------------|--------------------------------|
| Deflection angle (mrad)                 | 114                            |
| Magnetic field @ 2.5GeV (T)             | 1.22                           |
| Gap (W×H) (mm)                          | 155 × 30                       |
| Coil (turn)                             | 1                              |
| Core length (m)                         | 0.99                           |
| Ceramic tube size (inside) (mm)         | 86 × 16 × 1200                  |
| Ti coating surface resistance (Ω/γ)     | 100                            |
| Maximum peak current (kA)               | 27 (32)                        |
| Repetition rate (Hz)                    | 25 (12.5)                      |
| Output current waveform                 | Half sinusoid                   |
| Pulse width (µs)                        | 200                            |
| Stability of output current pulse height| 1 × 10⁻³                      |

![Photograph of the pulsed bending magnet.](image)

in Fig. 4. The slit structure was made on a stainless steel plate to reduce the heat due to eddy currents and 5 mm copper plates cooled by water are inserted between the core and the stainless steel plates. The core length is 0.99 m, and the gap height is 30 mm. A single-turn coil is used. Silicon nitride ceramics (Si₃N₄, NGK Co. Ltd. EC-141), which have good shock resistance, are used as coil support rods.

2.3.3. Ceramic chamber. An alumina ceramic beam chamber was inserted into the magnet; a photograph of it is shown in Fig. 5. The ceramic chamber has a racetrack-type inner wall. A 1200 mm long ceramic tube with a thin Ti–Mo conducting layer is used. The surface resistance is set around 100 Ω/cm² so that the temperature rise of the ceramic by the eddy current becomes less than 10°C. Since Kovar has the same expansion coefficient as the ceramic, it was chosen as the metal braze, which provides a low-stress hermetic seal to the ceramic and a flexible transition between the ceramic and the massive flange. Mo–Mn is selected for the braze metallization. As shown in Fig. 6, a special removable flange is used for one side of the chamber so that the chamber can be inserted from one side to the other.
2.3.4. Power supply system. The power supply is located at the klystron gallery just above the magnet. They are connected with 40 coaxial cables of 7 m. In order to reduce the noise from the pulsed bending magnet system, an exclusive earth ground is prepared and a trigger signal is sent through the optical fiber cable.

Figure 7 shows a schematic diagram of the power supply. A Mitsubishi FT1000A-50A thyristor was selected as the energy discharge switch. In total, 24 thyristors, 6 series and 4 parallels, were used. The maximum peak current is 27 kA at a 25 Hz repetition rate and 32 kA, at 12.5 Hz operation. The output current pulse shape is half-sinusoidal with a duration of 200 μs. The stability of the output current is 0.1%. Since the PF injection beam repetition rate may be changed randomly, the pulse height stability must be independent of the repetition rate. To get this stability, some circuit boards are stored in the constant temperature reservoir and the feedback circuit parameters were well tuned. Concerning the relatively long period drift, though the charged voltage drift was 0.1%, the drift of the magnetic field is observed as 0.23%. This drift may be due to the increase of the resistance caused by the temperature rise of the thyristor modules and cables. In order to cancel this drift, the output current is monitored with a 16-bit 20 MHz sampling transition recorder.

The power supply is controlled by a programmable logic controller (PLC), supervised by the Experimental Physics and Industrial Control (EPICS) system. Local control of the power supply
can be done through the touch panel and PLC. Since the bunch charge of PF injection must be much smaller than that of KEKB injection, a beam-charge interlock system was developed for radiation safety [12]. The trigger timing system was upgraded for simultaneous injection, as described in Sect. 4.1 [13, 14].

2.4. Commissioning for simultaneous top-up injection

2.4.1. Overview. During simultaneous top-up for the 3 independent rings, the energy profiles and charges are controlled at every 20 ms interval, as shown in Fig. 8. The energies for all beam modes are the same up to the end of sector 1. From the beginning of sector 2, the HER beam is accelerated up to 8 GeV by the end of the linac. The energy of the PF beam is kept constant between sectors 2 and 3. In sectors 4 and 5, the beams are decelerated to 2.5 GeV by shifting the low-level rf (LLRF) phases about 180° with respect to the acceleration phase. As for the LER, the positron beam produced at the target, which is placed between sectors 1 and 2, is accelerated up to 3.5 GeV in the rest of the linac by shifting the LLRF phase 180 degrees with respect to the electron beam acceleration. The primary electron charge for the positron production before the target is two orders higher than that for the PF. For HER and LER injection, two bunches can be accelerated in the same rf pulse, separated by 96 ns. The charges are controlled by changing the parameters of the electron gun at 50 Hz. There are three grid pulsers of the same type for PF, KEKB LER, and HER.
injection, which require electron bunch charges of 0.1 nC, 10 nC, and 1 nC, respectively. Each output of the three grid pulser is input to a signal combiner module with a single output port.

2.4.2. Positron production target with a bypass hole. Before the summer of 2008, the target for positron production was frequently inserted into and removed from the beam line for LER injection. The life time of the bellows for the target limited the HER and LER injection cycles to more than five minutes. Therefore, a new tungsten crystalline target with a side hole was newly installed so that HER and PF operations could be done without removing the target. In this scheme, the electron beams can pass through the bypass hole by using a bump orbit [15].

2.4.3. Pulsed steering magnets. To make a target bump, four pulsed steering magnets were installed: three for the horizontal kick and one for the vertical one. Their maximum kick angles are 1 mrad for a 4 GeV beam. The magnet has a gap of 35 mm and a length of 150 mm. Ceramic chambers coated with Mn–Mo were installed for the pulsed steering magnets. An additional six pulsed steering magnets were installed for the beam orbit corrections on both the horizontal and the vertical directions at the end of sectors 2, 3, and 4. Their kick strengths are controllable to three values, corresponding to the three beam modes at 50 Hz.

2.4.4. Compatible optics and orbit correction for simultaneous top-up injection. The settings of the quadrupole magnets in the compatible optics for the three beam modes are schematically shown in Fig. 9. In this scheme, beams with different energies can be transported along the linac by using the constant DC magnet settings. Two independent optics, one dedicated to LER injection optics and the other to HER/PF injection optics [16], have been successfully employed so far. Based on this experience, the better setting of quadrupole magnets in each section was chosen from these two optics so that all three types of beams could be effectively transported. At sectors A and B, high current optics for LER injection is used. At sector R, the original optics has been adopted as the common one. Between sectors C and 1, HER- and PF-compatible optics with rather weak focusing at the target is used, otherwise the electron beam cannot be matched to the positron optics after the target. This causes the positron yield to slightly decrease in comparison with the positron-dedicated optics. For the beam line downstream of the target, the positron optics for LER injection are set for matching the lower energy beam.

To match the optics between the linac and the BT line, we used wire scanners at the end of linac and at the entrance of the BT line, as shown in Fig. 10 [17]. After setting the compatible optics mentioned above, the optics at the end of the linac were matched to the LER beam. As shown in Fig. 11(a), however, the settings of the triplet quadrupole magnets (in red circles) were too strong for the PF low-energy beam, and the beta-functions were too large at the entrance of the PF-BT line. This is caused by the fact that the next quadrupole magnets are located far from the triplet magnets. For the PF beam, we reduced the strength of the triplet quadrupole fields at the end of

Fig. 9. Settings of quadrupole magnets. The horizontal direction shows the axis along the linac beam line.
the linac by nearly half so that both the horizontal and vertical beta-functions are suppressed within 60 m, as shown in Fig. 11(b). The new optics of the PF-BT line has been designed as shown in Fig. 11(c), in which the beta-functions of Fig. 11(b) are used as the initial values and the beams can be stably delivered through the PF-BT. On the other hand, the beams for both LER and HER injection could be re-matched to the optics parameters at the entrance of each BT line with the wire scanners.

Eventually, simultaneous top-up injection to the three different rings was successful for daily operation in April 2010. Figures 13 and 14 show the stored beam current of KEKB and PF during simultaneous top-up operation, respectively. The stored beam current stabilities of the KEKB and PF rings are much improved to about 0.05% and 0.01%, respectively. These results are far superior to the original operation performance of a drop of around 50% in stored beam current, and significantly improve the experimental performance of both the KEKB and PF rings.
Fig. 12. Beam orbits from the linac to BT for the three rings measured with the fast read-out BPMs. The horizontal and vertical orbits and charges in each beam-mode are shown. Red circles show places where pulsed steering magnets are installed.

