DESIGN OF SWITCHING MAGNET FOR 20-MEV BEAMLINES AT PEFP*

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Abstract

The PEFP (Proton Engineering Frontier Project) proton linac is designed to have two proton beam extraction lines at the 20-MeV and 100-MeV end. The 20-MeV extraction line is branched out into 5 beamlines by using the switching magnet. The magnet bends the proton beam by +20, +10, 0, -10, -20 degrees, respectively, and has an AC frequency of 2.5 Hz with a programmable ac power supply. It employs an H-shape, 0.45 T magnetic fields, 500 mm effective length, and 50 mm pole gap. Laminated steel of 0.5 mm reduces the eddy currents in the yoke, but some heat radiation from the stainless steel of vacuum chamber is inevitable. This paper presents the magnet specification and primary design.

INTRODUCTION

An AC switching magnet is used to distribute proton beam to 5 beamlines. Figure 1 shows the concept of AC switching magnet. The magnet is excited with a repetition frequency of 2.5 Hz. Figure 2 shows the required magnetic field waveform that has 25 ms of rise time and flattop respectively. The eddy currents from vacuum chamber and magnet core reduce the magnetic field and make the phase delay. Table 1 lists the main parameters of AC switching magnet. Cooling methods for coil and vacuum chamber must be considered.

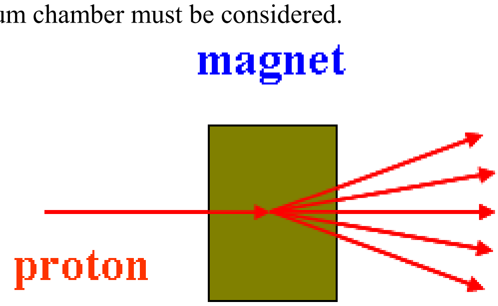

Figure 1: Concept diagram of AC switching magnet.

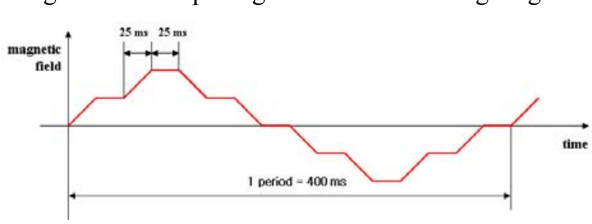

Figure 2: Required magnetic field waveform.

Table 1: Parameters of the switching magnet.

Parameters	Values
Proton energy	20 MeV
Deflection angle	±20, ±10 deg
Magnetic field (20 deg)	0.45 Tesla
Magnetic field integral (20 deg)	0.2268 Tm
Magnet sizes (Width/Height/Length)	882/420/426 mm
Effective length	500 mm
Pole gap	50 mm
Lamination thickness	0.5 mm
Rms current	196 A
Current density	4.6 A/mm^2
Rms voltage	56 V
Resistance per magnet	29 mΩ
Inductance	19 mH
Coil turns per pole	28 (4x7)
Coil size	9.5x9.5 mm 5φ
Switch frequency	2.5 Hz
Rise / Flattop time	25/25 ms
Average power loss (Coil/chamber/yoke)	1123/1332/53 W

Iron Core and Coil

Used iron core is 50PN510 that is non-oriented electrical steel of 0.96 packing factor and 0.5 mm thickness lamination. The effects of lamination are reflected in the different permeability and conductivity in three axes. The pole width of the magnet is 0.44 m and return yoke thickness is 0.13 m as shown in Figure 3. Coil is 9.5 mm square copper with a diameter of 5 mm cooling hole. The current density is 4.6 A/mm^2 that requires the water-cooling system. The shape of conductor is racetrack.

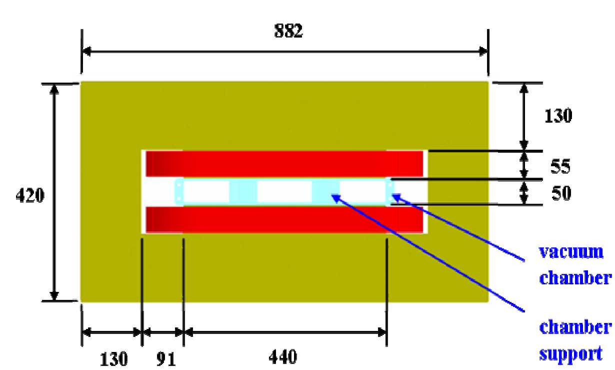

Figure 3: Iron core size with vacuum chamber.

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Vacuum Chamber

The stainless steel (316S) is used for vacuum chamber. The permeability of welded 316S is about 1.1 in cgs units. There is 4 mm deflection at the center of vacuum chamber in case of 5 mm thickness of top and bottom plates. Also magnetic field decreases and phase delay comes large because of the eddy current. To reduce these effects, we have changed 5 mm to 2 mm thickness and added the supports in vacuum chamber. Figure 4 shows the support structure in the vacuum chamber that has chopped blocks of 20x50 mm^2 and 6x90 mm^2 cross-sections. Figure 5 shows the cooling channels of vacuum chamber. The shortest distance between the thin supports and the proton orbit is 22 mm. Table 2 lists the vacuum chamber specifications.

