HIGH-INTENSITY AND LOW-EMITTANCE UPGRADE OF 7-GeV INJECTOR LINAC TOWARDS SuperKEKB

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Abstract

After a decade of successful operation at KEKB a new asymmetric electron/positron collider, SuperKEKB, is being constructed upgrading KEKB. It aims at a luminosity of $8 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, 40-times higher than that of KEKB, in order to study the flavor physics of elementary particles further, by mainly squeezing the beams at the collision point. The injector linac should provide high-intensity and low-emittance beams of 7-GeV electron and 4-GeV positron by newly installing a RF-gun, a flux concentrator, and a damping ring with careful management of emittance and energy spread to be 20 mm mrad and 0.1%. It should also perform simultaneous top-up injections into four storage rings by pulse-to-pulse beam modulations not to interfere between three facilities of SuperKEKB, Photon Factory and PF-AR. This paper describes the injector design decisions and present status of the construction. SuperKEKB will be commissioned within FY2014

INTRODUCTION

During a decade of successful operation, KEKB asymmetric electron/positron collider offered important insights into the flavor structure of elementary particles [1]. KEKB is being upgraded towards SuperKEKB with a design to achieve 40 times higher luminosity in order to elucidate new physics beyond the standard model of elementary particle physics. The injector linac should be upgraded to enable a beam size of 50 nm at the collision point and twice-larger stored beam currents with short expected lifetimes of 10 minutes. The requirements to the injector are the emittance of 20 mm mrad and the energy spread of 0.1% for both of electron and positron at the end of linac, and the bunch charge of 5 nC for electron and 4 nC for positron. Two bunches in a pulse are expected at a rate of 50 Hz.

Low-emittance and high-current electron would be delivered employing a photo-cathode RF gun. High-current positron would be generated using a flux concentrator and large aperture accelerating structures, and then it is damped to low emittance through a damping ring (DR). All the storage rings of SuperKEKB HER, LER, PF and PF-AR should be filled in top-up injection mode by using pulse-to-pulse modulation (PPM) at 50Hz (Fig. 2). Recent progress is described in following sections.

RF GUN

Low emittance electron beam source and its transport are indispensable to realize nano-beam scheme for higher collision rate at SuperKEKB. While DR is employed for positron emittance reduction, the same solution is not possible for electron because of the cost and space. Thus, a photo-cathode RF gun has been developed. Generation of a high-charge electron bunch up to 5 nC is already challenging, and it is also preferable to generate a bunch more than 10 nC as a primary beam for positron generation.

The primary target of the gun is the bunch charge of 5 nC and the emittance of 10 mm mrad to give a room for slight emittance blow-up along the linac. Each component of RF gun, such as a laser, a photo cathode or a cavity, was examined carefully for the stable long-term operation. As a baseline, the combination was chosen with Nd:YAG laser for higher power, $\mathrm{LaB_6}$ cathode for longer lifetime and reasonable quantum efficiency, and side-coupled disk and washer (DAW) cavity for larger aperture and focusing (Fig. 1). The combination was installed at a test station 3-2 at the middle of linac.

Laser and microwave systems were tuned carefully. However, the performance of the cathode was not favorable, and then it was replaced with $\mathrm{Ir_5Ce}$ cathode [2]. After further tuning at the laser optical system and beam transport, 4.8-nC beam was achieved, which is the designed beam current, and 4.4-nC beam was transferred to the end of linac. This baseline electron source can be used at the beginning of the commissioning.

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

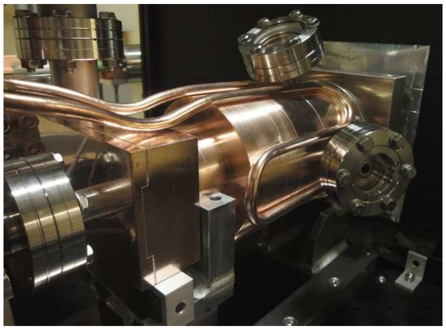

Figure 1: DAW-type cavity for the baseline RF gun.

