DESIGN OF THE POSITRON TRANSPORT SYSTEM FOR SUPERKEKB

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Abstract

SuperKEKB, an upgrade plan of KEKB, aims to boost the luminosity up to $8 \times 10^{35}$ /cm$^2$/s, using low emittance beams. The horizontal and vertical emittances of the injected positron beam are 12.4 nm and 0.9 nm, respectively, which are one to two orders smaller than those of KEKB. The required injection beam intensity must be more than quadrupled, since the stored current is twice as that of KEKB and the beam lifetime is as short as 400 sec. The positron injector system consists of the electron LINAC, a positron target, L-band linac for capture system, S-band linac, collimators, an energy compression system (ECS), a 1.1 GeV damping ring (DR), a bunch compression system (BCS), S- and C-band linacs, and a beam transport line to the low-energy ring (LER). This paper reports a design of the positron beam transport system from the L-band linac to the LER. A tracking simulation has shown that the beam is contained within both of transverse and longitudinal acceptance of the LER with sufficient margin.

INTRODUCTION

The KEKB B-factory will be upgraded to SuperKEKB[1], aiming at a higher luminosity of $8 \times 10^{35}$ /cm$^2$/s, by colliding low emittance beams. The upgrade is based on so-called "Nano Beam" scheme, in which the horizontal beam emittances are reduced, in comparison to KEKB, from 18 nm to 3.2 nm and from 24 nm to 2.4 nm for the LER (4 GeV positrons) and the HER (8 GeV electrons), respectively. Then the vertical beam size at the interaction point is squeezed from 1 $\mu$m to 50 nm. The stored beam currents are also increased from 1.7 A to 3.6 A and from 1.3 A to 2.62 A for the LER and the HER, respectively. The beam lifetimes will decrease from 100 minutes to 400 seconds and from 200 minutes to 800 seconds for the LER and the HER, respectively. To maintain the stored current with enough margin, the intensity of positron beams should be more than 4 nC/bunch, assuming two bunches/linac-pulse in repetition rate of 50 Hz at maximum[2]. The injected beams must have sufficiently small emittances in both of transverse and longitudinal plane to match the tight acceptances of the collider rings. To achieve higher intensity of positrons, we will adopt a new matching device after the positron target and a L-band capture section to increase the acceptance. The motion of positrons created by the target are tracked in the solenoid and accelerating electric field in the capture section. The distribution of the positrons at the exit of the target is estimated using EGS4 code. The thickness of the target (W) is 4.0$X_0$. Both of horizontal and vertical beam sizes are $\sigma_{x,y} = 0.5$ mm, and the bunch length is $\sigma_z = 1.6$ mm. Gaussian distributions are assumed except for the energy spread. In this code, no effect from space charges, wake fields nor beam-loadings are involved. Particle tracking in a solenoid field and acceleration field until the end of the capture section has been performed with a code which integrates equations of motion with 4th order Runge-Kutta method. Geometrical constraint by disk apertures in the L-band structures, and by vacuum ducts are taken into account. After the capture section, tracking simulations are performed.

The layout of the transport lines for the positron beam is shown in Fig. 1. Optics from the positron capture section to the DR and extraction from the DR to the LINAC are newly designed. Tracking simulations are carried out to confirm the injection emittances within the acceptances of the LER. This paper consists of the following four parts:

1. From the capture section through LINAC Sector 2.
2. Transport from the LINAC to the DR (LTR).
3. Optics design from the DR to the LINAC (RTL).
4. Tracking simulation from the DR to the LER.

LINENR 2

The injector LINAC[4] has 7 sectors, Sector A and B before 180° arc (“J-Arc”) and Sectors C, 1 to 5 after J-Arc. The energy of J-Arc is 1.7 GeV, and a positron target is installed in the head of Sector 2 where the energy of primary electrons is 4 GeV. The capture efficiency of positrons will be increased by enlarging following acceptances: the longitudinal acceptance by a longer wave length of L-band instead of S-band, transverse acceptance by larger aperture of the L-band structure, and energy acceptance by adiabatic matching devices. As a new matching device, a flux concentrator or a superconducting solenoid will be installed. Positrons created at the target are captured with L-band with wider aperture, 30 mm in diameter. After that, chicane separating electrons and positrons, and quadrupoles are installed. The L-band and the successive S-band sections are 20 m and 130 m long, respectively. The $\beta$-functions, beam sizes, and the lattice after the capture section are shown in Fig. 2. Positrons are accelerated from 120 MeV to 1.1 GeV in Sector 2. Since the quadrupoles are attached outside of the structures, achievable field gradient is relatively low, that limits the acceptance. The FODO optics is adopted in the L-band and the first half of the S-band regions while in the rest of the S-band the triplet optics is chosen.

The motion of positrons created by the target are tracked in the solenoid and accelerating electric field in the capture section. The distribution of the positrons at the exit of the target is estimated using EGS4 code. The thickness of the target (W) is 4.0$X_0$. Both of horizontal and vertical beam sizes are $\sigma_{x,y} = 0.5$ mm, and the bunch length is $\sigma_z = 1.6$ mm. Gaussian distributions are assumed except for the energy spread. In this code, no effect from space charges, wake fields nor beam-loadings are involved. Particle tracking in a solenoid field and acceleration field until the end of the capture section has been performed with a code which integrates equations of motion with 4th order Runge-Kutta method. Geometrical constraint by disk apertures in the L-band structures, and by vacuum ducts are taken into account. After the capture section, tracking simulations are performed.

