KEK e+/e- INJECTOR LINAC

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Abstract

The KEK injector linac feeds the beams into four rings. It is called J-Linac. The SuperKEKB main rings are high-energy rings (HER) and low-energy rings (LER). The linac injects a 7.0 GeV electron beam to the HER and a 4.0 GeV positron beam to the LER. It also injects electron beams into the two light source rings. We successfully performed this simultaneous four-ring injection. We achieved this complex simultaneous injection using two electron guns, a positron source with a flux concentrator, and pulsed magnets. In SuperKEKB phase 3 operation, 2.0 nC electron and 3.0 nC positron beam injections were achieved.

INTRODUCTION

The KEK electron/positron injector linac was designed to inject different types of beams into four different rings. This injector achieved simultaneous four-ring injection at 50 pps. SuperKEKB has two rings: the HER and LER [1]. The other rings are the light source rings of the PF and PF-AR rings. An electron beam with an energy of 7.0 GeV and a positron beam with an energy of 4.0 GeV are required for the HER and LER, respectively. The energies of the PF ring and PF-AR are 2.5 GeV and 6.5 GeV, respectively.

The injector linac consists of eight sectors (sector A-C and 1-5) and a bending sector (J-arc) with a total length of 600 m. This shape resembled that of J, as shown in Fig. 1. One sector has eight klystrons, and one klystron drives four 2-m accelerating structures. The energy is adjusted from pulse to pulse by switching the accelerating or standby mode of each accelerating structure.

We used two types of electron gun: a photocathode RF gun and a thermionic cathode DC gun. An RF gun with a high-power laser was used to generate a low-emittance electron beam for the HER injection [2]. The RF gun charge and emittance design values were 5.0 nC and 6 mm-mrad, respectively. Positrons were generated by hitting a primary electron beam onto a tungsten target. These positrons were focused with flux concentrator (FC) [3] and accelerated with large aperture S-band (LAS) [4] accelerating structures. We obtained a 4.0 nC positron beam with a 10 nC primary electron beam. The generated and accelerated 1.1 GeV positron beam was injected into a damping ring to reduce the emittance. A pulse-bend magnet merged these two electron gun lines, and these beams were injected into a common acceleration beam-line. A thermionic gun was used as the electron source for the light source rings.

Sector A to 2 has common optics that use DC magnets. However, sector 3 to 5 has independent optics using pulse magnets. These pulse quadrupole and steering magnet systems were developed for the SuperKEKB project and can change the optics at 50 pps.

We achieved this complex four-ring simultaneous injection using two types of electron guns: a positron source and pulsed magnet system [5].

LINAC BEAM STATUS FOR SUPERKEKB

The SuperKEKB phase 3 operation began in 2019. The linac beam quality was gradually improved. Table 1 lists the current beam status and final goal. The energy was set to the required value, and a sufficient energy margin was maintained by providing standby units. The amounts of bunch charges in operation didn't reach the target values. However, these were almost sufficient for 2022b. The emittance was improved in a step-by-step manner. Simultaneous injection to four rings and damping ring was completed.

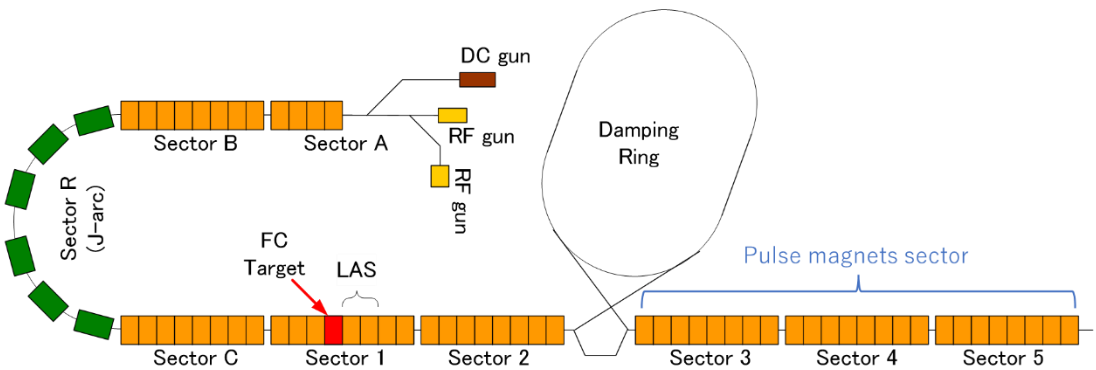

Figure 1: KEK injector linac.