Fig. 13. Stored beam current of HER (red line in the top figure), LER (red line in the middle figure), and luminosity (yellow line in the bottom figure) of KEKB in the simultaneous top-up operation (24 h).
3. New accelerator components

3.1. C-band accelerating structure and pulse compressor

An accelerator module of the KEKB injector linac is composed of a 40 MW S-band klystron, a SLED-type rf pulse compressor, and four 2 m-long disk-loaded accelerating structures. rf power from the SLED is divided equally and fed into the four structures. A module typically has an energy gain of 160 MeV and the average field gradient is 21 MV/m. In the design consideration stage of the KEKB upgrade, the injector linac was required to raise the positron injection energy from 3.5 to 8 GeV for the case of an electron–positron energy switch. At that time, an accelerator in the C-band frequency had been proposed in the linear collider R&D, and a high-power C-band klystron, an accelerating structure, and other rf components had been developed [18]. Thus, replacing some of the S-band accelerator modules with C-band ones, which have twice as high acceleration field gradients, was a possible scheme for the KEKB injector upgrade.

For the configuration of a C-band module, we considered two cases. The first case is a "tournament" configuration of four 1 m-long structures, as shown in Fig. 15(a). This is a compressed layout of the existing S-band module. The other case is that the rf power from the pulse compressor is divided into two 2 m-long structures, where we can save many dummy loads and power dividers. However, a vacuum level in the middle of a 2 m-long structure was expected to be too high. As a slight modification, we adopted a series connection of two 1 m-long structures with a waveguide, as shown in Fig. 15(b). In contrast to most accelerating structures fabricated by brazing the cavity cells at other facilities, the S-band structure for the KEKB linac was fabricated by electroplating a copper layer outside of the regular cells. We also adopted the electroplating method for the C-band structure fabrication, since we can make good use of the rich experience of manufacturing the S-band accelerating structures.

Table 4 shows the C-band accelerating structure parameters together with the S-band ones. The first prototype C-band accelerating structure for the KEKB linac was developed in 2003, based on a half-scaled design of an existing S-band travelling-wave disk-loaded structure (type-A) used in the KEKB linac [19], as shown in Fig. 16. Unfortunately, the standard cross-sectional dimension of the C-band waveguide WRJ-187 (47.55 mm × 22.15 mm) is not exactly half the size of the S-band waveguide WR-284 (72.14 mm × 34.04 mm), hence the C-band coupler cavity dimension (cavity diameter and coupling iris width) cannot be scaled directly. Instead, we optimized these coupler dimension parameters by rf measurements and step-by-step machining the prototype, as shown in Fig. 17.
first prototype structure was fabricated at Mitsubishi Heavy Industry (MHI) in Nagoya. A high-power test was performed at a test stand in KEK and installed in the KEKB linac beam line. The energy gain by the single 1 m-long structure operated with 40 MW rf power directly from a klystron was measured in a beam study and the estimated average field gradient was above 40 MV/m [19].

As of June 2012, the KEKB linac has two C-band accelerator modules; the first module is in series connection configuration, the second module in in tournament configuration, and four identical models are installed. Both of the C-band modules are used in daily beam injection. A C-band high-power dummy load was also developed for absorbing rf powers from the output coupler of the accelerating structures and power dividers [20, 21].

In the KEKB linac, a SLED-type S-band pulse compressor was used to boost the peak rf power. It was composed of a pair of two-hole coupling type TE015 mode cavities [22]. In the C-band frequency, the TE015 mode cavity gives a smaller Q factor and a field multiplication factor is not sufficient. Instead, we adopted a TE038 mode cavity, which can give a sufficient Q factor, as used in the S-band LEP injector linac (LIPS) [23]. As a nickname, we call this C-band pulse compressor SKIP (SuperKEKB Injector Pulse Compressor) [24]. A photograph and its main parameters are shown in Fig. 15.

Table 4. S-band and C-band accelerating structure regular cavity parameters.

|                         | S-band (type-A) | C-band (type-U) | C-band (type-D) |
|-------------------------|-----------------|-----------------|-----------------|
| Operation frequency (MHz) | 2856            | 5712            | 5712            |
| # of regular cells      | 54              | 54              | 54              |
| Disk iris diameter 2a (mm) | 24.950 (first cell) | 14.500 (first cell) | 12.475 (first cell) |
| Disk thickness (mm)     | 5.0             | 2.5             | 2.5             |
| Cell length (mm)        | 35.0            | 17.5            | 17.5            |
| Attenuation parameter τ | 0.30            | 0.30            | 0.43            |
| Power loss (%)          | 45              | 45              | 61              |
| Shunt impedance (MO/m)  | 57.3            | 65 (first cell) 75 (last cell) | 74.6 (first cell) 85.1 (last cell) |
| Q factor                | 13 700          | 9740 (first cell) 9700 (last cell) | 9700 (first cell) 9680 (last cell) |
| Group velocity vg/c (%) | 1.37            | 3.1 (first cell) 1.9 (last cell) | 1.9 (first cell) 1.0 (last cell) |
| Filling time (ns)       | 462             | 135             | 234             |
| Field gradient with SLED (MV/m) | 21        | 42              | 42              |
| Structure length (m)    | 2.1             | 1.1             | 1.1             |
| Weight (kg)             | 120             | 30              | 30              |
Fig. 18 and Table 5, respectively. In this cavity dimension, the TM138 and TE12,11 modes have resonant frequencies of less than a few MHz in the vicinity of the TE038 mode. A groove in the end-plate of the cavity detunes these modes, and coupling by two holes a half wave-length apart in a waveguide effectively reduces the coupling to these modes. Modes that can have large coupling even with this two-hole configuration are well isolated in frequency at −20 MHz (TE02,10) and +28 MHz (TE244). Figure 19 shows the electric field distribution of the TE038 mode in the SKIP cavity calculated by the CST studio [25]. We take the coupling hole diameter as a
maximum within the limit of the waveguide height. This is to make the coupling plate thickness as large as possible for mechanical stability while keeping a satisfactory coupling strength. We make the edge radius in the coupling hole relatively large to make the surface field strength low. Operation with a peak power of 200 MW (after pulse compression) was achieved at the test stand. Two SKIP compressors were installed in the KEKB injector linac and used for beam operation.

3.2. Development of the compact modulator system

A compact modulator was developed for the C-band rf system. A simplified schematic diagram of the modulator system is shown in Fig. 20. The modulator is a conventional line-type modulator with a 1:15 step-up transformer, a pulse circuit section consisting of a thyratron and two parallel pulse-forming networks (PFN) with 14 sections, and a 50 kV switching power supply to charge the PFN so as to realize a compact modulator. In order to save cost, the existing components of the S-band modulator were utilized as much as possible [26]. With a pulse-transformer turn ratio of 1:15, the modulator primary peak voltage, current, and output impedance are 23.3 kV, 4.8 kA, and 4.7 $\Omega$, respectively. Therefore, it is possible to utilize most existing components in the pulse circuit section, such as the PFN capacitors and inductors, the thyratron circuit, and the cabinet. The specification of the compact modulator is summarized in Table 6 together with the S-band modulator. Figure 21 shows an overall view of the compact modulator and the existing S-band one. The size of the modulator is reduced by one-third of the S-band one.

The switching power supply was developed by Toshiba Electro-Wave Products Co. in collaboration with KEK [27]. The power supply is designed to be able to deliver 30 kJ/s with a maximum output voltage of 50 kV. Table 7 summarizes the specification of the power supply.
Fig. 20. Simplified schematic diagram of the compact modulator.

