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UPGRADE OF KEK ELECTRON/POSITRON LINAC CONTROL SYSTEM FOR THE BOTH SuperKEKB AND LIGHT SOURCES

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Abstract

KEK injector linac has delivered electrons and positrons for particle physics and photon science experiments for more than 30 years. It is being upgraded for the SuperKEKB project, which 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 from the injector. And many hardware components are being tested and installed. Even during the 6-year upgrade, it was requested to inject beams into light sources storage rings of PF and PF-AR. Furthermore, the beam demanding approaches from those storage rings are different. SuperKEKB would demand highest performance, and unscheduled interruption may be acceptable if the performance would be improved. However, light sources expect a stable operation without any unscheduled break, mainly because most users run experiments for a short period. In order to deal with the both requirements several measures are taken for operation, construction and maintenance strategy including simultaneous top-up injections.

INTRODUCTION

SuperKEKB, an asymmetric-energy electron-positron double-ring collider, is being commissioned with beams. The construction has been performed since 2010 till the end of FY 2017. It is expected to increase our understanding of new physics beyond the standard model of elementary particle physics with a 40-times higher collision rate compared to the world's highest luminosity at the previous project KEKB, by doubling the stored beam current and employing the nano-beam collision scheme [1, 2].

SuperKEKB consists of electron positron full-energy injector linac, 7-GeV electron ring (HER), 4-GeV positron ring (LER), and positron damping ring (DR), that is being constructed. The electron positron injector linac has delivered electrons and positrons for particle physics and photon science experiments since 1982. It has been rejuvenated since 2010 towards SuperKEKB collider for its extremely high luminosity, that requires injection beams with high current and low emittance in transverse and longitudinal directions [3, 4].

However, the injector linac had to continue the injection into two light-source storage rings of PF and PF-AR even during the SuperKEKB construction period, and then it is

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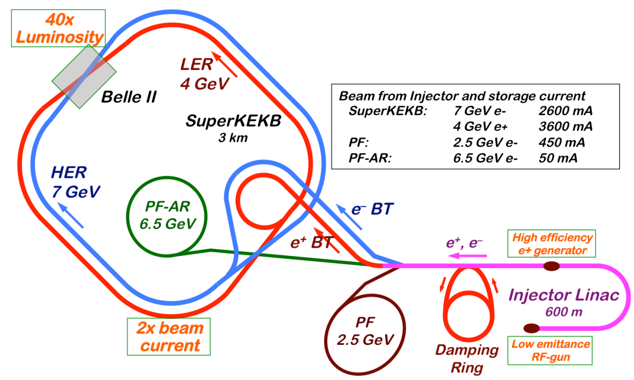

Figure 1: The configuration of electron/positron accelerator complex at KEK with linac and four storage rings of SuperKEKB-HER, LER, PF and PF-AR.

required to deliver beams into four multi-purpose storage rings with different qualities realizing the simultaneous top-up injections (Fig. 1).

BEAM INJECTIONS FOR PARTICLE PHYSICS AND PHOTON SCIENCE

Natures of beam demanding approaches from those experiments of particle physics at SuperKEKB and photon science at PF/PF-AR are so different that the operation becomes tough to be planned, especially for the construction and maintenance period.

The particle physics experiment at SuperKEKB always pursues the limit of performance. They expect highest possible experimental data with long-term integrated performance (between every large international conference). It may continue for more than ten years. They often take risks of a short-term shutdown if the integrated performance would increase. Such a particle physics experiment at SuperKEKB may be characterized as below.

- Experiment by long-term and fixed user group.
- Performance oriented.
- Pursuing yearly integrated performance.
- Tendency to avoid preventive maintenance.
- May have enthusiasm for improvements.
- Can develop common understanding between experiment and accelerator groups.
- Operators are trained through everyday operation.

On the other hand, the photon science experiments at PF and PF-AR are performed for only a few days at a time, and the stability is most required over the performance improve-

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ment. Especially, a non-scheduled outage should be avoided and a preventive maintenance is preferred. Such photon science experiments at PF and PF-AR may be characterized as below.

