BEAM FEEDBACK SYSTEM CHALLENGES AT SuperKEKB INJECTOR LINAC

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Abstract

The SuperKEKB electron/positron asymmetric collider, currently under construction, is designed to elucidate new physics beyond the standard model of elementary particle physics. This goal will only be achieved by precise measurements with a luminosity that is 40 times as high as that of the KEKB. The injector linac is to be upgraded to enable a beam size of 50 nm at the collision point, which is 20 times smaller than that of the KEKB, and a doubling of the stored beam current with a short lifetime of 10 min. At the same time, two light-source rings, the PF and PF-AR, will be filled in top-up injection mode. To this end, the linac will need to be operated with precise beam controls. Dual-layer controls with EPICS and MRF event systems are being enhanced to support precise pulse-to-pulse beam modulation (PPM) at 50 Hz. A virtual accelerator (VA) concept is introduced here to enable a single linac to be modeled as four VAs switched by PPM, where each VA corresponds to one of the four top-up injections into the storage rings. Each VA is associated with independent beam orbit and energy feedback loops to maintain the required beam qualities. The requirements of the SuperKEKB HER and LER for the beam emittance, energy spread, and charge are especially challenging.

INTRODUCTION

During a decade of successful operation, the data obtained from the KEKB asymmetric electron/positron collider has provided important insight into the flavor structure of elementary particles [1]. The KEKB for B-physics is being upgraded towards SuperKEKB to achieve a target luminosity of $8 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ that is 40 times higher than the current luminosity in an effort to elucidate new physics beyond the standard model of elementary particle physics. The injector linac will be upgraded to enable a beam size of 50 nm at the collision point and a doubling of the stored beam currents of the 3.6-A positrons in the 4-GeV low-energy ring (LER) and the 2.6-A electrons in the 7-GeV high-energy ring (HER), both with short expected lifetimes of 10 min [2]. The linac will require full-energy injection with an energy spread of 0.1%, beam emittances of 20 and 10 mm·mrad at the end of the linac, and electron and positron bunch charges of 5 and 4 nC, respectively. Two bunches in a pulse are expected at a pulse rate of 50 Hz.

Low-emittance, high-current electrons will be delivered by employing a photocathode RF gun, and high-current positrons will be generated using a flux concentrator (FC) and large-aperture accelerating structures, before being damped to a low emittance through a damping ring (DR). The injector will inject electrons into two light-source rings: the Photon Factory (PF) and the PF Advanced Ring (PF-AR). All four storage rings of the SuperKEKB (the HER, LER, PF and PF-AR) will be filled in top-up injection mode (Fig. 1) using pulse-to-pulse modulation (PPM) at 50 Hz, effectively allowing the injector to perform virtually simultaneous injections [3].

A number of beam orbit and energy feedback loops were installed to maintain the beam stability for KEKB injections, particularly when the stability of the machine was not well understood [4]. For SuperKEKB injections, these feedback systems will need to be improved to meet the additional requirements of low-emittance, high-intensity beams and virtually simultaneous top-up injections into the four rings. We describe an upgrade plan for these feedback systems here by introducing the concept of virtual accelerators (VAs).

PULSE-TO-PULSE MODULATION CONTROL

The control system at KEKB is based on the Experimental Physics and Industrial Control System (EPICS) [5] and scripting languages. EPICS realizes the abstraction of the accelerator equipment layer, and the scripting languages, including SADscript [6], successfully achieve the integration of innovative ideas into the accelerator operation [7]. Following advances and developments in hardware devices and EPICS, the "channel access (CA) everywhere" concept was adopted to enable new subsystem deployment.

Later in the KEKB project, for a higher experimental performance and light sources that share the same injector, it became favorable to inject beams in top-up mode into all the storage rings. In the PF, a stable stored beam current is necessary for precise experimental results, and for the KEKB, stability was also desired for sensitive beam collision tuning to increase the luminosity. To that end, simultaneous top-up injection was established for three storage rings (HER, LER, and PF) in 2009.

