A STUDY OF THE PRISM-FFAG MAGNET

Y. Arimoto*, Masaharu Aoki, Yoshitaka Kuno, Yasutoshi Kuriyama, Tomohiro Matsushima,
Kengo Nakahara, Suehiro Nakaoka, Akira Sato, Makoto Yoshida,
Osaka University, Osaka, Japan
Yoshihisa Iwashita, Kyoto ICR, Uji, Kyoto, Japan
Masamitsu Aiba, Shinji Machida, Yoshiharu Mori, Chihiro Ohmori, Takeichiro Yokoi,
Masahiro Yoshimoto, Koji Yoshimura, KEK, Ibaraki, Japan
Shiro Ninomiya, RCNP, Osaka, Japan

Abstract

A magnet design for a PRISM-FFAG synchrotron is presented. The magnet type adopted for the PRISM-FFAG is a scaled-radial-sector and DFD triplet. The design was done by using a 3D calculation code. Tracking simulations were performed with the calculated magnetic-field mapping.

INTRODUCTION

PRISM is a facility to provide a high intensity, high purity, and high brightness muon beam based on a novel technique of phase rotation, which is usually used in a synchrotron [1, 2, 3]. PRISM consists of 1) a pion capture section, 2) a pion decay and muon transport section, and 3) a phase rotation section. In the pion-capture section, pions produced backward from a target are collected with a surrounding solenoid magnet of about 10 Tesla. Pions decay to muons in the succeeding decay region, and the muons are transported to the phase rotation section, where the phase space of the muons are phase-rotated by a synchrotron oscillation. In PRISM, a Fixed-Field Alternating Gradient (FFAG) synchrotron is used as a phase rotator.

PRISM aims at high intensity of 10^{11}-10^{12} muons / sec and the energy spread of less than 2 % at central energy of 20 MeV/c. To achieve such high intensity, PRISM has a high gradient RF system [4]. and the FFAG magnets which have a large acceptance. From the PRISM-FFAG ring, the required acceptance is more than 20,000 π mm mrad in the horizontal phase space and 3,000 π mm mrad in the vertical one. To achieve this acceptance, the PRISM-FFAG magnet needs to have wide geometrical aperture more than 100 cm in horizontal and 30 cm in vertical. The magnets have been designed by using a 3D magnetic field calculation program.

MAGNET CONFIGURATION FOR THE PRISM-FFAG RING

The PRISM-FFAG ring consists of 10 triplet magnets and has 10 straight sections. One straight section is for muon injection and another one is for extraction. In the rest of 8 sections, a total of 8 RF cavities can be installed.

We adopted a scaled-radial-sector-type FFAG with triplet focusing. This type has a magnet whose entrance and exit faces are on the radial line drawn from the machine center. There are normal and reverse bending magnets with nonlinear gradient, which provide focus and defocus property in each transverse plane. Focusing and defocusing actions comes also from an angle between the entrance and exit orbits and the magnet face. This configuration has advantages that the field clamp effects which is expected between the adjacent focusing defocusing magnet and each straight section becomes larger, compared to the separated function configuration.

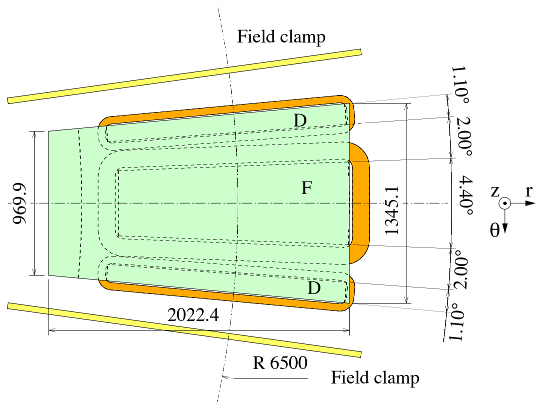

Figure 1: Top view of PRISM-FFAG magnet

A top view of the magnets is shown in Fig. 1. The triplet magnet consists of one focusing (F) magnet, two defocusing (D) magnets, and two field clamps which reduce a fringing magnetic field at the RF location to avoid saturation inside the RF cores located on straight section. The F and D poles are magnetically short-circuited by common iron top poles. This configuration make reduction of a magnetic flux density in return yoke, compared to the magnets whose the F and D magnet are separated off. At the same time, a total yoke weight can be reduced, and in fact, it can be reduced by 30 %, compared to the separated magnets.

