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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 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].

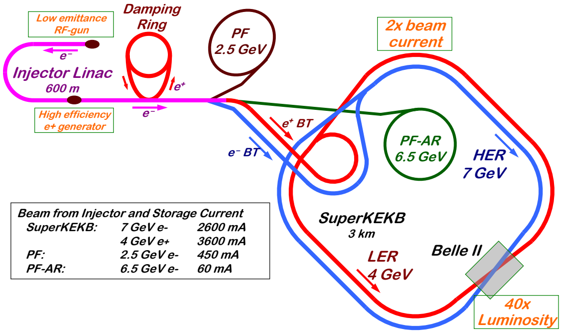

Figure 1: Layout of electron/positron accelerator complex with beam properties from the injector linac into four storage rings of SuperKEKB-HER, LER, PF and PF-AR.

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.

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[*] kazuro.furukawa@kek.jp

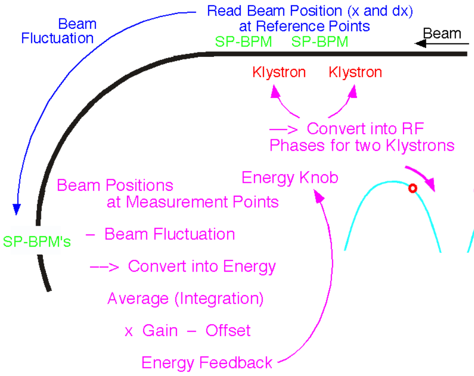
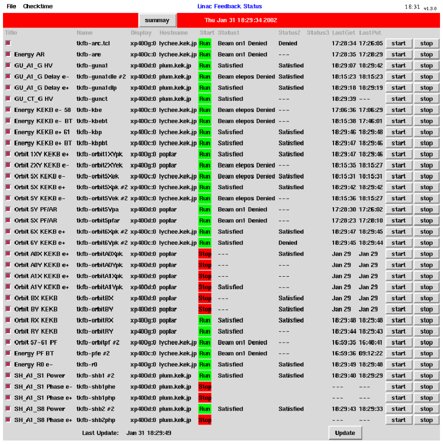


Figure 2: A Simple PI control was applied between BPMs and RF systems.