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Table 1: Beam Status of the Final Goal and Current Performance

	2022ab		Final goal	
Beam	e+	e-	e+	e-
Energy [GeV]	7.0	4.0	7.0	4.0
Bunch charge [nC]	(1st, 2nd) 3.0, 2.5	(1st, 2nd) 2.0, 1.5	(1st, 2nd) 4.0, 4.0	(1st, 2nd) 4.0, 4.0
Normalized emittance [mm-mrad]	(Hor., Ver.) 120, 5	(Hor., Ver.) 20-50, 20-50	(Hor., Ver.) 100, 15	(Hor., Ver.) 40, 20

Electron beam

Figure 2 shows the one-year history of the electron beam charge for the HER. 2022, stable 2 nC beam generation was achieved using a laser feedback system [6]. The amount of charge was almost sufficient in the current situation. However, the HER sometimes requires a higher bunch charge. We must increase this for the next SuperKEKB operation.

Emittance preservation is an essential issue for electron beams because a damping ring is not available for the electron beam. The emittance measured at the beamline near the RF gun is good, as shown in Fig. 3. At the linac end, the emittance is also good immediately after orbit adjustment. However, a long period with no adjustment causes gradual emittance growth; the latter part of the graph in Fig. 3 illustrates this. The cause of this emittance growth is suspected to be the long-term RF phase drift. However, the reason for this is not clearly understood, and further investigation is required.

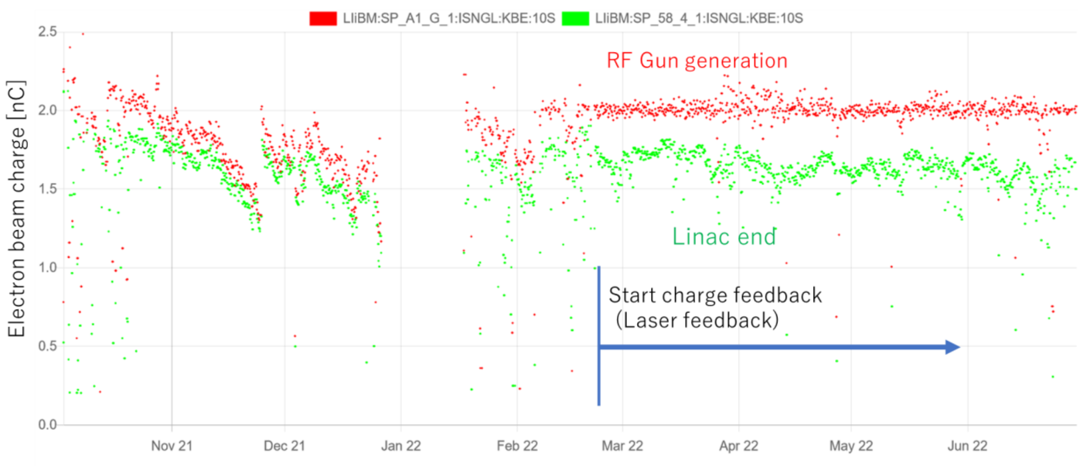

Figure 2: History of electron beam charge for the HER.

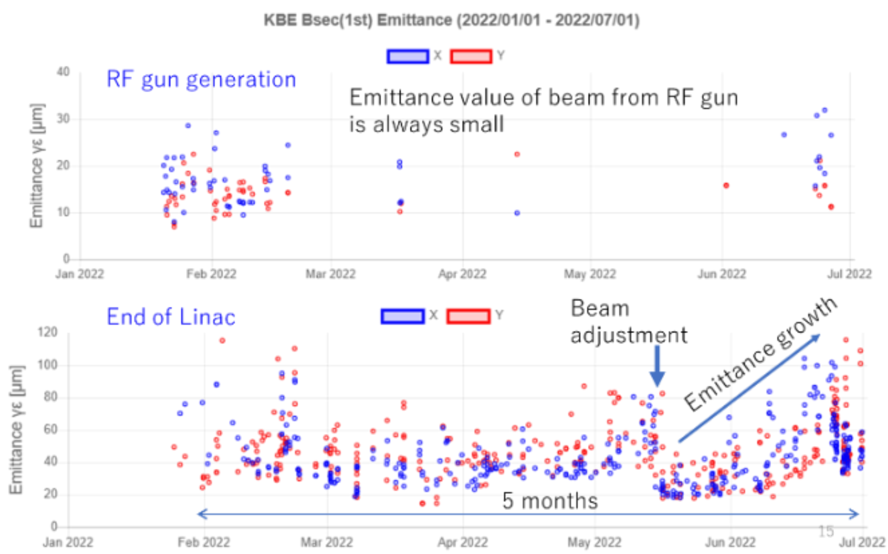

Figure 3: Long-term emittance value history of the electron beam. Emittance of RF gun beam (upper) and end of linac (lower).