In the scaled-radial-sector-FFAG synchrotron, the distribution of a FFAG magnetic field is given by

$$B(r) = B_0(r/r_0)^k, \tag{1}$$

where r is the distance from the machine center to the equilibrium orbit and k is a field index and is constant for the

---

* arimoto@kuno-g.phys.sci.osaka-u.ac.jp

machine [5]. The above magnetic field distribution is generated with the pole shape, which changes the gap distance inversely proportional to $B(r)$. But, in a practical design, since the F and D poles are placed closed to each other and some amount of the magnetic flux flow from the F pole to the D pole, the pole-face curve function has to be adjusted so as to obtain the ideal magnetic field distribution on the median plane. In Fig 2, a cross section view of the F magnet is shown. The aperture size of the magnet is 30 cm in vertical and 100 cm in horizontal. Eight trim coils are installed just below the main pole. The trim coils are necessary to change the field index of the FFAG magnet field, and also to correct for possible field errors, which can be caused by, for instance, misalignment of the magnets, or piece to piece variation for the BH curve of the yoke iron material, etc. To make smooth magnetic field distribution, it is necessary to increase a number of the trim coils as many as possible. However, it leads to high cost. To avoid this and have smooth field distribution, flat plate conductors are used for each trim coils, instead of wires. The flat conductors reduce the fluctuation of magnetic field even if the coil number is little.

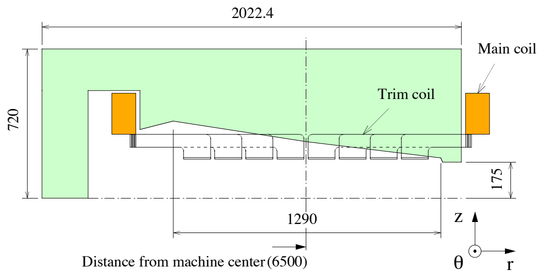

Figure 2: Cross section view of F magnet

The magnets have shunt yokes at the radially-inside of the magnet and an open aperture at the radially-outside. This allows us to have a muon beam injected or extracted radially outside of the FFAG ring.

DESIGN OF THE MAGNETS

The triplet magnet is designed with the 3D magnetic filed analysis code, TOSCA (Vector Fields LTD Co.). The optimization is performed iteratively by changing the pole shape and the main coil currents so that the field-index k value, the magnetic field density B_z, and the F/D ratio on the median plane, could have constant values over the magnet aperture. Here, the F/D ratio is a ratio of the magnetic field integral for the focus component and the defocus component over the circumference of the one cell.

Since the magnetic field is not sharply dropped to zero at the boundary, we use the BL integral, which is a integrated magnetic flux density along the circular path centered on the machine center. BL integral is given by

$$B_F L(r) = \int B_z(r)|_{B_z(r)>0} r d\theta \quad \text{(Focus)}, \tag{2}$$

$$B_D L(r) = \int B_z(r)|_{B_z(r)<0} r d\theta \quad \text{(Defocus)}. \tag{3}$$

Using the BL integral, the k value and the F/D ratio can be defined by,

$$k + 1 = \frac{\partial BL(r)}{\partial r} \frac{r}{BL(r)}, \tag{4}$$

$$F/D = B_F L(r)/B_D L(r). \tag{5}$$

The target values of these parameters, which are determined by lattice studies, are shown in table 1.

Table 1: Main parameters of PRISM-FFAG magnet

Parameters	values
cell number	10
k value	4.6
aperture	30 cm × 100 cm
average radius	6.5m
$B_F L$ at r = 6.5 m	0.0855 T·m/half cell
$B_D L$ at r = 6.5 m	0.0143 T·m/half cell
F/D ratio	6
F/2 angle	2.2 degree
D angle	1.1 degree

CALCULATION RESULTS

The calculated results are shown in Fig. 3- 5. Fig. 3 shows the B_z distribution as a function of θ. In this figure, an origin of the abscissa is a center of the F magnet. The different symbols indicate the fields at different radial positions from machine center. It can be seen that the direction of B_z flips from positive to negative, which is necessary to achieve alternating gradient focusing.

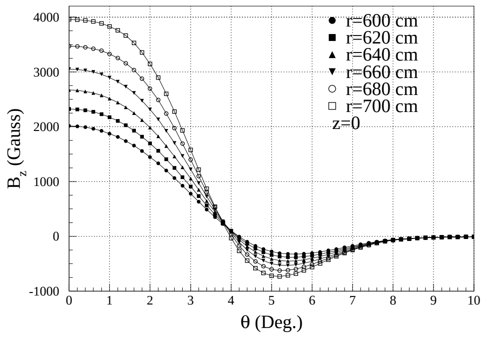

Figure 3: B_z distribution as a function of θ on median plane

Fig. 4 shows the k+1 value of the BL integral, plotted as a function of r. The solid circles indicate the k+1 values for

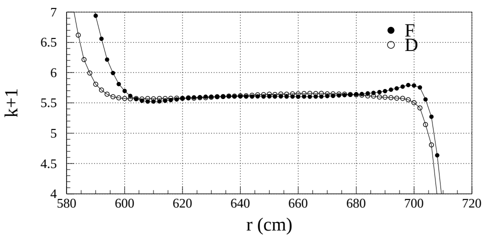

Figure 4: $k + 1$ value of BL integral on median plane

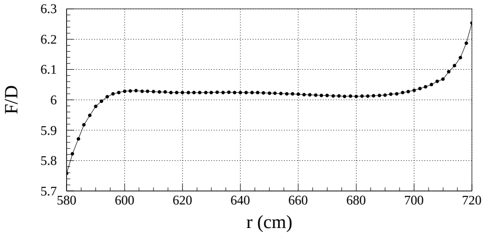

Figure 5: F/D ratio of BL integral on median plane

the focus component and the open ones indicate those for the defocus component. It can be seen that the k+1 values of the both components are well adjusted to be constant in the range from 600 cm to 700 cm within 3 %.