Title	Name	Display	Hostname	Start	Status1	Status2	Status3	LastGet	LastPut		
	tkfb-arc.tcl	xp400g:0	lychee.kek.jp	Run	Beam on1 Denied	Denied		17:28:34	17:26:05	start	stop
Energy AR	tkfb-are	xp400c:0	lychee.kek.jp	Run	Beam on1 Denied	---		17:28:35	17:28:29	start	stop
GU_A1_G HV	tkfb-guna1	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:07	18:29:42	start	stop
GU_A1_G Delay e-	tkfb-guna1dle #2	xp400d:0	plum.kek.jp	Run	Beam elepos Denied	Satisfied		18:15:23	18:15:23	start	stop
GU_A1_G Delay e+	tkfb-guna1dlp	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:18	18:29:19	start	stop
GU_CT_G HV	tkfb-gunct	xp400d:0	plum.kek.jp	Run	Satisfied	---		18:29:39	---	start	stop
Energy KEKB e- 58	tkfb-kbe	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		17:06:36	17:06:29	start	stop
Energy KEKB e- BT	tkfb-kbebt	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		18:15:38	17:46:01	start	stop
Energy KEKB e+ 61	tkfb-kbp	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:46	18:29:48	start	stop
Energy KEKB e+ BT	tkfb-kbpbt	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:47	18:29:46	start	stop
Orbit 1XY KEKB e+	tkfb-orbit1XYpk	xp400g:0	poplar	Run	Satisfied	Satisfied		18:29:47	18:29:46	start	stop
Orbit 2XY KEKB e-	tkfb-orbit2XYek	xp400g:0	poplar	Run	Beam elepos Denied	---		18:15:35	18:15:27	start	stop
Orbit 5X KEKB e-	tkfb-orbit5Xek	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	Satisfied		18:15:31	18:15:31	start	stop
Orbit 5X KEKB e+	tkfb-orbit5Xpk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:42	18:29:42	start	stop
Orbit 5Y KEKB e-	tkfb-orbit5Yek #2	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		18:15:36	18:15:27	start	stop
Orbit 5Y PF/AR	tkfb-orbit5Ypa	xp400d:0	poplar	Run	Beam on1 Denied	---		17:28:30	17:26:02	start	stop
Orbit 5X PF/AR	tkfb-orbit5pfar	xp400d:0	poplar	Run	Beam on1 Denied	---		17:28:23	17:28:10	start	stop
Orbit 6X KEKB e+	tkfb-orbit6Xpk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:47	18:29:45	start	stop
Orbit 6Y KEKB e+	tkfb-orbit6Ypk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Denied		18:29:45	18:29:44	start	stop
Orbit A0X KEKB e+	tkfb-orbitA0Xpk	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit A0Y KEKB e+	tkfb-orbitA0Ypk	xp400d:0	poplar	Stop	---	---		Jan 29	Jan 29	start	stop
Orbit A1X KEKB e+	tkfb-orbitA1Xpk	xp400d:0	poplar	Stop	---	---		Jan 29	Jan 29	start	stop
Orbit A1Y KEKB e+	tkfb-orbitA1Ypk	xp400d:0	poplar	Stop	Satisfied	---		Jan 29	Jan 29	start	stop
Orbit BX KEKB	tkfb-orbitBX	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit BY KEKB	tkfb-orbitBY	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit RX KEKB	tkfb-orbitRX	xp400g:0	poplar	Run	Satisfied	Satisfied		18:29:48	18:29:48	start	stop
Orbit RY KEKB	tkfb-orbitRY	xp400g:0	poplar	Run	Satisfied	---		18:29:44	18:29:43	start	stop
Orbit 57-61 PF	tkfb-orbitpf #2	xp400g:0	lychee.kek.jp	Run	Beam on1 Denied	---		16:59:35	16:48:41	start	stop
Energy PF BT	tkfb-pfe #2	xp400c:0	lychee.kek.jp	Run	Beam on1 Denied	---		16:59:36	09:12:22	start	stop
Energy R0 e-	tkfb-r0	xp400g:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:49	18:29:48	start	stop
SH_A1_S1 Power	tkfb-shb1 #2	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:40	18:29:29	start	stop
SH_A1_S1 Phase e-	tkfb-shb1phe	xp400d:0	plum.kek.jp	Stop				---	---	start	stop
SH_A1_S1 Phase e+	tkfb-shb1php	xp400d:0	plum.kek.jp	Stop				---	---	start	stop
SH_A1_S8 Power	tkfb-shb2 #2	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:43	18:29:33	start	stop
SH_A1_S8 Phase e+	tkfb-shb2php	xp400d:0	plum.kek.jp	Stop				---	---	start	stop

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Figure 3: Management tool for a number of feedback loops.

When the KEKB project started, the collision experiment was performed in experimental runs. A single run started with turning off the Belle detector high voltage (HV), then electrons and positrons were injected into the main storage rings, the high voltage was re-applied, and the data acquisition continued until the integrated luminosity reached an optimal value. Such an operational mode is often referred to as a decay mode in light source experiment.

The optimal run length in decay mode experiment depends on many factors like injection time, beam life times as well as the collision status. If the operation is stable, the value can be determined based on the average integral luminosity. For such an optimization in decay mode operation a specific tool was developed as in Fig. 4 (J.W. Flanagan *et al.*).

Because the period with the detector HV turned off doesn't contribute to the experimental results, it was important to shorten the period, especially the injection time. As the positron storage current was higher, it was eagerly hoped to increase the positron beam. Much effort was made to improve the injection rates in order to keep up with the powerful PEP-II injector at SLAC. However, certain efforts to increase the beam charge triggered discharge phenomena in the accelerating structures, and two of them at the bunching section and the positron target had to be replaced after a year of intensive operation.