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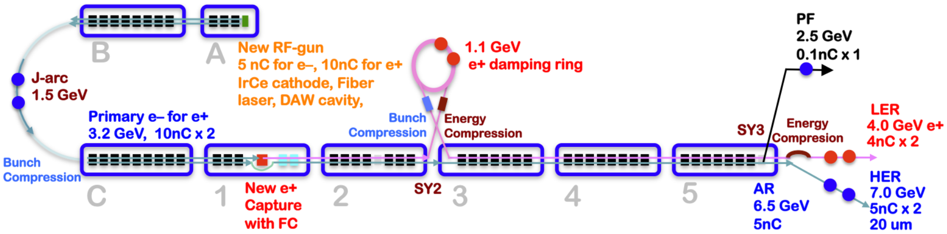

Figure 2: Layout of injector linac.

mitigation by a rectangular bunch shape should be manipulated carefully (temporal manipulation). Another test station A-1 with a Yb-doped fiber oscillator, a fiber amplifier, a Yb:YAG thin-disk regenerative amplifier, a thin-disk multi-pass amplifier, and two-stage frequency doublers was installed to examine such a high-power and shaped laser pulse [3, 4]. A quasi traveling-wave side-couple cavity will replace the DAW cavity soon for further focusing and higher gradient [5]. The beam test goes well at lower beam charge of 0.3 nC without shape manipulation at first for the initial beam commissioning in autumn 2013.

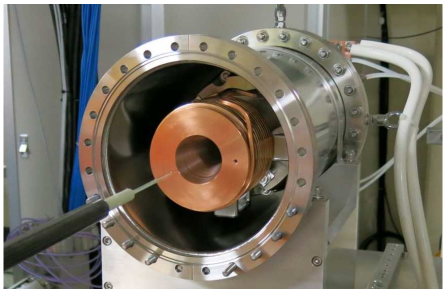

Figure 3: Flux concentrator under field measurement.

POSITRON ENHANCEMENT

The positron beam generated in the KEKB injector was approximately $0.8\text{nC} \times 2$ bunches at 50 Hz. It should be enhanced up to 4 nC in stages, because of the design of SuperKEKB with twice larger beam current and much smaller beam lifetime down to 10 minutes. A high charge positron bunch will be generated with a conventional tungsten target and will be captured employing a flux concentrator and large aperture accelerating structure with velocity bunching. As the generated beam emittance is large, it will be damped employing DR at the energy of 1.1 GeV.

Flux Concentrator to capture more positron

One of the keys to increase the positron yield is the development of focusing pulsed coil just after the positron generation target. An air core pulsed coil was employed in the previous KEKB project. For SuperKEKB, it will be replaced by a pulsed flux concentrator (FC) with a high field of 4 Tesla. 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 of several Tesla. Achievable field strength is mainly determined by a hole diameter and a primary pulsed current.

The design of the FC was examined based on the collaboration with BINP, SLAC, Frascati and IHEP. While a BINP-type was considered as a future upgrade with higher field, a conventional SLAC/Frascati/IHEP-type FC was fabricated in KEK with a spiral slit for the preliminary positron beam commissioning in December 2013 (Fig. 3). After a magnetic field measurement, it was tested at a peak current up to 6 kilo ampere, a half of the nominal current, without any issues such as discharges.

Several modified types of FCs would be fabricated and compared for different shapes even with a new entrance cone design [6]. Simulation studies from primary electron to DR including FC and large aperture structures were performed for higher field, better field symmetry, higher positron capturing ratio and lower beam loss. The target protection scheme is also under development not to make the energy deposit exceed a known limit [7].

L-band system as backup

The initial plan of the positron enhancement employed L-band (1298 MHz) accelerator structure with a larger aperture and longer wavelength compared with other S-band structure. The frequency was chosen considering the integer relation between linac and ring frequencies, filtering feature to reject satellite bunches, and development synergy with the linear collider project. Besides the large positron acceptance, elimination of S-band satellite bunches might be effective to reduce the beam loss at DR. It was also planned to utilize L-band for the beam bunch compression system after the extraction from DR.

The design and the fabrication of the system started in FY2010 with a 40-MW klystron and an accelerating structure (12 MV/m at 15 MW). In parallel the detailed design was examined with iterative beam simulations of positron capturing and acceleration, and it was found that a comparable performance could be achieved with a large aperture S-band structure and the velocity-bunching scheme. It is also known that S-band system has advantage for the cost and maintainability. Thus, it was decided to employ S-band system at least at the first stage of the project.

Nevertheless, since the margin for the requirement is narrow and L-band system should be ready as a backup scheme, high-power tests of newly-developed components were performed in FY2012. A klystron was confirmed to operate at sufficient parameters (30 MW, 1.5 μs). A new 2m-long constant gradient travelling wave structure was also tested up to 6 MW within a limited conditioning time. A low-weight aluminum vacuum wave guide and a SiC dummy load gave satisfactory performance.

In order to eliminate the vacant space between the accelerating structure and the positron focusing solenoid magnets and to reduce the size of the solenoids the development of a collinear RF load was conducted. Several of cells at the end of the structure were covered with thermal-sprayed RF absorber (Kanthal alloy). Various tests of thermal spray of the absorber were performed to optimize the suitable method for the load. It was technically evaluated by debonding test of the sprayed surface and the measurement of the gas emission in vacuum. A test load was constructed for the high power test. So far no essential issue has been found [8].

