DESIGN AND PERFORMANCE OF OPTICS FOR MULTI-ENERGY INJECTOR LINAC

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Abstract

We have designed multi-energy linac optics for the simultaneous injection of KEKB high energy electron ring(8 GeV) and PF electron ring(2.5 GeV). Acceleration and deceleration of the injection beam and optics to transport beams of two different energies are considered. Fast phase-switch of the sub-booster rf and pulse-timing of each klystron are utilized to adjust appropriate beam energy since solid-state phase shifters and timing system can be performed within 20 msec∼1 sec in pulse-to-pulse basis. The same magnetic field for the focusing and steering magnets are used because the magnetic field can not change so fast in the case of the DC magnets. We present the design scheme of the multi-energy injector linac and the performance evaluated by beam experiments.

INTRODUCTION

Injector linac provides injection beams for four storage rings, KEKB high energy electron ring(HER), KEKB low energy positron ring(LER), PF-AR electron ring, and PF electron ring. The injection beams for these rings have different energies and intensities. KEKB is a positron and electron collider for the B-factory to study the CP violation and so on. Thus, the continuous injection to keep higher beam currents is important and indispensable for the higher luminosity. On the other hand, homogeneous intensity of the synchrotron light is expected for light sources such as PF. In order to achieve the purpose, a top-up injection has been proposed to compensate the loss of the beam current due to beam lifetime.

Recently, a requirement of simultaneous injection between KEKB-HER and PF arises to satisfy these requirements. The *simultaneous injection* means that a beam mode is switched between injection for the different rings alternately instead of an acceleration of two different beams with one rf pulse. The energy of KEKB-HER is 8 GeV and 2.5 GeV for PF. It is necessary to transport beams of the different energies without loss up to the downstream of the injector linac. The charge intensity for the injection of KEKB-HER is 1 nC and 0.1∼0.2 nC for PF. Injector linac does not deal with different energies but also different intensities of the injection beam. The repetition rate of the injector linac is 50 Hz at maximum. In the case of the simultaneous injection, a repetition of 10 Hz is dedicated for the injection of KEKB and 1 Hz repetition for the PF injection. Fast beam-mode switch and beam handling are necessary to make this operation possible.

Bending magnet(BM581) is located at sector 5 which is the end of the injector linac. Injection beams are separated by this bending magnet for either the KEKB-HER transport line or the PF transport line. The BM581 is the DC magnet now, however, it will be replaced with a pulse magnet near future.

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DESIGN OF OPTICS

Figure 1 shows a bird's-eye view of the injector linac. An electron beam is created by the electron gun at sector A and passing through the bunching section. The electron beam is accelerated up to 1.7 GeV between sector A and B in front of 180° arc(J-Arc). In the case of the KEKB-HER injection, the electron beam is accelerated up to 8 GeV between sector C and 5 which follow J-Arc. On the other hand, a deceleration is utilized to make 2.5 GeV electron beam for the PF to make a beam line the beams of different energies passing through as much as short. The electron beam is accelerated up to 5 GeV between sector C and 2, then the electron beam is decelerated to 2.5 GeV up to the end of the injector linac. The klystrons in the half of sector 3 are switched from an acceleration to a stand-by mode and the phase of the sub-booster rf in sector 3∼5 is shifted by 180° to make the deceleration in principle. The discrepancy of the beam energy between the KEKB-HER and PF injection is occurred from sector 3. Energy feedback system[1] at sector 5 is used to adjust beam energies for these injections finely.

