

KEKB INJECTION DEVELOPMENTS

K. Furukawa*, Injector Linac group

High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
SOKENDAI (The Graduate University for Advanced Studies), Tsukuba, 305-0801, Japan

Abstract

The e^-/e^+ SuperKEKB collider is now under commissioning. As e^-/e^+ beam injection for SuperKEKB greatly depends on the efforts during the previous KEKB project, the injection developments during KEKB are outlined as well as the improvements towards SuperKEKB. When KEKB was commissioned, approximately ten experimental runs per day were performed with e^-/e^+ injections in between. As another collider PEP-II had a powerful injector SLAC, the KEKB injector had to make a few improvements seriously, such as injection of two bunches in a pulse, continuous injection scheme, eventual simultaneous top-up injections, as well as many operational optimizations. The design of SuperKEKB further required the beam quality improvements especially in the lower beam emittance for the nano-beam scheme, as well as in the beam current for the higher ring stored current and the shorter lifetime.

INTRODUCTION

The energy-asymmetric electron-positron collider, KEKB B-Factory, had been operated successfully for 11 years from 1999 to 2010. It had contributed to the intensity frontier of particle physics by achieving the world highest luminosity at the time. During that period the operation of the collider became much advanced compared with the previous project TRISTAN [1].

In order to meet the beam injection requirements to the collider the injector went through a major reconstruction. The goal was essentially a higher injection rate with a full-energy injection and was mainly achieved by increasing the electron injection energy from 2.5 GeV up to 8 GeV. As the injection aperture became rather small down to 30 ps, the ring RF frequency was modified to have an integer relation between the injector and the ring [2]. The injector accomplished substantial progress during the KEKB period as well. Challenges from many different viewpoints were made to improve the machine. While many of them did not immediately provide meaningful contributions, accumulation of those trials brought significant difference in the performance of injector operation [3].

The collider has been upgraded for the SuperKEKB project since 2010 and is expected to be able to further elucidate the flavor physics of elementary particles with 40-fold improved luminosity, by doubling the stored beam current and also by the nano-beam scheme to shrink the beam size down to a twentieth at the interaction point [4, 5].

The upgrade for SuperKEKB was again a major challenge at the injector. The nano-beam scheme demands fairly small

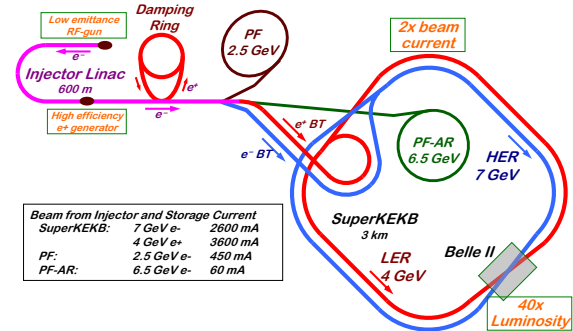


Figure 1: Layout of electron/positron accelerator complex with beam properties from the injector linac into four storage rings of SuperKEKB-HER, LER, PF and PF-AR.

transverse and longitudinal phase space as well as several times higher beam charge of the injection beams. The electron beam would be realized employing a newly designed RF gun [6]. The positron beam would be achieved with combination of a newly installed flux concentrator and a damping ring [7, 8].

Figure 1 shows the accelerator complex configuration at KEK. The injector linac delivers the beams not only to the SuperKEKB high-energy ring (HER) and low-energy ring (LER) but also to light sources of photon factory (PF) and photon factory advanced ring (PF-AR). Even during the SuperKEKB upgrade construction the injector was required to inject the beam into two light source storage rings [9].

Those injection developments during KEKB operation and SuperKEKB upgrade are described in this paper.

KEKB OPERATION

Two B factories of PEP-II and KEKB were operational at the same time [10]. While the SLAC injector to PEP-II was powerful enough, every endeavor at injector was made to satisfy the stable injection into KEKB.

For example, as the beam fluctuation was large in the early stage of the KEKB project, many stabilization loops were installed for beam properties like energies and orbits [11]. For energy stabilization a simple PI (proportional-integral) loop was applied between BPMs (beam position monitors) and RF systems as in Fig. 2. Many of those loops were dependent on the beam modes where the beams were injected. Thus, a feedback loop management tool was constructed to supervise those many closed loops as in Fig. 3.

