HIGH INTENSITY MUON BEAM FACILITIES WITH FFAG

Yoshitaka KUNO, Osaka University, Osaka, Japan

Abstract

We present the PRISM project in Japan to construct a dedicated muon beam facility with high intensity, high purity and high luminosity, based on FFAG (fixed field alternating gradient synchrotron) technology. The main purpose of the PRISM project is to search for an exotic process of charged lepton mixing, in particular a muon-to-electron conversion process. High luminosity, namely narrow energy spread, can be achieved by phase rotation in the PRISM FFAG ring. The PRISM FFAG ring is now under construction at Osaka University. The design and the construction status of the PRISM FFAG ring are presented.

INTRODUCTION

The muon system has been attracting much interest from theorists and experimentalists in the field of particle physics, since supersymmetric extension of the standard model of particle physics predicts large branching ratios of such processes, and the muon, among the other particles, is known to be the most promising playing ground. To carry out such searches, a beam of many muons with high quality is needed.

A muon beam with high intensity, high purity and high luminosity would be available, based on the concept of a neutrino factory front end. Even before a neutrino factory is realized, a dedicated muon beam facility of high intensity can be achieved as a prototype of the neutrino factory front end. In fact, the Japanese scheme of a neutrino factory is based on a series of FFAGs to accelerate muons. PRISM could be regarded as an initiating phase, and at the same time, important experiments with the muons can be carried out.

The muon-to-electron conversion is explained as follows. A negative muon is stopped in a target material, and it cascades down to a $1s$ state of a muonic atom. The fate of the muon is either decaying or being captured by a nucleus. In muon capture, a neutrino is emitted. However, the process where an electron, instead of a neutrino, is emitted, can be considered. This process is called muon-to-electron conversion. For this process, the lepton flavor number is changed by one unit, and therefore is not allowed in the standard model of particle physics. The signature of the muon-to-electron conversion is a mono-energetic electron of its energy of about a muon mass. Major backgrounds are muon decay in orbit of a muonic atom, radiative pion capture, radiative muon capture, and cosmic rays. To remove the backgrounds, the resolution of the electron detection is critical. And to achieve this, the muon-stopping target must be very thin. And therefore, the energy spread of the muon beam should be small to keep the muon stopping efficiency the same. And also the pion contamination in a beam should be removed as much as possible, since radiative pion capture followed by asymmetric photon conversion is another critical background.

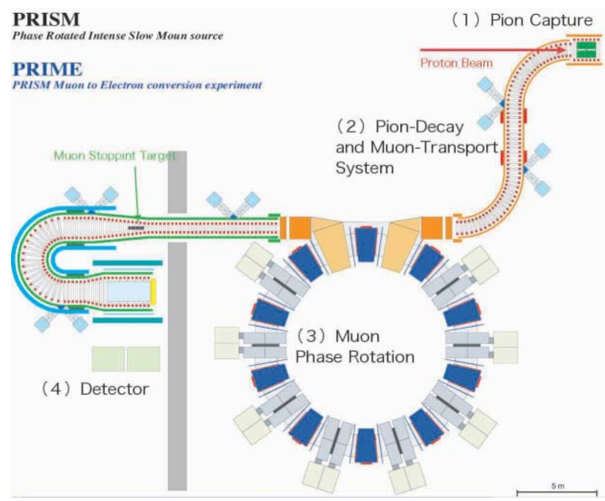

Figure 1: PRISM layout.

PRISM

PRISM is a dedicated facility to produce a muon beam with high intensity, high purity (no pion contamination), and high luminosity (narrow energy spread) [1]. The whole PRISM layout is presented in Fig.1. PRISM stands for a Phase Rotated Intense Slow muon source. PRISM is designed to carry out a search for the muon-to-electron conversion at a sensitivity of 10^{-18}. The aimed muon intensity of PRISM is $10^{11}-10^{12}$/sec. The central muon momentum is 68 MeV/c. High intensity can be achieved by solenoid pion capture with large solid angle.