Table 6. Specification of the compact C-band and existing S-band modulators.

|                     | S-band | C-band |
|---------------------|--------|--------|
| Klystron            |        |        |
| Output power (MW)   | 46     | 50     |
| rf pulse width (µs) | 4.0    | 2.0    |
| Efficiency (%)      | 45     | 45     |
| Pervance (µA/V³/²)  | 2.1    | 1.55   |
| Beam voltage (kV)   | 298    | 350    |
| Repetition rate (pps)| 50    | 50     |
| Pulse transformer   |        |        |
| Step-up ratio       | 1:13.5 | 1:15   |
| Primary voltage (kV)| 22.0  | 23.3   |
| Primary current (kA)| 4.6   | 4.8    |
| PFN (2 Par. PFN)    |        |        |
| Impedance (Ω)       | 4.6    | 4.7    |
| No. of cells        | 40     | 28     |
| Cell inductance (µH)| 1.31   | 1.37   |
| Cell capacitance (nF)| 15.5  | 15.5   |
| Total capacitance (µF)| 0.62  | 0.434  |
| Pulse width (µs)    | 5.7    | 4.1    |
| Thyratron            |        |        |
| Anode voltage (kV)  | 44     | 47     |
| Anode current (kA)  | 4.6    | 4.8    |
| PFN charging        | Resonant charging | Switching charging |

Fig. 21. Overall view of the existing S-band and the compact C-band modulators.
The power supply is based on an IGBT-switched 33 kHz inverter. It has a voltage regulation of less than 0.2% peak-to-peak and fed with a three-phase ac voltage of 420 V.

Figure 22 shows the PFN charging voltage and current waveforms at 42 kV during a high power test. The short-term performance on the PFN charged voltage stability was 0.3% (p–p).

Table 7. Specification of the switching power supply.

| Specification                        | Value                   |
|--------------------------------------|-------------------------|
| Maximum output voltage               | 50 kV                   |
| Average capacitor charging power     | 30 kJ/s                 |
| Voltage regulation                   | 0.2% peak-to-peak       |
| Efficiency                           | 89%                     |
| Switching frequency                  | 33 kHz                  |
| Input voltage                        | 420 V, 3 phase, 50 Hz AC|
| Cooling                              | Water, 4.5 liter/min.   |
| Weight                               | 170 kg                  |
| Size                                  | 19’’ rack mount          |
|                                      | 480 mm (W), 750 mm (D), 680 mm (H) |

**Fig. 22.** PFN charging voltage (10 kV/div., 4 ms/div.) and charging current (0.4 A/div., 4 ms/div.) waveforms at 42 kV. Upper trace is the zoomed-in charging voltage flat-top (500 V/div., 1 ms/div.).

**Fig. 23.** Expanded pulse-top waveform of the klystron voltage (7.5 kV/div., 400 ns/div.).

The power supply is based on an IGBT-switched 33 kHz inverter. It has a voltage regulation of less than 0.2% peak-to-peak and fed with a three-phase ac voltage of 420 V.

Figure 22 shows the PFN charging voltage and current waveforms at 42 kV during a high power test. The short-term performance on the PFN charged voltage stability was 0.3% (p–p). The
3.3. **New C-band rf source and rf window**

C-band rf sources (5712 MHz, 2 μs, maximum 50 MW) were developed by the Mitsubishi Electric Corporation in collaboration with KEK. The klystron (PV-5050K) is designed to have a higher acceleration gradient of more than 40 MV/m. The required specification of the C-band klystron is summarized in Table 8. The beam perveance was selected so as to match the current PFN impedance. The maximum gradient between the anode and the Wehnelt is about 21 MV/m, which is similar to the S-band 50 MW klystron [28]. The klystron has 5 cavities including input and output cavities. The 5th output cavity has a travelling wave structure (4 cells, 2π/3 mode) in order to decrease the electric field to less than 35 MV/m at 50 MW output. The single mix-mode rf window is adopted to transmit 50 MW since the rf outputs from two waveguides are combined.

Design work was carried out by using MAGIC, which has been used to design X-band klystrons [29]. The schematic of the klystron is shown in Fig. 24. The beam trajectory by simulation is shown in Fig. 25. After the optimization of the output structure, the maximum gradient becomes 34.7 MV/m at an output power of 50.6 MW. The measured output performance is shown in Fig. 26 together with the simulation results. 50 MW output is obtained at a cathode voltage of 338 kV, a beam current of 305 A, and an input rf of 229 W. Though the applied cathode voltage is lower than the simulation value (350 kV), rf input for saturation is almost the same between the simulation and test results, as shown in Fig. 27.

The rf window is required to transmit rf power of 50 MW (5712 MHz, 2 μs, 50 pps) [30]. The criteria of the C-band rf window are determined based on the electric fields of the S-band rf window, as summarized in Table 9. The S-band window has a long life with a mean time between failure of more than 100,000 h under an rf transmission of 50 MW (2856 MHz, 4 μs, 50 pps), though leakage of the klystrons is one of the reasons for klystron failures [31]. By mixing the TE11 mode and the TM11 mode, lower electric fields can be accomplished, thus making a ‘mix-mode window’ [32]. A high-purity alumina ceramic of HA-997 (99.7% purity, NTK Co.) with a high durability for the transmission of high power has been adopted [33]. The window is constructed with a combination of three rings. The five parameters in Fig. 28, which are necessary to match the two different modes in the same length, are optimized using HFSS [21]. The electric fields at the center and edge of the disk are about 20% and 50% lower than the present S-band window, respectively, as shown in Fig. 29.

| Table 8. Required specification of the C-band klystron. |
|-----------------------------------------------|
| Frequency                                      | 5712 MHz |
| Output power                                   | > 50 MW  |
| Beam high voltage                              | 350 kV   |
| Beam current                                   | 320 A    |
| Perveance                                      | 1.53 μP  |
| Pulse width                                    | 2.5 μs   |
| Repetition                                     | 50 Hz    |
| Gain                                           | > 50 dB  |
| Efficiency                                     | > 45%    |
Fig. 24. Schematic of the klystron.

Fig. 25. Beam trajectory simulated by MAGIC at an rf output power of 50 MW.

Fig. 26. High power test results together with simulation results.
The electric fields were measured by a perturbation method using this low-level model [34]. A cube (3 mm) of rutile with high permittivity is used in the measurements due to the low electric fields around the ceramic surface. The measured fields are shown in Fig. 30. The electric fields were measured from the center of the rectangular waveguide (\( z = 2 \times 100 \) mm) to the center of the ceramic disk (\( z = 0 \)). The measured and calculated data show good agreements.

For the high power test of the rf window, a resonant ring has also been designed. The resonance condition of the ring is controlled by the operation frequency after adjusting the total length roughly by spacers. The window has been tested up to 300 MW [30]. The window after operation showed no damage, and it was installed in the klystron test stand. The rf losses were measured by varying the temperature of the cooling water. The results are shown in Fig. 31. The loss was 10 W at a transmission power of 10 kW, which is almost the same as the present S-band window. Since the ceramic thickness is 30% thicker than the S-band window, the effective rf losses per unit length are smaller than that of the S-band window.

**Table 9.** Electric properties of the S-band rf window.

| Parameter                                      | Value              |
|------------------------------------------------|--------------------|
| Center of the ceramic                          | 3.7 MV/m (50 MW)   |
| Edge of the ceramic                            | 1.7 MV/m (50 MW)   |
| Maximum electric field on the surface of the ceramic | 5.5 MV/m (50MW)   |
| Bandwidth (VSWR < 1.2)                         | 600 MHz            |

**Fig. 27.** Input–output characteristics at 50 MW output.

**Fig. 28.** Schematic of the C-band window. The length of the first ring (P1), second ring (P2), third ring (P3), and the inner radius of the second (P4) and third (P5) rings are the parameters to be optimized.
3.4. Positron production target using tungsten single-crystal

A new tungsten single-crystalline target for positron production has been applied to the positron source of the KEKB injector linac for the first time [35]. The linac operation with the crystalline target for positron production was carried out from September 2006 to June 2007. Before the target installation, systematic studies were carried out with tungsten crystals of various thicknesses using 4 GeV electron beams at a test beam line during the period 2000–2005 [36]. The thickness of...
the tungsten crystal was finally optimized at 4 GeV in 2006. Then the optimized tungsten crystalline target was installed at the KEKB positron source without making any significant modifications in September 2006. During this period, data on positron production, particularly the positron-production efficiencies (PPEs), and positron-production stabilities were obtained [37].

