USE OF PERMANENT MAGNET FOR DIRECT BEAM INJECTION SYSTEM AT KEK

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Abstract

To both existing electron storage rings PF and PF-AR (Photon Factory and PF-Advanced Ring, respectively) a beam is injected at 2.5 GeV by sharing the time with B-factory accelerator KEKB using the same electron linac. Most injection time is being spent by the electron injection at 8 GeV to KEKB-HER (High Energy Ring) and positron at 3.5 GeV to KEKB-LER (Low Energy Ring). To inject electron to PF or PF-AR, however, the beam energy adjusted to their injection energy suppressing and tuning the accelerating voltage of the linac cavities and recovered to the previous state after finishing the 2.5 GeV injection. To avoid these complexity of beam tuning and the time loss for the KEKB beam injection, electron beam pulses are extracted midway at 2.5 GeV from the accelerating pulse train by using a kicker magnet to the planned beam transport line of the fixed energy electron for which the hybrid permanent magnets are being considered from the economical viewpoint of the construction and running costs and also from an aspect of utilizing the limited space for installation. The design of these magnets are presented including the beam optics.

1 INTRODUCTION

Frequent electron and positron injections (average ~20 fills a day at present) will be required to make up for a short beam life time at the high luminosity run more than ~10^{33} $s^{-1}cm^{-2}$. Both PF and PF-AR rings are filled with electrons at 2.5 GeV and KEKB with electrons of 8 GeV and positrons of 3.5 GeV. An injector linac, formerly built for PF ring and also served as an injector to an accumulation ring (AR, the present PF-AR) of the TRISTAN main ring (MR), has been modified greatly to inject electrons and positrons at their full energies. As a result an electron gun, pre-buncher and buncher for 2.5 GeV to PF and PF-AR injections are installed at an intermediate position of the linac. During injection to PF or PF-AR, most of linac sectors are suppressed of the accelerating voltage except for required ones to attain an injection energy. The PF injection is few times a day, about 10 min for each fill, but the AR injection about 10 times a day at present because of its short beam lifetime.

To overcome the complex mode exchange, the direct beam injection lines to PF and PF-AR are considered. Installing a new beam transport line parallel to linac, the electron beam extracted at 2.5 GeV with a kicker magnet is transported along this new line and switched to PF or PF-AR with a beam switch magnet [1].

Recent development of the high performance permanent magnet, high remanent field, large coercive force and high energy product, makes possible its application to the field of the high energy accelerators. Their magnets require the highly homogeneous magnetic field over the beam aperture to guide the beam. In the accelerator application the deviation of the field distribution must stay within the limit imposed by the beam optics. To assure the field quality, the hybrid permanent magnet with machined iron poles will be employed.

There are many product series of permanent magnets ranging from alnico to rare-earth magnets. In the present study, however, we focus on the performance of the hybrid permanent magnets so as to apply them to the beam transport line. The use of the permanent magnets benefits in the reduction of the fabrication and running costs. We select two kinds of materials, Sr ferrite and SmCo, for the evaluation of the magnet performance [2].

2 PERMANENT MAGNET MATERIALS

The basic properties of the permanent magnet are expressed by the demagnetization curve at the second quadrant on which the operating point (H, B) of the magnetic circuit is determined. Most important properties are the residual induction and the coercive force. As an available energy is $HB/8\pi$, its maximum $(HB)_{\max}$ is given by the point where the demagnetizing curve and the hyperbola $HB = const$ are tangent. $(HB)_{\max}$ is the maximum energy product expressed by a unit of Mega-gauss Oersted (MG·Oe). Magnetic properties are summarized for typical materials in Table 1 [3].

Table 1: Characteristics of typical permanent magnet.

Material	Residual induction (kG)	Coercive force (kOe)	Max. energy product (MGOe)	Curie temperature (°C)
alnico	5.0~14.0	0.5~1.6	1.1~11	850
Fe-Cr-Co	8.0~14.5	0.4~0.8	1.1~7.0	670
Sr ferrite	3.0~4.5	1.6~3.95	2.0~4.8	450~460
SmCo	8.0~12.0	4.0~10.7	16~32	710~820
NdFeB	9.8~14.5	9.0~14.1	23~49	310

Alnico is the metallic alloy with 1.1~11 MG·Oe and has an excellent magnetic stability against temperature, but it is rather expensive.

Ferrite is a double oxide $MOFe_2O_3$, iron oxide Fe_2O_3 being a main component and M is Co (cobalt ferrite), Ba (barium ferrite), Sr (strontium ferrite), and etc. Among them Sr ferrite is most popular because it is cheep and chemically stable besides it has large coercive force and large resistivity. Its maximum energy product is 2.0~4.8 MG·Oe.

$SmCo_5$ and Sm_2Co_7 have a vary large energy product (16~32 MG·Oe). It is very expensive, about ten times more expensive than Sr ferrite. Neodymium iron boron $Nd_2Fe_{14}B$ has the largest energy product (23~49 MG·Oe) at present.