Phase Rotation with FFAG

Narrow energy spread can be achieved by phase rotation (20% $\rightarrow$ 2 %). The phase rotation is a technique used in accelerators, namely to accelerate slow particlesand decelerate fast particles by applying high RF electric field. To achieve phase rotation, either a linear system or circular ring system can be considered. But, a ring system is better because of a smaller number of RF cavities, smaller electric power required, and compactness. As a circular ring system, a cyclotron can not be a candidate because of isochronous feature, A synchrotron has a problem to its limited acceptance, whereas a muon beam has a large

0-7803-8859-3/05/$20.00 ©2005 IEEE

emittance. Then, a FFAG (Fixed Field Alternating Gradient synchrotron) could be only best candidate, since it has large transverse acceptance and longitudinal (momentum) acceptance. Also rapid phase rotation has to be done to minimize muon loss due to its natural decay. From that reason, FFAG is also suitable.

Types of FFAG

There are two types of FFAGs. One is scaling type FFAG, and the other is non-scaling type FFAG. For the scaling type FFAG, the betatron tune is constant for various momenta (zero chromaticity), but non-linear magnetic field components should be used. On the other hand, for the non-scaling type FFAG, the betatron tune is not constant for different momenta, and linear magnetic field components can be used. The former is demonstrated for electron and proton machines, but the latter has not been demonstrated yet. The scaling type FFAG has been adopted for PRISM.

For the scaling type FFAG, two types of magnets can be considered so far. One is radial sector type, and the other is spiral type. The magnetic field for radial sector type should be given as

$$B(r) = B_0 \cdot \left(\frac{r}{r_0}\right)^k \qquad (1)$$

where B_0 is a reference magnetic field at radius r_0. k is a field gradient index. For PRISM, the radial sector magnet has been chosen.

PRISM FFAG R&D

The construction of the PRISM FFAG ring was funded at Osaka University in Japanese fiscal year (JFY) 2003. The construction period will be from JFY2003 to JFY2007.

The requirements on the PRISM FFAG ring are as follows.

- High gradient RF to achieve quick phase rotation because of short lifetime of the muon,
- large geometrical acceptance because of broad original emittance of the muon, and
- large momentum acceptance.

PRISM FFAG Optics Design

The radial sector type of scaling FFAG was selected for the PRISM FFAG ring. The beam lattice consists of an optical cell of DFD triplet, where D and F are defocusing (bending outward) and focusing (bending inward), respectively. The PRISM FFAG ring has a total of ten (or eight) cells. Since the magnetic field of the PRISM FFAG ring is non-linear, charged particle tracking in non uniform magnetic field has to be done. The lattice parameters for the PRISM FFAG ring are summarized in Table 1.

For tracking, Geant4 is used and 3-dimensional field calculation code is used. From the tracking simulation, we have determined the horizontal and vertical betatron tunes. For this operation point, it was found that large acceptance of the PRISM FFAG ring has been achieved. They are about $40,000\pi$mm·mrad for horizontal, and $6,500\pi$mm·mrad for vertical. The horizontal and vertical acceptances are shown in Fig.2. It is a factor of about four larger than the originally-estimated acceptance. The momentum acceptance of the ring were studied, and it is found that ±20 % from the designed central momentum of 60 MeV/c can be achieved, as shown in Fig.3.

Table 1: PRISM FFAG ring specifications

Item	Specifications
Number of cells	10 (8)
Field Index	5 (from 4.6 to 5.2)
Mean radius	6.5 m
Full gap height	30 cm (V) × 100 cm (H)
Opening angle	4.4° (horizontal) , 1.86° (vertical)
Betatron tune	2.86 (horizontal), 1.86 (vertical)
F/D ratio	6
BL_F	0.171 T·m at r=6.5m
BL_D	0.029 T·m at r=6.5 m