Quadrupole magnets and steering magnets are DC magnets in the focusing system. Magnetic fields of DC magnets to confine the beam inside the accelerating structures can not change fast in a pulse-to-pulse basis, though the beam energy can be controlled enough fast by using solid-state phase shifters of sub-booster rf and timing system of klystrons. This implies that the same magnetic fields of quadrupole and steering magnets should be utilized to transport beams having different characteristics. The optics between sector 3 and 5 is considered for the 2.5 GeV beam as the reference. The optics for the 2.5 GeV beam is based on the normal cell whose betatron phase advance is 90°. On the other hand, the betatron phase advance for the 8 GeV beam becomes about 30° because of the same magnetic field as the 2.5 GeV beam. Figure 2 shows the

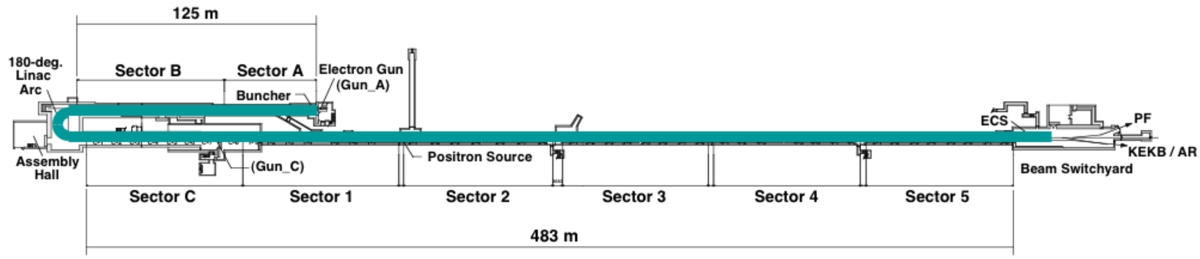

Figure 1: Bird's-eye view of injector linac.

optics between sector C and 5 for the multi-energy linac. The top figure shows the betatron function for the 2.5 GeV optics and middle shows that of the 8 GeV optics. The bottom figure indicates the beam energy along the beam line. Most combinations of the quadrupole magnets are triplets, though there are doublets of quadrupole magnets partially. The doublet cell consists of a focusing and a defocusing quadrupole magnet and the triplet cell consists of a defocusing magnet between a pair of identical focusing magnets. The optics is designed with matching procedures with adjusting the strength of these quadrupole magnets. The optics is calculated by using SAD(Strategic Accelerator Design)[2]. SAD is an integrated code for optics design, particle tracking, machine tuning, etc., and has been used for years at several machines such as KEKB and KEK–ATF.

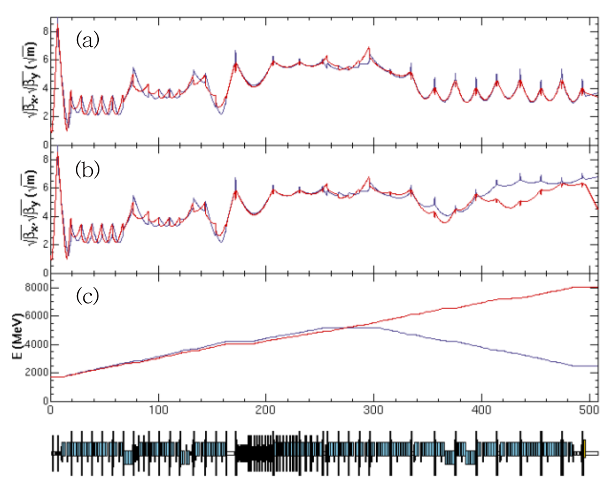

Figure 2: Optics between sector C and 5 for 2.5 GeV(a) and 8 GeV(b). Blue line shows horizontal and red line shows vertical beta functions. Beam energy is shown in the bottom.

