OPTICS AND MAGNET DESIGN FOR PROTON BEAM TRANSPORT LINE AT PEFP*

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Abstract

The 100-MeV PEFP proton linac is designed to have two proton beam extraction lines at the 20-MeV and 100-MeV end, for users' experiments. Each extraction line will house 5 to 6 beamlines. The beam optics for the proton beam transport line has been designed with the TRACE code. The optics design is such as to meet the users' various requests of the beam size and intensity at the beam target for their experiments. To distribute the proton beam to the beamlines, an AC-type magnet has been designed to have a cyclic frequency of 15 Hz. We will describe the optics and magnet design for the 20-MeV proton beam transport line.

INTRODUCTION

The 100-MeV PEFP (Proton Engineering Frontier Project) proton linac [1] is supposed to generate proton beam with the peak current of 20 mA, the pulse length of 2 ms, and the repetition rate of 120 Hz. It will provide two proton beam extraction lines at the 20-MeV and 100-MeV end, for users' experiments [1]. Each extraction line will be branched to 5 to 6 beamlines, which enable multiple users to do their experiments at the same time. It necessitates an AC type magnet to distribute the proton beam to the beamlines.

OPTICS DESIGN

Figure 1 depicts the layout of the 20 MeV proton beam extraction line. The beam extraction point is at the end of DTL1 where the proton beam energy reaches 20 MeV. We need two 45° dipole magnets for beam extraction from the main proton linac and one dipole AC magnet to distribute the proton beam to 5 beamlines shown in Fig. 1.

The optics should be designed so as to meet the users' various requests of the beam size and intensity at the beam target for their experiments. There should be a few quadrupole magnets to focus the beam at the transport line and to adjust the beam size at the target located at the end of each beamline. The optics of each beamline has been designed to be independently controlled without perturbing other beamlines.

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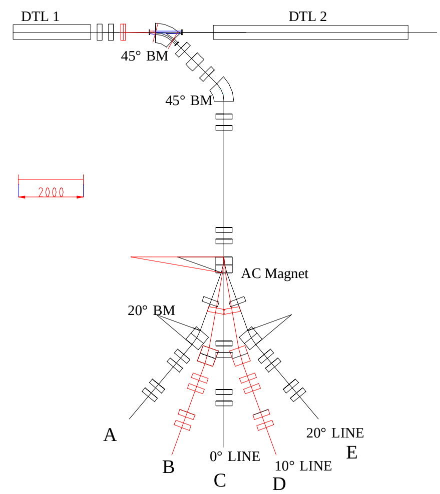


Figure 1: Layout of the 20 MeV proton beam extraction line.

Proton Beam Distribution to Beamlines

The magnet to distribute the proton beam to 5 beamlines will be an AC-type magnet which has been designed to have a cyclic frequency of 15 Hz (period: 66.6 ms) as shown in Figure 2. As the period of the 120 Hz beam is 8.3 ms, 8 beam pulses are available during one period of the AC current. If the beam is supplied at 120 Hz, each beamline at the 20-MeV transport line can use the beam at 15 (A, E) or 30 Hz (B, C, D).

Since the beam pulse has a finite length of 2 ms and the bending field of AC magnet is sinusoidal in time, the tail of each beam pulse receives a different bending force from that of the head. Table 1 lists the calculated bending angle differences. It shows that beamline C, the straight one, is the most serious and the two beamlines with 20° bending angle have the preferable zero difference. In this estimation it is assumed that the length of the AC magnet is 0.5 meter and the beam pulse length is 0.5 ms.

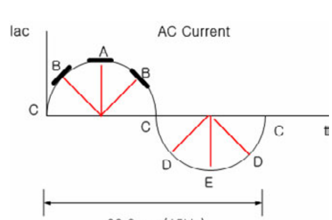


Figure 2: AC current shape. A, B, C, D, E denotes each beamline.

Table 1: Bending angle difference of the 0.5-ms long beam.