In order to enhance the luminosity in the KEKB colliding experiment, it was strongly required that the injected positron beams should be increased as much as possible. In a conventional positron source, positrons are produced by high-energy electrons hitting a heavy-metal target. The produced low-momentum positrons are captured and accelerated in the succeeding positron capture section. For the KEKB injector linac, the maximum production efficiencies are obtained with an optimized target thickness of 4 X0 (radiation length) and with a typical momentum acceptance of 5–25 MeV/c for 4 GeV incident electrons. An increase in the positron intensity with a conventional metal target should lead to an increase in the incident electron intensity and energy. However, the allowable heat load on the target limits the beam power of the incident electrons. This was the reason why we developed a new tungsten crystalline target for positron production.

The use of a crystal-assisted positron source for improving the PPE was first proposed by Chehab et al. in 1989 [38]. This approach is beneficial as it improves the PPE and also reduces the heat load on the crystal target as well. When high-energy electrons impinge on such a single crystal in the direction of the crystal axis, intense low-energy photons are produced owing to channeling radiation and coherent bremsstrahlung [39]. These intense photons could generate a large number of $e^+e^-$ pairs in the same crystal target. A larger number of positrons is expected to be produced from a crystalline target than from a conventional heavy-metal target.

The KEKB positron source comprises a positron production target and a positron capture section. The target is composed of a tungsten single-crystal, and the capture section is employed as a so-called quarter wave transformer (QWT). The design and performance of the KEKB positron source have been described elsewhere [1, 40]. Positrons were generated by the impingement of a 4 GeV primary electron beam on the crystalline target. The average beam power was 2 kW at a maximum repetition rate of 50 Hz. The typical transverse beam radius was 0.7 mm (rms). The typical horizontal and vertical normalized emittances were 660 mm·mmrad (rms) and 360 mm·mmrad (rms), respectively, at the target. The horizontal (vertical) angular spread at the target was estimated to be 0.2 (0.1) mmrad (rms). These angular spreads must be within the critical angle, which is 0.61 mmrad, for axial channeling at 4 GeV in a tungsten crystal [39]. The positron capture section comprises a 45 mm-long pulse solenoid with a field strength of 2 T, an 8 m-long DC solenoid with a field strength of 0.4 T, and four accelerating structures—two 1 m long and two 2 m long—installed inside the DC solenoid. Positrons with an average energy of 10 MeV are generated from the target. These positrons are captured by the two types of solenoidal magnetic fields (created by the pulse solenoid and DC solenoid), and then accelerated in the succeeding accelerator sections up to an energy of ~70 MeV. The geometrical acceptance of the capture section is ~420 mm·mmrad and the typical momentum acceptance is ~24% at a momentum of 10 MeV/c.

Figure 32(a) shows a mechanical drawing of the target assembly with a tungsten crystalline target. The crystal target with a thickness of 10.5 mm and a cross section of 5 mm × 5 mm is fixed at the center of a cylindrical copper body for water cooling with a hot isostatic pressing technique. The geometrical structure of the copper body for the previously used tungsten target is exactly the same as that of the tungsten crystalline target assembly, apart from the difference in the geometrical shape of the tungsten target. Figure 32(b) also shows the target assembly successfully installed in a vacuum chamber. The heat on the target is conducted through a cooling water channel wound
around a copper body of 50 mm diameter. The target assembly was carefully fabricated so that the central axis of the cylindrical copper body was corresponded exactly to the crystal axis, \(\langle 111\rangle\), within an accuracy of \(\pm 1\) mrad.

Beam tests were carried out by adjusting the incident angles of the primary electron beam at the crystal target with two sets (horizontal and vertical) of upstream steering magnets. The charge of the primary electron beam was 7.5 nC/bunch on average during the beam tests. The incident angles were controlled within angular ranges of \(\pm 2\) mrad. After optimization of the two sets of steering magnets, both the positron and primary electron charges were simultaneously measured with the upstream and downstream BPMs.

The distributions of the PPEs (defined by \(N_{e^+}/N_{e^-}\)) were obtained for each beam pulse at the linac beam line, where \(N_{e^+}\) was the number of positrons captured in the positron capture section and \(N_{e^-}\) was the number of the primary electrons. The results show that the PPEs of the first (second) bunch are \(0.25 \pm 0.01\) (\(0.26 \pm 0.01\)) on average for the tungsten crystal target. The increase in positrons for the 1st (2nd) bunch from the tungsten crystal is \(25 \pm 2\%\) (\(28 \pm 2\%\)) on average, in comparison with those obtained from the previously used tungsten target, where the errors indicate one standard deviation uncertainties. The PPEs of both bunches are consistent with each other within experimental errors. These results are quantitatively in agreement with our previous results obtained by experimental studies, described in a previous paper [36].

The new crystal-assisted positron source has been stably operating in the KEKB operation without any significant reduction of the PPE for ten months. For more long-term KEKB operation, it would be useful to apply a dedicated feedback control to the incident angles of the primary electron beam with two successive BPMs in order to keep the PPE as high as possible.

4. Beam control and monitor system

4.1. Event-based timing and control system

As described in Sect. 2, it became indispensable to perform simultaneous top-up injection into the three storage rings of KEKB-HER, KEKB-LER, and PF to obtain stable experimental results. To
this end, it was necessary to construct a 50 Hz pulse-to-pulse beam modulation system. Initially, it took 30 s to 5 min to switch the beam modes between the three rings because beam energies and charges were more than 3 times and 100 times different, respectively.

While an EPICS-based accelerator control system was used to operate the linac, a global and synchronous control system was additionally needed in order to realize the new injection scheme, which needed to cover many devices spread over more than a kilometer. Actually, FPGA (field programmable gate array) and SFP (small form-factor pluggable) technologies became commercially available, and they were reliable and flexible. A combination of FPGA and SFP was employed in the accelerator controls in many ways, and the event-based control modules were very adequate for our purpose [41]. Those modules provided global and synchronous controls in the range of 10 picoseconds to 10 milliseconds [42].

An event generator (EVG) in the VME form-factor was installed at the center of the linac with some external timing synchronization circuits. Seventeen VME event receivers (EVRs) were distributed along the linac and at the ring injection system, and were connected with the EVG via SFPs and optical fibers in a star-like topology, as shown in Fig. 33. The EVG and EVRs were operated by the vxWorks real-time operating system and EPICS software toolkits. Control events were transmitted through SFP and the firmware on FPGA ensured synchronous operation. More than 5000 EPICS process variables were implemented to construct the synchronous controls.

A pulse-by-pulse beam mode train was constructed automatically based on the arbitration between injection frequency requests from the three rings as well as human operator requests. Each element of the train corresponded to a beam pulse in one of the 20 ms time slots. The train could have any length up to 10 seconds (500 elements) and could be modified at any time. The train was interpreted by EVG pulse-by-pulse and corresponding control events were generated and transmitted. EVRs received and interpreted these events one by one and provided necessary controls depending on the attached devices. More than 130 parameters were modulated at 50 Hz, including timing signals and analog signals for the LLRF and magnets [43].

The event-based control system described here enabled simultaneous top-up injection, and the beam currents were stabilized, which contributed to the physics experiment results.

Fig. 33. Overall configuration of the event-based control system. A single event generator supervises 17 event receiver stations, which cover the 1 km facility.
4.2. Energy spread monitor and feedback

A non-destructive energy-spread monitor (ESM) using multi-stripline electrodes has been newly developed in order to measure and control the energy spread of single-bunch electron and positron beams at the KEKB injector linac. Since KEKB is a factory machine, well-controlled operation of the injector linac is strongly required for keeping the injection rate as high as possible and for maintaining stable operation. For this purpose, beam diagnostic and monitoring tools are essential in order to control the energy spreads of beams along with stable control of the beam positions and energies [44, 45]. The energy-spread feedback control is not only expected to keep the injection rate higher but also to reduce the background level to the detector and the radiation damage to the accelerator components. A dedicated energy-spread feedback control with non-destructive ESMs may help to cure such problems.