Irreversible and reversible thermal demagnetization of the permanent magnet are observed but the former is a one-time loss depending only on the lowest temperature for Sr ferrite or the highest temperature for SmCo to which the magnet has been exposed. Freezing Sr ferrite to condition can remove the irreversible demagnetization [4]. This kind of stabilization is called a thermal seasoning.

An intrinsic temperature coefficient of the residual inductance is -0.02~-0.03%/°C for alnico, -0.03~-0.05 for Fe-Cr-Co, -0.18~-0.20 for ferrite, -0.02~-0.043 for SmCo and -0.09~-0.13 for NdFeB. A large temperature effect on the field strength is expected for the Sr ferrite magnet, requiring a measure to compensate the temperature effect. At Fermilab several packages of 30%Ni-70%Fe alloy strips, having a low Curie temperature (~50-70°C) and permeability with a strong function of temperature, interspersed longitudinally between Sr ferrite bricks subtract flux in a fashion to null out the overall thermal dependence of the integrated field strength to less than 0.01%/°C [5].

3 BEAM TRANSPORT LINES

3.1 Extracted beam transport line to switch yard

The pre-buncher and buncher at the sector C-8, just downstream of quadrupole QF-C7-4 (see Fig.1), are replaced with a kicker magnet whose excitation duration is short enough to allow for an extraction of one beam pulse from 50 Hz pulse train without effecting rest beam pulses to KEKB. At this point the beam energy should be adjusted to 2.5 GeV for every injection mode (the present value is 2.85909 GeV). This energy reduction can be compensated by the following sectors. A trigger signal to fire the kicker magnet can be supplied by the existing timing system allowing the beam injection to a selected bucket of the PF or PF-AR ring. A diagnostic beam energy monitor can be equipped after the kicker magnet to feedback for the beam energy regulation [6]. One electron bunch is extracted horizontally and bent back to a straight beam transport line parallel to linac. Distance of the new beam line from the linac axis is assumed as 2.3 m for the present study. The linac beam level from the floor is 1.2 m. If the higher beam level is required, the vertical beam offset is possible using the vertical bending magnets following the horizontal bending magnets. The beam level is assumed as 1.8 m by the vertical offset of 0.6 m so as to maintain this level halfway to the PF injection line and to the beginning of the existing last curved section of the PF-AR injection line.

After the beam is elevated, the irregular section containing the horizontal and vertical dipoles is connected to the regular section through the transition section. As the regular section is very long (about 370 m), a compact regular cell of a quadrupole triplet is considered to accommodate one beam position monitor per cell enabling both horizontal and vertical readings at the center of the middle focusing quadrupole. Twiss parameters of the beam transport line (about 500 m long) is shown in Fig.2 which are obtained by TRANSPORT code. Magnet elements of this transport line is given in Table 2.

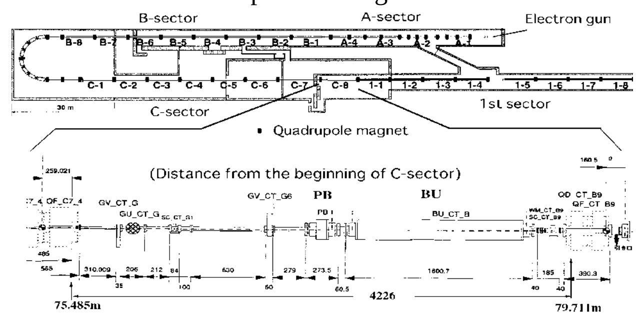

Figure 1: Beam extraction section. PB (pre-buncher) and BU (buncher) are replaced with a kicker magnet.

Table 2: Magnet parameters of the new injection lines. Elements with an asterisk are additional magnets.

magnet x number	K-value	length (m)	field (T/m or T)
Extracted beam to switch yard, (3.1-1) Hor. offset section			
QF* x 2	0.551	0.2	22.971
QD* x 1	-0.502	0.2	-20.944
BH* x 2	6.871 deg	2.0	0.5
(3.1-2) Ver. offset and transition section			
QD* x 5	-0.206~-0.500	0.2	-10.820~-20.841
QF* x 4	0.353~0.500	0.2	14.731~20.857
BV* x 4	4.096 deg	1.2	0.497
(3.1-3) Regular section (21 triplets)			
QF* x 22	0.670	0.4	13.971
QD* x 43	-0.340	0.2	-14.193
PF-AR ring injection line, (3.3-1) Curved section - 1			
QD* x 1	-0.186	0.2	-7.761
QF* x 1	0.271	0.2	11.306
QD* x 2	-0.346~-0.470	0.35	-8.255~-11.202
QF* x 1	0.400	0.35	9.524
QF* x 5	0.130~0.320	0.5	2.169~5.338
QD* x 4	-0.198~-0.332	0.5	-3.295~-5.543
BSW*	5.83 deg	2.0	0.424
BH* x 5	5.83 deg	2.0	0.424
(3.3-2) Straight section			
QF* x 6	0.097~0.443	0.5	1.615~7.380
QD* x 6	-0.109~-0.377	0.5	-1.813~-6.282
(3.3-3) Curved section - 2			
QD x 10	-0.128~-0.318	0.36	-2.96~-7.37
QF x 8	0.173~0.354	0.36	4.00~8.21
BH x 19	5.384~7.558 deg	1.0	0.78~1.10
BV x 4	4.779 deg	1.0	0.695
BSP x 2	2.406~4.368 deg	1.0	0.29~0.53

3.2 PF-ring injection line

At the beam switch yard the first dipole magnet following the last quadrupole triplet of the linac beam line serves as a beam switching element. It is operated as a bipolar mode and the beam is dumped when it is not excited or in the case of power supply faults. If it is excited in either polarities, the beam is deflected to the PF or PF-AR injection line. Fig.3 gives the location of the beam switch magnet (BSW).

