REJUVENATION OF 7-GeV SuperKEKB INJECTOR LINAC

K. Furukawa*, Y. Enomoto, M. Akemoto, D. Arakawa, Y. Arakida, H. Ego, A. Enomoto, T. Higo, H. Honma, N. Iida, M. Ikeda, H. Kaji, K. Kakihara, T. Kamitani, H. Katagiri, M. Kawamura, M. Kurashina, S. Matsumoto, T. Matsumoto, H. Matsushita, S. Michizono, K. Mikawa, T. Miura, F. Miyahara, H. Nakajima, K. Nakao, T. Natsui, M. Nishida, Y. Ogawa, Y. Ohnishi, S. Ohsawa, F. Qiu, I. Satake, M. Satoh, Y. Seimiya, A. Shirakawa, H. Sugimura, T. Suwada, T. Takenaka, M. Tanaka, N. Toge, Y. Yano, K. Yokoyama, M. Yoshida, R. Zhang, X. Zhou

High Energy Accelerator Research Organization (KEK), Oho, Tsukuba, 305-0801, Japan, and SOKENDAI (The Graduate University for Advanced Studies), Oho, Tsukuba, 305-0801, Japan

Abstract

KEK injector linac has delivered electrons and positrons for particle physics and photon science experiments for more than 30 years. It was upgraded for the SuperKEKB project, which aims at a 40-fold increase in luminosity over the previous project KEKB, in order to increase our understanding of flavor physics beyond the standard model of elementary particle physics. SuperKEKB energy-asymmetric electron-positron collider with its extremely high luminosity requires a high current, low emittance and low energy spread injection beam from the injector. The electron beam is generated by a new type of RF gun, that provides a much higher beam current to correspond to a large stored beam current and a short lifetime in the ring. The positron source is another major challenge that enhances the positron bunch intensity from 1 to 4 nC by increasing the positron capture efficiency, and the positron beam emittance is reduced from 2000 µm to 10 µm in the vertical plane by introducing a damping ring, followed by the bunch compressor and energy compressor. The summary of the rejuvenation is reported.

INTRODUCTION

SuperKEKB is being commissioned as an asymmetric-energy electron-positron double-ring collider [1]. It has been upgraded since 2010 after a decade of successful operation of the KEKB project. The Phase-1 beam commissioning was performed in 2016 without the collision, in which the stored beam current of about 1 ampere was achieved. With the interaction region constructed, the Phase-2 beam commissioning has been performed since March 2018, and the first collision was observed [2]. The commissioning will continue till coming July, and then the Phase-3 beam commissioning is planned from 2019.

While the facilities in the KEKB project was reused as much as possible for SuperKEKB, many components were reconstructed or newly introduced in order to fulfill the advanced requirements for a 40-fold increased luminosity.

INJECTOR LINAC

The electron–positron injector linac at KEK has delivered electrons and positrons for particle physics and photon science experiments since 1982. The injector continues to deliver various beams to SuperKEKB and light source rings as depicted in Fig. 1. The injections for light sources were performed even during construction for SuperKEKB since 2010, and balanced scheduling between the construction and beam delivery was considered. The construction was much affected by the large earthquake in 2011 because the girders were designed with the soft structure concept [3]. The longest shutdown period of 5 months was allocated in 2017, during which the largest scale installation was performed.

The SuperKEKB with extremely high luminosity requires injection beams with high current and low emittance in the transverse and longitudinal directions. As the beam lifetime at SuperKEKB is extremely short, simultaneous top-up injections into four storage rings and a DR should be per-

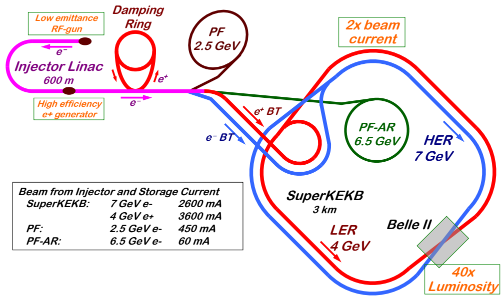

Figure 1: Layout of electron/positron accelerator complex with beam properties from the injector to four storage rings.

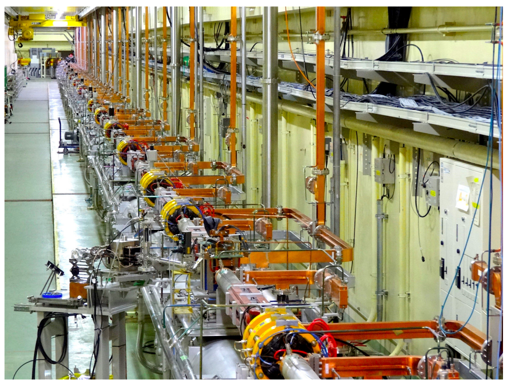

Figure 2: A typical part of the injector at the A and B sectors.

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* kazuro.furukawa@kek.jp

Table 1: Required and achieved parameters of injection beams, positron and electron, respectively.

