An Fixed Field Alternating Gradient Ring for a High Intensity Monochromatic Muon Source

Akira Sato

Depertment of Physics, Osaka University,
1-1 Machikane-yama, Toyonaka, Osaka 560-0043, Japan

Abstract. Design and construction status of a Fixed Field Alternating Gradient (FFAG) ring for a high intensity monochromatic muon source are described. It has very large transverse acceptance of 40,000 πmm·mrad for horizontal and 6,500 πmm·mrad. Phase rotation of muon beam is performed in the FFAG with high field gradient RF cavities.

Keywords: muon source, FFAG
PACS: 29.20.-c

INTRODUCTION

Lepton flavor violating (LFV) processes in charged lepton sector has high potential to discover the physics beyond the standard model. Among candidates of LFV processes, we have a plan to search muon to electron conversion at the nuclei with a new muon source called "PRISM (Phase Rotated Intense Muon source)" [1] [2]. The PRISM collaboration consists of particle and accelerator physicists from Osaka university, Kyoto university, and KEK in Japan. PRISM would provide the intense muon beam with low energy, monochromatic, and high purity, dedicated to stopped muon experiments. The aimed beam characteristics are listed in Table 1. Such beam characteristics would be obtained by a combination of (1) a power full proton driver, (2) a pion capture system using super-conducting solenoidal magnets, (3) a muon transfer solenoid cannel, and (4) a phase rotator to energy spread of the muon beam narrower.

A fixed field alternating gradient (FFAG) type ring phase rotator is a one of unique features of PRISM. The monochromatic muon beam is obtained by longitudinal phase rotation in this PRISM-FFAG; muons with higher energy are decelerated and muons with lower energy are accelerated by RF field in the FFAG ring. PRISM-FFAG will be constructed by the end of JFY 2007. Design and construction status of PRISM-FFAG is descried in the following sections.

TABLE 1. The aimed beam characteristics of PRISM

Intensity	$10^{11} - 10^{12} \mu^{\pm}$/sec
Kinetic energy of μ	20 MeV (= 68 MeV/c)
Kinetic energy spread	$\pm 0.5 - 1.0$ MeV
Beam Repetition	$100 - 1000$ Hz
pion contamination	$> 10^{-18}$

OPTICS DESIGN

In order to obtain aimed performance of the muon beam, PRISM-FFAG was imposed requirements listed below.

1. Large transverse acceptance is very important to achieve high intensity muon beam. A transverse acceptance of more than 20000π mm·mrad for the horizontal plane and more than 3000π mm·mrad for the vertical plane are required.
2. A momentum acceptance of 68MeV/$c\pm$ 20% is necessary.
3. Field index k should be chosen so that a transition energy is enough far from energies of above momentum region.
4. RF cavities should be installed to ring as many as possible to achieve quick phase rotation with in a few micro-second. Therefore, long straight sections to install the cavities are required.

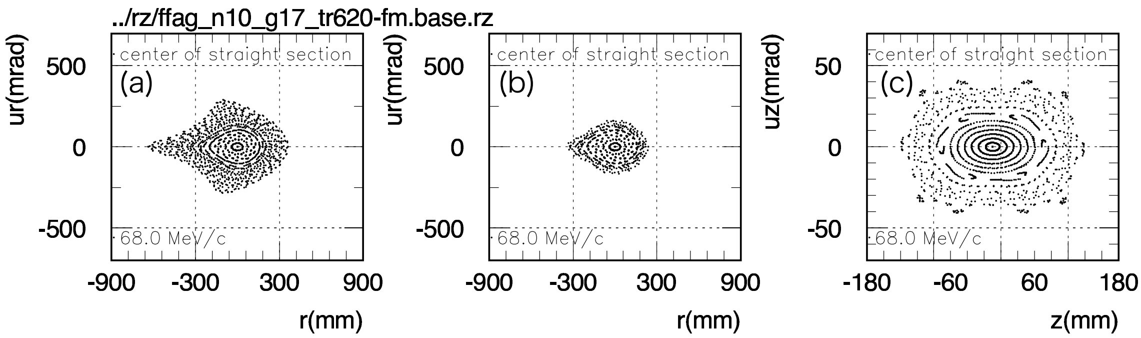

FIGURE 1. Phase plots. For horizontal plane with zero initial vertical amplitude (left), with small initial vertical amplitude(center). For vertical plane with zero initial horizontal amplitude (right)

5. Stray fields to RF cores should be small, since DC magnetic flux can reduce a performance of the RF cores. Magnetic fluxes in the cores should be less than 100 gauss, although a distance between the magnet and the RF core would be small because of above requirement.
6. To locate PRISM in a possible site, J-PARC and so on, a compact FFAG ring, about 10m in diameter, is feasible.