Sometimes, a two-bunch operation as shown in Fig. 4 has been attempted. However, the injection rate of the second bunch tended to be low, and we had to perform the one-bunch operation. As shown in Fig. 4, there appears to be no problem with the beam orbit. The emittance or energy spread of the second bunch would have a problem. Two-bunch operation is one of the challenges to be solved in the next operational term.

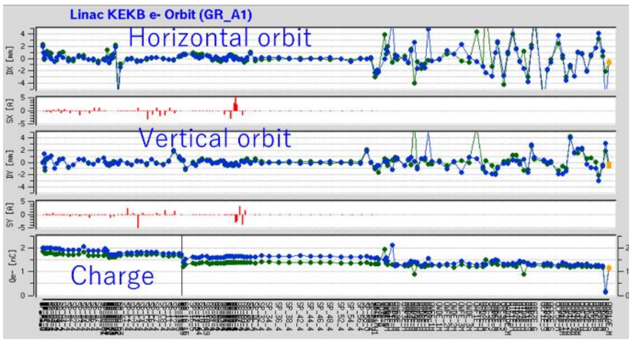

Figure 4: Two-bunch operation of the electron beam.

The stabilization of high-power laser systems also increases beam charge. We want to establish a method for emittance preservation inside the linac for high-charge operation for the next SuperKEKB operation. The issue of increased emittance in the beam transport (BT) line between the linac and ring also must be resolved. Studies on two-bunch operation and emittance preservation are essential.

Positron beam

Figure 5 shows a one-year history of the positron beam charge, including the primary electron beam charge for the LER. The beam charge was 3 nC, which is close to the final target. The thermionic gun generated a primary electron beam with a charge of 12 nC. The length of the bunch extracted from the cathode is 1 ns. We used two sub-harmonic bunchers (SHB) to compress the bunch length. The frequencies of SHB1 and SHB2 were 114 MHz and 572 MHz, respectively, and these were used to make the bunch length sufficiently shorter than the S-band RF wavelength. We used a streak camera to adjust the RF phase of the SHBs and an S-band buncher for beam bunching. In addition, we succeeded in a two-bunch operation. The second bunch charge was almost the same as the first bunch charge. We maintained a stable two-bunch injection to the LER.

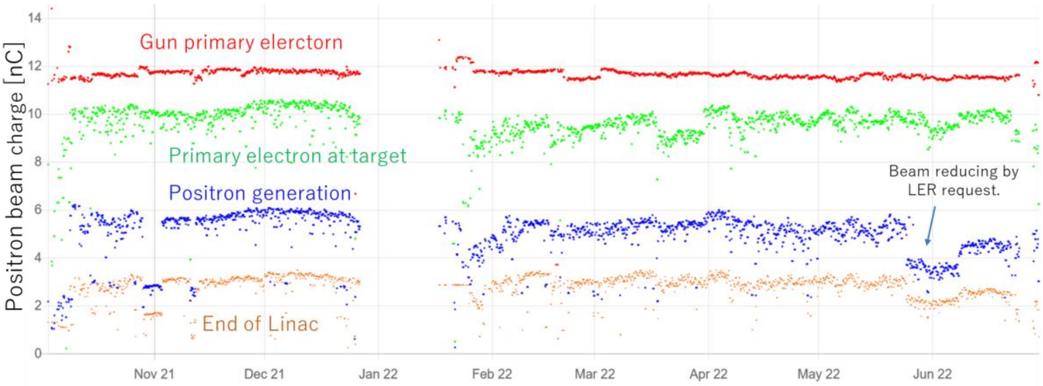

Figure 5: History of the positron beam charge for the LER.

