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DESIGN STUDY OF A FAST KICKER MAGNET APPLIED TO THE BEAMLINE OF A PROTON THERAPY FACILITY

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Abstract

A proton therapy facility based on an isochronous superconducting cyclotron is under development in HUST (Huazhong University of Science and Technology). A fast kicker magnet will be installed in the upstream of the degrader to perform the beam switch function by kicking the proton beam to the downstream beam stop. The rising and falling time of the kicker is about 100 µs, and the maximum repetition rate is 500 Hz. This paper introduces simulation and optimization of the eddy current and dynamic magnetic field of the fast kicker, by using FEM code OPERA-3D. For kicker materials, laminated steel and soft ferrite are compared and the MnZn ferrite is chosen. Designing considerations includes the eddy current effect, field hysteresis, and mechanical structure of the kicker will also be introduced.

INTRODUCTION

HUST proton therapy facility (HUST-PTF) is based on an isochronous superconducting cyclotron and spot scanning technique. Two 360-degree rotation gantry treatment-rooms and one fixed beamline treatment station will be constructed at first stage. A detail description of the facility parameters can be found in Ref. [1]. During the treatment process of the pencil beam spot scanning, the proton beam is applied to the patient for only a few milliseconds, and then kicked away. After repositioning and/or readjustment of the beam energy, the beam is directed back to the patient [2]. A fast kicker magnet will be installed in the upstream of the degrader, to perform the 'beam off' function by kicking the proton beam to the downstream beam stop.

This paper mainly compares two material schemes for the kicker magnet yoke and analyses the eddy current and field hysteresis effect of kicker magnets. The design of mechanical structure is also introduced.

PHYSICAL SPECIFICATIONS

The kicker magnet system is one of the key components of spot scanning technique. The layout of the kicker system is shown in Fig 1. In HUST-PTF, vertical kicker scheme is adopted. The main parameters of the kicker magnet are listed in Table 1. The kicker magnet is located at 1.24 m before the degrader. There is a quadrupole (Q3) between the kicker magnet and the degrader, whose defocusing direction is the same to the kicker deflected direct

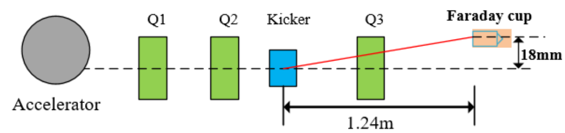

Figure 1: Layout of kicker system.

ion. The proton beam is deflected by the kicker magnet, then passing through a drift, the quadrupole between the kicker magnet and the degrader will further bend the proton beam to a Faraday cup (FC). According to the simulation of beam trajectory, the gap and pole width of kicker magnet is determined, the distance from beam stop to the center of the kicker magnet is about 1.24 m. The minimum integral field is 0.0252 T·m, deflecting the 250 MeV proton beam an angle about 10.36 mrad. The beam offset at the FC is about 18 mm (7 mm for the beam size, 3 mm for the thickness of FC, 8 mm for the radius of FC). As for the power supply, the kicker magnet is excited by pulse current with a maximum repetition frequency of 500 Hz and a rising/falling time of 100 µs. The current ramping speed is up to 5040 kA/s and the magnetic field ramping speed is up to 1010 T/s.

Table 1: Parameters of the Kicker Magnet

Name	Parameter
Deflection angle	10.36 mrad
Magnet gap	50 mm
Integral field	0.0252 T·m
Magnet length	200 mm
Number of coil turn	4 Turns/pole
Field strength	0.101 T
Good field region	±30 mm (vertical) ±14 mm (horizontal)
Coil Induction	44 µH
Max repetition Frequency	500 Hz
Rise/fall time	100 µs

MAGNET DESIGN

Kicker magnet applied to HUST-PTF is a window frame type magnet with two bedstead coils. To insure the required rapid change of the magnetic field, eddy currents in the core must be evaluated. Soft ferrite or laminated silicon sheets can be chosen as the material of the magnet cores.

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Simulation and Parameter Setting

To study the eddy current effect in kicker magnet, the 3D transient electromagnetic simulation and steady-state thermal simulation are performed in the Vector Fields Opera 18 simulation code [3]. The procedure of electromagnetic and thermal analysis is shown in Fig 2.

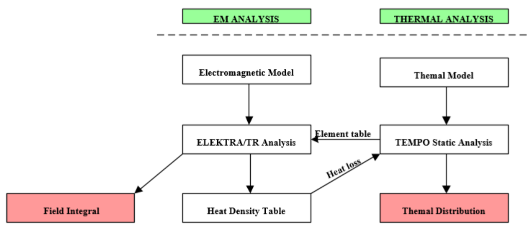

Figure 2: Procedure of electromagnetic and thermal analysis.