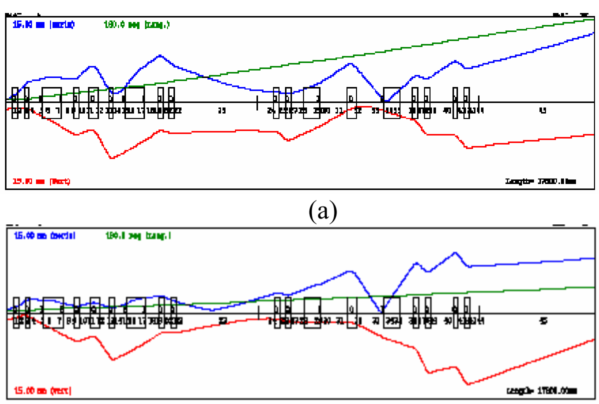
Beam Line	Bending Angle at AC Magnet [deg]	AC Magnet B-field [T]	AC Current theta [deg]	Bend angle difference bet. head and tail
C	0	0	0	0.94 deg
B, D	10	0.2266	30	0.8 deg
A, E	20	0.4532	90	0.0 deg

Optics Design

The beam optics for the proton beam transport line has been designed with the TRACE code. The beam transport line is divided into two parts; beam extraction and bean distribution. The optics is DBA (Double Bend Achromat) in both parts.

In the distribution part, after the dipole magnet two quadrupole doublets are introduced to have enough margin to control the beam size at the target at the end of each beamline. Before the target, an energy degrader to reduce the proton beam energy, a modulator, and a collimator will be added [2]. The optics has been designed to handle the orbit change due to these additional components.

Figure 3 shows the beam envelope of the 20° beamlines with different beam currents. The space-charge effect is not small at 20 MeV of proton beam. But the designed optics can handle this effect.

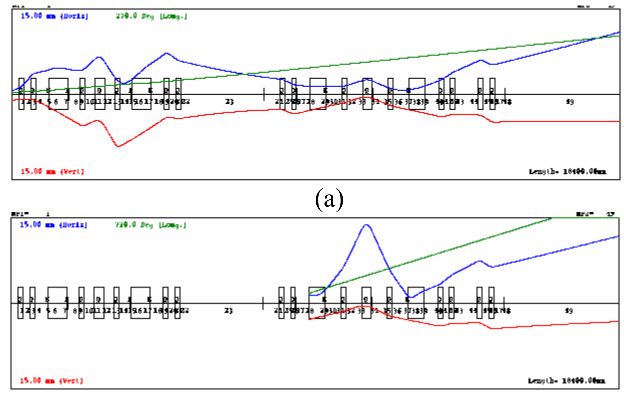


(a)

(b)

Figure 3: Bean envelope of the 20° beamline with different beam currents: (a) 25 mA, (b) 0 mA.

Figure 4 shows the effect of the bending angle difference at the 10° beamline described in the previous subsection. The equivalent beam energy difference between centre and tail of the 0.5-ms long pulse is 1.5 MeV. The calculation shows a big change in the horizontal beam sizes after the AC Magnet, but a small change at the end of the beamline due to the achromatic optic. In Fig. 4(b) the ray tracing starts from the AC magnet located at the centre of the beamline. Before the AC magnet the Twiss parameters in the longitudinal direction are; α = 41.7, β=16.88, ε = 411.5 π Deg keV. Including the effect of the bending angle difference of the AC magnet, the Twiss parameters are changed to: α = 345.5, β=16.88, ε = 411.5 π Deg keV.



(a)

(b)

Figure 4: Beam envelope of the 10° beamline calculated by the TRACE code: (a) without the effect of different bending force, (b) includes the effect. The blue line represents the horizontal beam extent, the red line the vertical beam extent, and the green line the longitudinal extent. The vertical scale of beam size is 15 mm.

MAGNET DESIGN

We will describe the preliminary design of the 45° dipole magnet and quadrupole magnet here. The magnets have been conservatively designed to achieve the required field accuracy without special material and complicated shape. The magnetostatic calculations have been made using the OPERA-3D/TOSCA computer code. To estimate the multipole components, we have calculated their orbit integrals. The quantity of interest is the ratio of the n-th multipole field to the fundamental field, that is, the integrated normalized multipole components:

