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 8×10^{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 8×10^{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 μm 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. On the other hand, to obtain low emittance positrons, we build a damping ring[3] (DR). The DR will be constructed in the middle of LINAC where 1.1 GeV-positrons are available. Positrons are resumed to the LINAC after staying for 40 ms, which corresponds to two linac-pulse.

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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.

LINAC SECTOR 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 positron, and quadrupoles are installed. The L-band and the successive S-band sections are 20 m and 130 m long, respectively. The β-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 $4.0X_0$. Both of horizontal and vertical beam sizes are $\sigma_{\rm x,y}$=0.5 mm, and the bunch length is $\sigma_{\rm z}$=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 integrate 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

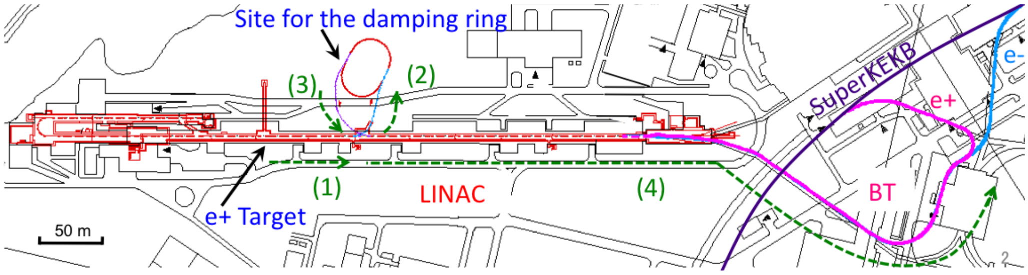


Figure 1: Schematic view of LINAC to SuperKEKB-LER.

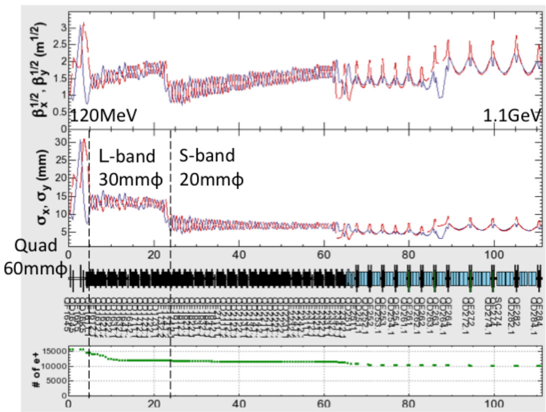


Figure 2: The β-functions, beam sizes(hard edge) and number of positrons after the capture section to the end of Sector 2.

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 the 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

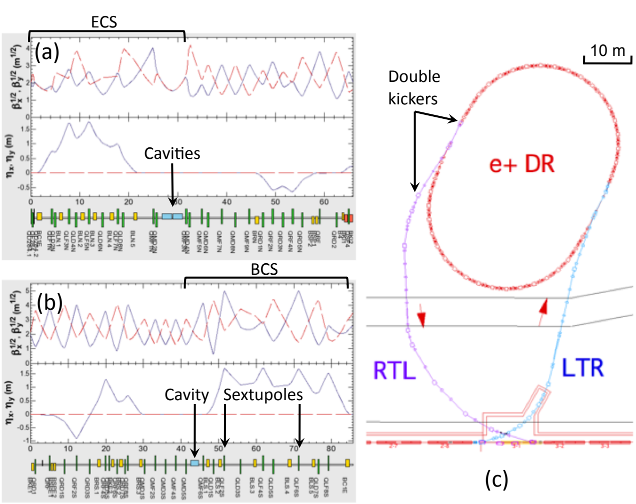


Figure 3: The β-functions and dispersion functions, for (a) LTR and (b) RTL. Solid (black) and dot (red) lines indicate the horizontal and vertical functions, respectively. (c) The layout of LTR, DR and RTL.

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 (δ) 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 ($\delta_{\rm in}$) 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 ($\delta_{\rm out}$) (c). The transformations of (z, δ) are $z_{\rm out} = z_{\rm in} + g(\delta_{\rm in})$ and $\delta_{\rm out} = \delta_{\rm in} + k(z_{\rm out})$, where $g(\delta)$ is a non-linear correlation function between z and δ in the arc obtained by fitting the optics, and $k(z) \equiv \frac{eV_c}{E_0} \sin\left(\frac{2\pi f}{c} z\right)$, 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}=-1.0 m and V_c=24 MV assuming the energy acceptance of the DR to be 0.8%. The resulting width of energy window(δ_{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.