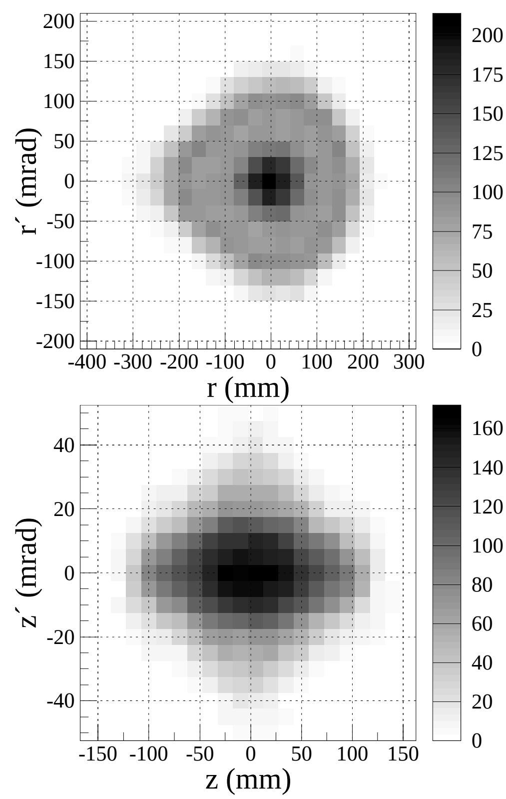

Figure 2: Horinzontal (top) and vertical (bottom) acceptance of the PRISM FFAG ring. The gray scale represents the intensities.

The chromaticity has been studied, and it is found to (almost) hold in the momentum region of interest (from 50 MeV/c to 90 MeV/c), as shown in Fig.4.

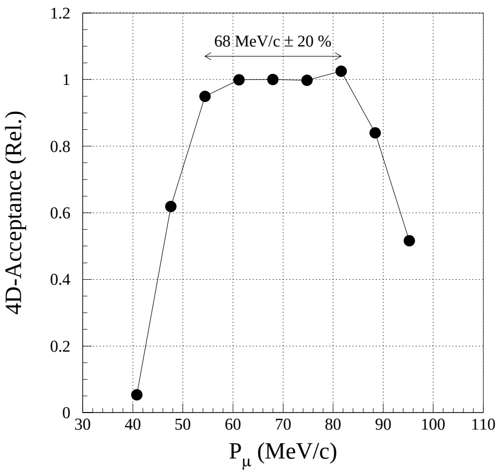

Figure 3: Momentum acceptance of the PRISM FFAG ring.

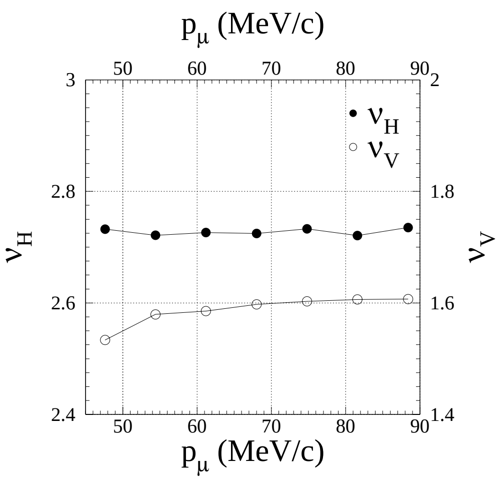

Figure 4: Horinzontal and vertical betatron tunes as a function of muon momenta, showing zero-chromaticity for the PRISM FFAG ring.

PRISM FFAG Magnet Design

As stated, the PRISM FFAG ring is formed by DFD triplets. Each FFAG magnet is a radial sector type. The DFD triplet are combined into one magnet. Namely, the F and D magnets have the common iron top and bottom plates. So that, some fraction of magnetic fluxes from the F magnet go through the top and bottom iron plates and return into the D magnets, or vice-versa. This reduces the magnetic flux at the return yoke to prevent iron saturation. It is useful so that a total iron weight can be reduced. The reduction is about 30 % in this case. Possible complexity due to coupling between the F and D magnets might not be a serious issue, since the magnetic field setting is fixed. The field clamping plates are placed at both entrances so as to reduce a residual magnetic field at the location of the RF cavities, which are placed between the DFD triplet magnets. Since the core made of magnetic alloy (MA) is used, a residual field at the core should be reduced as much as possible. Also, if the residual field is not small. the field deformation due to it would introduce the distortion of the closed orbits.