The fluctuation of 3 % in the k values is so small that it does not almost affect to the beam quality, known from our tracking. Fig 5 shows the F/D ratio of the BL integral, plotted as a function of r. These values are flat over 600∼700 cm, and sufficiently satisfy the requirements from our lattice studies.

The F/D ratios can be changed by adjusting the main coil currents of the F and D magnets. However, when the current ratio of the F and D coils are changed, the k values also change. So, the trim coil currents also should be adjusted so as $thek$ values not to change. Fig. 6 shows the F/D ratio as a function of r. There are three cases in this figure. Triangles, squares, and circles indicate respectively the F/D ratio when the main coil currents of the F magnet are set to 63.1, 67.9 and 26.0 kA· and that of the D magnet are 13.75, 17.7, and 26.0 kA·T. Except for in the case of the F/D ratio of 6, the trim coil currents are applied to the F and D magnet so that the k+1 values become to be 5.6. It can be seen that the F/D ratios can be set to change by adjusting the main coils and the trim coils.

TRACKING SIMULATIONS

The beam tracking is performed by the GEANT3 simulation code with the calculated magnetic field. In this simulation, the k+1 value and the F/D ratio are, respectively, set to 5.6 and 6.1 and all the trim coil currents are turned off. The initial muons uniformly are distributed in the 4-D phase space. In Fig 7, the particles which can survive after 8 turns are plotted in a phase space. The left figure is the phase space projected to the horizontal-phase-space plane and the right one is that projected to vertical one. From these figures, it can be seen that the horizontal acceptance is 40,000 π mm mrad and the vertical one is 6,500 π mm mrad. This acceptance is much larger than the originally estimated acceptance for the PRISM-FFAG.

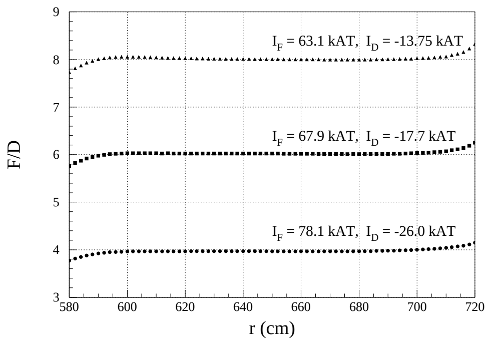

Figure 6: F/D ratio of BL integral on median plane

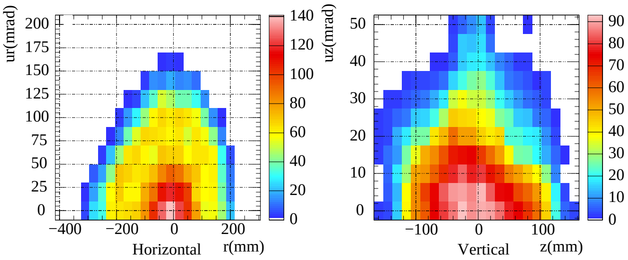

Figure 7: Phase space plot

SUMMARY

The magnet design have been done for the PRISM-FFAG synchrotron by using the 3D field calculation code. The magnets have large apertures of 100 cm in horizontal and 30 cm in vertical. From tracking simulation, it have been confirmed that the phase space acceptance of 40,000 π mm mrad in horizontal and 6,500 π mm mrad can be achieved. This acceptance is much larger than our original requirements. By adjusting the trim coils and the main coils currents, it is known that the F/D ratio can be changed from 4 to 8.

REFERENCES

[1] A. Sato, Nucl. Phys. A **721** (2003) 1083.

[2] M. Yoshida, et al., “THE PRISM PROJECT”, SAST03, Tsukuba, Nov. 2004.

[3] A. Sato, et al., “FFAG AS PHASE ROTATOR FOR THE PRISM PROJECT”, EPAC’04, Lucerne, July 2004.

[4] C. Ohmori et al., ”ULTRA-HIGH FIELD GRADIENT RF SYSTEM FOR PRISM-MUON BUNCH ROTATION”, SAST03, Tsukuba, Nov. 2004.

[5] K. R. Symon, D. W. Kerst, L. W. Jones, L. J. Laslett, and K. M. Terwilliger, Phys. Rev. 103 (1956) 1837.