The 2022ab SuperKEKB operation achieved a stable 3.0 nC two-bunch positron beam operation. Many improvements were made to achieve this stable positron beam operation. Figure 6 shows the long-term positron beam charge history. Before 2020, the beam charge was low, resulting in FC breakdown problem. This problem was solved by adopting a new robust FC and refining the applied voltage waveform [7]. Modifications were made in 2020 to increase the positron beam transportation in the LAS structure immediately after the FC. The LAS structures are in a long solenoid magnet with a transverse kick owing to their asymmetric structure. Steering magnets were added inside the solenoid magnet to compensate for the transverse kick. In 2021, positron beam transportation remarkably increased, as shown in Fig. 6. Since then, the amount of charge has been gradually increased by increasing the primary beam and improving beam transport.

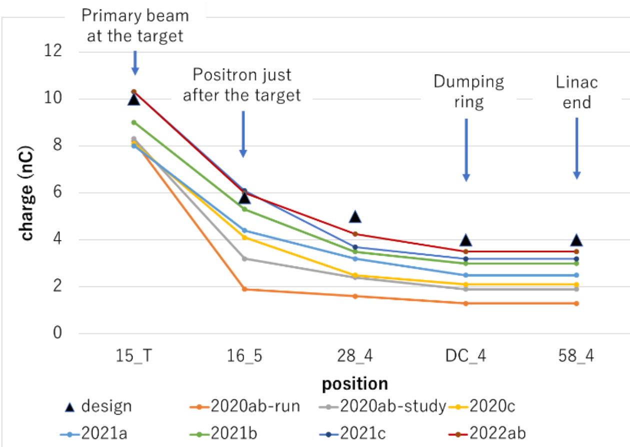

Figure 6: Long-term (a few years) charge history of the positron beam.

LINAC UPGRADE PLAN

Currently, we are working on various linac upgrades [8]. KEK injectors have a long history, and various measures against aging and performance improvements are required.

One important issue is the replacement of accelerating structures. Old accelerating structures are operated at lower voltages owing to field emission or breakdown problems. In addition, the cooling channels are often broken. Therefore, the development of new accelerating structures is an urgent issue. We tested the newly developed structure and a new pulse compression system. Figure 7 shows the new accelerating structure, and Fig. 8 shows the spherical-cavity-type pulse compressor (SCPC) [9]. The new accelerating structure and SCPC have provided high accelerating voltages in the conditioning system, and we are testing them online. The introduction of these new structures will increase the overall injector acceleration voltage in the future.

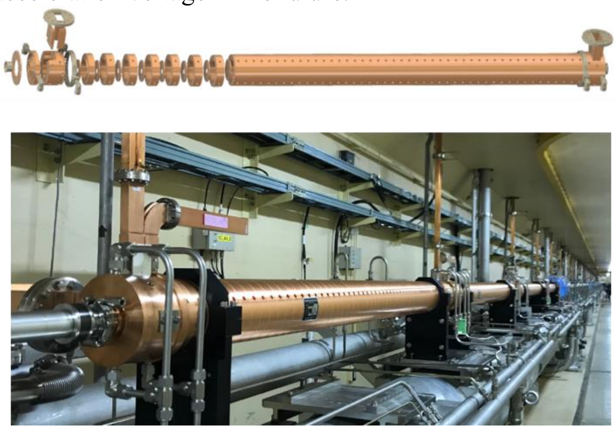

Figure 7: New accelerating structure.

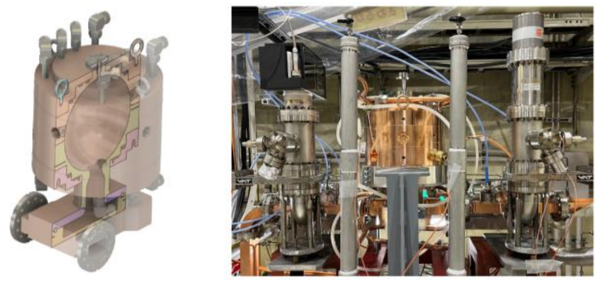

Figure 8: SCPC.

Pulse magnet upgrades are also important. Pulse magnets have already been installed in sector 3 to 5. However, DC magnets are used in sector A to 2. We must transport positron primary and electron beams in J-arc with common optics. Beam adjustment can be complicated and sometimes causes beam loss. Therefore, pulsed magnets should be installed near the J-arc. Magnets with large apertures are required in the J-arc. However, the pulse quadrupole magnets currently in use only have narrow apertures for low emittance. Developing a new magnet with a large aperture and a high-current magnet driver is necessary. The new pulse-magnet diameter was designed to be 44 mm, whereas the existing pulse-magnet aperture was 20 mm. Accordingly, the maximum current of the new pulse-magnet driver had to be increased from 300 A to 600 A. This high-power pulse-magnet driver is currently being tested.