In order to fulfill above requirements, magnets should have a large aperture, and their opening angle should be enough small. Triplet or doublet magnets would be feasible to obtain longer straight sections. In such magnets, not only non-linear effects but also magnetic fringing fields are important to study the beam dynamics of FFAGs. Although 3D tracking using realistic 3D magnetic field maps made with programs such as TOSCA is the best solution to study the dynamics of FFAGs, it takes long time to make such field maps. On the other hand, the synchrotron optics code such as SAD was used to search initial parameters. It is useful for rough estimate and enables rapid studies, but it is very difficult to predict tune correctly.

On a design process of the PRISM-FFAG, quasi-realistic 3D magnetic field maps were used to study the beam dynamics [3]. The quasi-realistic 3D magnetic fields were calculated applying spline interpolation to POISSON 2D fields. This method can model realistic effects of the fringing fields, and enables quick iterations in search of the optics parameters such as tune compared with that of using TOSCA fields.

Particle tracking simulation in the quasi-realistic fields was performed using a program based on GEANT3.21 to search the best optics parameter set for PRISM-FFAG. Parameters to be studied are: Number of sectors, Combination of magnets: DFD, FDF, FD, Field index (k value), Ratio of the magnitude of focusing field to that of defocusing field: (F/D ratio), and Gap size of magnets.

We payed attention to the transverse acceptance, which should be as large as possible. Figure 1 shows results of the particle tracking. Figure 1-(a) is a phase plot on horizontal for the case that the initial vertical amplitude is set to zero. It has huge horizontal acceptance of more than 100,000 πmm·mrad. However, particles with huge amplitude in the horizontal plane are unstable. Figure 1-(b) shows a horizontal phase plot with very small initial vertical amplitude. This FFAG has strong coupling between horizontal and vertical dynamics. In order to estimate volumes in the r-r'-z-z' space, 4D acceptance was introduced. Grid points in the latticed 4D space were set as initial phases for tracking. Particles which turn more than eight in the FFAG are regarded as accepted. Eight turns is enough to finish the phase rotation for PRISM. Figure 2 shows results of the 4D acceptance study for N=8 and N=10 cases. Lattices with N=10 have larger acceptance then that of N=8 lattices, because of smaller horizontal phase advance. Taking resonance lines and the transition energy into account, parameters were selected to be the beam acceptance as large as possible. Present parameters of PRISM-FFAG are shown in Table 2. A schematic layout is shown in Fig.3.

MAGNET DESIGN

We adopted a scaled radial sector type FFAG with a triplet focusing magnet (DFD). Figure 4 shows 3D model and drawings of the PRISM-FFAG magnet [4] . We designed a C-shaped FFAG magnet so that the beam can extract/inject from/to the ring passing outside of the magnets. Two field clumps are at both end in order to avoid stray fields to the RF cavities. It has very large aperture of H :100 cm $\times$ V : 30 cm. The field gradient is generated by the pole shapes. It shape was decided so as to satisfy scaling conditions. Two sets of trim coils are installed on the top/bottom of beam

