CONSTRUCTION OF SIX-SECTOR FFAG RING FOR MUON PHASE ROTATION*

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Abstract

To demonstrate phase-space rotation technique, a six-cell FFAG ring has been constructed. The FFAG ring consists of full size of scaling-FFAG magnets which have been designed for muon phase rotation ring, and a high gradient rf cavity. For the six-cell experiment, six magnets has been aligned, and beam duct has been designed and installed. In this paper, it will be described about the construction procedure, apparatus, and measurement of magnetic field.

INTRODUCTION

PRISM is a next-generation of muon source which provide high purity, high intense and high brightness beam. In PRISM, a PRISM-FFAG ring is one of key components which make a muon beam to have narrow energy width by phase-space rotation technique. To demonstrate the phase-space rotation, a PRISM-FFAG ring has been constructed. This ring is scaled down ring compared to the practical PRISM-FFAG ring. This ring consist of six FFAG magnets while the practical ring consists of ten magnets [1]. However the magnet designed for the practical ring are used [2].

Our motivations are experimental study of transverse and longitudinal dynamics and to clarify problems in commissioning of the practical ring.

The construction of the six-cell ring was started at September, 2007. First beam was measured which traveled by 240 degree turn at March, 2008. The measurement of beam optics is under way[3]. In this paper, the construction method, apparatus, and measurement of magnetic field are described.

MAGNETS INSTALLATION AND ALIGNMENT

The ring was constructed at an experimental room of Research Center for Nuclear Physics at Osaka University.

The installation has been done by pulling the magnets on rollers without the crane in the room because of mass limitation of the crane. The magnets on the adjustment stage are moved by pulling and settled on marking positions. The magnet is roughly set with accuracy of $\pm$ 2 mm by referring the marks drawn on a floor.

Precise alignment has been done by using an autolevel, a theodrite and an aluminum scale. The alignment procedure is as follows; firstly, median plane of the magnets are aligned by using the autolevel. The level is adjusted by using jack bolts of the magnet stage. This accuracy is expected to be about 0.2 mm. Secondly, rotation angle about a vertical axis and radial position were aligned. The alignment of the rotation angle is done using theodrite placed on a top of a center pole which stands at the ring center by referring mark lines on a top of the magnets. The radial position is adjusted by referring the aluminum scale which is put between the center marker on the pole and a precise target on the top of the magnet. The accuracy of absolute radius is determined by thermal coefficient of thermal expansion (2.4×10^{-5} °C^{-1}). Design length of the aluminum scale is 3272 mm. Assuming that temperature uncertainty is 5 degree, the accuracy is about 0.5 mm. This accuracy is enough for this experiment.

APPARATUS

The top view of the FFAG ring is shown in Fig. 1. The ring consist of one RF cavity and six FFAG magnets. The RF cavity is one gap and consists of four magnetic alloy cores. Detail of the RF cavity is described in [4].

Two type of magnets are used in the ring. One is a magnet which have a field clamp and the other one is that of no field clamp. The magnet with the field clamp is located at cell 1 and 2 and the field clamps are attached facing the RF cavity to reduce leak field into the magnetic alloy cores. Three Power supplies is used for the all magnets. One power supply provides to all F coils. Because of voltage limitation, the current is divided into two coil set, cell 2-4 and cell 1,5,6. The other power supplies provide to D coils and one of them is for the coils with field clamps and the other is for ones without field clamp. Current of these three power supplies are controlled by DCCT and the stability of less than 0.1% is achieved. Even though all magnets are excited, the magnetic field on the rf cavity surface is 4 Gauss

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at maximum and so small that magnetic saturation of MA cores is avoidable.

The beam duct is almost hexagonal shape and the distance from the ring center to center of straight section is 3081 mm. The beam duct have no bellows, the connection of final duct is done by inserting thin companion flange between two duct flanges which is gapped with bolts. A shape of cross sectional view is trapezoid and the inner hight and inner width are 132 mm and 376 mm, respectively.

^{241}Am is placed at the injection chamber and alpha particles emitted at energy of 5486 keV. The alpha particles are degraded by an aluminum foil into an optimum momentum for this ring (98 MeV/c). In the injector chamber, auto-rotational stage and auto-linear stage are installed and injection angle and position in radial direction can be changed.

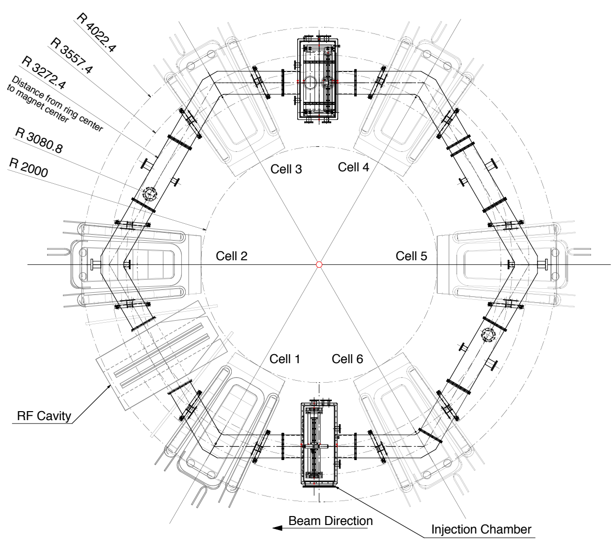

Figure 1: Entire layout of the six-cell FFAG ring.