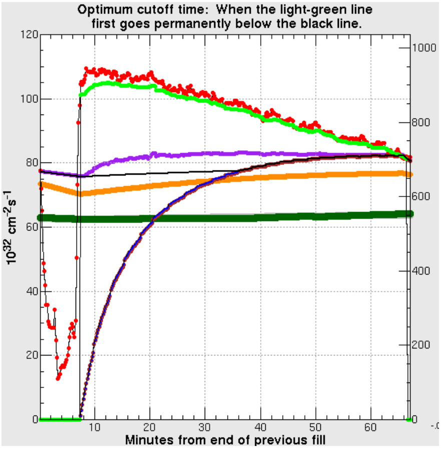

Figure 4: Plot from run length optimization tool to determine the proper run length realtime.

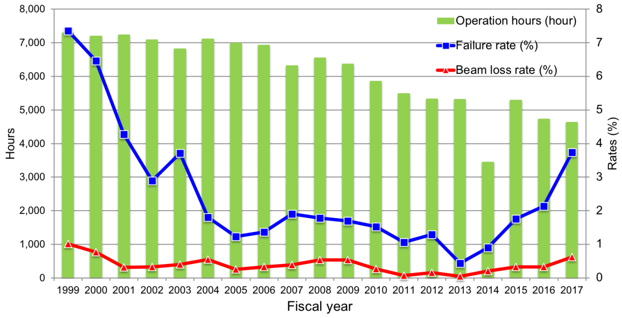

Figure 5: Injector operation hours, failure rate with performance degradation, and beam loss rate.

Figure 5 shows yearly operation statistics of the injector linac with operational hours, minor machine failures that brought performance degradation, and major failures that brought loss of beam injection. While the failure rate was high with intense endeavor at the early phase of KEKB, moderate operational condition was later examined and employed to have stable operation. A recent rise of the failure rate means preparation of new devices for SuperKEKB, and should eventually be suppressed.

TWO-BUNCH ACCELERATION

In order to overcome the difficulties it was proposed to add another bunch in a pulse [12]. Due to the design of high-power modulators for microwave generation the number of pulses in a second is limited up to 50 Hz. If two bunches are accelerated in a pulse, the injection rate could be doubled. The minimum bunch separation between those two bunches had to be 96.3 ns because the highest common RF frequency between the linac and the rings was 10.39 MHz. Those two bunches can be arranged at the both sides of the peak of the microwave pulse.

An additional grid pulser was combined with existent one to deliver dual pulses to the thermionic gun cathode [13]. The both beam bunches were analyzed carefully to be injected into the ring. Modifications to the beam instrumenta-

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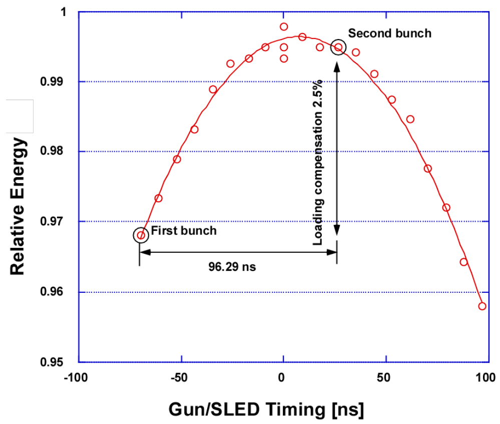

Figure 6: Beam loading compensation to equalize bunch energies in two-bunch acceleration.

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, 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.

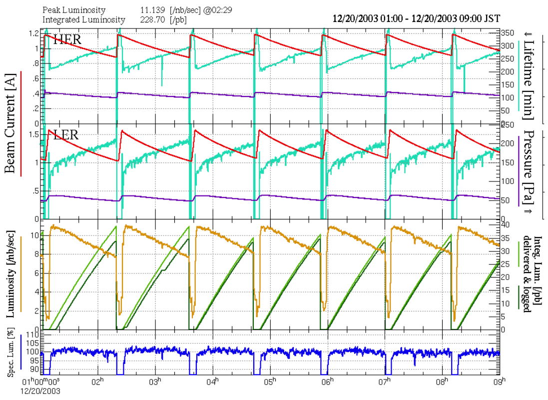

Figure 7: Storage beam currents and luminosity for 8 hours before the continuous injeciton was applied.

