# SuperKEKB ELECTRON POSITRON INJECTOR LINAC UPGRADE FOR HIGHER CHARGE AND LOWER EMITTANCE

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*Abstract*

KEK electron positron injector LINAC has established simultaneous top-up injections in 2019 for 5 rings of SuperKEKB DR, LER, HER, PF ring and PF-AR as a base of the both elementary particle physics and photon science experiments even under a quite short beam lifetime. It improved the injection stabilities while the SuperKEKB broke the world record of the collision luminosity of the previous project KEKB. As the collision performance improves, the beam-beam effect makes the dynamic aperture shrink, and the beam lifetime reduces further. Thus, it became inevitable for the injector to be upgraded in order to resolve the contradictory improvements of higher charge and lower emittance of injection beams regarding beam wakefield till 2025. The upgrade plan is described including pulsed magnets, an energy compression system, accelerating structures, girders, positron generator and so on.

## INTRODUCTION

The KEK electron positron injector LINAC [1, 2] established the simultaneous top-up injections in to 5 storage rings in 2019 in order to support both the SuperKEKB particle collider experiment with DR, LER and HER rings [3], and photon science experiment at PF ring and PF-AR as depicted in Fig. 1. It succeeded in improving the efficiency of the SuperKEKB collision experiment by 237% before and after the introduction of the simultaneous top-up injections [4]. This injection scheme became indispensable because the beam lifetime of the SuperKEKB ring is quite short, especially at the LER positron ring less than 10 minutes in 2021. Based on this operation arrangement, the injector LINAC gradually improves the injection performance and contributes to the achievement of the world record of collision luminosity of SuperKEKB [5].

It has been recognized that the dynamic aperture of the rings becomes small and the beam lifetime is shorter as the beam-beam interactions becomes noticeable. While expanding the storage and injection physical aperture, it is required to urge the injector to enhance the injection beam property. Straightforward multiplication of the LINAC beam may drastically increase the injection beam emittance by the wakefield effect in the accelerating structure. Therefore, it is necessary to reduce the emittance in parallel. We are planning to improve the performance of the injector in line with the progress of the improvement of collision performance in storage rings, and the outline the plan is presented including the modification and expansion of the equipment.

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## INJECTOR IN KEK ACCELERATOR COMPLEX

In order to realize the advanced injection into SuperKEKB, we have been remodeling the injector since 2011 while maintaining the injection for the two light sources, PF ring and PF-AR. For a low emittance high charge electron beam, we have developed an RF electron gun that employs a combination of a quasi-travelling wave side-coupled cavity (QTWSC), an iridium-cerium alloy photocathode, and a high-power solid-state laser system, and promoted its stabilization [6].

The typical injection beam is limited up to 2 nC per bunch and 2 bunches at 50 Hz because of the emittance blow-up by wakefield effect in the downstream LINAC and coherent synchrotron radiation (CSR) effect in the beam transport. For the high current positron beam, a tungsten target is irradiated with the electron beam from a thermionic gun, and the positron is captured by the pulsed magnetic field of about 5 T in a flux concentrator (FC) and a long solenoid section with magnetic field of 0.5 T. After decelerating and bunching with a large-diameter S-band accelerating structure, the positron beam is accelerated to the damping ring (DR). Initially, there was concern that a discharge would occur in the 0.2 mm gap of FC, but the issue was solved by employing copper-nickel alloy [7].

In order to establish the simultaneous top-up injections with pulse-to-pulse modulation (PPM), various high-precision pulsed operation devices such as pulsed magnets [8] and beam instrumentation have been developed, and we have succeeded in realizing independent beam operation for each storage ring by developing the event-based wide-area synchronous beam control mechanism [9].

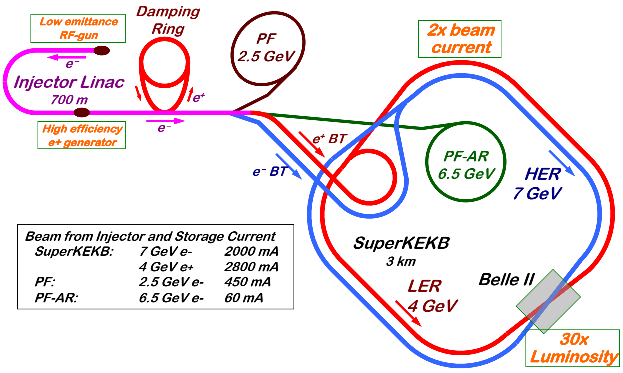


Figure 1: Layout of KEK electron/positron accelerator complex.