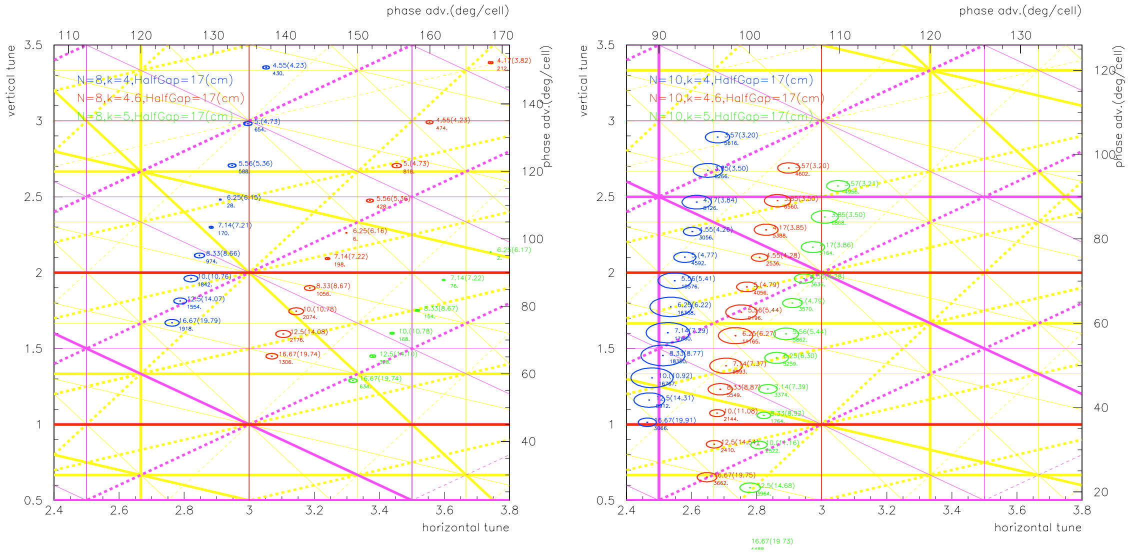

FIGURE 2. 4D acceptance are plotted on tune diagrams for N=8(left) and N=10(right). Area size of circle is proportional to the 4D acceptance.

TABLE 2. Present parameters of PRISM-FFAG

Number of sectors	10
Magnet type	Radial sector
	DFD triplet
Field index (*k*-value)	4.6
F/D ratio	6.2
Opening angle of magnets	F/2 : 2.2deg.
	D : 2.2deg.
Half gap of magnets	17cm
Maximum field	Focus. : 0.4 Tesla
	Defocus. : 0.065 Tesla
Tune	horizontal : 2.73
	vertical : 1.58

chamber to enable *k*-value variable. The magnets have small opening angle, so that the ring has enough space to locate RF cavities.

The magnetic field calculated using TOSCA is plotted in Fig.5. Tracking simulations using this TOSCA field were performed. The present design of PRISM-FFAG has zero chromaticity for the aimed momentum range as shown in Fig.6. The 4D acceptance is about 1G $mm^2 \cdot mrad^2$. Figure 7 shows projections of the 4D acceptance volume to horizontal and vertical planes. They have enough large transverse acceptance of 40,000 πmm·mrad for horizontal and 6,500 πmm·mrad.

RF SYSTEM

RF system is important to finish phase rotation before muon decay. Very high field gradient of 200kV/m at the low frequency (4∼5 MHz) is necessary for PRISM-FFAG. Such RF system has been designed using ultra-thin magnetic alloy (MA) cavities [5].

An RF system, which consists of an amplifier and an anode power supply and an auxiliary power supply, has been build. RF tests are underway. RF voltage of ± 43kV/gap has already achieved with a test cavity, which has a shunt impedance of 735 Ω at 5MHz. It promises a field gradient with a PRISM cavity, which would have a shunt impedance of 900 Ω, to be 165kV/m. A simulation result of phase rotation in the PRISM-FFAG ring is shown in Fig.8. The initial momentum spread of 68MeV/c± 20% is reduced to ± 2% in 6 turns (=1.5μs). A muon surviving rate is 56%.