The construction of beam dumps at the middle of the both electron and positron beam transports to HER and LER have assisted the beam quality measurement without injection. It was extremely useful and used everyday.

* kazuro.furukawa@kek.jp

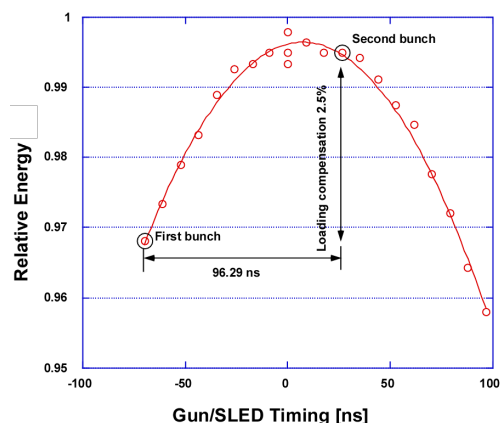


Figure 6: Beam loading compensation to equalize bunch energies in two-bunch acceleration.

tion were important to evaluate the properties of those two bunches separately and simultaneously without losing the accuracy. Among several beam properties, BPMs, a bunch monitor (streak camera) and wire scanners were improved. Transverse and longitudinal wakefield compensations were crucial. Figure 6 shows an example how energies of those two bunches were equalized by changing the RF pulse timing. Those energies were observed continuously and equalized by a closed loop [14].

While timings of gun and RF systems were carefully tuned, properties of those bunches had slight discrepancies. Nevertheless, the injection rate was improved at least by 65%.

Three-bunch acceleration was once considered for SuperKEKB by flattening RF pulses. It turned out to be cost ineffective.

CONTINUOUS INJECTION

If it was possible to eliminate the period with the detector HV turned off, the integral luminosity should be significantly improved. Such an experimental mode is called top-up (top-off) injection or continuous injection. However, the effect of injection beam background had to be suppressed. The injection beam background to Belle detector was carefully examined in order to realize the continuous injection. While the both KEKB and Belle were improved, central drift chamber (CDC) and time of flight (TOP) detectors as well as the data taking system were especially improved. The data acquisition was vetoed for 2 ms just after the injection.

Figure 7 and 8 show the machine status history for 8 hours before and after the introduction of the continuous injection to the KEKB operation. The detector HV was always applied in the latter case. This new injection mode was another major step forward in early 2004, and approximately 26% gain was achieved in the integral luminosity [15].

In the continuous injection made the run length optimization became meaningless, and shorter switching time between electron and positron injections was pursued. Figure 9 plots the number of beam mode transitions per year between injections into four storage rings of KEKB-HER,

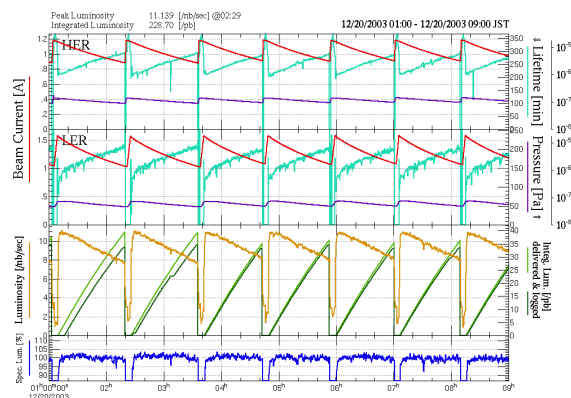


Figure 7: Storage beam currents and luminosity for 8 hours before the continuous injection was applied.

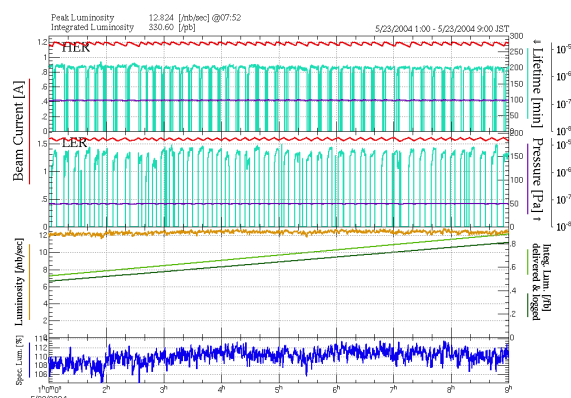


Figure 8: Machine history for 8 hours after the continuous injection was applied. Nearly 30% increase in integral luminosity was achieved.