The excitation current of coils is a trapezoidal wave with a ramp/down time of 100 µs and a steady time of 900 µs, Electromagnet simulations with the adaptive time step are carried out on the ELEKTRA/TR program to obtain the field integral and eddy current loss in a period. The time setting is dense at the rise/down time to get a precise simulation result. The coordinates table of centroid in each element generated from the unsolved TEMPO model is then imported into the ELEKTRA/TR program to evaluate the heat loss [4]. A table file of average heat density value over a cycle is calculated by

$$HEAT = \frac{\sum_{i=1}^{n} heat_i * (t_i - t_{i-1})}{t_n}, \tag{1}$$

where *HEAT* is the average power of each element, n is the total number of simulation point, t_i is the simulation setting time of point i.

Then the average power of each element is import to the unsolved TEMPO Static Analysis and carried out, the temperature distribution of the kicker magnet will be presented.

In electromagnet simulations, the laminated steel is defined as anisotropic with a packing factor about 0.95, and there is no current along the laminated direction. The MnZn ferrite is regard as one block, it is isotropy with low conductivity. For TEMPO/SS, the magnet is assumed to be natural cooling with the transfer coefficient of 14 W/(K·m^2) and the ambient temperature 20°C. The detail parameters of laminated steel are shown in Table 2, and the detail parameters of MnZn ferrite is shown in Table 3.

Laminated Steel Yoke

Generally, laminated silicon steel sheets for iron core are used to reduce the eddy current and the heat loss. However, the laminated magnets are still not free from the eddy current, it will reduce the magnetic field rising speed. and the hysteresis effect is going to be large. Slits in the end laminations of iron core are proven to be an effective method to reduce the eddy current [5]. The laminated steel yoke with slits is considered for the magnet design. The field integral curves of current raising process are shown in Fig. 3. Within 100 µs, the field integral can reach 82.7%. With slits in the end of limited laminated steel yoke, the field integral can only reach 83.8%. The field integral curves of current falling process are shown Fig. 4. When the current is falling down to zero, the remanence is respect to be large. and it takes a long time to eliminate remanence. The temperature distributions are shown in Fig. 5. The maximum temperature decrease from 99.5°C to 71.6°C. This means slits in the end laminations of iron core can reduce eddy heat efficiently, but it does little for the response speed.

Table 2: Parameters of Laminated Steel

Name	Laminated Direction	Other Direction
Conductivity	3.5e+6 S/m	0
transfer coefficient	5.4 W/m/K	368 W/m/K

Table 3: Parameters of MnZn Ferrite

Name	MnZn
Conductivity	0.33 S/m
transfer coefficient	5 W/m/K

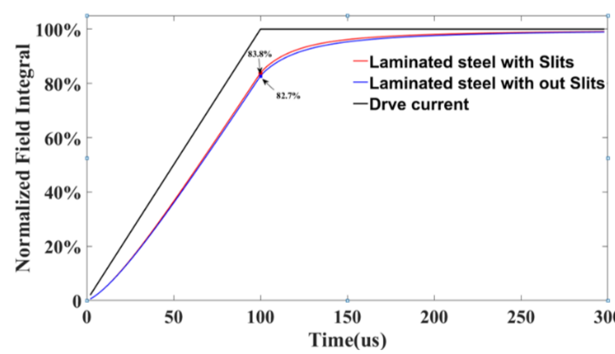

Figure 3: The field integral curves of current raising process.

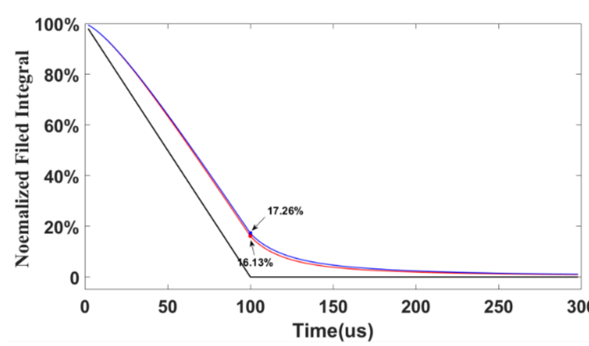

Figure 4: The field integral curves of current falling process.

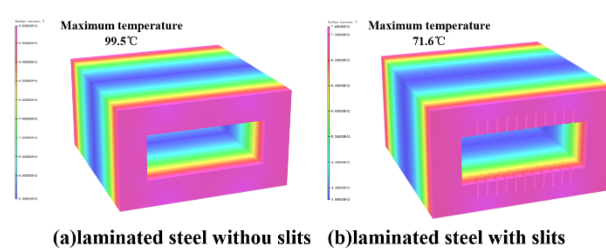

Figure 5: The temperature distribution: (a) laminated steel without slits; (b) laminated steel with slits.