Table 1: Required Injector Beam Parameters

| Beam | Positron | Electron | |
|---|---|---|---|
| Beam energy | 4.0 | 7.007 | GeV |
| Normalized emittance $\gamma\varepsilon_{x/y}$ | 100/15 | 40/20 | µm |
| Energy spread | 0.16 | 0.07 | % |
| Bunch charge | 4 | 4 | nC |
| No. of bunches/pulse | 2 | 2 | |
| Repetition rate | 50 | | Hz |

The required beam specifications for SuperKEKB are shown in Table 1. It is essential to manage the effects of longitudinal and transverse wakefield in the accelerating structure and CSR in the beam transport line as the beam charge increases. At the same time, the short-term and long-term stabilization of the equipment is also indispensable. Thus, the LINAC upgrade is planned and being implemented in seven categories, namely; pulsed magnets, an energy compression system and movable girders for transverse and longitudinal emittance mitigation, the rf gun and the positron capture section for enhanced beam charge, and accelerating structures and number of capacitors with PCB for aging management.

## LOW EMITTANCE PRESERVATION

The possible emittance blow-up caused by wakefield effect with alignment errors has been evaluated and found that the errors of accelerating structures and quadrupole magnets should be within 0.1 mm for a short distance and 0.3 mm for a long distance for the SuperKEKB injection [10, 11]. After the Great East Japan Earthquake has destroyed the alignment by more than 1 cm, it was vigorously recovered [12]. The beam orbit in the downstream LINAC became well organized as the installation of pulsed magnets was necessary in order to realize the simultaneous top-up injections [8]. However, the beam orbit deviation and optics errors in the upstream part are quite large, and the deviations sometimes reach 1 mm or more from the center. It is considered that pulsed magnets and possibly movable girders need to be additionally installed (Fig. 2).

One of the reasons of orbit deviation was attributed to the building distortion, and it was found that the seasonal

Figure 2: Example of pulsed magnets installed in the linac.

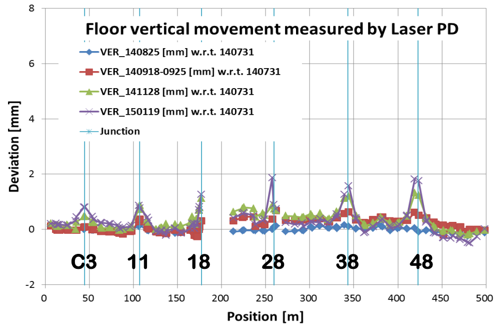


Figure 3: Seasonal floor movement in LINAC tunnel.

vertical movement of seven expansion joints in the LINAC tunnel reaches 1∼2 mm per half year as in Fig. 3 [13].

Errors in the beam optical functions, especially a dispersion function in acceleration sections, may produce an erroneous emittance growth. Thus, beam mode-dependent optics corrections by using pulsed quadrupoles are important [14].

It was considered that the beam impedance in the transport line from LINAC to the ring is small and it should have been transparent for beam properties. However, the longitudinal bunch structure from LINAC might induce CSR and the higher-order magnetic fields in the bending magnets cause XY-coupling. We will examine the emittance blow-up with increasing bunch charge up to 4 nC, and investigate the way to mitigate it.

The two bunches in a pulse separated by 96 ns are differentiated using the microwave timing presently [15]. However, this technique doesn't provide fully independent tuning capability.

### *Pulsed Magnets*

In the previous project KEKB the injection optics requirement was not strict and the optics condition for each beam mode was matched in each beam transport line instead of inside LINAC even though the beam energies were several times different. Such strategy, however, does not work for the beam quality in SuperKEKB because of possible orbit deviation and residual dispersion in LINAC. Thus, hundred of pulsed orbit-correctors and quadrupole magnets were installed mainly downstream at first as described above [8]. In upstream LINAC we need to further install pulsed magnets for higher beam charge in order to overcome the charge difference ratio of about hundred between beam modes.

Power regeneration was realized for those pulsed quadrupoles and 80% of the electromagnetic power sent to the coils is recovered for the next pulse.

### *Fast Corrector Coils*

Pulsed magnets are utilized to control beam optics and orbit with independent field strength for each pulse at 20 ms intervals, and the pulse width is about 1 ms. On the other hand, orbits of two bunches in a pulse need to be controlled independently by fast corrector coils. Therefore, we are developing fast pulsed power supplies and coils with ceramics embedded electrodes [16]. We expect a rise time less than 100 ns to correct one of two bunches with only 96-ns apart.