$$b_n = \int B_n \, dz \Big/ \int B_f \, dz \,,$$

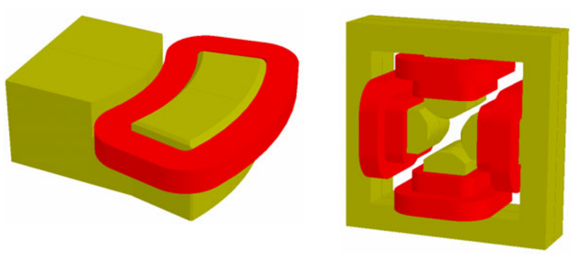
where B_n is the multipole component, B_f is the fundamental. At the ends, the pole sides are bevelled to reduce multipole components. Automatic procedures have been written in OPERA-3D language to model the magnet and to calculate the integral of multipole components. For effective calculation we used the mixed elements (linear and quadratic type), which are concentrated near the pole gap. Solid pieces of 50PN395(S10C) steel will be used for magnet cores, which is easily obtainable in Korea.

Dipole Magnet

The designed dipole magnet is conventional, C-type, curved yoke magnet. The radius of curvature is a small number of 0.68 m, producing a large sagitta, which makes a curved yoke. Even with the fringe field at curved magnet edges, the real trajectory of the beam would deviate from the ideal one by about 6 mm. Main parameters of the dipole magnet are given in Table 2 and the half model for the numerical calculations is given in Fig. 5(a). The low current density of 3.1 A/mm^2 will reduce the loads on the water-cooling system and the electrical system.

Table 2: The parameters of the dipole magnet

Type	C-type, Curved
Bend angle	45^o
Beam entrance/exit angle	12^o
Flux density	0.86 T
Pole gap	50 mm
Radius of curvature	680 mm
Good field width	±20 mm
Magnetic field deviation	< 1E-3
Current density	3.1 A/mm^2
Effective length	600 mm



(a) (b)

Figure 5: The TOSCA model: (a) Half model of dipole magnet with conductor, (b) quadrupole magnet.

Quadrupole Magnet

The designed quadrupole magnet is air-cooled, solid pieces, simple rectangular type. Main parameters of the quadrupole are listed in Table 3. The 45^o chamfers on the pole tips are made to reduce multipole components. Fig. 6 and Table 4 show the calculated multipole field components vs. beam coordinate with various chamfer heights, and the minimum dodecapole component is mandated for chamfer height of 4mm.

Table 3: The parameters of the quadrupole magnet.

Field gradient	10 T/m
Aperture diameter	65 mm
Good field diameter	50 mm
Pole shape	Hyperbola
Pole tip chamfer	4×4 (mm×mm)
Multipole components	< 1E-3
Current density	1.8 A/mm^2
Yoke length	116 / 268 mm
Effective length	150 / 300 mm

Table 4: Calculated multipole components with various chamfer heights.

Chamfer height [mm]	Integrated normalized multipole components		
	b_6 (E-3)	b_{10} (E-3)	b_{14} (E-3)
0	-3.294	0.226	0.039
2	-1.831	-0.096	0.082
4	-0.206	-0.153	0.060
6	0.974	-0.123	0.055

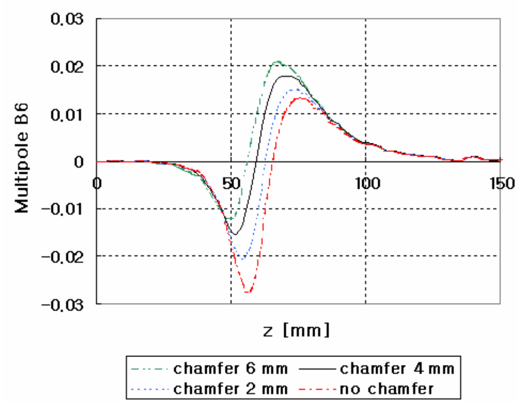


Figure 6: Plots of dodecapole components (B6) vs. z , the beam coordinate, with various chamfer height.

CONCLUSION

The beam optics of the 20-MeV proton beam transport line for the proton beam users' experiments has been designed with the TRACE code. There will be 5 beamlines: a straight line, two beamlines with 20° bending angle, the other two with 10° bending angle. The magnet to distribute the proton beam to the above 5 beamlines is an AC-type magnet. The preliminary design of the 45^o dipole magnet and quadrupole magnet has been finished.

ACKNOWLEDGEMENT

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