Based on previous work [46, 47], it was demonstrated that multipole moments of a beam could be successfully measured depending upon the transverse beam sizes with the use of stripline-type BPMs. It was also clearly shown that the BPMs were applicable for transverse beam-size measurements pulse-by-pulse. Based on the multipole-moment measurement, the energy spread can be transformed to the corresponding spatial transverse spread at a large energy-dispersion section because the electromagnetic field distribution induced by the beam on the stripline electrodes of ESM may be modified due to the variations in the spatial transverse spread [47].

The ESM was designed based on numerical analyses that were carried out by applying them to the multipole moments of electromagnetic fields generated by a beam [48]. Figure 34 shows a schematic cross-sectional drawing of the designed ESM. The detailed mechanical design of the structure has been reported previously [49], and it is briefly summarized here. The ESM is a conventional stripline-type monitor with eight electrodes fabricated from stainless steel (SUS304) with $\pi/4$ rotational symmetry. The stripline length ($L = 132.5$ mm) was determined to be as long as could possibly be installed into the limited spaces in the beam line, so as to increase the signal-to-noise ratio. The pipe radius ($R = 23.4$ mm) and the angular width ($\alpha = 15^\circ$) of the electrode were chosen so as to comprise a $50 \, \Omega$-transmission line. Eight pickups with a relatively narrow angular width are mounted with a tilt of $\pi/8$ radian at the symmetrical polar coordinates. A $50 \, \Omega$ vacuum feedthrough (SMA) is connected to the upstream side of each electrode, while the downstream end is short-circuited to a vacuum pipe in order to simplify the mechanical manufacturing process.

(a)  
(b)

Fig. 34. (a) Schematic cross-sectional drawing of the energy-spread monitor and (b) the ESM installed at the third switchyard for the KEKB electron beam.
Three locations for the energy-feedback controls have been installed at the injector linac. Energy-spread feedback controls were implemented along the beam line in order to stabilize the energy spreads of the beams at different locations along with other beam-orbit and energy feedback controls. One energy-feedback control is at the large energy dispersion section in the J-arc, and the other two are at the beam switchyard. The energy spreads of the 1.7 GeV electron and primary electron beams for positron production are stabilized at the J-arc. The energy spreads of the 3.5 GeV positron and 8 GeV electron beams are controlled at the end of the beam switchyard. These energy-feedback controls have successfully stabilized the energy spread of each beam at different locations without any interference with the orbit- and energy-feedback control system during daily operation. The software structure on the data acquisition and feedback algorithm is reported in detail elsewhere [50, 51].

The main purpose of this feedback control is to suppress the fluctuation in the energy spread caused by the drift in the sub-booster klystron rf phases, which mainly originates from variations in the facility environmental parameters (room temperature and cooling-water temperature, etc.) with a relatively long-term period in the klystron gallery. The performance of the energy-spread feedback control was investigated with the primary electron beam for positron production at the J-arc under the nominal operation condition for KEKB injection. Figure 35 shows a typical example of the correlation scatter plot and projected energy-spread distributions for the primary electron beam in two-bunch acceleration mode with the feedback control on and off over seven days. In this measurement, the other beam-feedback controls, the energy and orbit feedbacks, were also working well without any interference with the energy-spread feedback control. Here, the solid lines indicate Gaussian

![Fig. 35. Correlation scatter plot and the projected energy spread distributions for the first and second bunches of the primary electron beam for positron production in the two-bunch acceleration mode measured at the J-arc section with the feedback control on and off.](image)
fitting functions for the first and second bunches with the feedback control on and off. The energy
spreads of the two bunches were stabilized within $0.50 \pm 0.02\%$ ($0.51 \pm 0.08\%$) with the feedback
control on (off) for the first bunch, and within $0.55 \pm 0.06\%$ ($0.62 \pm 0.08\%$) with the feedback
control on (off) for the second bunch. The errors indicate one-sigma standard deviations in the
Gaussian fitting functions. The energy-spread values with the feedback control on are very consistent
with the designed energy spread at the J-arc. The results clearly show that the fluctuations in the
energy spread were satisfactorily reduced over the time period with the feedback control on. It is
worth stressing here that although the same rf phase for the sub-booster klystron was set by following
the feedback control in order to simultaneously stabilize the two bunches, the stability of the energy
spread for the first bunch was better than that for the second bunch. This might come from the beam-
loading effect caused by the first bunch at the pre-injector. There were no remarkable differences in
the measured energy spread for the injection electron beam at the J-arc with the feedback control on
and off during the same seven days. The energy spread was $0.33 \pm 0.01\%$ during KEKB injection.
Thanks to the successful energy-spread feedback control at the J-arc under the nominal operation
condition, the first (second) bunch of the 3.5 GeV positron beam at the beam switchyard has
been satisfactorily stabilized within $0.39 \pm 0.01\%$ ($0.36 \pm 0.03\%$) even without the feedback
control at the downstream location. Thus, the energy-spread feedback control system has been suc-
cessfully working in daily operation for the KEKB collider experiment.

4.3. Fast data acquisition system for the BPM

A non-destructive BPM is an indispensable diagnostic tool for stable beam operation. In the KEKB
injector linac, 96 BPMs with four stripline-type electrodes have been installed and utilized for beam
position measurement and feedback [44]. The previous BPM control system comprises two work-
stations based on hp Tru64 UNIX and twenty dedicated DAQ systems. Many X-server terminals
and Windows-based PCs are utilized as the client machines. The measured beam position can be
available via a command-line program and graphical user interface provided by the Tcl/Tk scripting
language.

The original DAQ system was installed in the linac klystron gallery at nearly equal intervals along
the beam line. Each DAQ system takes charge of signal processing from approximately 4 BPMs.
A schematic drawing of the original DAQ system is shown in Fig. 36. It comprises a VME computer,
a digital oscilloscope as an analog signal digitizer, and two signal combiners in a cable combiner
box. The VME computer crate contains a CPU board with a 68 060 microprocessor managed by
the OS-9 real-time operating system and a general purpose interface bus (GPIB) board. The GPIB
board is used for data communication between a VME CPU and an oscilloscope, which is a
Tektronix TDS680B/C with a sampling rate of 5 GSa/s and an A/DC resolution of 8 bits. It has
an analog bandwidth of 1 GHz.

The four signals of bipolar shape coming from one BPM are fed to two signal combiners. One of
these combiners sums the signals of horizontally placed electrodes and the other sums the signals of
vertically placed electrodes. The signal-combining scheme allows us to reduce the number of
required A/DC channels and increase the number of BPMs controlled by one DAQ system. In the
combiner box, cables corresponding to a time delay of 7 ns are used to avoid the waveform overlap-
ing. The two combined signals are digitalized by an oscilloscope at a sampling rate of 5 GHz. The
digitalized signals are analyzed by a VME computer in order to calculate the beam parameters, which
are the beam charge and horizontal and vertical beam positions. In this data processing, the cable loss
factors and calibration coefficients with third-order polynomial are taken into account. The trigger pulse signals, which are synchronized with the linac beam, are generated by using 16-bit digital time-delay modules at the central timing station. These are provided to all oscilloscopes at a 0.7 Hz cycle. Though the maximum repetition rate for beam operation is 50 Hz for KEKB injection, this is not acceptable for the normal operation of the oscilloscope because of the oscilloscope performance. For this reason, the trigger pulse is reduced to a sufficiently low repetition rate to digitalize the waveform.

For the simultaneous top-up operation as mentioned in Sect. 2, all beam positions by pulse-to-pulse should be measured since each beam of 50 Hz repetition could be delivered using three different rings. The old DAQ system has been replaced by a new one because the repetitive DAQ speed of the old one was limited by about 1 Hz. In the new system, the existing VME CPUs and old oscilloscopes have been replaced by fast WindowsXP-based digital oscilloscopes (Tektronix DPO7104). The new DAQ system has a sampling rate of 10 GSa/s, an A/DC resolution of 8 bits, and an analog bandwidth of 1 GHz. Its speed performance is beyond 150 Hz for the 4-channel simultaneous acquisition of 10 kilo data points. It shows a good enough performance for our purpose.