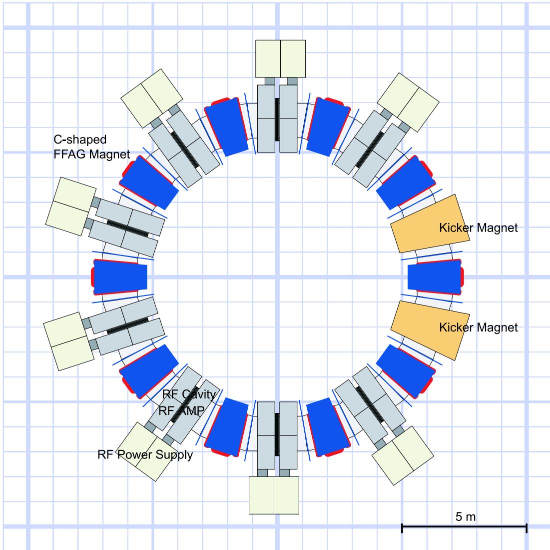

FIGURE 3. Schematic layout of the PRISM-FFAG

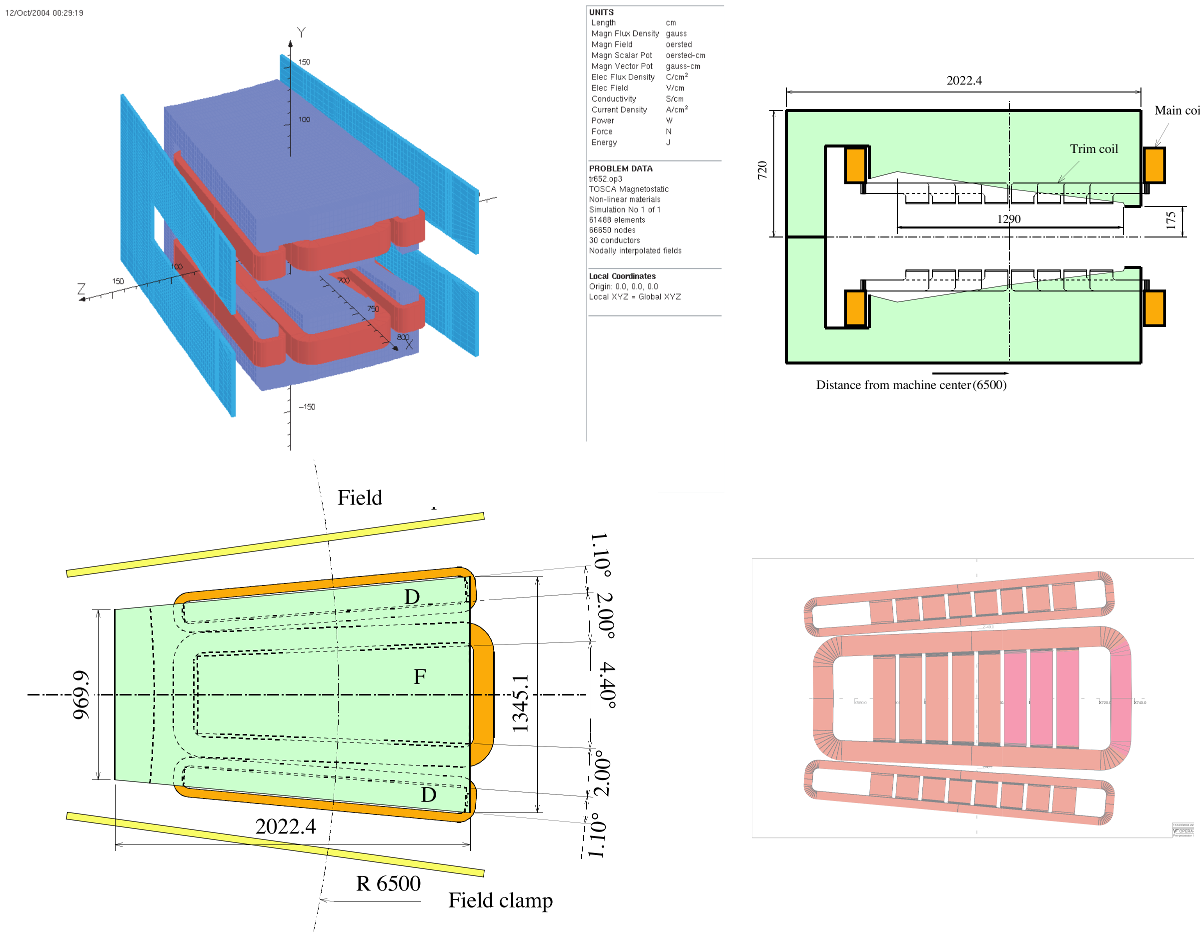

FIGURE 4. PRISM-FFAG magnet