Stage	**KEKB**	**Phase-I**	**Phase-II**		**Phase-III**	
	achieved	achieved	requirement	present	1st year plan	final requirement
Energy (GeV)	3.5 / 8.0	4.0 / 7.0	4.0 / 7.0		4.0 / 7.0	
Stored current (A)	1.6 / 1.1	1 / 1	1.8 / 1.3		3.6 / 2.6	
Life time (min.)	150 / 200	100 / 100	- / -		- / -	6 / 6
Bunch charge (nC)	1 / 1	0.4 / 1	0.5 / 1	1.4 / 2.5	2 / 2	4 / 4
Hor. Emittance (μrad)	1400 / 310	1000 / 130	200 / 150	200 / 50	100 / 40	100 / 40
Ver. Emittance (μrad)	- / -	- / -	40 / 50	5 / 50	15 / 20	15 / 20
Energy spread (%)	0.13 / 0.13	0.5 / 0.5	0.16 / 0.10	- / -	0.16 / 0.07	0.16 / 0.07

formed by pulse-to-pulse modulations (PPMs) in order to avoid interference between three facilities: SuperKEKB, Photon Factory (PF), and PF Advanced Ring (PF-AR).

The 600-m injector linac is composed of 60 high-power accelerating units with RF energy doublers followed by a beam switchyard with an energy compression system as shown in Fig. 2 [4]. The injector should meet the requirements of the SuperKEKB rings, with a small aperture at the interaction region, doubled stored beam currents, and short expected lifetimes. Low-emittance, high-current electrons will be delivered by employing a photo-cathode RF gun. High-current primary electrons for positron production are generated by a thermionic gun, and then high-current positrons will be produced using a flux concentrator (FC) and large-aperture accelerating structures (LASs), which are then damped to low emittance through a damping ring (DR) [5]. Design parameters of the injection beams are listed in Table 1.

ELECTRON SOURCES

A low-emittance electron beam source and its transport are essential to realize SuperKEKB's nano-beam scheme for higher collision rates. Although DR is employed to reduce the positron emittance, cost and space restrictions make the same solution infeasible for electrons. Thus, we have developed a photo-cathode high-current RF gun.

The primary target of the gun is a bunch charge of 4 nC and an emittance of 10 mm·mrad to allow minor emittance blow-up along the linac. Each component of the RF gun, such as the laser, photo cathode, and cavity, was examined carefully for stable long-term operation. A laser system with an Yb-doped fiber oscillator, a fiber amplifier, a thin-disk multipass amplifier, and two-stage frequency doublers was installed to examine high-power, shaped laser pulses [6]. A combination was chosen for a baseline, with an Nd:YAG laser amplifier for higher power, Ir_5Ce cathode for longer lifetime and reasonable quantum efficiency, and a quasi-traveling-wave side-couple (QTWSC) cavity for higher accelerating gradient and focusing (Fig. 3) [7]. A beam up to 4.4 nC was successfully transferred to the end of the linac with this combination.

However, to deliver an electron beam with the required characteristics, space-charge-effect mitigation by a longer bunch length (30 ps) and energy-spread mitigation by a rect-

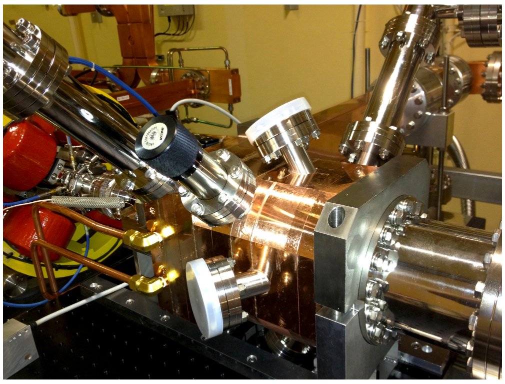

Figure 3: QTWSC cavity with a high acceleration gradient.

angular bunch shape should be manipulated carefully (temporal manipulation). Another laser station with an Yb:YAG thin-disk regenerative amplifier or multipass amplifier will be developed [8].

POSITRON GENERATOR

The positron beam generated in the KEKB injector was approximately 0.8nC × 2 bunches at 50 Hz. It should be enhanced to a dual-bunch 4 nC beam in stages. A high-charge positron bunch will be generated with a conventional 14-mm thick tungsten target, and will be captured by employing an FC and LASs with velocity bunching, followed by a series of solenoid coils and a hundred of focusing magnets as depicted in Fig. 4 [9]. As the generated beam emittance is large, it will be damped by employing a DR at 1.1 GeV.

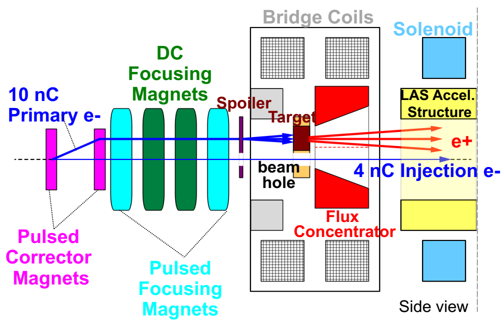

Figure 4: Positron target with a hole beside is attached in front of FC followed by LASs and solenoid coils.