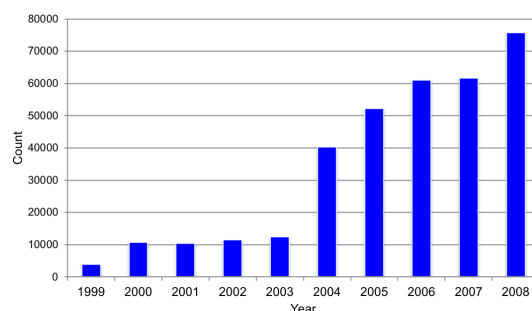


Figure 9: Beam mode transitions per year between injections into KEKB-HER, KEKB-LER, PF and PF-AR.

KEKB-LER, PF and PF-AR. At the beginning it took several minutes to change 500 device parameters. Later, the devices and the software as well as quality assurance measures were improved and the transition time was shortened down to 20 seconds, and the modes were switched about 360 times per day in 2008.

SIMULTANEOUS TOP-UP INJECTIONS

Even faster beam mode transition had been examined since 2005 just after the continuous injection was introduced. Many devices in the injector were redesigned to make their

property changes within a pulse *i.e.* 20 ms. Such a fast beam mode transition should enable the simultaneous top-up injection at KEKB-HER, LER and PF. The fast energy change required installation of fast low-level microwave (LLRF) controls, for example. Most of the 60 high-power microwave stations were used to accelerate 8-GeV electron beam for KEKB-HER injection, while 1/3 of them were used to decelerate the high-energy beam down for PF injection with very different LLRF configuration. As beam charges for PF injection and positron generation were 100-times different, those longitudinal wakefield had to be compensated by LLRF configuration as well.

Following items were a part of 150 control parameters that were modulated every pulse, and many more monitored points.

- voltage and picosecond timing for electron gun
- LLRF timings and phases for 14 RF stations
- high-power RF timings for 60 RF stations
- 14 pulsed magnets and solenoids
- injection RF phases and bucket selections for KEKB rings
- 150 BPMs at linac and BT

The control system was also redesigned with a concept of dual tier controls as in Fig.10 [16]. Existent EPICS (Experimental Physics and Industrial Control System) controls provided the equipment parameters for one of beam modes, which were arranged asynchronously. Event-based global and synchronized controls with MRF event and timing transmission system sent an event notification fiducial every 20 ms to realize pulse-to-pulse injector modulations (PPM).

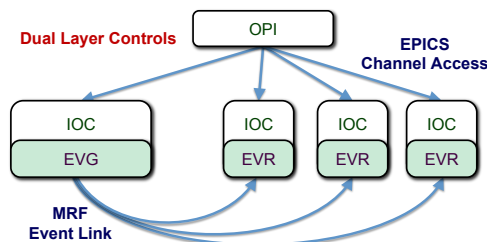


Figure 10: Dual-tier controls with EPICS CA at the top and fast event synchronized controls at the bottom.

The event generator sent timing signals and event control data to many event-receiver stations arranged in a star-like topology. Each link between the event generator and a receiver consisted of a single optical fiber, and provided both synchronized timing signals (with a precision of approximately 10 ps) and synchronized controls through a realtime software mechanism (with a precision of about 10 μ s). Recent technological advances in field-programmable gate arrays (FPGAs) and small form-factor pluggable transceivers (SFPs) had enabled reliable controls in this configuration.

The simultaneous injection was established at early 2009, and succeeded in stabilizing the stored beam current to 0.05% (1mA) at the KEKB HER and LER and 0.01% (0.05mA) at PF. It contributed PF for higher quality light source experiments. For KEKB, crab cavities were intro-

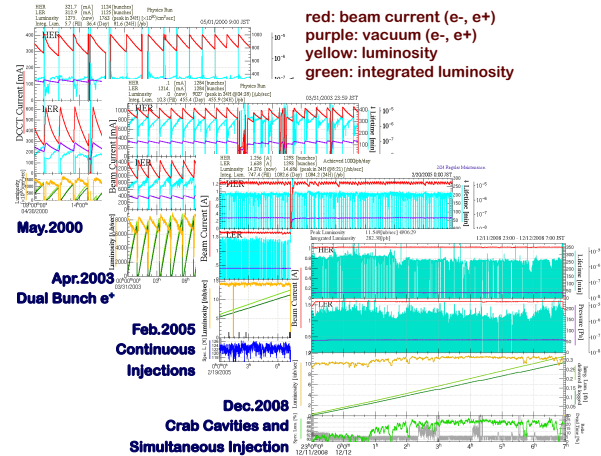


Figure 11: Progress of KEKB injector operation.