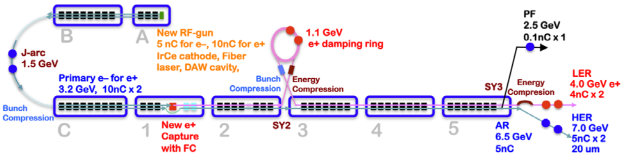

Figure 1: Layout of the SuperKEKB injector linac and beam delivery system to the four storage rings of the experimental facilities.

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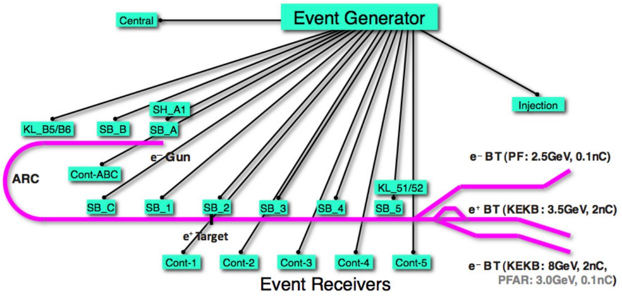

Figure 2: Overall configuration of the event-based control system at the injector linac. A total of 18 event-receiver stations are spread across the 1-km-diameter facility.

Global and fast controls were then established for pulse-to-pulse beam modulation (PPM), or virtual accelerators (VAs) [8]. The control system, based on 10-year-old hardware and conventional EPICS software, was inadequate for controlling the beam within 20 ms, and so a new control system with an event notification mechanism that was capable of regulating ∼150 parameters at 50 Hz was installed. This event-based control system managed the low-level RF, high-power RF, pulsed magnets, electron gun, injection systems, and beam instrumentation, that were spread over a distance of 1 km. While the event-based control system was supervised by EPICS software, it had a dedicated communication link for fast, global, and robust control [9].

The event generator sent timing signals and control data to 18 event-receiver stations arranged in a star-like topology (Fig. 2). 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 control 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 (SFP) transceivers have enabled reliable control in this configuration.

VME-based event control modules in the generator (EVG230) and the receiver (EVR230RF) from MRF [10] were utilized in the system. The event generator provides several events per pulse depending on the injection ring, and device controls are synchronized to the linac RF clock.

The same "dual-tier" control system with the conventional EPICS and event-based control, depicted in Fig. 3, will also be essential for the SuperKEKB. Simultaneous injection will be maintained, as the beam lifetime will be more limited at the SuperKEKB HER and LER. Several more event-receiver stations will be installed to cover additional pulsed accelerator equipment and beam instrumentation. Event generators and receivers from SINAP are also being evaluated, especially for the DR integration [11]. A number of other parameters will have to be managed precisely in a pulse-to-pulse manner to realize lower emittance beams for a higher luminosity [12].

The event-based control tier manages global and fast controls over a pico- to microsecond range, while the EPICS control tier covers slower parameter controls for the event-based controls, as well as existing conventional controls. The EPICS tier arbitrates operation requests of average beam-repetition rates from the three rings, and schedules different beams pulse by pulse.[1] Such requests occur every several seconds, and the beam mode schedule is reprogrammed at the event-control tier through the EPICS CA upon each request. This dual-tier control system is also an optimal configuration for next-generation accelerator systems.

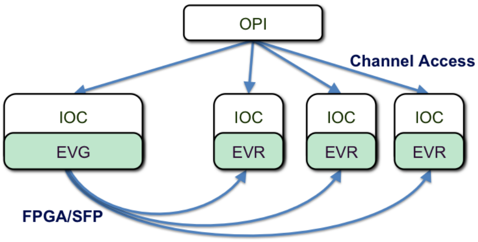

Figure 3: Dual-tier controls with EPICS CA at the top and fast event synchronized control at the bottom.

EMITTANCE PRESERVATION

Low-emittance, high-current electron and positron beams will be generated by upgrading the linac with facilities such as an RF gun, an FC, and a DR. If the accelerator equipment is aligned perfectly and the machine is stable, then beams are injected to the rings without emittance degradation. Based on beam dynamics simulations with an advanced bunch compressor, it is found that the local and global alignment tolerances are 0.1 and 0.3 mm, respectively, depending on the bunch length. However, alignment of the 600-m linac itself is a challenge, and furthermore, the Great East Japan Earthquake in 2011 disturbed the alignment by several millimeters.