A new device, the fast kicker, was also introduced. This kicks only on the second bunch. Sometimes, the orbit of the first and second bunches become separated owing to their energy deviation. The fast kicker was introduced to directly compensate for this orbit misalignment. The time separation between the first and second bunches was only 96 ns. The fast kicker will be tested in the next operational term.

We plan to introduce an energy compression system (ECS) in the electron beam line. Currently, the ECS is used only for the positron beam line. The 4 nC electron beam is affected significantly by its longitudinal wakefields, and it makes a large energy spread. Therefore, an electron ECS is necessary in the future.

Currently, we have to save the electric power consumed in the linac operation. In accelerators, particularly linear accelerators, the klystron efficiency dominates a large portion of the power loss. In the KEK linac, the efficiency of the conventional S-band klystrons is only 45%, which can be significantly improved. The conventional klystron output is 50 MW. We aim for an 80 MW of RF power output with the same modulator to increase the efficiency of the klystrons. We have begun designing a multibeam klystron (MBK) with an efficiency greater than 70%. In the future, installing a high-power klystron and a new accelerating structure are expected to significantly improve the performance of the KEK linac.

We will continue to make various upgrades for SuperKEKB.

SUMMARY

In the first half of 2022, the KEK injector linac provided electron/positron beams in the SuperKEKB phase 3 operation. Sufficient charge of electron/positron beams could be injected into the HER and LER while achieving simultaneous four-ring injection. During this period, various issues were identified. Emittance preservation and establishment of a two-bunch operation are required for the electron beam. The beam loss must be reduced in both the primary and positron beams. All systems of the injector are required to operate with many controlled long-term drifts. Various upgrades are planned to improve the injector performance. Replacement with new accelerating structures is gradually progressing. A pulse magnet upgrade is planned for flexible beam operation. We are currently developing high-efficiency klystrons to save power.

To further improve the performance of SuperKEKB, we will continue to perform beam studies and various upgrades in the KEK injector linac.

REFERENCES

[1] Y. Funakoshi *et al.*, “The SuperKEKB Has Broken the World Record of the Luminosity”, in Proc. IPAC'22, Bangkok,

Thailand, Jun. 2022, pp. 1-5. doi:10.18429/JACoW-IPAC2022-MOPLXGD1

[2] T. Natsui, D. Satoh, M. Yoshida, R. Zhang, and X. Zhou, "Injector Linac Upgrade and New RF Gun Development for SuperKEKB", in *Proc. eeFACT'16*, Daresbury, UK, Oct. 2016, pp. 74-78. doi:10.18429/JACoW-eeFACT2016-TUT2H2

[3] T. Kamitani *et al.*, "SuperKEKB Positron Source Construction Status", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 579-581. doi:10.18429/JACoW-IPAC2014-MOPRI004

[4] S. Matsumoto, T. Higo, K. Kakihara, T. Kamitani, and M. Tanaka, "Large-aperture Travelling-wave Accelerator Structure for Positron Capture of SuperKEKB Injector Linac", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 3872-3874. doi:10.18429/JACoW-IPAC2014-THPRI047

[5] Y. Enomoto *et al.,* "Pulse-to-pulse Beam Modulation for 4 Storage Rings with 64 Pulsed Magnets", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 609-614.

[6] R. Zhang, H. K. Kumano, N. Toyotomi, M. Yoshida, and X. Zhou, "Laser System for SuperKEKB RF Gun in Phase III Commissioning", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2914-2916. doi:10.18429/JACoW-IPAC2022-THPOTK059

[7] Y. Enomoto, K. Abe, N. Okada, and T. Takatomi, "A New Flux Concentrator Made of Cu Alloy for the SuperKEKB Positron Source", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2954-2956. doi:10.18429/JACoW-IPAC2021-WEPAB144

[8] K. Furukawa *et al.*, "SuperKEKB Electron Positron Injector Linac Upgrade for Higher Charge and Lower Emittance", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2461-2464. doi:10.18429/JACoW-IPAC2022-THPOST011

[9] Y. Bando *et al.*, "High power test of S-band spherical-cavity type pulse compressor." *Proceedings of the 18th annual meeting of Particle Accelerator Society of Japan*, Japan, 2021, p. 998