BEAM EXPERIMENT

It is necessary for the matching procedure of the optics to measure Twiss parameters at the entrance of the beam line. The initial Twiss parameters at the beginning of sector C are measured by using wire scanners[3] at sector C. The electron beam with 1 nC charge intensity per pulse is transported to an analyzer line downstream of the injector linac to measure the beam profile and energy. The deceleration for the 2.5 GeV beam is set with the procedure that the half of klystrons at sector 3 are stand-by mode and the phases of the sub-booster in sector 3∼5 are shifted. The optics is calculated using the result of the wire scanners and the quadrupole magnets are set to the strength of the magnetic fields according to the calculation for the 2.5 GeV optics. The phase of the sub-booster rf for the deceleration mode should be shifted by 180° from the acceleration mode as long as the phase is on the crest. However, the acceleration phase is shifted by about 6° from the crest phase to reduce the effects of the longitudinal wake field induced by the head of bunch which decreases the energy of electrons at the tail of the bunch. The deceleration phase is $\phi_{dec} = \phi_{acc} + 180° - 2\Delta\phi$, where $\Delta\phi$ is the relative phase shifted from the crest. The energy is adjusted finely by using the energy knob[1] of the energy feedback system at sector 5 with checking the beam position on the screen in the analyzer line. Conversely, the stand-by mode of the klystrons change to the acceleration mode and the phase of the sub-booster rf changes to the acceleration phase to make the 8 GeV mode for the KEKB-HER injection.

The beam orbits and charge intensity per pulse for the 2.5 GeV and 8 GeV beam mode are shown in Fig. 3. The orbit after orbit corrections is indicated in Fig. 3. The linear equation

$$\begin{aligned} \Delta x_i &= R_{ij}\Delta\theta_j \\ &= \frac{e}{p_j} R_{ij}(BL)_j \end{aligned} \quad (1)$$

describes the orbit correction, where Δx_i is the measured beam position from the reference position at i-th BPM, $\Delta\theta_j$ is the kick angle of the steering magnet, and R_{ij} is the response matrix that consists of (1,2) element of the transfer matrix from the j-th steering to the i-th BPM. The kick angle is alternatively written by the integrated magnetic field, BL, normalized by the momentum, where p_j is the beam momentum at j-th steering. The measured position at 2.5 GeV and 8 GeV can be combined as one vector and two response matrix for 2.5 GeV and 8 GeV can be also combined as one matrix. Then, the magnetic field for each steering to satisfy both 2.5 GeV and 8 GeV orbit corrections can be derived by solving the linear equations with a Singular

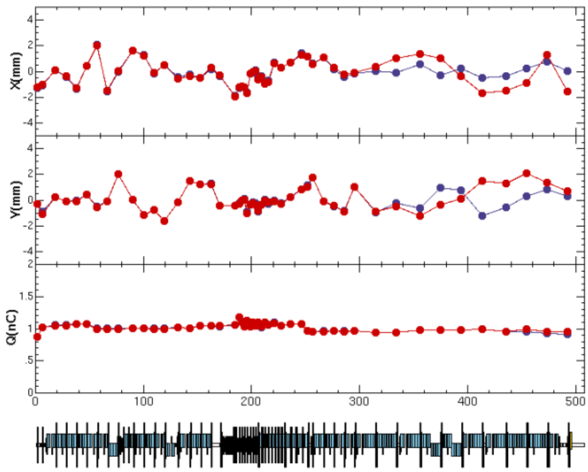

Figure 3: Orbits and beam charge per pulse between sector C and 5. Blue line shows 2.5 GeV and red line shows 8 GeV electron beam.

Value Decomposition(SVD). As shown in Fig. 3, beam orbits is within ±2 mm in the both plane which is an enough tolerance for the beam injection.

Table 1 shows measured emittances and Twiss parameters at the bending magnet(BM581). The emittances and Twiss parameters are derived by the least-square method. Fitting procedure is performed by minimizing χ^2 defined as:

$$\chi^2 = \sum_{l=1}^{4} \frac{1}{\sigma^2_{\Sigma_l}} \left(\Sigma_l - \sum_{k=1}^{3} M_{lk} o_k \right)^2 , \qquad (2)$$

where

$$\begin{aligned} \Sigma &= (\sigma_1^2, \sigma_2^2, \sigma_3^2, \sigma_4^2), \\ o &= (\varepsilon\beta, \varepsilon\alpha, \varepsilon(1+\alpha^2)/\beta) , \\ M &= \begin{pmatrix} m_{11,1}^2 & -2m_{11,1}m_{12,1} & m_{12,1}^2 \\ m_{11,2}^2 & -2m_{11,2}m_{12,2} & m_{12,2}^2 \\ m_{11,3}^2 & -2m_{11,3}m_{12,3} & m_{12,3}^2 \\ m_{11,4}^2 & -2m_{11,4}m_{12,4} & m_{12,4}^2 \end{pmatrix} . \end{aligned}$$