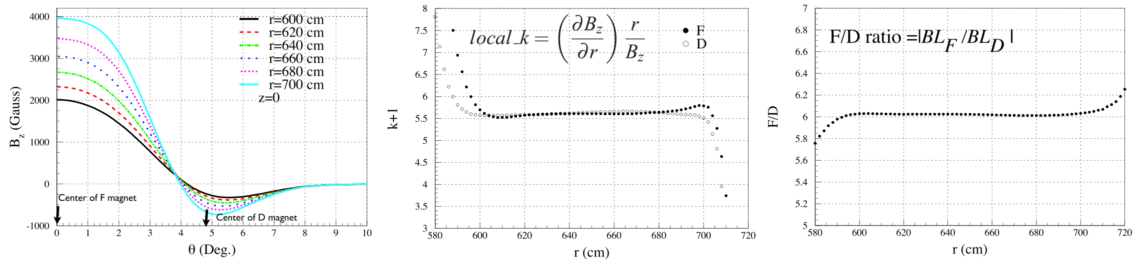

FIGURE 5. Magnetic field calculated by TOSCA.

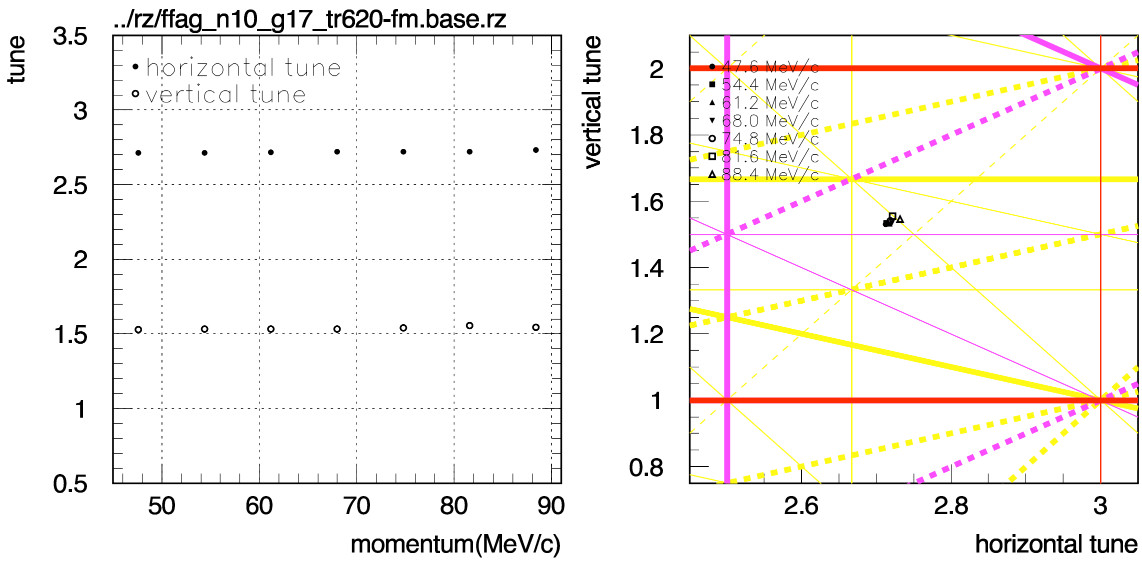

FIGURE 6. Momentum dependence of horizontal and vertical tune.