- Experiments by short-term and many groups.
- Stability oriented.
- Avoiding risks of unexpected outage.
- Prefer routine preventive maintenance.
- Peaceful operation.
- Bit of distance between experiment and accelerator groups.
- Operators learn through document.

Short-term and many groups

Because the injector should support the both experiments, the time and budget allocation optimization should be balanced between those very different experiments.

Operation and Maintenance

The difference between those experimental requirements affects the modes of operation and maintenance. In the past at the beginning of the TRISTAN project, the injector was operated continuously as long as possible without any maintenance. However, it was understood that such operation and maintenance strategy doesn't provide maximum average performance.

When the KEKB project was started, the injector rejuvenation had to be performed even continuing the light-source injections. Thus, the scheduled maintenance was preferable for the construction. As photon science experiments preferred preventive maintenance, later it was decided to have 8-hour maintenance every other week.

For particle physics experiment at SLAC it seems that the accelerator was operated continuously until "Repair Opportunity Day" was declared when major failures were accumulated. Such strategy was possible if the users were not multi-purpose.

During the KEKB upgrade it was possible to allocate 9-month shutdown in 1997, and major injector devices were installed during that long shutdown [5]. For the SuperKEKB upgrade it was difficult to schedule a long shutdown time until 5-month shutdown was allocated in 2017. During that time light-source injection was performed.

Comparison to Other Facilities

Injectors at other facilities were often required to support multi-purpose experiments as well. For example, the SLAC/SLC linear collider initially injected electrons into the NSRL light source. However, it became difficult to allocate the beam for the light source as SLC took the higher priority. Thus, it was decided to construct a separate injector, and the both experiments could be performed independently.

The electron injector at DESY/HERA also required to deliver the beam into the light source. Contrary to SLC, HERA didn't require continuous injection and the both rings shared the same injector without any difficulties.

SIMULTANEOUS INJECTION AND VIRTUAL ACCELERATOR CONCEPT

At the beginning of KEKB project, the injector filled the storage rings once in about an hour [6]. The situation resembled to DESY/HERA, and four rings shared a single injector. In the later phase of KEKB it became important to perform top-up injections into the both KEKB and PF experiments to maintain the stable experimental conditions. The stable beam currents in the collider rings were essential to keep the collision condition with crab cavities. At the same time the photon experiments requested top-up injection for higher precision data. As the SuperKEKB storage rings will have shorter beam lifetime, the situation becomes closer to SLC, and a solution is needed.

It is not easy to meet the requests from both of the particle physics and photon science experiments. Since the later phase of KEKB project, a concept has been introduced of which a single injector behaving as multiple virtual accelerators for corresponding storage rings.

Simultaneous Injections

The injector linac can accelerate beams 50 times a second. If device parameters for microwave generators, magnets and guns are modulated every 20 milliseconds, a single injector can perform top-up injections into multiple storage rings as if it injects beams simultaneously. Such simultaneous injections have been realized since 2009 [7, 8].

The system was controlled globally and synchronously by an event-based pulse-to-pulse modulation (PPM) control system [9]. In the system ten software beam modes are defined, and four of them were corresponding to injections into storage rings of KEKB-HER, KEKB-LER, PF and PF-AR. Each beam mode is accompanied with several fast event codes, and each event code can distribute to whole accelerator complex with a single byte information and precise timing information of approximately 10 picoseconds. About 200 device parameters along the accelerator are modulated in response to one of those event codes.

At the end of the KEKB project typical injections per second were 12 times for KEKB-HER, 25~37 times for KEKB-LER and 0.2 times for PF. PF-AR will be included in simultaneous injections as a new beam transport line was constructed in 2017 [10].

