DESIGN AND PERFORMANCE OF OPTICS FOR MULTI-ENERGY INJECTOR LINAC

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Abstract

KEK injector linac provides an injection beam for four storage rings, KEKB high energy electron ring(HER), low energy positron ring(LER), PF-AR electron ring, and PF electron ring. The injection beams for these rings have different energies and intensities. Recently, a requirement of simultaneous injection among these rings arises to make a top-up injection possible. Magnetic field of the DC magnets to confine the beam to the accelerating structures can not be changed during a pulse-to-pulse, although the beam energy can be controlled by fast rf phase shifters of the klystrons. This implies that a common magnetic field of the bending magnets and the quadrupole magnets should be utilized to deliver beams having different characteristics. Therefore, we have designed a multi-energy optics for the KEKB-HER electron ring(8 GeV, 1 nC/pulse), the PF electron ring(2.5 GeV, 0.1 nC/pulse), and the KEKB-LER positron ring(3.5 GeV, 0.4 nC/pulse). We present a performance of the multi-energy injector linac for the PF ring and the KEKB-HER.

INTRODUCTION

A new injection scheme has been developed, which is so called a pulse-to-pulse injection with multi-energy linac for the KEKB-HER, the KEKB-LER, the PF ring. The pulse-to-pulse injection means that the beam can be switched and injected to the desired rings within 20 msec at a minimum duration. However, the beam energy is different among these rings. Difficulties arise from that most of magnets can not change the magnetic field by a pulse-to-pulse duration. Therefore, we have developed a new optics to use a common magnetic field for the different beam energies, such as 2.5 GeV for the PF and 8 GeV for the KEKB-HER. The KEKB-LER injection has been still tested and under development in this scheme, however, the strategy is a similar way of the PF and the KEKB-HER.

The injector linac has 7 sectors, A-sector and B-sector before 180° arc(J-arc) and 1-sector to 5-sector after the J-arc. The energy of the J-arc is 1.7 GeV and the multi-energy scheme focuses on the region from the C-sector to the 5-sector. A pulse bend is placed in the 5-sector and the 2.5 GeV beam is kicked out to the transport line of the PF ring, while the 8 GeV beam passes through the ECS(the energy compression system) to the KEKB-HER transport line.

OPTICS

A fundamental block of the linac is an acceleration unit that consists of an S-band klystron and four 2 m-long accelerating structures. The klystron drives these accelerating structures which have a common phase of the microwaves. The accelerating structures in the acceleration unit have the same field gradient in principle. Eight acceleration units make a sector, typically. A sub-booster supplies microwaves to each klystron in the sector and adjusts the phase for a beam passage.

A doublet or a triplet of quadrupole magnets is placed in every one or two acceleration unit and makes a cell of a periodic lattice. In the case of an electron injection, an electron beam is accelerated from 1.7 GeV up to 4.8 GeV between the C-sector and the 3-sector. A positron target to make a positron beam is placed in the 2-sector. In the case of a positron injection, a primary electron beam hits the positron target and positrons are generated by means of electro-magnetic showers. On the other hand, a small hall(ϕ=3 mm) is placed in the vicinity of the target so that an electron beam can pass through the positron target for the electron injection. In order to make this possible, it is necessary to squeeze the beta function at the hall as small as possible and to make a local bump orbit by using pulse steerings in the horizontal plane.

The electron beam injected to the PF ring is decelerated down from 4.8 GeV to 2.5 GeV between the 3-sector and the 5-sector, while the electron beam is accelerated up to 8 GeV for the KEKB-HER. In the multi-energy region, the phases of the sub-boosters are shifted by 180° approximately between the acceleration and the deceleration. In practice, an off-crest phase typically shifted by 6° from the crest phase is used to compensate the energy difference between the head and the tail of a bunch due to the wake field. The deceleration phase is

$$\phi_{dec} = \phi_{acc} + 180^\circ - 2\Delta\phi, \qquad (1)$$

where $\Delta\phi$ is the phase shift from the crest phase. Further more, a few klystrons in the 3-sector would be a stand-by mode to adjust the beam energy so as to be 2.5 GeV. The stand-by mode implies an off-timing trigger for the beam passage. Both the 2.5 GeV and 8 GeV beam would be adjusted by the energy-feedback system[1] precisely. The energy feedback system consists of a set of two klystrons and adjust the phase. The off-crest phases are used in the opposite side of the crest for each klystron to compensate the energy spread. Those sub-boosters and the energy feedback system utilize a phase shifter with a solid-sate device and can change the phase by a pulse-to-pulse duration.