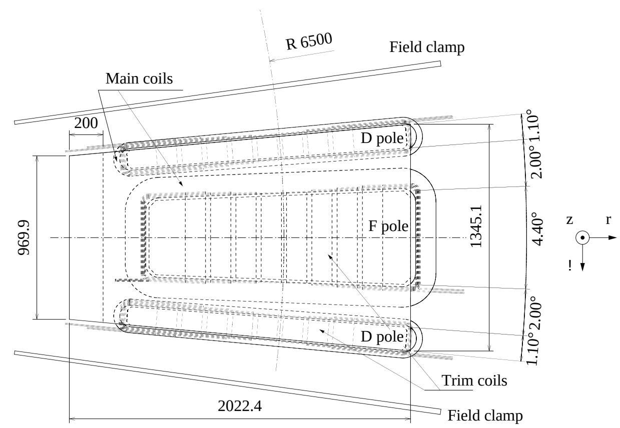

Figure 5: Plane view of one DFD magnets for the PRISM FFAG ring.

The FFAG field distribution, given in Eq.(1), is generated with the pole shape, where the gap distance changes inversely proportional to the magnitude of magnetic field $B(r)$ at radius r. In reality, owing to magnetic flux leakage, the pole shape is needed to adjust. In Fig.6, a cross-sectioned side 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 below the main coils. They are required to change the field index of the FFAG magnet field, and also to correct for possible field errors or misalignment. The trim coils are made of flat plate conductors, instead of wires, so as to make smooth field distribution in the wide region.

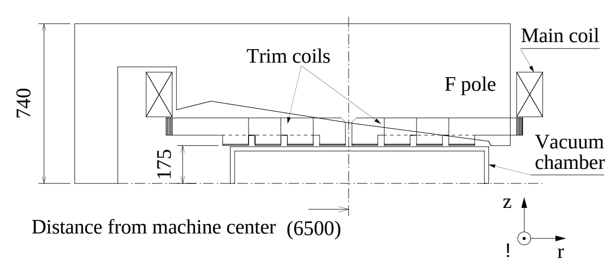

Figure 6: Side view of one F magnet for the PRISM FFAG ring.

The FFAG magnets were designed with a 3-D magnetic field analysis code, TOSCA (Vector Field LTD Co.). The optimization was performed iteratively by changing the pole shapes, and the main coil currents. The goal is that the field index, k, the magnetic field density, B, and the ratio of the F and D magnets (F/D ratio), on the median plan of the magnet gap, should be constant over the required magnet aperture. It is noted that the field index k would govern the horizontal betatron tune, while the F/D ratio would do the vertical betatron tune. The designed values of the above are shown in Table 1.

0-7803-8859-3/05/$20.00 ©2005 IEEE

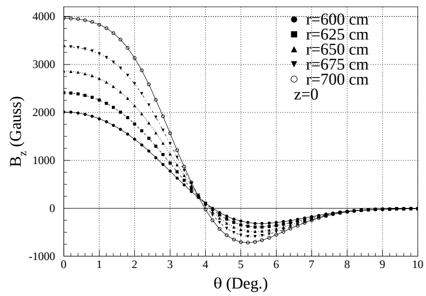

Figure 7: Azimuthal distribution of the magnetic field of the PRISM FFAG ring.

The magnetic field distribution along the azimuthal direction can be shown in Fig.7, where the origin of the horizontal axis is the center of the F magnet. Different symbols represent the magnetic fields at different radial positions.Since the magnetic field drops not sharply at the edge, the ”BL” field integral, which is integrated magnetic flux density along the azimuthal path, defined as follows.

$$BL_F(r) = \int rB(r)|_{B(r)>0} d\theta \qquad (2)$$

$$BL_D(r) = \int rB(r)|_{B(r)<0} d\theta \qquad (3)$$

These ”BL” values would follow the followings.

$$\left(\frac{\partial BL(r)}{\partial r}\right) \cdot \frac{r}{BL(r)} = k+1 \qquad (4)$$

$$\frac{BL_F(r)}{BL_D(r)} = F/D \qquad (5)$$

The $k+1$ values of the ”BL” field integral is shown as a function of radial position in Fig.8, where the open circles represent the focusing components, whereas the closed circles do the defocusing ones. It can be seen that the $k+1$ values of the both components are well adjusted to be constant in the region from 600 cm to 700 cm, within accuracy of 3 %. This accuracy meets the requirement from the beam optics, which was demonstrated by our tracking simulation as well.