In the new system, each output of the combiner box is divided again into two signals with equal amplitude. Since it is impossible to change the vertical scale of the oscilloscope in 20 ms intervals, CH1/CH2 and CH3/CH4 are used for the measurement of low-charge (0.1–1 nC) and high-charge

Fig. 36. Schematic drawing of the original BPM DAQ system.
(10 nC) beams, respectively, as shown in Fig. 37. The new DAQ software is running on the fast oscilloscope, and each system can work as an EPICS input/output controller (IOC). The calculated beam position and charge are stored on the EPICS record corresponding to each beam mode. The current beam mode information can be retrieved via the EPICS record of the event system, which is renewed every 20 ms. The beam position measurement precision of the new system has been evaluated by using the 3-BPM method [44], and its result shows around 50 μm for both the horizontal and vertical directions. This measurement precision surpasses that for the previous system, 100 μm. A similar system has been installed and operated for the BPM of the beam transport line [52].

4.4. Upgrade of screen-monitor-control system

The screen-monitor-control system has been newly upgraded in preparation for the Super KEKB-factory project. The screen monitor (SC) of the KEKB linac is a beam diagnostics device to measure transverse beam profiles with a fluorescent screen. The screen material is made of 99.5% Al₂O₃ and 0.5% CrO₃ (AF995R, Demarquest Co.), with which a sufficient amount of fluorescent light can be obtained when electron and positron beams impinge on the screen. By detecting
the fluorescent light with a camera embedded with a charge-coupled device (CCD), the transverse spatial profiles of the beam can be easily measured.

Compact SCs were previously developed in 1995 for the KEKB project. About 110 compact SCs were installed into the beam line at that time. The mechanical design was reported in detail elsewhere [53], and a new VME-based computer control system was also developed in order to perform fast and stable control of the monitor system [54]. The compactness of the monitor along with the fast control system made it possible to decrease the driving time of the monitor (∼0.2 sec) from its home position to the center of the beam line.

The SC system worked stably until the end of KEKB operation at the end of June 2010. However, after ∼15 years from the commencement of the KEKB operation, it was very difficult to maintain the control system because most VME modules had gone out of production. This is the reason why we need to develop a new control system.

A block diagram of the SC system is shown in Fig. 38. The screen actuator comprises a driving rod and an air cylinder driven by compressed air through a solenoid valve. The screen actuator controls the screen motion into the center of the beam line. Fluorescent light emitted from the screen through a glass viewport is guided down to floor level by optical mirrors, and the fluorescent light is detected by a CCD camera. The video signals from the camera are sent to a monitor control station at the klystron gallery, where a video-signal selector selects a particular channel corresponding to the required SC by following the implementation of the control system. Then, the selected video signal is sent to the main control room through optical-fiber cables after converting the electrical signal to an optical signal with an electro-optic converter (E/O module). The beam-profile image can be monitored with a TV monitor.

Fig. 38. Block diagram of the screen-monitor system.
The new control system is a PLC-based control system (CPU: MPC8347E/ YOKOGAWA [55], 533 MHz) in which Linux-based server programs are running in the EPICS environment, as shown in Fig. 39. The basic functions provided by the server are actuator control and selection of the specified video signal. When the server receives a control request from an operator interface (OPI) through the linac control network, it selects a channel of the digital relay output (DO) module corresponding to the specified screen, and then the DO implements the actuator control, as shown in Fig. 39. The limit switch signal of the actuator positions is fed into a digital input (DI) module. The DO module is also used as a video-signal selector in which a video signal outputs from 8 input channels.

The software of the new control system has been developed in an EPICS- and Linux-based environment [56]. Through an OPI, an operator gives a command to work a specified SC. An IOC program on the PLC selects a specified I/O channel through a device support corresponding to the specified SC according to a database. At the same time, a sequencer program reads the position status of all other SCs. The main OPI program was developed by using the Python script language, and another OPI was developed for program testing by using Motif Editor and Display Manager in the EPICS environment. Twelve four-VME-based control systems in total were finally replaced in summer 2011 with new PLC-based ones. The new SC system has now been working well as a whole without any fatal problems.

5. Operation and safety system

5.1. Progress in beam operation and statistics

5.1.1. Overview. After successful initial operation of the injector linac for KEKB, two major milestones have been achieved in the progress of operation, drastically improving both the peak and integrated luminosity of KEKB, as described in the previous sections: positron two-bunch operation for KEKB, and simultaneous top-up injection into three different rings (KEKB HER/LER and PF, Sect. 2).
5.1.2. Positron two-bunch operation. In order to double the positron intensity, the number of bunches generated in the linac was increased to two, which is ultimately the maximum due to the non-integer relations between the rf frequencies of the linac and the KEKB rings. This requires that high-intensity, two-bunch electron beams should be stably accelerated to the positron production target for sufficient yield of positrons. Thus, steady acceleration and transport of high-intensity electron beams has become crucial in linac operation. High-intensity two-bunch electron beams mainly suffer from two kinds of problems besides single-bunch wake effects: multi-bunch wake effects in both longitudinal and transverse directions. The longitudinal-wake effect causes an energy difference between the two bunches, while the transverse one may induce orbit deviation between the two bunches. The energy difference caused by the longitudinal wake field of the first bunch is equalized utilizing the SLED gain curve, as shown in Fig. 40, while the orbit deviation of the two bunches is minimized by adjusting the beam steering. In these careful beam tunings, the primary two-bunch electron beam with bunch charges of 8 nC each has been stably accelerated to the positron target so that the positron charge has been doubled, as shown in Fig. 41.

![Fig. 40. Loading compensation of a high-current, two-bunch beam.](image1)

![Fig. 41. Orbits and charges of two-bunch primary-electron and positron beams: blue dots indicate the first bunch and green the second bunch. The positron target is located in the middle along the linac: the upstream direction shows primary electron beams and the downstream positron beams.](image2)
5.1.3. **Simultaneous injection into three different rings.** The three rings require totally different beams: energy from 2.5 GeV to 8 GeV, charge from 0.1 nC to 1 nC (10 nC for positron production), and different kinds of particles (positrons and electrons, Table 10). In order to meet these requirements without any pulsed quadrupole magnets, a common optics for the different beams has been established so that the three beams can be successfully accelerated and transported to the rings as described in Sect. 2. The energy of each beam is adjusted to that of each ring by fully utilizing the event system described in Sect. 4.1, while minimizing the regions at different energies along the linac for the common optics. The rf system was upgraded in 2000 for KEKB. Since various frequencies are used in the linac (such as 10.385 MHz and 508.2 MHz for KEKB, and 114.2 MHz, 571.2 MHz, and 2856 MHz for the linac), stable phase relations between these signals are important for simultaneous injection. By using a newly developed thermostatic chamber (temperature stability of $\pm 0.02^\circ$C), the phase drifts of these signals are kept to less than a few picoseconds [57, 58].

Beam tuning for simultaneous injection has been quite complicated, especially due to the limited number of pulsed steering coils for orbit correction: the simultaneous orbit correction method is applied in the last section of the linac where careful beam switching to each ring is needed. Simultaneous injection has thus been continued without any serious operational problems so as to contribute to the great improvement of the KEKB accelerator performance.

|       | Particle  | Energy (GeV) | Charge (nC) |
|-------|-----------|-------------|-------------|
| KEKB HER | Electron  | 8           | 1           |
| KEKB LER | Positron | 3.5         | 1           |
|         | Primary electron | 4         | 8           |
| PF     | Electron  | 2.5         | 0.1         |

5.1.4. **Operation statistics.** Even with the sophisticated operation mode in the linac, the characteristics of all the beams for the four rings have been maintained very satisfactorily. Figure 42 shows the operation history of the linac since the beginning of the PF commissioning: the magenta curve shows the operation time in years and the green line shows the integrated total operation time, while the blue curve indicates the percentage of time for machine failures. After an initial growth in the

![Fig. 42. Operation history of the KEK electron/positron injector linac.](http://ptep.oxfordjournals.org/Downloaded from http://ptep.oxfordjournals.org/)
machine failure time, this has gradually decreased so that the machine availability has surpassed 99%.