duced in early 2007 to realize a head-on collision and to enhance the collision luminosity. However, it turned out later that the collision condition was extremely sensitive to the beam currents in HER and LER. In that way the simultaneous injection contributed to KEKB luminosity by stabilizing the collision condition with crab cavities as well.

Figure 11 shows the typical operational progress of the KEKB injection during 11-years of operation. Accumulation of technical challenges and experiences would be a basis of the next project, and much further developments would be inevitable.

SuperKEKB

The SuperKEKB project aims at a 40-fold increase in luminosity over the previous project of KEKB in order to increase our understanding of flavor physics. This project requires ten-times smaller emittance and five-times larger current in injection beam. Many improvements are implemented at the injector [17, 18].

As partially described in the first section, a damping ring was incorporated at the middle of the injector linac in order to shrink the large positron emittance. A direct beam transport line was constructed to inject electrons into PF-AR at an independent energy and to realized simultaneous injections among four storage rings of HER, LER, PF and PF-AR. Those changes led to a substantial modification of the injection operation.

When the simultaneous injection is performed, parameters for each operation mode are independent. Thus, the simultaneous injection is essentially that virtual accelerators (PPM VAs) are switched every 20 ms corresponding to separate beam injections for four storage rings as in Fig.12. A single injector linac may behave as four VAs to inject their beams into four separate storage rings. Each PPM VA may accompany several beam stabilization closed loops, that are independent of loops in other VAs [19].

An additional PPM VA may be created not for any injection but for beam property measurements and optimizations, characterized as a stealth beam mode. As the beam quality

requirement for SuperKEKB is demanding, the arrangement of stealth beam mode would be indispensable in the near future.

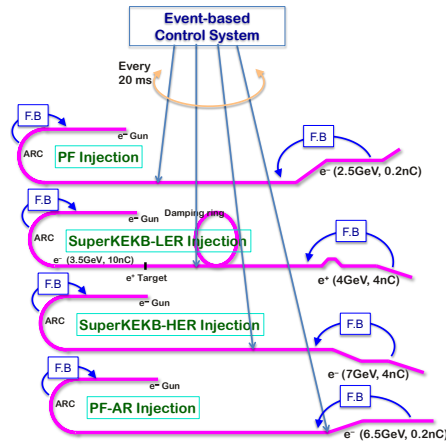


Figure 12: Single injector linac behaves as four virtual accelerators (VAs) to inject their beams into four separate storage rings. Each VA would be associated with several beam stabilization loops.

CONCLUSION

We learned a lot during KEKB injection operation. It contributed to achieve the world highest luminosity. Injection into SuperKEKB is another challenge with higher beam charge and lower transverse/longitudinal emittance. Steady progress towards designed injection beam would be achieved in steps. Then, we may need to improve the injection further with stealth beam measurement and optimization for example.

ACKNOWLEDGEMENTS

The author is grateful to all the staff and operators in KEKB/SuperKEKB project for their suggestions and continuous encouragement.

REFERENCES

- [1] K. Oide, “KEKB B-Factor, The Luminosity Frontier”, *Prog. Theor. Phys.*, vol. **122**, pp. 69–80, 2009, doi:10.1143/PTP.122.69
- [2] I. Abe *et al.*, “The KEKB Injector Linac”, *Nucl. Instrum. Meth.*, vol. **A 499**, pp. 167–190, 2003, doi:10.1016/S0168-9002(02)01787-4
- [3] M. Akemoto *et al.*, “The KEKB injector linac”, *Prog. Theor. Exp. Phys.*, vol. **2013**, p. 03A002, 2013, doi:10.1093/ptep/ptt011
- [4] Y. Ohnishi *et al.*, “Accelerator Design at SuperKEKB”, *Prog. Theor. Exp. Phys.*, vol. **2013**, p. 03A011, 2013, doi:10.1093/ptep/pts083
- [5] K. Akai, K. Furukawa, H. Koiso, “SuperKEKB Collider”, *Nucl. Instrum. Meth.*, vol. **A 907**, pp. 188–199, 2018, doi:10.1016/j.nima.2018.08.017
- [6] M. Yoshida *et al.*, “Generation and Acceleration of Low-emittance, High-current Electron Beams for SuperKEKB”,