To the PF injection line, the beam passes over the KEKB injection lines with the vertical separation of 0.6 m. The PF ring beam level is higher than the linac axis by 3.5 m and the beam is vertically translated along the slope. The 1.8 m beam level, therefore, will be maintained to the first vertical bending magnet. Twiss parameters from the beginning of the C-sector to the PF injection septum through the new beam line is shown in Fig.2. The present magnet parameters of PF injection line are modified to follow the new beam parameters at the BSW magnet.

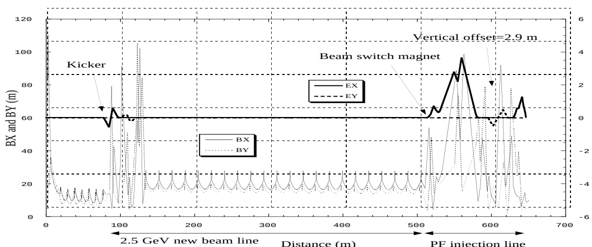

Figure 2: Twiss parameters to the PF ring from the beginning of the C-sector through the new beam line

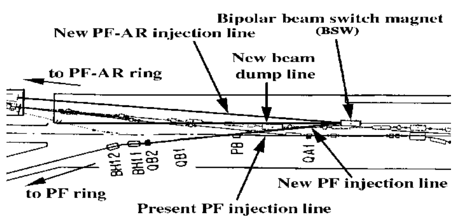

Figure 3: Beam switch magnet at the switch yard

3.3 PF-AR-ring beam injection line

As the present injection line is common to the KEKB electron transport line except for the last curved section, the beam switch magnet is followed by a new 2.5 GeV PF-AR beam line which is connected to the existing last curved section at 1.8 m beam level. Twiss parameters are given in Fig.4 from the beginning of the C-sector to the end of the PF-AR injection line.

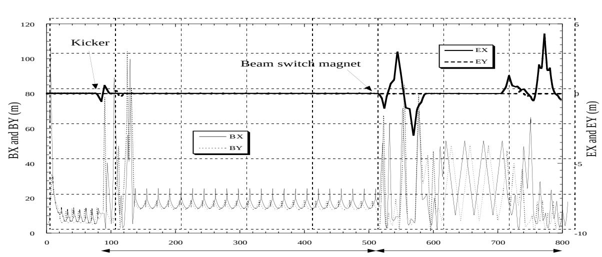

Figure 4: Twiss parameters of the PF-AR injection line from the beginning of the C-sector of linac

The PF-AR injection line is divided into 3 sections, curved section-1, straight section and curved section-2. As the curved section-2 (last curved section) is independent of the KEKB injection lines, it is used by adjusting the excitation parameters so as to connect twiss parameters at both ends as given in Table 2. The straight section has enough length (about 100 m) to accommodate several regular cells. Although it is possible to use quadrupole triplets, a small number of FODO cells is adopted allowing larger betatron function.

4 HYBRID PERMANENT QUADS

Although all magnets except for the kicker and beam switch magnets are the candidates for the hybrid permanent magnets, quads at the regular sections beside the linac, where a large number of triplet quads are used, can be made of the permanent magnet of which configuration is shown in Fig.5. Required field gradients are 13.97 and 14.19 T/m for focusing (0.4 m length) and defocusing (0.2 m) quad, respectively.

Comparisons between Sr ferrite and SmCo are shown in Fig.6. SmCo has a superior field property for the same quad structure. If the required integrated field strength is assumed, the total volume of Sr ferrite must be increased at least by the factor of 3.

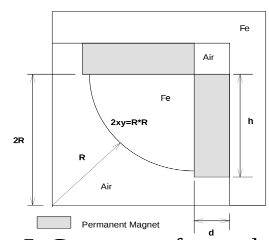

Figure 5: Geometry of a quadrant of a hybrid quad

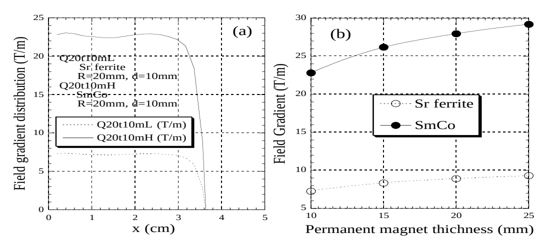

Figure 6: (a) Field gradient distributions for the hybrid permanent magnet (10 mm thickness) and (b) the gradient variation for different thicknesses

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