5.2. Safety system upgrade for simultaneous top-up injection

Before simultaneous top-up injection started, there were four injection modes in the linac beam operation, “KEKB mode”, “PF-ring mode”, “PF-AR mode”, and “linac mode”. “Linac mode” is not a beam injection mode but a stand-alone operation for linac beam study or tuning. Two modes could not be selected at the same time since each mode was exclusive. When all the safety interlock conditions were established, once a mode button on the linac operation panel was selected and a “beam request” signal came from the corresponding ring accelerator, the mode was held and the linac was ready for the beam injection.

Since September 2005, two injection modes, “KEKB” and “PF-ring”, have been combined into “KEKB and PF-ring mode”. This is used for simultaneous top-up injection and for conventional independent injection as well. The beam request from the rings is still indispensable in the new injection mode, since unexpected beam injection to the rings should be protected. In this safety system update, we have slightly rearranged the layout of the linac operation panel and reprogrammed the interlock logical software on the PLC.

In March 2009, the mode selection rule was changed again. “Linac mode” can be set concurrently with “KEKB and PF-ring mode”. If injection is performed to the PF-ring and not to KEKB, we can study the KEKB beam under linac stand-alone conditions, and vice versa.

5.3. Beam-charge interlock system

A new beam-charge interlock (BCI) system has been developed for radiation safety and machine protection at the KEKB injector linac. The new BCI system restricts the integrated amount of beam charges delivered to the four different storage rings (KEKB LER/HER, PF, and PF-AR) at six locations along the linac and beam transport lines. Although a software-based interlock system based on the beam-position monitor system was previously working, the system was replaced with the new hardware-based interlock system based on the wall-current monitor (WCM) system [59] to improve operational performance and reliability for a new injection scheme (so-called simultaneous top-up injection). The new BCI system generates and sends beam-abort-request signals directly to the radiation safety control system of the injector linac with hard-wired cables when the integrated amount of detected beam charges is beyond a certain prescribed threshold level. In such a case, the radiation safety control system stops the beam operation. The hardware and software developments have been described in detail elsewhere [12, 60, 61].

Based on the developed BCI system, several proper environments were advanced to the present linac operation in preparation for the Super KEKB-factory project. One is to increase the beam intensity of the linac for machine studies, the second is to enable stable and continuous injection over an hour to the PF-AR, the third is to enable easy beam tunings for PF injection with the use of a new beam dump, and the last is to enable simultaneous top-up injection for both the KEKB and PF rings [57, 58].

The maximal permissible integrated amounts of beam charges are prescribed at each location and they are defined as the integrated amount of beam charges measured per second and/or per hour, depending on each location. Thus, the injection beam intensity can be controlled every hour and/or every second. In particular, the instantaneous beam intensity has been relaxed by two times in
comparison with the previous operation of the linac. This modification has also enabled us to perform machine studies with high bunch charges in preparation for future projects.

A block diagram of the BCI system with the use of a WCM is shown in Fig. 43. Pulsed beam signals from the WCM are directly received by the detection electronics through a coaxial cable. The detection electronics detects the pulse signals by-pulse by-pulse at a detection rate greater than 50 Hz. It measures the integrated amount of signal charges based on a charge-integrating circuit, and it transforms the signal charges into beam charges with the use of beam-charge calibration coefficients obtained in bench tests [12].

A programmable logic controller (PLC) controls the detection electronics and receives integrated-beam-charge data from it every second. When the integrated amount of beam charges exceeds a certain threshold level prescribed at each location, the beam-abort request generated from the detection electronics is directly transmitted to the safety PLC of the radiation safety control system installed in the main control room. After receiving the beam-abort request, the safety PLC immediately inhibits the transmission of trigger signals to the electron gun.

The results of the beam tests and obtained operational performance are summarized in detail in Ref. [61]. The results show good linear relations of the beam charges integrated every second depending on the beam repetition rate obtained for one-bunch and two-bunch acceleration modes. The results also indicate good linearity within 1% and with a dynamic range of \( \approx 20 \) dB.

In nominal linac operation, the typical integrated intensities are \( \approx 3\% \) of the beam charges prescribed at the KEKB location, while the maximum integrated intensity attained is up to \( \approx 10\% \) (or \( \approx 6 \times 10^4 \) nC/h) of the beam charges. This level corresponds to the integrated beam charges in stable continuous injection operation, in which electron and positron injection is alternated every few minutes. Thus, we can understand that in nominal operation conditions the measured beam intensity is far enough away from the prescribed beam charges (5.76 \( \times 10^5 \) nC/h). We can also confirm that the BCI system was properly reset every clock hour, and it successfully continued the measurement after the reset without any time delay.

The BCI system enables other important data to be stored, i.e., the beam charges and the shot numbers integrated during 1 day and 1 week at each location. The 1-week beam-charge data
depending on the injection modes are required for radiation-safety records in the linac operation. We had no such type of data logging system until now. It is expected that these data will show important operational history, not only for radiation safety but also for the long-term stability and reproducibility of the linac operation.

6. Summary

The KEKB injector linac has been continuously improved, aiming at advanced and stable beam operation in this decade while maintaining injection for the four independent storage rings. The original beam injection for KEKB was carried out every 90 min while the injection for PF and PF-AR was conducted several times daily. To increase the integrated luminosity and stability of beam collision tuning, dual-bunch beam injection to KEKB resulted in a shortened beam injection time in April 2003. In addition, the beam injection interval was shortened to every several minutes in February 2005. The development of the new positron production target using crystalline tungsten had a great effect on enhancing the positron beam intensity. Four S-band accelerating structures were replaced by eight C-band structures to raise the energy margin and increase the reliability of daily beam operation.

In April 2010, we achieved simultaneous top-up injection for three independent rings (KEKB HER/LER and PF) by the practical application of the new fast BPM DAQ system, the event-based timing and control system, the pulsed magnet system, and the excellent compatible beam optics for three beam modes with different energies. With the great success of the simultaneous top-up operation, we achieved stored current stabilities of 0.05% and 0.01% for the KEKB and PF rings, respectively. Such high current stabilities can lead to great improvements in experimental efficiency in both the KEKB and PF rings. The achievement of this milestone has been brought about by the great effort made by all members of the injector linac, KEKB, and PF groups.