The beam size is measured by each wire scanner as σ_l, and σ_{Σ_l} is an error of the σ_l^2 measurements. The matrix M is the transfer matrix for Twiss parameters at the target position to each wire scanner. The derivation of the β, α from the design parameters, β_0, α_0 is evaluated by a B_{mag} parameter defined as:

$$B_{mag} \equiv \frac{1}{2} \left\{ \left(\frac{\beta}{\beta_0} + \frac{\beta_0}{\beta} \right) + \left(\alpha_0 \sqrt{\frac{\beta}{\beta_0}} + \alpha \sqrt{\frac{\beta_0}{\beta}} \right)^2 \right\} .$$

The B_{mag} implies a β matching in the optics.

As shown in Table 1, the normalized emittance of 8 GeV beam(1 nC) is consistent with that of 2.5 GeV beam(1 nC) within the measurement error. The emittance growth due to deceleration does not occur. However, the normalized emittance of 2.5 GeV with 0.2 nC beam is ten times larger than that of 2.5 GeV with 1 nC beam. The reason of the discrepancy is conceivable that the deceleration phase of 0.2 nC is the same as 1 nC beam at the experiment, though the effect of wake field is different between them. The emittance seems to be large because the energy spread of the beam becomes large and horizontal dispersion is not free at the measured region. The dispersion can be generated in the horizontal plane rather than the vertical plane since the alignment of the components such as accelerating structures and quadrupole magnets in the vertical is easier than the horizontal.

Table 1: Twiss parameters and emittances measured with wire scanners at sector 5.

E(GeV)	8	2.5	2.5
Q(nC)	1	1	0.2
α_x	-0.4 ± 0.2	0.2 ± 0.2	0.1 ± 0.1
β_x(m)	20 ± 2	33 ± 2	11 ± 1
α_y	0.2 ± 0.4	2.7 ± 1.3	3.1 ± 0.7
β_y(m)	24 ± 3	22 ± 11	19 ± 5
$\gamma\varepsilon_x(\mu$m)	96 ± 13	110 ± 16	1240 ± 110
$\gamma\varepsilon_y(\mu$m)	77 ± 22	43 ± 20	52 ± 11
$B_{mag,x}$	1.4	1.9	1.0
$B_{mag,y}$	1.2	2.8	3.6

SUMMARY

We present the optics to transport both 2.5 GeV and 8 GeV beam to the end of injector linac. Fast phase-switch of the sub-booster rf and pulse-timing of each klystron are utilized to adjust the beam energy. The magnetic field of the quadrupole and steering magnets for the 8 GeV beam is the same as that of the 2.5 GeV beam. The design of the optics is based on the optics for the 2.5 GeV beam. The betatron phase advance in a normal cell is 90° for the 2.5 GeV beam. Thus, the phase advance becomes about 30° for the 8 GeV beam. The beta function for the 8 GeV beam becomes larger than that of 2.5 GeV beam, however the emittance of the 8 GeV beam becomes smaller due to the adiabatic damping. The orbit correction is applied by using beam positions of the 2.5 GeV and the 8 GeV beam. The correction works successfully. The beam loss for the 2.5 GeV and 8 GeV beam does not occur. The beam quality satisfies the requirement of the injection for PF and KEKB-HER and confirmed by the experimental results. The matching procedure to a downstream beamline can be performed by the measurements of the wire scanners at sector 5 and the adjustment of the quadrupoles in sector C.

REFERENCES

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