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The DC magnets are used in the lattice for the quadrupole and steering magnets. Therefore, the beams which have a different energy must be transported with a common magnetic field from the 3-sector to the 5-sector(multi-energy region). The optics is designed for the 2.5 GeV beam as a base line since there is a matching section in the transport line for the KEKB ring and not for the PF ring. The beta functions and beam energies for the 2.5 and the 8 GeV beams are shown in Fig. 1. The betatron phase advance of the cell is 90° typically in most sectors. However, the phase advance in the multi-energy region should be optimized so as to make the beta function enough small for the the different beam energy. In the 2.5 GeV optics, the phase advance for each cell is designed to be 108° approximately in the 4-sector and the 5-sector. While, the phase advance of the cell would become 40°∼50° for the 8 GeV optics. The optics design would suppress a large beam size in the multi-energy region for the both 2.5 and 8 GeV beam.

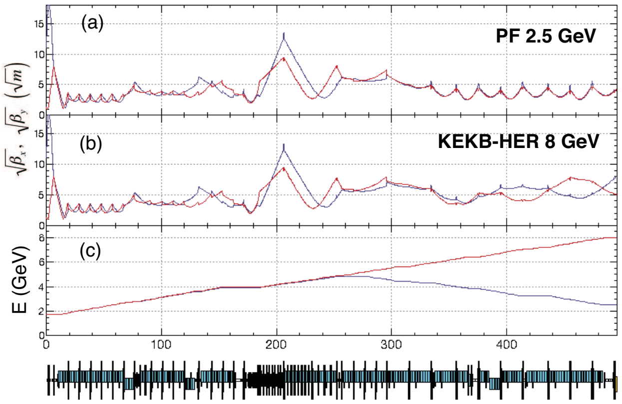

Figure 1: Optical parameters for (a) 2.5 GeV PF, (b) 8.0 GeV KEKB-HER, and (c) beam energy.

In the optics calculation, the SAD code[2] is utilized. We assumed that the beam energy at the exit of the buncher section in the A-sector would be 20 MeV which is measured by a energy analyzer cosists of a well calibrated bending magnet and a beam screen monitor. The beam energy is calculated by using a peak acceleration field of an accelerating structure, a phase, a klystron status[3]. The calculated energy would have errors due to a characteristic of the accelerating structure and the beam loading. Therefore, the absolute value of the beam energy should be adjusted to be the desired energy at the end of linac for each injection. A normalization factor is used to scale the beam energy to 1.7 GeV at the J-arc, 2.5 GeV for the PF ring, and 8 GeV for the KEKB-HER. The relative energy among the accelerating structures should be kept since the relartive error of the energy gain from the accelerating strucure would be small. Although the normalization factor is an overall factor, the normalization factor of 8 GeV is used for the 2.5 GeV beam in the common energy region which is between the J-arc and the entrance of the multi-energy region.

Twiss parameters at the entrance of the C-sector are matched so as to be the design values using the matching section in the J-arc. The matching procedure is based on emittance measurements with wire scanners[4]. From the C-sector to the 5-sector, k values correspond to the magnetic field of the quadrupoles are determined so that the beta functions become the design values by means of a fitting procedure with the SAD code.

CORRECTION OF OPTICS

The optics is corrected by a single-kick method. A single-kick orbit induced by a steering is measured by beam position monitors(BPM) which are placed next to each quadrupole magnet. Since the single-kick orbit is a relative orbit displacement by a single steering, we do not have to consider an absolute beam position.

The measured orbits are compared with the design orbits calculated by optical parameters based on the k value of the quadrupoles and the calculated beam ebergy described in the previous section. A fudge factor is introduced to correct the k value so that the measured orbits agree with the design orbits. The definition of the fudge factor, a_f, applied to the k value is written by

$$K_{ps} = a_f \cdot K_d, \tag{2}$$

where K_{ps} is a k value set to the real magnet and K_d is a k value of the design value. The deviation from the design of the k value of the m-th quadrupole can be estimated by solving following equations:

$$\Delta x_i^{(j)} = \sum_{m=1}^{M} R_{y,im}^{(j)} \Delta K_m \tag{3}$$

$$\Delta y_i^{(j)} = \sum_{m=1}^{M} R_{x,im}^{(j)} \Delta K_m \tag{4}$$

where $\Delta x_i^{(j)} = x_{m,i}^{(j)} - x_{d,i}^{(j)}$, $x_{m,i}^{(j)}$ and $x_{d,i}^{(j)}$ are the measured and the design orbit at the i-th BPM induced by the j-th steering in the horizontal plane, and y is the same as x. The response matrix, $R_{x,y}$ is calculated by the SAD code. The fudge factor is $a_{f,m}^{-1} = 1 + \Delta K_m / K_{d,m}$ and includes not only a field gradient error but also an energy error. Here, xy couplings are ignored because it is a higher order effect and it should be small.