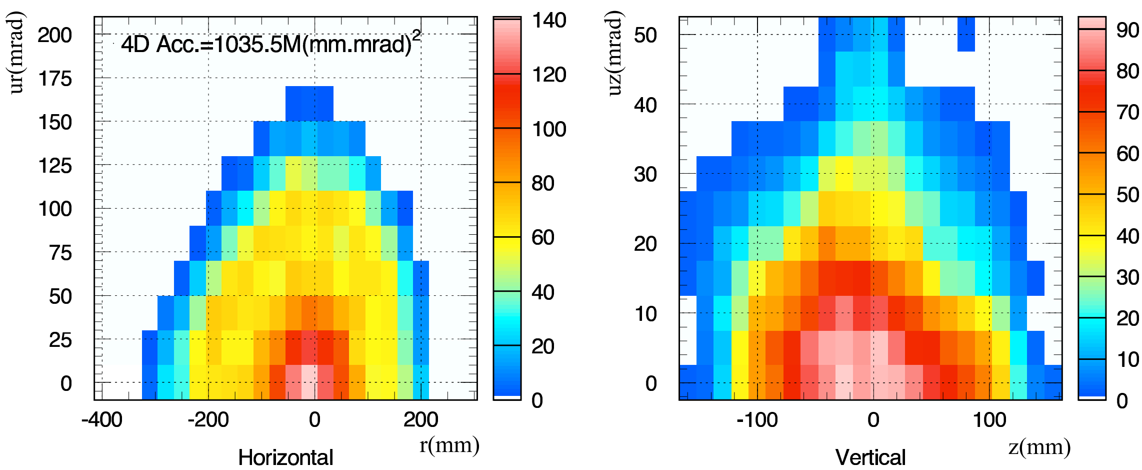

FIGURE 7. Projections of the 4D acceptance volume to horizontal and vertical planes.

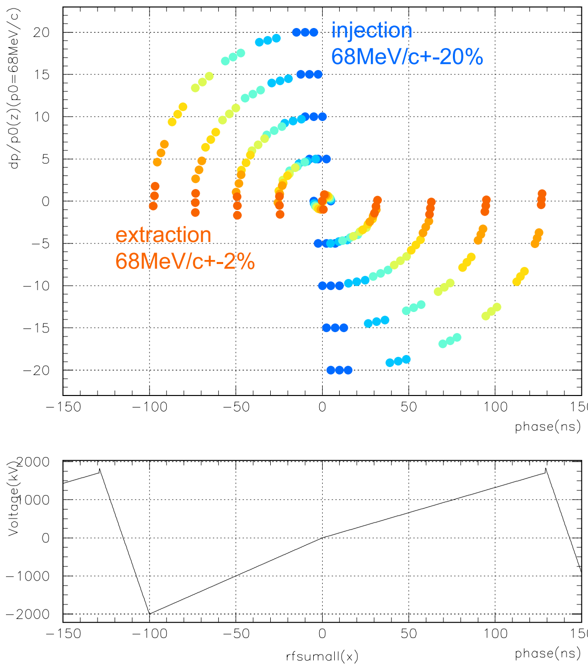

FIGURE 8. Simulation result of phase rotation in PRISM-FFAG. A field gradient of 152kV/m were assumed. 6 turns in the ring is enough for finishing the phase rotation. Initial momentum spread of 68MeV/$c\pm$ 20% is reduced to $\pm$ 2%. RF voltage applied is shown in the bottom figure.

SUMMARY

A FFAG for a high intense muon source is under construction. Its optics and magnet design have almost been finalized. The design of RF system has also almost been finished, and its construction and tests are underway. Commissioning and studies with the FFAG are scheduled in JFY 2006 to 2007.

ACKNOWLEDGMENTS

This work was supported by the Japan Society for the Promotion of Science under Grant-in-Aid for Creative Scientific Research (Project No. 15GS0211).

REFERENCES

1. Y. Mori, K. Yoshimura, N.Sasao, Y. Kuno, et al., "The PRISM Project - A Muon Source of the World-Highest Brightness by Phase Rotation", LOI for Nuclear and Particle Physics Experiments at the J-PARC (2003).
2. Y. Mori, K. Yoshimura, N.Sasao, Y. Kuno, et al., "An Experimental Search for the m-e Conversion Process Towards an Ultimate Sensitivity of the Order of 10^{-18}", LOI for Nuclear and Particle Physics Experiments at the J-PARC (2003).
3. A. Sato and S. Machida., " LATTICE DESIGN OF LARGE ACCEPTANCE FFAGS FOR THE PRISM PROJECT, " in Proceedings of the EPAC2004, TUPLT081.
4. Y.Arimoto et.al., "A Study of the PRISM-FFAG Magnet", in Proceedings of Cyclotrons2004.
5. C.Ohmori et al., "ULTRA-HIGH FIELD GRADIENT RF SYSTEM FOR PRISM-MUON BUNCH ROTATION", in Proceedings of SAST03.