POSITRON INJECTOR LINAC UPGRADE FOR SUPERKEKB

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Abstract

This paper reports on a present status of a positron injector linac upgrade for SuperKEKB. A development status of a flux concentrator for positron focusing is shown. An influence of offset layout of the flux concentrator and the target on a positron yield is described. Positron capture by L-band and large aperture S-band accelerating structures are compared in a viewpoint of satellite bunch elimination. Beam optical design compatible to electrons and positrons of different beam energies is discussed.

INTRODUCTION

The KEKB-factory is now under an upgrade to SuperKEKB for a forty times higher luminosity [1]. The injector linac is required to supply beams of higher charge and smaller emittance as shown in Table 1.

Table 1: Linac Beam Specifications

	KEKB (e^-/e^+)	**SuperKEKB** (e^-/e^+)
Injection Energy (GeV)	8.0 / 3.5	7.0 / 4.0
Bunch Intensity (nC)	1.0 / 1.0	5.0 / 4.0
Number of Bunch /pulse	2 / 2	2 / 2
Emittance (μm)	300 / 2100	20 / 92$_{[H]}$:7$_{[V]}$

To generate low emittance electron beams of 5 nC bunch intensity for injection, a photo-cathode RF gun is introduced [2] to replace the existing thermionic gun and the RF bunching section. The electron beams are accelerated up to 7.0 GeV over the entire linac and injected into the HER. Electron beams of 10 nC for positron production will also be generated with the RF gun. In a case high intensity operation of the RF gun is not stable, the thermionic gun is also used and the beams from these two guns are switched. To generate low emittance positron beams, a damping ring (DR) of 136 m circumference is introduced at a side of the linac and connected at the beam switch-yard No.2 (SY2). Beams generated in a positron capture section (PCS) are accelerated up to 1.1 GeV and injected into the DR. Positrons are extracted after 40 ms from the DR, injected back to the linac and accelerated up to 4.0 GeV for injection to the LER. Energy gain of the positrons from existing six accelerator modules (typically 160 MeV per each module) from the PCS to the SY2 is not sufficient for this 1.1 GeV injection to the DR. The PCS is relocated 40 m upstream to have a sufficient energy margin for the DR. To increase positron beam intensity four times as much, capture efficiency is enhanced in two aspects. At first, an existing 2-T pulsed coil of short field length (45 mm) right behind a positron production target, is replaced with a flux concentrator (FC) type of 5-T pulsed solenoid of long field length (200 mm). An adiabatic matching characteristics of a solenoidal field distribution with a FC, gives wider energy acceptance for positrons. As a second aspect, existing S-band accelerating structures with conventional aperture (21 mm in diameter) used in a solenoidal field of the PCS are replaced with large aperture S-band (LAS) structures (30 mm) or L-band structures (35 mm) to enlarge transverse phase space acceptance. Total length of the PCS is extended from 8 m to 16 m to boost positron beam energy from the PCS from 80 to 120 MeV. This increase of the beam energy at a transition from solenoidal to quadrupole focusing region is effective in reducing beam loss around an optical matching section.

In December of 2013, we will start a preliminary positron beam commissioning of the injector linac within limited operation parameters. A beam commissioning with the DR will be started in February of 2015. Development, fabrication and installation of the components are ongoing to be in time for the schedule.

In the following sections, as topics of significance in the positron injector linac upgrade, flux concentrator development, target protection and offset positron production, large aperture accelerating structures development, satellite bunch elimination and electron/positron compatible optics design are described .

FLUX CONCENTRATOR DEVELOPMENT

Flux concentrator 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 a 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. They are constrained from a required aperture size, a power supply capacity and break-

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down limit. We have been collaborating with BINP, SLAC, Frascati and IHEP on the FC development for KEKB linac upgrade. We have performed a high power operation test of a BINP-type FC at KEK and experienced a breakdown problem. The prototype is disassembled and under careful inspection at BINP. For a coming preliminary positron beam commissioning in December of 2013, we will use a more conventional FC, two type are considered as candidates. One is a spiral slit FC based on the SLAC design. Frascati and IHEP also have been using this type of FC. The other type is a simple straight slit FC. A peak longitudinal field strength at a same current is lower with the SLAC type, but a contribution of a transverse field component which is not axial-symmetric is also smaller. Considering an effect of target offset from a field center described later, evaluation of positron capture efficiency by a particle tracking using detailed 3D field distribution is ongoing. Since the FC is installed right behind the target and its radio-activation level will be very high and a replacement work will not be easy. Thus, an engineering design to avoid mechanical failure or water and vacuum leakage problems is critically important. Decision of installation model among the candidates will be made soon with a comparison in the capture efficiency performance and engineering design consideration.