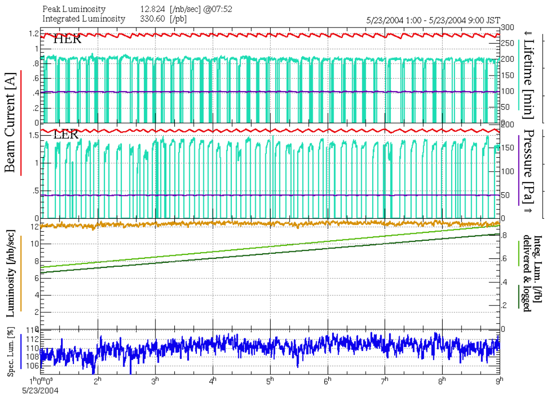

Figure 8: Machine history for 8 hours after the continuous injection was applied. Nearly 30% increase in integral luminosity was achieved.

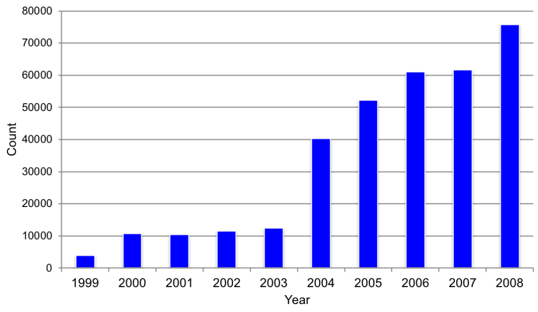

Figure 9: Beam mode transitions per year between injections into KEKB-HER, KEKB-LER, PF and PF-AR.

SIMULTANEOUS TOP-UP INJECTIONS

Even faster beam mode transition had been examined since 2005 just after the continuous injection was introduced.

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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).

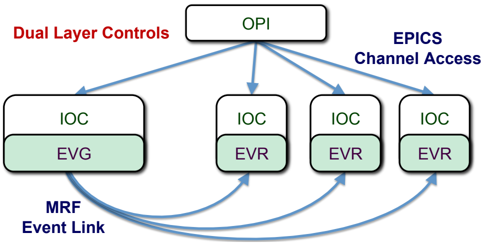

Figure 10: Dual-tier controls with EPICS CA at the top and fast event synchronized controls at the bottom.

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 μs). 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 introduced 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.

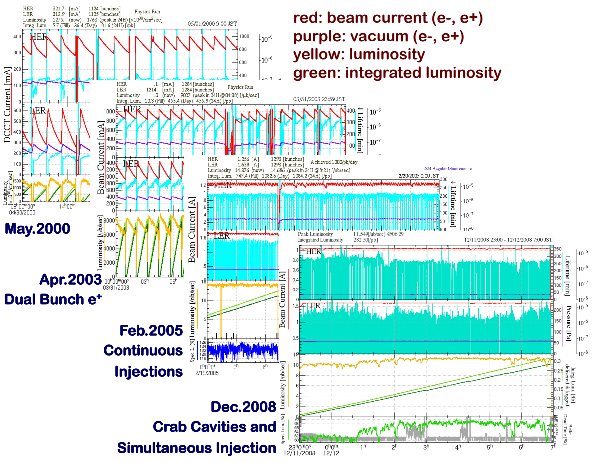

Figure 11: Progress of KEKB injector operation.

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.

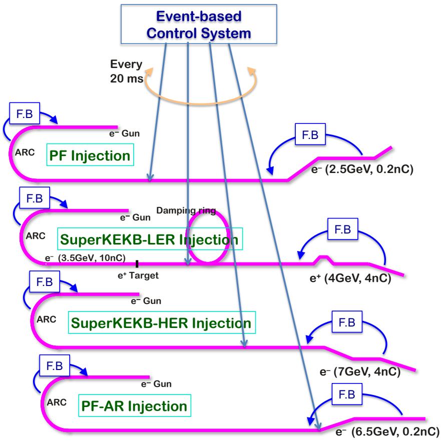

Figure 12: Single injector linac behaves as four virtual accelerators (VAs) to inject their beams into four separate storage rings. Each VA would be associated with several beam stabilization loops.

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

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