If the machine is not aligned well, then the beam is kicked transversely by the focusing magnets and passes through the accelerating structures at an off-center position, inducing a transverse wakefield. This wakefield then kicks the tail of the beam bunch causing it to form a banana shape, which generates projected emittance blow-up [13]. If the distortion is small and non-linear effects are ignored, then we should be able to determine an initial beam orbit that will cancel the distortions in both the horizontal and vertical planes [14].

It is important to adopt this emittance preservation mechanism along the linac, and we must also be prepared to handle beam orbit and other instabilities by employing feedback loops.

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[1] Under typical operating conditions, the average injection rates with KEKB were 25 Hz for the LER, 12.5 Hz for the HER, and 0.5 Hz for the PF, which were frequently changed to maintain the stored beam current automatically.

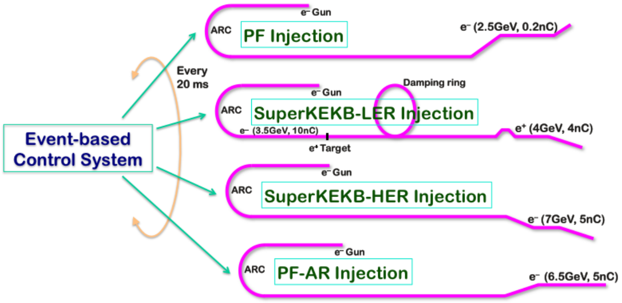

Figure 4: Single injector linac modeled as four PPM VAs managed by an event-based control system.

VIRTUAL ACCELERATOR MODELS

There are two types of VAs that are both important to this project. The first is a VA constructed virtually within a computer simulation to represent a real accelerator. This "simulation VA" is often utilized to improve the performance by comparing beams between virtual and real accelerators or to design the accelerator before construction is completed [15]. As EPICS has a switch to change process variables to simulation mode, several institutes employ such a mechanism.

The second VA type is one that corresponds to PPM beam modes. Each of the "PPM VAs" maintains independent variable parameters, and machine operators treat those PPM VAs as separate machines that exist in a single real machine. For the injector linac, we may need to consider a group of PPM VAs consisting of (Fig. 4)

- a 7-GeV electron injector for the SuperKEKB HER,
- a 4-GeV positron injector for the SuperKEKB LER,
- a 2.5-GeV electron injector for the PF, and
- a 6.5-GeV electron injector for the PF-AR.

Positrons are kept in the DR for more than 40 ms to reduce the beam emittance, and the same beam spans a temporal distance of more than two pulses. Most of the beam characteristics are lost in the DR, but the beam charge and timing against MR are maintained. Furthermore, a single pulse may contain dual bunches separated by 96 ns, and these two bunches should be handled separately because the second bunch is affected by the wakefield of the first bunch.

While all the PPM VAs share about 1000 common parameters, each PPM VA maintains an independent set of around 200 synchronous parameters. Common parameters correspond to equipment that does not vary from pulse to pulse. As the synchronous parameters can change in PPM, each parameter can have multiple values (currently up to ten), and one set of these values are associated with one PPM VA. Both the common and independent parameters will need to be optimized to achieve the beam properties of the respective PPM VA. Thus, a simulation VA is required for each PPM VA. Since our present simulation environment based on SAD/SADscript is not designed to handle such common parameter optimization between several VAs, the optimization process will need to be iterated.

Depending on the location in the injector linac, the beam energies in the PPM VAs are very different, which makes the iteration optimization somewhat complicated. To simplify the process, we subdivide the linac into several segments as listed in Table 1.

Table 1: Possible Segment Energies (GeV)

Segment	HER	LER	PF	PF-AR
Gun to positron target	3.5	3.5	3.5	3.5
Positron target to DR	4.6	1.1	4.6	4.6
DR to the end of linac	7.0	4.0	2.5	6.5

BEAM EMITTANCE CONTROL

Depending on the alignment result and the stability of the injector, the management strategy of the beam emittance may vary. Initially, we will only be able to monitor the beam characteristics as much as our resources will allow. We are in the process of enhancing the synchronized beam instrumentation such as the strip-line beam position monitors (BPMs) [16], wire scanners for the beam emittance [17], and a beam deflector for single-shot sliced emittance [3], as well as equipment monitors [18].