POSITRON PRODUCTION TARGET

We have used 14 mm thick (4.0 radiation lengths) amorphous tungsten and later 10 mm thick crystal tungsten for the positron production target. In the beam commissioning for SuperKEKB, an amorphous tungsten will be used to avoid precise axis alignment mechanism. For a pulse-by-pulse switching of electron and positron injections, a small hole for electron beam passage is bored a few mm apart from a center of the target. To optimized a positron yield, the target was placed on a common central axis of the pulsed coil and the DC solenoids in the KEKB linac. Thus, electron beam entered into solenoid field at a few mm offset from the axis and traveled through an excursion orbit by a fringe field. It becomes a problem at SuperKEKB, since an electron beam for injection have a small emittance as 20 μm. Emittance growth in this excursion orbit is not acceptable and a hole for electron passage should be centered on the axis of the DC solenoids. An aperture diameter of the FC is only 7 mm in the present design and the tungsten target of 4 mm diameter and the hole of 2 mm diameter should be well contained in the aperture. As a consequence, center axis of the FC has 2 mm offset from the beam line and target center has 1.5 mm offset from the FC center. We expected the offsets degrade the positron yield 20 to 30 % by a preliminary simulation study. More detailed study on this offset effect is to be done by the tracking simulation.

LARGE APERTURE CAPTURE SECTION

To enlarge a transverse phase space acceptance of the PCS, accelerating structures with larger aperture will be used. As a first candidate, we started R and D for L-band structure which had an appropriate field strength and an aperture diameter as described in Table 2. A first prototype L-band structure has been fabricated and under a high-power RF processing in a test stand. Since a large outer dimension of an RF coupler of the structure gives strong impact on a DC solenoid design, an L-band structure of slimmer body is in consideration by installing a dummy load inside the structure in a collinear geometry. In a selection of the L-band frequency, we cannot use simple half frequency (1428 MHz) of the S-band because it is not compatible with 2 bunch operation with 96 ns interval which was defined from phase synchronization constraint of the linac and the storage rings. Instead, we adopted 1298 MHz which is 5/11 of the S-band frequency. This co-prime frequency relationship was found to be useful in elimination of satellite bunch particles as described later.

The other candidate is a large aperture S-band (LAS) structure as described in Table 2. It has a larger aperture diameter (30 mm) compared with conventional S-band structures (21 mm). The LAS has a very large group velocity and a field strength is relatively low, however operation with a pulse compression by the SLED gives comparable field strength. The LAS structures are used not only in the PCS, but in subsequent two accelerator modules of quadrupole focusing region to improve transverse acceptance as described in the next section.

Table 2: Specifications of Large Aperture Structures

	L-band	LAS
RF frequency (MHz)	1298.182	2856.000
number of cells	24 + 2	57 + 2
accel. length (mm)	2001	2064
disk aperture 2a (mm)	39.4 → 35.0	31.9 → 30.0
group veloc. v_g/c (%)	0.61 → 0.39	4.2 → 3.5
shunt imp. r_0 (MΩ/m)	45.7 → 47.6	46.1 → 48.4
filling time T_f (μs)	1.360	0.180
accel. field (MV/m)	12.2@15MW	6.93@10MW
same with SLED	–	16.42

Positrons emerged from the target have wide range of energy due to a cascade shower process and long bunch tail due to path differences in spiral orbits. Simulation studies show that a positron capture in decelerating phase and a formation of a main bunch by RF phase slip is useful to reduce particles at tails of an energy distribution [3]. However, particles which are not captured in the main bunch, experience further phase slips. They can be captured in subsequent phase positions and form satellite bunches. They can have comparable beam energy as those in the main bunch and will not be eliminated by an energy collimation. A fraction of satellite particles go out of RF buckets are lost at the DR injection. Due to a civil engineering constraint, a beam loss at DR is strictly limited to be below 0.2 % of a design beam intensity (4 nC x 2 bunch). Thus, elimination of satellite particles in the linac is a critical issue for a DR operation.