In the optics correction, we use 22 kinds of single-kick orbits typically to obtain fudge factors of the quadrupole magnets and the fudge factors are determined at the 2.5 GeV lattice. During the optics correction, we found a miss connection of power supplies to quadrupole magnets. In this case, both a large fudge factor and a large field gradient error are appeared at a specified quadrupole magnet(QD484, QF484). In this manner, the single-kick method is also effective to find a machine error. The fudge factor after fixing the connection problem is shown in Fig. 2(c). The fudge factors are within 3%. Figure 2 shows a comparison of the measured and the design single-kick orbit for the 2.5 GeV beam before and after the optics correction. Introducing the fudge factors, the measured single-kick orbit is consistent with the design orbit. All other single-kick orbits are similar to Fig. 2 and consistent with each design orbit.

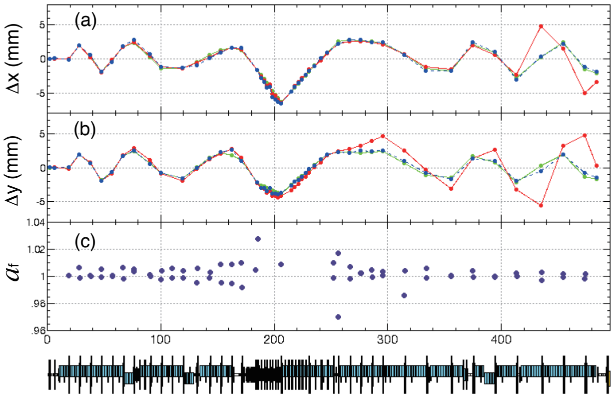

Figure 2: (a): Horizontal orbits for design(green), measured before correction(red), and measured after correction(blue). (b): The vertical orbits are the same as the horizontal. (c): Fudge factors for quadrupoles.

The optics is evaluated by the wire scanner in the 5-sector. The measured optical parameters for 2.5 GeV in front of the pulse bend are listed in Table 1. The optical parameters are well matched to the design values since the B$_{mag}$ parameters are very close to 1.

Table 1: Optical parameters for 2.5 GeV measured by the wire scanner in the 5-sector.

	horizontal	**vertical**	unit
Beta function	10.36	13.08	m
Normalized emittance	288	161	μm
B$_{mag}$	1.01	1.05	

ORBIT CORRECTION AND FEEDBACK

Beam orbits are required to be fixed and stable at the end of linac. A position and an angle of the 2.5 GeV beam should be zero at the pulse bend. At the same time, a position and an angle of the 8 GeV beam should also be zero at the ECS. We have developed a tuning technique to adjust both orbits for 2.5 GeV and 8 GeV simultaneously by using a common magnetic field of DC steerings. In order to adjust the orbit for 8 GeV, a local bump method is utilized. While the local bump is closed at 2.5 GeV, the local bump is not closed at 8 GeV in general. Therefore, the orbit for 8 GeV can be adjusted independent on the 2.5 GeV orbit. On the other hand, the beam orbit for 2.5 GeV is controlled by two steerings. However, these two steerings would affect the orbit for 8 GeV. In spite of this, the orbit response of two steerings can be canceled by adjusting the local bump height. The orbits for 2.5 GeV and 8 GeV can be adjusted by solving a following equation:

$$\begin{pmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta X_1 \\ \Delta X_2 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ n_{31} & n_{32} & n_{33} & n_{34} \\ n_{41} & n_{42} & n_{43} & n_{44} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \theta_2 \\ h_1 \\ h_2 \end{pmatrix}, \quad (5)$$

where x and X are a beam position for 2.5 GeV and 8 GeV, respectively, θ is a kick angle of a steering, and h is a local bump height. The orbit response matrix, m_{ij} and n_{ij}, is calculated by the SAD code. Vertical positions, y and Y, are adjusted by the similar way of the horizontal positions. In this procedure, the positions at two BPMs is necessary at least to adjust the position and the angle. We use two local bumps and two steerings to control the orbits. The phase advance between two local bumps is about 90° which corresponds to two cells of the lattice in the case of 8 GeV.

We consider the orbit feedback system by using this technique. This is a slow orbit feedback since the steerings are DC magnets and beam positions measure by BPMs for 2 sec intervals so far. The slow orbit feedback for the multi-energy beam can suppress an orbit drift for a long term .

CONCLUSION

We have present the optics designed for the multi-energy injector linac. The beams which have the different energies, such as 2.5 GeV and 8 GeV, can be successfully transported to the end of linac with a common magnetic field of the quadrupoles and steerings. As the next step, the multi-energy injector linac together with the positron injection to the KEKB-LER, the beam energy of 3.5 GeV, is under development.

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