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MnZn Ferrite Yoke

Due to low electric conductivity, MnZn ferrite usually works in 1 kHz–1 MHz. In low frequency, it has little eddy current, and there's almost no temperature rise, but it is easy to saturate in the corners. The drive current and field integral curve are shown in Figs. 6 and 7. In the rising processing, the integral field can be up to 100% within 100 µs. In the falling processing, the remanence is almost zero. As for the temperature rising, the temperature of the yoke is only the ambient temperature about 20°C. The magnetic field distribution is shown in Fig. 8, and there is little saturation region.

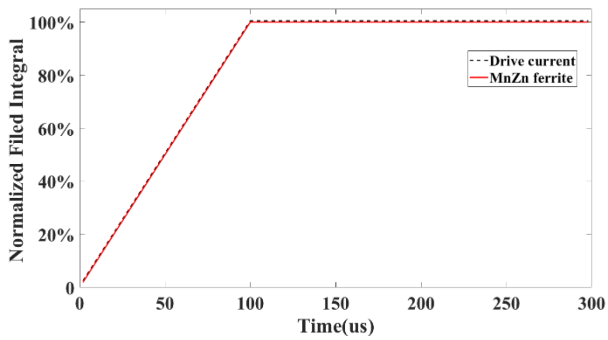

Figure 6: The MnZn ferrite field integral curves of current rising process.

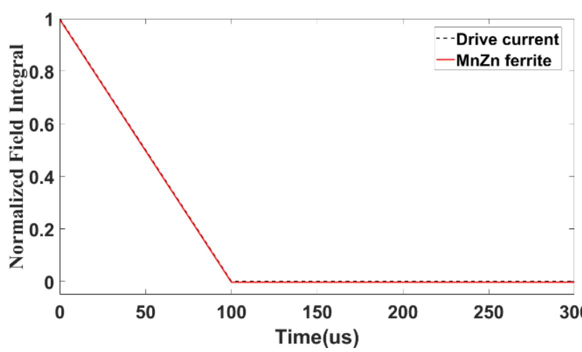

Figure 7: The MnZn ferrite field integral curves of current falling process.

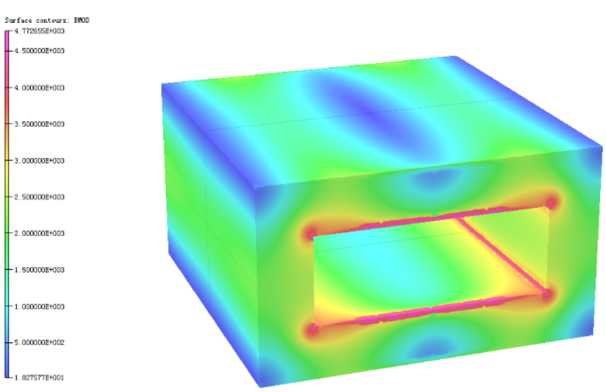

Figure 8: The field distribution of MnZn ferrite.

Mechanical Structure

The mechanical performance of ferrite is hard and fragile. When the volume is too large, the homogeneity would become worse. In HUST-PTF, the kicker magnet is made out of six blocks attached to steel plates with runaway type ceramic vacuum chamber. The inner aperture is 15 mm for horizontal, 34 mm for vertical. The kicker magnet is fixed by four bolts. see in Fig. 9.

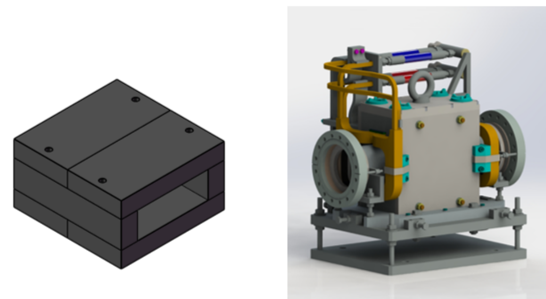

Figure 9: The ferrite yoke of the fast kicker magnet with runaway type ceramic vacuum chamber.

CONCLUSION

This paper shows the layout of the kicker magnet in HUST-PTF and describes the design consideration of the magnet yoke. The simulation methord of eddy current and temperature rise in fast ramp magnet is introduced. Two different materials are compared for the kicker magnet yoke: 1) laminated steel; 2) MnZn ferrite material. The eddy current in laminated steel is large. With slits in the end of laminated steel, the temperature can reach the requirement of the steel, the maximum temperature is 71℃, but the field hysteresis and remanence is expected to be large. Within 100us, the normalized integral field changes from 82.7% to 83.8%, and it takes a long time to eliminate the remanence. As for the MnZn ferrite, the field integral follows the change of the current, and the temperature of the yoke is only the ambient temperature about 20℃, there is no field hysteresis caused by eddy current, and the field saturation region is little. Finally, MnZn ferrite is chosen, and the yoke is made out of 6 blokes, fixed with bolts through embedded holes and the vacuum is runaway type ceramic vacuum chamber.

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