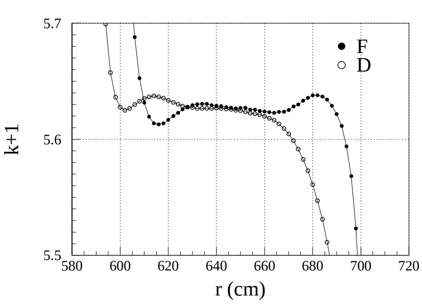

Figure 8: The $k+1$ values of the field integral ”BL” on the median plane.

The F/D ratio of the ”BL” field integral is shown as a function of radial position in Fig.9. The F/D ratio is found to be constant over the region from 600 to 700 cm. Again, it meets the requirement from the beam optics. To change the vertical betatron tune, the F/D ratio can be changed, and it is done by changing the magnet currents of the F and D magnets. However, when their currents are changed, the k values also changes. Therefore, the correction from the trim coils are needed. Some simulation on the trim currents to restore the k values flat over the region of interest, after changing the F/D ratio.

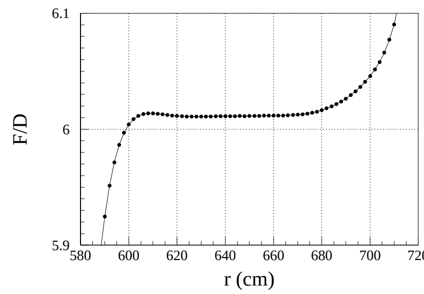

Figure 9: The F/D ratio of the field integral ”BL” on the median plane.

The engineering design of the PRISM FFAG magnets have been done. The PRISM FFAG magnets are under construction now. Some of the F magnet coils and all of the D magnet coils were completed. Biding for the magnet yokes has just been opened recently. Two of the magnet yokes will be delivered in 2005, and the rest will come in the next year. Then, the magnet assembly will be done.

PRISM RF R&D

The RF amplifier and power supply were constructed, and tested at Osaka University. By using a test cavity of 700 k ohm borrowed from JAERI, a gap voltage of 86 keV (peak-to-peak) was achieved at a frequency of 5 MHz. It corresponds to electric field gradient of the final system, of 150 kV/m. In addition a long term test of burst length of 30 μsec and 100 Hz repetition was done for about 6 hours. The PRISM RF cavity was recently constructed, and RF cores made of magnetic alloy (Finemet) were obtained. The core showed 156 ohm impedance at 5 MHz. A test with the PRISM RF and the amplifier and power supply is planned to be carried out soon.

By using the RF voltage which would be achievable, simulation of phase rotation has been done. $\pm$20 % of the momentum width can be rotated in 6 turns. The final momentum spread is determined mostly by the initial time spread of a proton beam. If the proton beam spread is assumed to be 10 nsec, the final momentum spread of $\pm$ 2 % can be achieved.

Future Plan

The PRISM FFAG ring construction is thus underway, and will be completed by 2007. At this moment, the budget request for the whole PRISM facility, which includes the solenoid pion capture, muon transport, and a detector for the search for $\mu - e$ conversion, is being made from Osaka university. The plan is to complete the PRISM and test it at Rearch Center of Nuclear Physics (RCNP), Osaka University. It has a proton cyclotron of 400 MeV, which is above the pion production threshold, with about 5 μA current in maximum. As the second phase, PRISM will be brought to highly-intense proton facility to carry out the search for the $\mu - e$ conversion process.

REFERENCES

[1] The PRISM Working Group, ”The PRISM Project - A Muon Source of the World-Highest Brightmess by Phase Rotation -”, submitted to J-PARC Letter of Intent L24, unpublished, http://www-ps.kek.jp/jhf-np/LOIlist/LOIlist.html

0-7803-8859-3/05/$20.00 ©2005 IEEE