In a case we use six 2-m long L-band structures in the PCS, satellite bunches are formed in L-band wave-length intervals. Due to the co-prime relationship to the S-band wave-length, satellite bunches are accelerated or decelerated in abnormal phases in the downstream S-band linac modules and are eliminated in the linac or in an energy collimation. It is shown that a beam loss at DR injection will be suppressed to be an allowable level 0.05% [3]. In a case of a hybrid of two L-band and four LAS structures, the loss becomes 0.2%, but still acceptable. To suppress an initial construction cost by avoiding L-band component construction, it is recommended to start a beam commissioning with a configuration of all LAS structures in the PCS. In this case, the loss becomes 0.4% and further improvement is necessary. A preliminary simulation study indicates that raising S-band deceleration field around 20 MV/m can reduce satellites. More detailed study will be done soon.

POSITRON/ELECTRON COMPATIBLE OPTICS

By using accelerating structures with larger aperture, a transverse acceptance of the PCS which corresponds to an RMS emittance is enlarged from 2000 μm to 4000 μm. As described in the previous section, the PCS is relocated to a 40 m upstream position and a beam energy from this section is raised from 80 MeV to 120 MeV. As a consequence of these changes, a quadrupole focusing system after the PCS till the SY2 needs an upgrade and an addition and rearrangement of quadrupole and steering magnets will be made. In the two accelerator modules after the PCS, LAS structures of 30 mm aperture diameter are used to enlarge the transverse acceptance and quadrupoles are installed in 70 cm interval outside of the structures. In the subsequent three modules, ordinary S-band structures of 20 mm aperture are used and quadrupoles are placed in the same interval. In the subsequent four modules, quadrupole triplets are placed between the S-band structure and the interval changes from 3m to 5m according to the beam energy.

In this region between the positron production target and the SY2 before the DR, both of low energy, huge emittance positrons and high energy, low emittance electrons pass through the same quadrupole focusing system. Almost all quadrupoles in this region are DC magnets. To avoid a beam loss of the positrons, focusing strengths are optimized for them. Thus, electrons are focused in a ready-made quadrupole fields which are weak for the energy of electrons. Slight optimization to moderate electron beam size is performed within a range in which the positron optics is not significantly modified. Fig. 1 shows beam size of the positrons and the electrons.

Even with this compromised optics for the electrons, the beam sizes are kept sufficiently small. For independent orbit control of the positrons and the electrons, 12 pulsed steering magnet pairs are installed in addition to existing DC steerings. Orbit correction performance and emittance growth with this limited number of steerings should be checked by simulations and underway.

In the region after the DR till the end of the linac, both of the electrons and the positrons have low emittance and not precisely same but high energy. Quadrupole triplets and steerings are placed in 20 m interval. Total number of magnets are not so large for this region and there are no quadrupoles outside the structure, hence we decide all the quadrupoles and steerings here to be pulsed magnets. It will be useful for a precise independent matching to the storage rings and for an independent orbit control to suppress emittance growths for positrons and electrons.

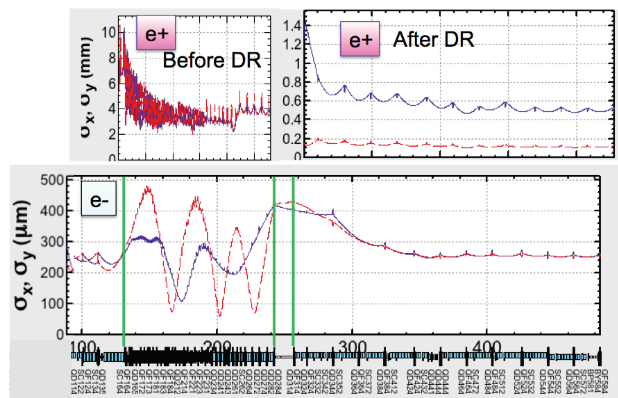

Figure 1: Positron/electron beam optics design.

SUMMARY

The KEKB positron injector linac is under an upgrade for SuperKEKB. Two types of flux concentrator in different slit geometry are in comparison by simulations and a prototype fabrication. An influence of an offset layout of the FC and the target is discussed. As accelerating structures to be used in the capture section, L-band and large aperture S-band structures are compared in a viewpoint of satellite bunch elimination. Performance of a compatible optics for electrons and positrons of different beam energies with DC quadrupoles is studied. A preliminary positron beam commissioning of the injector linac will be started in December of 2013.

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