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carried out with SAD code[5], where longitudinal wake field is included, using Yokoya’s expression[6]. Number of particles survived along the line are plotted at the bottom frame in Fig.2. At the end of Sector 2, positron intensity is 8.7 nC/bunch against primary electrons of 10 nC/bunch. The horizontal and vertical emittances (normalized) are 1.37(2940) μm and 1.29(2770) μm, respectively.

OPTICS DESIGN OF LTR

LTR is the injection line to the DR, whose length is about 60 m. Since the energy spread of the beam from LINAC is too large to inject to the DR whose energy acceptance is 0.8%(or 1.3%, dependent on the cavity voltage), it must be compressed prior to injection through an energy compression system (ECS) in LTR. The optics, and layout of LTR are shown in Fig. 3-(a) and (c). The $R_{56}$ component generated in the first arc of LTR and the subsequent cavity voltage ($V_c$) make a rotation in the longitudinal phase space. Since the energy distribution ($\delta$) is long-tailed and not a simple Gaussian, as shown in Fig. 4-(a), it is difficult to determine the ECS parameters, $R_{56}$ and $V_c$, without using tracking simulation. We have scanned the parameters and the energy window at the first arc by using simulated particles, as shown in Fig. 4, using a simplified map of arc and acceleration. At first, we assume the width of energy window ($\delta_{\text{in}}$) and count the number of particles in the window. Moving the window offset along the energy, we search the best offset such that particle transmission maximizes (b). After that, the ECS parameters are scanned to find the best combination with which 100% of particles go into the energy acceptance of the DR ($\delta_{\text{out}}$) (c).

The transformations of $(z, \delta)$ are

$$z_{\text{out}} = z_{\text{in}} + g(\delta_{\text{in}})$$

and

$$\delta_{\text{out}} = \delta_{\text{in}} + k(z_{\text{out}}),$$

where $g(\delta)$ is a non-linear correlation function between $z$ and $\delta$ in the arc obtained by fitting the optics, and $k(z) \equiv \frac{eV_c}{E_0} \sin \left( \frac{2\pi f_z z}{c} \right)$, where $E_0$ and $f$ are the beam energy and the RF frequency, respectively. In this case, the best parameters, shown as a small circle in Fig. 4-(d), are $R_{56}=-0.64$ m and $V_c=40$ MV assuming the energy acceptance of the DR to be 0.8%. The resulting width of energy window ($\delta_{\text{in}}$) is $\pm 2.83\%$, with which 25% particles lose at the first arc, and the final charge is 6.5 nC/bunch. These ECS parameters have flexibilities. For instance, a combination of $R_{56}=-0.64$ m and $V_c=40$ MV changes the energy spread 3.5% to 1.5%, resulting 7.8 nC/bunch. So this ECS is adjustable for a wide range of the DR energy acceptance from 0.8% to 1.5%. The horizontal and vertical physical emittances at the DR injection point are 1.47 μm and 1.29 μm, respectively.

OPTICS DESIGN OF RTL

The extracted beam from the DR is sent back to LINAC via the RTL line as shown in Fig. 3-(c). From the DR, two bunches are extracted by one pulse of an extraction kicker.
LINAC is ±0.9% in hard edge whereas an acceptance of the beam transport line (BT)[7] is ±0.375%(3σ). Therefore another ECS is needed before the BT line. Since the BT line has a large $R_{56}$ component of 5.5 m, the bunch length is lengthened before injection to the LER.

The LER has acceptances $\varepsilon_x \approx 1.200 \text{ mm}$, $\varepsilon_y \approx 4 \text{ mm}$, $\Delta z \approx 66 \text{ mm}$, and $\sigma_\delta \approx 1.1\%$. As for the horizontal, the maximum injection amplitude calculated with the emittance of the injected beam and the effective width of the injection septum of 4 mm, is $2I_x \approx 800 \text{ mm}$. Therefore the injected beam profiles are small compared to the above acceptances. Thus the transported beam from the DR can be injected into the LER acceptances with enough margin. Since the beam energy is changed from KEKB (3.5 GeV) to SuperKEKB (4 GeV), the absolute value of $R_{56}$ of the ECS at the BT line will be 58.5% of current value. Even using the new ECS, $\sigma_z$ and $\sigma_\delta$ will be 11.7 mm and 0.51%, which is still small enough.

The transport efficiency from DR to LER is about 95%. The main beam loss is due to the collimation of a long energy tail at ECS, which is allowable level.

### Table

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<td>6.52</td>
<td>6.51</td>
<td>6.47</td>
<td>6.16</td>
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### Figures

**Figure 4:** Distributions of beam energy spread $\delta$ (a) at the end of Sector 2, (b) after cut by collimators at the first arc of LTR and (c) after the ECS. (d) density plots of $R_{56}$ and $V_c$. Parameters at the brightest color show the largest number of particles in the momentum acceptance of the DR.

**Figure 5:** Distributions at the key points. (a) profiles in the longitudinal phase space, (b) histograms of $z$, (c) histograms of $\delta$. Table shows width (hard edge or 3σ) of $z$ and $\delta$, $\varepsilon_x$ and $\varepsilon_y$ with their normalized emittances, beam energy and charge intensity.

## REFERENCES

[1] M. Masuzawa et al., IPAC2010, FRXBMH01