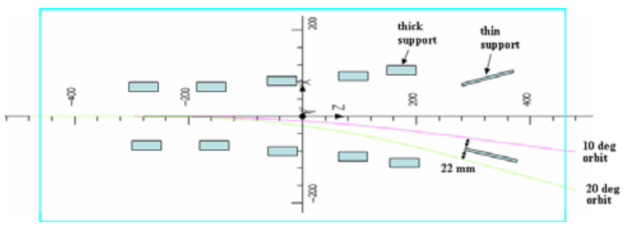

Figure 4: Supports in vacuum chamber with orbits of 10 and 20 degree deflections.

Table 2: Vacuum chamber specifications.

Parameters	Specifications
Material	Stainless steel
Permeability (weld)	1.1
Inner width	440 mm
Height	48 mm
Thickness (top/side)	2/18 mm
Length	946 mm
Cooling channel diameter	4 mm
Clearance with pole tip	1 mm
Thick support cross section	20x50 mm^2
Thin support cross section	6x90 mm^2

Figure 5: Cross section of the cooling channels at the corners of vacuum chamber.

SIMULATIONS

The magnetic rigidity of 20 MeV proton beams is 0.6496 T-m and magnetic field integral for 20° bending is 0.2268 T-m. In optics design, the required effective length is 0.5 m and the magnetic field strength at the center of magnet is 0.45 T. The magnet was modelled in three dimensions using ELEKTRA code with linear finite element. That code calculates orbits of charged particle, eddy currents, energies, and power losses. Figure 6 is the surface contours of the magnetic field at this magnet model.

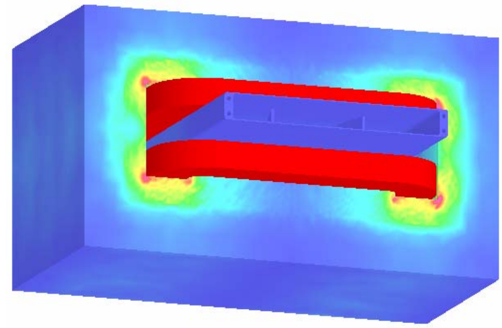

Figure 6: Surface contours of magnetic field by ELEKTRA code.

We can recognize the magnetic field decrease and phase delay because of the eddy current. So “current bump” is needed to make the flattop shapes of magnetic field waveform as shown in Figure 7. The time step of calculations is 5 msec and the number of time steps is 40 for half period in Figure 7.

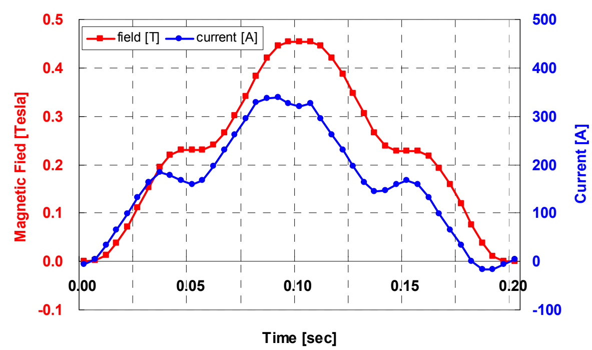

Figure 7: Calculated current and magnetic field for half period.

The power losses of the vacuum chamber become large at rapid changes of current. Figure 8 shows the calculation results of currents and vacuum chamber losses for half period. The peak loss of vacuum chamber is 3188 W, and the average value is 1332 W. Because the most heat is generated at the side parts of the chamber, 4 cooling channels at the corners of chamber are enough to cool the heat. The power loss of coils is 1129 W that is cooled by cooling channel at the center of coils. Iron core loss is 53 W that is small due to the lamination effect. Effective length is determined as $L_{eff} = \int Bds \;/\; B_0$, where, B_0 is magnetic field at the magnet center and $\int Bds$ is magnetic field integral along the proton orbit.

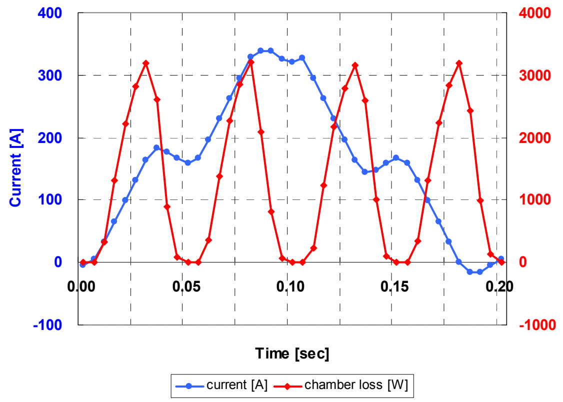

Figure 8: Currents and vacuum chamber losses for half period.

Integral range is 0.946 m as the same length of the vacuum chamber that includes the magnet length of 0.426 m. The calculated effective length is 0.500 m for 20-degree deflection, but 0.494 m for 10-degree deflection. Relative multipole components are calculated along the proton orbit as following:

$$b_n = \frac{\int B_n ds}{\int B_1 ds} \tag{1}$$

The relative quadrupole component is about 1 % due to oblique exit angle of proton with magnet end face, and the higher components are less than 0.1 %.

CONCLUSION

We have designed the AC switching magnet. This magnet distributes proton beam to 5 beamlines at 20 MeV proton beam extraction line. Detail analysis is performed by OPERA ELEKTRA code. We can estimate the current profiles, magnetic field distributions and power losses.

ACKNOWLEDGRMENTS

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