- in *Proc. LINAC’14*, Geneva, Switzerland, Sep. 2014, paper MOIOB03, pp. 21–25, url: jacow.org/LINAC2014/papers/moiob03.pdf
- [7] T. Kamitani *et al.*, “SuperKEKB Positron Source Construction Status”, in *Proc. IPAC’14*, Dresden, Germany, Jun. 2014, paper MOPRI004, pp. 579–581, doi:10.18429/JACoW-IPAC2014-MOPRI004
- [8] M. Kikuchi *et al.*, “Design of Positron Damping Ring for Super-KEKB”, in *Proc. IPAC’10*, Kyoto, Japan, May. 2010, paper TUPEB054, pp. 1641–1643, url: jacow.org/IPAC10/papers/tupeb054.pdf
- [9] K. Furukawa *et al.*, “Upgrade of KEK Electron/positron Linac Control System for the both SuperKEKB and Light Sources”, in *Proc. ICALEPCS’17*, Barcelona, Spain, Oct. 2017, paper THMPL02, pp. 1257–1260, doi:10.18429/JACoW-ICALEPCS2017-THMPL02
- [10] J. Seeman, “PEP-II and KEKB Operational Status”, in *Proc. PAC’05*, Knoxville, USA, May 2005, paper MOAA003, pp. 276–280, url: jacow.org/p05/PAPERS/MOAA003.pdf
- [11] K. Furukawa *et al.*, “Beam Switching and Beam Feedback Systems at KEKB Linac”, in *Proc. LINAC’00*, Monterey, USA, Aug. 2000, paper TUE10, pp. 633–635, url: jacow.org/100/papers/TUE10.pdf
- [12] Y. Ogawa *et al.*, “High-Intensity, Two-Bunch Acceleration for Doubling Positron Production at the KEKB Linac”, in *Proc. HEACC’01*, Tsukuba, Japan, Mar. 2001, paper P1h1f05, url: conference.kek.jp/heacc2001/pdf/p1h1f05.pdf
- [13] S. Ohsawa *et al.*, “Increase of Positrons by a High-Intensity Two-Bunch Acceleration Scheme at the KEKB Linac”, in *Proc. PAC’01*, Chicago, USA, Jun. 2001, paper RPPH026, pp. 3284–3286, url: jacow.org/p01/PAPERS/RPPH026.PDF
- [14] K. Furukawa *et al.*, “Beam Feedback Systems and BPM Read-Out System for the Two-Bunch Acceleration at the KEKB Linac”, in *Proc. ICALEPCS’01*, San Jose, USA, Nov. 2001, paper WECT006, pp. 266–268, url: jacow.org/ica01/papers/WECT006.pdf
- [15] T. Abe *et al.*, “Commissioning of KEKB”, *Prog. Theor. Exp. Phys.*, vol. **2013**, p. 03A010, 2013, doi:10.1093/ptep/pts101
- [16] A. Akiyama *et al.*, “Accelerator Control System at KEKB and the Linac”, *Prog. Theor. Exp. Phys.*, vol. **2013**, p. 03A008, 2013, doi:10.1093/ptep/pts081
- [17] K. Furukawa *et al.*, “Rejuvenation of 7-GeV SuperKEKB Injector Linac”, in *Proc. IPAC’18*, Vancouver, Canada, Apr. 2018, paper MOPMF073, pp. 300–303, doi:10.18429/JACoW-IPAC2018-MOPMF073
- [18] Y. Seimiya *et al.*, “Low Emittance Beam Transport for e–e+ LINAC”, presented at *eeFACT’18*, Hong Kong, Sep. 2018, paper TUPAB02, this workshop.
- [19] K. Furukawa *et al.*, “Beam Feedback System Challenges at SuperKEKB Injector Linac”, in *Proc. ICALEPCS’13*, San Francisco, USA, Oct. 2013, paper FRCOBAB04, pp. 1497–1500, url: jacow.org/ICALEPCS2013/papers/frcobab04.pdf