EMITTANCE PRESERVATION

If a beam bunch accelerated in the structure has an offset from the center, generated wakefield induces transverse force to the tail, and projected emittance can be very large. In order to suppress the effect, mechanical alignment of quadrupole magnets and structures up to 100 μm and precise beam handling are required. The beam orbit should be manipulated to find a low-emittance condition empirically, then the orbit should be stabilized. The beam bunch shape should be also manipulated employing laser pulse shaping, a magnetic chicane, and an arc section.

Several tests were performed to manipulate the beam bunch shape. In order to compress the bunch, one of the beam optics parameters, R56, was designed and was confirmed (Fig. 4). As the direct longitudinal profile measurement was not possible yet, it was evaluated by measuring dispersion functions.

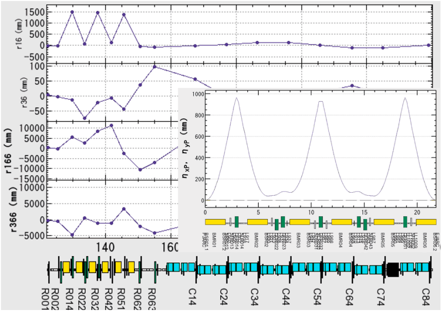

Figure 4: Designed optics parameter (right) was reproduced in the beam test (upper left).

Alignment

It is desirable to have alignment down to 100 μm locally and 300 μm globally along 120-m and 480-m straight lines. Local measurement was performed by a conventional laser tracker. However, as the linac tunnel was narrow, global measurement was challenging. Thus, a new long baseline laser beam was developed, which was stabilized by a precise angle adjuster, guided through vacuum pipes under the accelerator girders and measured by position sensitive photo detectors. The measurement precision was 60 μm over 480-m straight line [9].

BEAM INSTRUMENTATION, CONTROLS

Four storage rings should be filled in top-up injection mode simultaneously as described before. To this end, the linac should be operated with precise beam controls. Dual-layer controls with EPICS and event-based systems were being enhanced to support beam operation with precise pulse-to-pulse modulation (PPM) at 50Hz. A virtual accelerator (VA) concept is being introduced to enable a single linac behaving as four VAs switched by PPM, where each VA corresponds to one of four top-up injections into SuperKEKB HER, LER, PF and PF-AR. And each VA should be accompanied with independent beam feedback stabilization loops to preserve the orbit with low-emittance condition.

It is also important to install adequate safety systems since the beam intensity is very different between beam modes [11].

Several developments have been underway for beam instrumentation as well. An X-band deflector was designed to measure the vertical beam emittance at the end of the linac for SuperKEKB. Since the 1-m-long deflector developed for LCLS (SLAC) can fit to the design well, the same design was adopted. The construction work was conducted under the Japan-US cooperation framework. The cells were made in Japan and assembled at SLAC. It was finally vacuum baked and fiducialized at SLAC (Fig. 5).

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

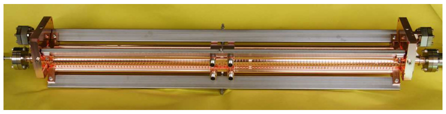

Figure 5: A 1-m-long X-band deflector for single-shot and sliced vertical emittance measurement.

CONCLUSION AND FUTURE

The injector linac is being upgraded towards SuperKEKB. Low-current linac commissioning will be performed in autumn, 2013, and the first injection will start at the beginning of 2015.

REFERENCES

[1] M. Akemoto *et al.*, Prog. Theor. Exp. Phys. (2013) 03A002.

[2] D. Satoh *et al.*, these proceedings (IPAC13, MOPFI023).

[3] X. Zhou *et al.*, these proceedings (IPAC13, WEPME018).

[4] M. Yoshida *et al.*, these proceedings (IPAC13, TUPFI004).

[5] T. Natsui *et al.*, these proceedings (IPAC13, TUOCB103).

[6] L. Zang *et al.*, these proceedings (IPAC13, MOPFI018).

[7] L. Zang *et al.*, these proceedings (IPAC13, MOPFI017).

[8] F. Miyahara *et al.*, these proceedings (IPAC13, WEPFI019).

[9] M. Satoh *et al.*, these proceedings (IPAC13, WEPME016).

[10] A. Akiyama *et al.*, Prog. Theor. Exp. Phys. (2013) 03A008.

[11] A. Shirakawa *et al.*, these proceedings (IPAC13, THPEA007).