### *Movable Girders*

As mentioned earlier, the annual and localized deviations of the devices up to 2 mm at the expansion joints are considered to cause a large wakefield effect. Thus, we have developed a movable girder with a load up to 1 t and a precision of 10 µm to remotely drive the accelerating structures and the quadrupole magnets [17]. The beam effect will be evaluated.

## ENERGY SPREAD MITIGATION

For the issue of longitudinal emittance we originally planned to accelerate longitudinally rectangular-shaped beam from the RF electron gun [6]. Ytterbium-doped YAG fiber and thin disk laser with an excellent frequency response was developed to provide a shaped laser pulse. However, the high current beam more than 1 nC per bunch was unstable.

Therefore, a neodymium-doped YAG laser has been adopted to achieve a higher beam current. As the time response is limited for longitudinal shaping, only a Gaussian shape is available and as a result, the energy spread is expected to greatly expand at 4 nC per bunch.

### *Energy Compression System*

An energy compression system for positrons with magnetic chicane and accelerating structures was constructed from the beginning as the energy spread is large because of the bunch compression system after the damping ring. As mentioned above, an energy compression system became necessary for high-current electrons. Therefore, we are planning to construct an energy compression system (ECS) by using R56 in the beam transport line. As the distance from the power modulator is large, circular S-band waveguides will be applied to suppress the power loss.

Since the origin of the emittance growth in the beam transport line hasn't been identified, we are carefully discussing the interference between the ECS design and possible effects such as CSR. It is possible that the longitudinal bunch structure has to be manipulated in order to suppress CSR, for which we could utilize pulsed quadrupoles that will be installed.

## HIGHER BUNCH CHARGE

If we can achieve low emittance and low energy spread beams, we expect to be able to inject into SuperKEKB rings with the condition shown in Table 1. Depending on the progress of collision operation and the beam lifetime in the future, however, it may be necessary to enhance the beam charge further especially for positrons such as 6 nC per bunch as a future possibility.

Several possible optimizations could be applied in the positron capturing section. Presently, the transverse distance between the target and the hole to pass electrons is 3.5 mm, and electrons are at the center of accelerating structure behind in order to suppress the wakefield. If the distance could be shortened, positrons would be closer to the center. The orbit inside of the long solenoid section had not observed because of electron and positron pairs and the tight equipment arrangement. Recently, a new beam position monitor that can distinguish generated positrons from electrons that is only 150 ps apart [18] and the orbit could be controlled with newly installed pulsed correctors. The beam optimizations in these areas are being considered.

## REACHABLE ENERGY

The collision experiment at SuperKEKB is usually performed with energy that generates $\Upsilon$(4S) state of B mesons, but an experiment at $\Upsilon$(6S) state with 440-MeV higher is anticipated.

150 accelerating structures of total 230 in LINAC are 40 years old with initial designed gradient of 8 MeV/m but with 20 MeV/m now. As they are degraded by long-time discharges and cooling water leaks, the accelerating gradient becomes lower and we cannot reach $\Upsilon$(6S) state. Therefore, we are replacing 16 accelerating structures before 2023 as in Fig. 4, in order to realize the experiment at $\Upsilon$(6S) state [19]. We will determine whether further replacements are necessary or not.

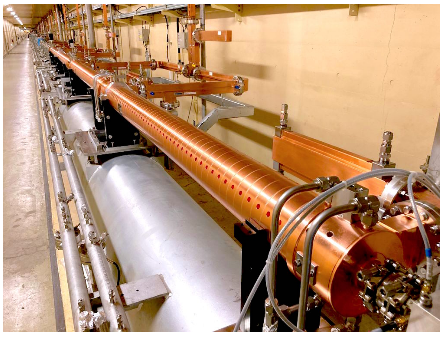

Figure 4: New S-band accelerating structures installed in the tunnel.

The capacitors in the high-power klystron modulators are more than 30 years old, and may contain small amount of Polychlorinated Biphenyls (PCBs). It is necessary to replace them all as they need destructive inspections for PCBs. We are planning to replace about 700 capacitors with ceramic containers in several years in order to maintain the voltage.

## CONCLUSION

The KEK electron-positron injector LINAC will be further upgraded in seven categories for lower longitudinal and transverse emittance and higher beam charge as well as the countermeasures against aging components. While no insurmountable difficulties are foreseen in the construction, a deliberate operational plan would be constructed soon.

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