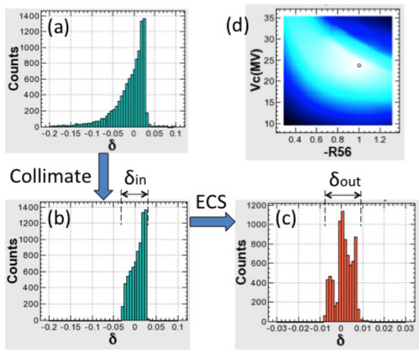


Figure 4: Distributions of beam energy spread δ (a) at the end of Sector 2, (b) after cut by collimators at the first arc of LTR and (c) after the ECS. (d) density plots of R_{56} and V_c. Parameters at the brightest color show the largest number of particles in the momentum acceptance of the DR.

The difference of the kick angles for the two bunches should be less than 0.69% to make the difference smaller than the beam spread. If we have to ensure the above condition for the two bunches, a double kicker system will be installed in RTL.

Since the bunch length in the DR is too long (7.7–11 mm) to be accommodated by the C-band structure in Sector 4, it is compressed by a bunch compression system (BCS), incorporated in RTL. The optics of RTL are shown in Fig. 3-(b). Beam distributions and the beam parameters at various positions are shown in Fig. 5. For BCS, an S-band structure is installed in front of the second arc where R_{56} component is generated. The accelerating voltage is no longer linear for such a long bunch. We checked if the particles with the distributions in the longitudinal phase space can go back to LINAC after Sector 3. The particles for the tracking are generated with $\varepsilon, \sigma_z, \sigma_\delta$ assuming Gaussian shapes. The BCS parameters, V_c is 22 MV and R_{56} is -1.05 m, compress σ_z from 11 mm to 0.716 mm which is small enough to be accepted in LINAC. The horizontal emittance is enlarged by non-linear dispersion effect at the second arc. However, if two sextupoles are placed close to the quadrupoles at the highest horizontal dispersion points, the horizontal emittance blowup is easily suppressed.

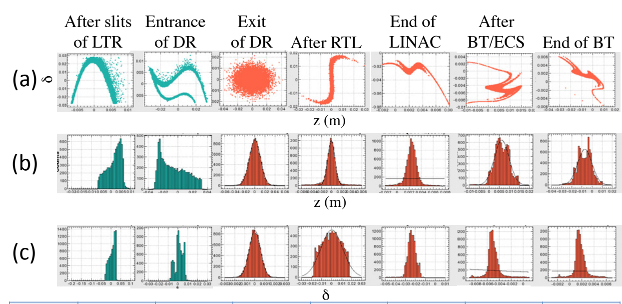
DR TO LER

The beam returned back to LINAC is accelerated to 4 GeV through the end of LINAC. A current optics in KEKB is used from Sector 3 to the injection point of LER. The effect of longitudinal wakes in the accelerating structures are included. We have not included the transverse wakes in LINAC after the DR generated through possible misalignments of components. The vertical emittance is enlarged by nonlinear dispersion at the vertical slope in the middle of BT. Using two skew-sextupoles put at the high vertical dispersion points on the slope, the vertical emittance blowup is easily suppressed.

As shown in Fig. 5, the energy spread at the end of LINAC is $\pm 0.9\%$ in hard edge whereas an acceptance of the beam transport line (BT)[7] is $\pm 0.375\%(3\sigma)$. 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 nm, $\varepsilon_y \approx$4 nm, $\Delta z \approx$66 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 $2J_x \approx$ 800 nm. 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, σ_z and σ_δ 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.



W(z) (mm)	±8.5	±31	±32.9	±2.15	±2.15	±8.5	±20
W(δ) (%)	±2.83	±0.8	±0.165	±1.8	±0.9	±0.25	±0.25
εx(nm) γεx(μm)	1380 3140	1470 3160	42.4 91.3	43.0 93.5	12.5 97.8	12.6 98.6	12.4 97.1
εy(nm) γεx(μm)	1320 2690	1290 2780	3.15 6.78	3.17 6.91	0.93 7.28	1.00 7.83	0.91 7.12
Energy (GeV)	1.1	1.1	1.1	1.1	4.0	4.0	4.0
Charge (nC)	6.52	6.52	6.52	6.51	6.47	6.47	6.16

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

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