While an air-core pulsed coil was employed in KEKB, it was replaced by a pulsed FC with a high field of 3.5 T in SuperKEKB. The FC is a pulsed solenoid composed of a primary coil and a copper cylinder with a conical hole inside. Induced eddy current flows through a thin slit to an inner surface and generates a strong field. The achievable field strength is mainly determined by the hole diameter and primary pulsed current. A 2-mm hole beside the target is used to pass the electron beam to be injected into the HER.

A thermionic gun is utilized to deliver a high-charge 10 nC primary electron beam for positron generation. Simulation studies from the thermionic electron gun to the DR, including the FC and LASs, were performed to optimize beam optics parameters with the target position, magnetic field, electric field, and collimator positions that lead to higher positron capturing ratios and lower beam loss. A target protection scheme, including a beam spoiler and a beam loss monitor, was also developed to prevent the energy deposit from exceeding a known limit [10].

RF SYSTEMS

Each of 60 high-power accelerating units is typically equipped with a pulse modulator, a S-band 50-MW klystron, a SLED-type energy doubler, and four 2-m long quasi-constant gradient accelerating structures. Those high-power RF modulators can operate at 50 Hz. All of them shorten the charging time by 1 ms, in order for the injection bucket selection system to synchronize the linac and rings. One-third of those modulators were replaced with compact inverter-type modulators to make space for new devices.

A 60-kW driver klystron was originally employed to drive a group of 8 high power accelerating units. However, many of units are required to operate independently in order to realize simultaneous injections. Thus, a 600-W solid-state RF driver was developed with an FPGA-based digital IQ modulator. They are directly connected with a master oscillator via temperature-stabilized optical links. The master oscillator provides several RF frequencies for linac and rings with integer relations between them.

As the beam quality is tightly dependent on the stability of the RF system, new RF monitors were developed. The monitor is equipped with five sets of IQ detectors and fast ADCs, an FPGA, and direct optical links to the event and EPICS control systems. About 70 monitors were installed to ensure the adequate RF stability for the beam specifications [11].

PULSED MAGNETS

A single injector linac would behave as four independent virtual accelerators (VAs) with hundreds of independent parameters modulated pulse-by-pulse at 50 Hz. In KEKB, pulse-to-pulse modulation (PPM) of injection beams was performed with moderate beam optics, and fine optics matching was performed at corresponding beam transport lines [12]. However, for SuperKEKB injection, beam orbit and optics management is necessary within a precision of 100 μm to suppress emittance blow-up [5].

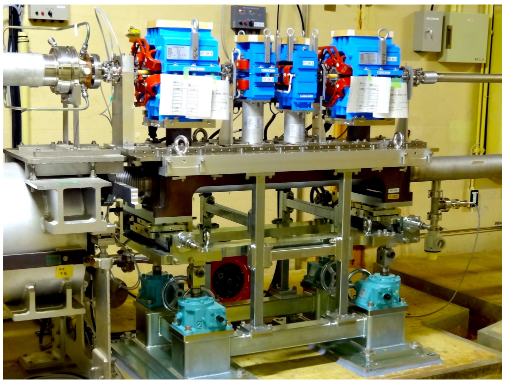

Figure 5: Two pulsed quads and two pulsed steerings with a newly designed girder.

Compact power supplies were developed for quadrupole magnets with advanced design specifications of 1 mH, 330 A, and 340 V, and a 2 ms pulse width with up to 70% energy recovery from the magnetic coils [13]. Power supplies for steering magnets were also designed for 3 mH and 10 A.

Pulsed magnets of 30 quadrupoles and 34 steerings were mass-produced and installed during a five-month shutdown in 2017. The pulsed magnets were examined and confirmed to satisfy the specification of 0.1% (rms) stability (Fig. 5).

INSTRUMENTATION AND CONTROLS

Four storage rings should be filled simultaneously in top-up injection mode, as previously described. To this end, the linac should be operated with precise beam controls. Dual-layer controls with EPICS and event-based systems have been enhanced to support beam operation with precise PPM at 50 Hz [12]. A VA concept was introduced to enable a single injector linac to behave as four independent VAs switched by PPM, in which each VA corresponds to one of four top-up injections into SuperKEKB's HER, LER, PF, and PF-AR. Each VA should be accompanied by independent beam feedback stabilization loops to preserve the orbit for low-emittance condition [14].

A single-shot sliced emittance measurement would be possible, and we hope to operate on an unused bunch (a stealth bunch measurement) using VA and PPM controls.

CONCLUSION

Steady progress was made in rejuvenating the injector linac. It successfully injected required beams for SuperKEKB Phase-1 and 2 commissioning. It will be further upgraded towards Phase-3 commissioning.

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