Simple beam stabilization feedback loops will first be installed for the beam orbit and energy with a proportional-integral (PI) control as in KEKB, where monitors are BPMs and actuators are steering magnets or low-level RF system. Pairs of point-to-point orbit stabilizers of 90-degree apart in the phase space, as well as energy stabilizers with energy-spread compensation will be employed [19]. We have found that these instruments are indispensable in locating the origin of the instability and for continuing beam studies under unusual beam conditions.

As noted, a certain beam orbit can be employed to cancel out the beam bunch distortions introduced by the wakefield. This orbit can be determined by scanning the initial point in the beam phase space and applying a specialized optimization feedback algorithm such as the downhill simplex to maintain the orbit. However, it is only after the beam has been commissioned that we are able to confirm how the orbit may be affected by the ground/girder alignment stability and equipment stability and what time constants these may have. We thus may need to apply different feedback techniques for the stabilization.

Each PPM VA will be associated with several feedback loops that will be applied to a set of process variables that correspond to the respective PPM VA. The process variable sets and feedback loops of each PPM VA are independent, as shown in Fig. 5.

If the time constant of the beam drift is sufficiently slow, then the feedback application programs will continue to be based on scripting languages, possibly accompanying a graphical user interface including the SADscript environment, which can solve linear (and nonlinear) beam optics online. This scheme is preferable for rapid development.

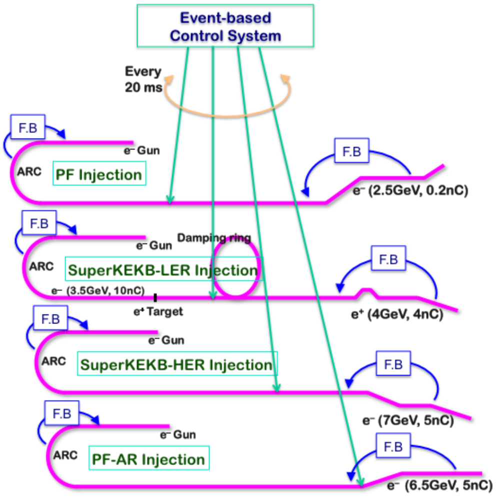

Figure 5: Each PPM VA would be associated with several beam feedback loops independent of the other PPM VAs. This figure indicates only the minimal beam energy feedback locations.

However, we will need to consider alternatives for routine operations depending on how often the beam optics change.

If the time constant is fast up to (but not including) pulse to pulse, then we can initially employ the EPICS ePID record. The beam optics parameters in the associated simulation VA should be calculated by a relevant helper application, and the feedback parameters should be tuned through CA. Eventually, we would need multi-monitor to multi-actuator loops, and a dedicated custom record may be necessary. A surveillance system of these feedback loops is also necessary for a routine robust operation.

In parallel to the feedback loop implementation, the associated simulation VAs would be improved by correcting the beam monitors and actuators. Such improvements should be shared between processes online.

CONCLUSION AND FUTURE

The advanced SuperKEKB design necessitates demanding requirements for the SuperKEKB injector linac. To achieve the expected beam parameters, PPM and emittance preservation controls were discussed. Two types of VAs, PPM VAs and simulation VAs, were introduced, and an implementation process for beam stabilization feedback loops were proposed based on these VAs. We note that the stabilization process may be affected by the device stability and the quality of alignment. The design and performance of the temporal manipulation of a laser pulse and the beam bunch compressors will also be important. Thus, we will need to provide a flexible environment in which to construct the beam operation system, and such an environment should be adapted to handle multiple VAs.

The commissioning of the injector will start in autumn 2013 at a limited power. While the mechanism that was tested in the KEKB project will be applied to the new instrumentation and equipment [19], we will need to determine the best direction for implementing the stabilization. More realistic beam commissioning will be performed in autumn 2014 and winter 2015 for the injector and ring, respectively.

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