Virtual Accelerator Concept

The event-based PPM controls enables not only pulse-to-pulse device controls but also pulse-to-pulse beam diagnosis readouts. Device controls and beam diagnosis under different beam modes are totally independent. For example, a beam stabilization feedback loop at the same physical location can behave independently under different beam modes [11]. Such a behavior of the single injector can be recognized as multiple virtual accelerators as in Fig. 2 [12].

As such virtual accelerators were realized, a conflict of beam requests from particle physics and photon science

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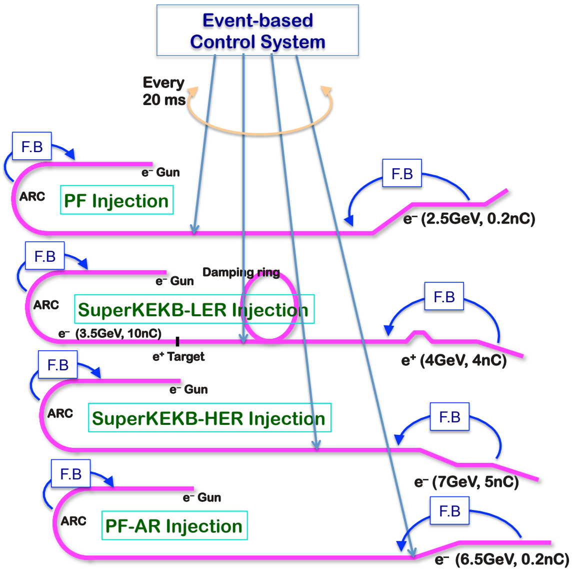

Figure 2: Single linac behaves as four virtual accelerators (VAs) to inject their beams into four separate storage rings. Each VA would be associated with several beam feedback loops, independent of loops in other VAs.

experiments with diverse beam qualities has been much relaxed.

PULSED MAGNETS

In the previous KEKB project, injection beams were pulse-to-pulse modulated with moderate beam optics, and optics matchings were performed at corresponding beam transport lines [11]. However, for SuperKEKB injection the precise beam orbit and optics management is necessary within 0.1 mm in order to suppress the emittance blow-up [13].

Small form-factor (3U) pulsed power supplies were developed for quadrupole magnets with advanced design of specifications of 1 mH, 330 A, 340 V and 2-ms pulse width with energy recovery from the magnetic coils up to 75%. Pulsed power supplies for steering magnets were designed as well for 3 mH and 10 A. Girders were also designed in-house which is ready for 0.1-mm alignment (Fig. 3).

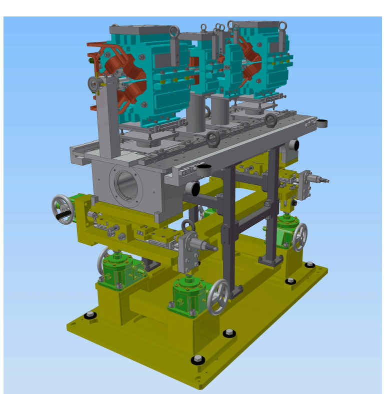

Figure 3: Girder design for pulsed magnets with precise alignment movers.

Those power supplies were designed with 0.5-ms flat top, and need pre-trigger before 3 ms before the beam. Such timing signals can be directly generated for SuperKEKB beams because linac and rings are tightly synchronized. It is, however, complicated to generate timing signals with a long delay for light sources, because those rings are injected on accidental timing coincidence and those rings compensate the circumferences by changing RF frequencies. The timing generation algorithm was developed to prepare pre-trigger and was confirmed.

Pulsed magnets of 30 quads and 36 steerings were mass-produced and installed during 5-month shutdown in 2017. They were confirmed to satisfy the specification of 0.1% (rms) stability at 50 Hz. And they will support the sophisticated multi-purpose operation scheme.

CONCLUSION

Prospective issues and solutions for a single injector linac at KEK are discussed to support the both particle physics and photon science experiments. While demands from those experiments have become much advanced, many of technical difficulties can be resolved by employing the virtual accelerator concept. It is expected to achieve the collision experiments in SuperKEKB soon as well as light source experiments at PF and PF-AR.

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