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References

[1] I. Abe et al., Nucl. Instrum. Methods Phys. Res., Sect. A 499, 167 (2003).
[2] A. Enomoto, Proc. LINAC96, p. 633 (1996).
[3] T. Kamitani et al., Proc. APAC’98, p. 429 (1998).
[4] K. Furukawa, N. Kamikubota, T. Suwada, and T. Obata, Proc. ICALEPCS2001, p. 266 (2001).
[5] S. Ohsawa, A. Enomoto, E. Kikutani, K. Furukawa, N. Iida, M. Ikeda, N. Kamikubota, T. Kamitani, H. Kobayashi, H. Koiso, T. Matsumoto, Y. Ogawa, Y. Ohnishi, K. Oide, and T. Suwada, Proc. PAC2001, p. 3284 (2001).
[6] Y. Ogawa, A. Enomoto, K. Furukawa, H. Kobayashi, T. Matsumoto, S. Ohsawa, and T. Suwada, Proc. HEACC2001 (2001).
[7] K. Ebihara, M. Kikuchi, H. Nakayama, Y. Sakamoto, I. Sato, K. Satoh, and M. Toda, “AR INJECTION LINE OF TRISTAN”, KEK Internal 85-17, February 1986.
[8] Strategic Accelerator Design (SAD). (Available at: http://acc-physics.kek.jp/SAD/ last accessed December 2012)
[9] N. Iida and M. Kikuchi, Proc. LINAC2006, p. 85 (2006).
[10] N. Iida et al., Proc. EPAC2006, p. 1505 (2006).
[11] M. Tawada, M. Kikuchi, T. Mimashi, S. Nagahashi, and A. Ueda, Proc. PAC’09, p. 175 (2009).
[12] T. Suwada, E. Kadokura, M. Satoh, and K. Furukawa, Rev. Sci. Instrum., 79, 023302 (2008).
[13] K. Furukawa, M. Satoh, T. Suwada, T. Kudou, S. Kusano, A. Kazakov, G. Lei, and G. Xu, Proc. LINAC2008, p. 404 (2008).
[14] K. Furukawa, T. Suwada, M. Satoh, E. Kadokura, and A. Kazakov, Proc. EPAC2006, p. 3071 (2006).
[15] T. Kamitani et al., Proc. XXIV Int. Linac Conf. (LINAC’08), p. 407 (2008).
[16] Y. Ohnishi, T. Kamitani, N. Iida, M. Kikuchi, K. Furukawa, M. Satoh, K. Yokoyama, and Y. Ogawa, Proc. XXIV Int. Linac Conf. (LINAC’08), p. 413 (2008).
[17] T. Kamitani et al., Proc. 7th European Particle Accelerator Conf. (EPAC2000), p. 1507 (2000).
[18] T. Shintake et al., Proc. EPAC96, p. 492 (1996).
[19] T. Kamitani, N. Delerue, M. Ikeda, K. Kakihi, S. Ohsawa, T. Ogoee, T. Sugimura, T. Takatomi, S. Yamaguchi, K. Yokoyama, and Y. Hozumi, Proc. LINAC 2004, p. 663 (2004).
[20] T. Sugimura, S. Ohsawa, S. Yamaguchi, T. Kamitani, T. Ogoee, M. Ikeda, and K. Kakihi, Proc. 28th Linear Accelerator Meeting in Japan, TP-12 (2003) [in Japanese].
[21] ANSYS HFSS (Available at: http://www.ansys.com/Products/Simulation+Technology/Electromagnetics/High-Performance+Electronic+Design/ANSYS+HFSS, date last accessed December 2012).
[22] H. Matsumoto et al., KEK preprint 92-179.
[23] A. Fiebig, R. Honbach, P. Marchand, and J. Pearce, CERN/PS 87-45 (1987).
[24] T. Sugimura, T. Kamitani, K. Yokoyama, K. Kakihi, M. Ikeda, and S. Ohsawa, Proc. LINAC 2004, p. 754 (2004).
[25] CST - Computer Simulation Technology (available at: http://www.cst.com/, date last accessed December 2012).
[26] H. Honma, T. Shidara, S. Anami, and I. Sato, Proc. LINAC94, p. 436 (1994).
[27] M. Akemoto, H. Honma, H. Nakajima, T. Shidara, and S. Fukuda, Proc. 5th Annual Meeting of Particle Accelerator Society of Japan and the 33rd Linear Accelerator Meeting in Japan, p. 892 (2008) [in Japanese].
[28] S. Fukuda, K. Hayashi, S. Maeda, S. Michizono, and Y. Saito, Appl. Surf. Sci. 146, 84 (1999).
[29] H. Tsutsui, “Two-dimensional modeling of klystron traveling-wave-type output structure and its empirical justification”, KEK Report 99-3, August 1999.
[30] S. Michizono, T. Matsumoto, K. Nakao, T. Takenaka, S. Fukuda, and K. Yoshida, Proc. LINAC2004, p. 745 (2004).
[31] S. Michizono, Y. Saito, T. Matsumoto, S. Fukuda, and S. Anami, Appl. Surf. Sci. 169–170, 742 (2001).
[32] S. Yu. Kazakov, KEK preprint 98-140 (1998).
[33] S. Michizono, Y. Saito, S. Yamaguchi, S. Anami, N. Matuda, and A. Kinbara, IEEE Trans. Electr. Insul. 28, 692 (1993).
[34] W. Steele, IEEE Trans. Microwave Theory Tech. 14, 70 (1966).
[35] T. Suwada et al., Phys. Rev. ST Accel. Beams 10, 073501 (2007).
[36] T. Suwada et al., Phys. Rev. E 67, 016502 (2003).
[37] T. Suwada and K. Furukawa, Proc. PAC’09, p. 518 (2009).
[38] R. Chehab, F. Couchot, A. R. Nyaiesh, F. Richard, and X. Artru, Proc. PAC’89, p. 283 (1989).
[39] V. N. Baier, V.M. Katkov, and V. M. Strakhovenko, Electromagnetic Processes at High Energies in Oriented Single Crystals (World Scientific, Singapore, 1998).
[40] A. Enomoto, T. Kamitani, T. Ogoee, K. Kakihi, S. Ohsawa, I. Sato, and A. Asami, Proc. EPAC’92, p. 524 (1992), Vol.1.
[41] T. Korhonen and M. Heiniger, Proc. ICALEPCS2001, p. 638 (2001).
[42] http://www.mrf.fi/ (last accessed December 2012).
[43] K. Furukawa, M. Satoh, T. Suwada, T. T. Nakamura, T. Kudou, S. Kusano, T. Nakamura, and A. Kazakov, Proc. ICALEPCS2009, p. 765 (2009).
[44] T. Suwada, N. Kamikubota, H. Fukuma, N. Akasaka, and H. Kobayashi, Nucl. Instrum. Meth. A 440, 307 (2000).
[45] K. Furukawa, A. Enomoto, N. Kamikubota, T. Kamitani, Y. Ogawa, S. Ohsawa, K. Oide, and T. Suwada, Proc. ICALEPCS’99, p. 248 (1999).
[46] R. H. Miller, J. E. Clendenin, M. B. James, and J. C. Sheppard, Proc. 12th Int. Conf. High-Energy Accelerators (HEAC’83), Illinois, U.S.A., 1983, pp. 602–605.
[47] T. Suwada, Jpn. J. Appl. Phys. 40, 890 (2001).
[48] T. Suwada, Proc. XXth Int. Linac Conf. (LINAC2000), p. 199 (2000) [SLAC Report No. SLAC-R-561, eConf C000821].
[49] T. Suwada, M. Satoh, and K. Furukawa, Phys. Rev. ST Accel. Beams 6, 032801 (2003).
[50] T. Suwada, M. Satoh, and K. Furukawa, Phys. Rev. ST Accel. Beams 8, 112802 (2005).
[51] J. J. DiStefano, III, A. R. Stubberud, and I. J. Williams, Theory and Problems of Feedback and Control Systems (McGraw-Hill, New York, 1990), 2nd ed., p. 22.
[52] T. Aoyama, T. Nakamura, K. Yoshii, N. Iida, M. Satoh, and K. Furukawa, Proc. ICALEPCS2009, p. 495 (2009).
[53] T. Suwada, A. Enomoto, T. Urano, and H. Kobayashi, Proc. 20th Linear Accelerator Meeting in Japan, p. 245 (1995).
[54] T. Suwada, N. Kamikubota, K. Furukawa, and H. Kobayashi, Proc. 22th Linear Accelerator Meeting in Japan, p. 329 (1997).
[55] Yokogawa (available at: http://www.yokogawa.com/, date last accessed December 2012).
[56] Experimental Physics and Industrial Control System (available at: http://www.aps.anl.gov/epics/, date last accessed December 2012).
[57] Y. Yano, S. Aizawa, and S. Fukuda, Proc. 27th Linear Accelerator Meeting, p. 320 (2002).
[58] Y. Yano, S. Aizawa, and S. Anami, Proc. 28th Linear Accelerator Meeting, p. 345 (2003).
[59] T. Suwada, K. Tamiya, T. Urano, H. Kobayashi, and A. Asami, Nucl. Instrum. Meth. A 396, 1 (1997).
[60] E. Kadokura, T. Suwada, M. Satoh, and K. Furukawa, Proc. ICALEPCS’07, p. 149 (2007).
[61] T. Suwada, E. Kadokura, M. Satoh, and K. Furukawa, Proc. XXIV Int. Linac Conf. (LINAC’08), p. 579 (2008).
[62] M. Satoh, Proc. 10th European Particle Accelerator Conf. (EPAC’06), p. 855 (2006).
[63] K. Furukawa, T. Suwada, M. Satoh, E. Kadokura, and A. Kazakov, Proc. 10th European Particle Accelerator Conf. (EPAC’06), p. 3071 (2006).