Two pump system which consist of turbo molecular pump and rotary pump are placed between cell-2 and cell-3 and between cell-5 and cell-6. Vacuum pressure of less than 2x10^{-3} Pa is achieved. It is too small for alpha particle to be changed the orbit by energy loss caused by collision with residual gas.

MEASUREMENT OF MAGNETIC FIELD

Individual Difference

Individual differences between the six-magnets are measured. In this measurement the position of the Hall probe is shown in Fig. 2. The height of the Hall probe is on the median plane. Firstly field gradient is measured at region of 40 mm^2 around the point with points separation of 20 mm. The measured field gradients are tabulated in Table 1. The Hall probe is fixed on a jig made from aluminum and the jig is put on a precise stage made from brass with locator pins (Fig.3). Position error of the Hall probe is measured flipping the jig by 180° about vertical axis. The measured

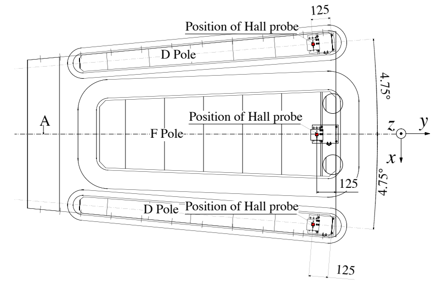

Figure 2: Position of field measurement for individual difference. (Plan view.)

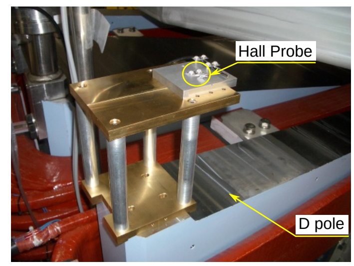

Figure 3: Photograph of the field measurement device set on the D pole.

difference at D pole and at F pole were 1.2 Gauss and 0.1 Gauss, respectively. It is deduced that this difference comes from position error in x direction because the gradient in y direction is ten times smaller than that of x direction. As the results, systematic position error of the Hall probe is 0.2 mm in x direction.

The measurement of the individual difference was performed at coil currents shown in Table 2. The results are shown in Fig. 4. Fig. 4-(a) and -(b) shows measured field for magnets which have the clamp. The solid line in each figures is a mean of the measurement data and dashed line is the TOSCA calculation. Fig. 4-(c) shows measured field of the magnets equipped no field clamp. The root mean square is 2.175 Gauss, and this value corresponds to 0.4% while field errors due to position error is 0.2%. So the individual difference of D pole is about 0.2%. Fig. 4-(d) and (e) shows the field of F poles which have field clamp and that of no field clamp, respectively. The difference of F pole between magnet equipped the clamp and no clamp is 0.1%. Root-mean-square of six magnets is 1.92 Gauss which corresponds to 0.05%. These differences are negligible.

Table 1: Field gradient around measurement points (unit: Gauss/mm).

Pole	$\partial B/\partial x$	$\partial B/\partial y$
D no clamp	2.93	0.340
D clamp side	2.84	-
F	$<1.17\times10^{-2}$	1.42

Table 2: Current and voltage of power supply for the magnet coils.

Power supply	Current [A]	Voltage [V]
D coil no clamp	447	156.4
D coil clamp side	606	44.4
F coil	2781	113

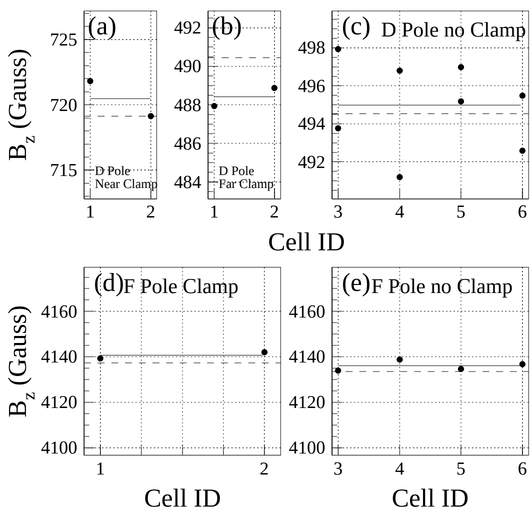

Figure 4: Individual difference of the PRISM-FFAG magnets. (a): D poles facing on the field clamp at cell 1 and 2. (b): The other D poles at cell 1 and 2. (c): D poles for magnets which have no clamp. (d): F poles which have a clamp. (e): F poles which have no clamp.

Measurement of Magnetic Field Profile

Magnetic field profile along axis of F pole center (line "A" in Fig.2) is measured by using the Hall probe which is attached on an aluminum scale. The Hall probe is aligned on the magnet-median-plane and inserted into the beam duct through a duct port. The measurement has been done for the magnets at cell 2 and cell 5. The measured profiles are shown in Fig. 5. Fig. 5-(a) is the profile of the magnet equipping the field clamp and Fig. 5-(b) is that of no clamp. The magnetic field profiles are almost same as TOSCA calculations. The profiles are expanded with multi-pole components around $r = 3500$ mm. By using the expanded coefficients, the magnetic field are expressed by,

$$B_z(r) = \sum_{n=0}^{\infty} A_n \frac{(r - r_0)^n}{n!}. \quad (1)$$

The expanded coefficients are shown in Table 3. The coefficients shows good agreement with TOSCA calculations until sectapole components.

SUMMARY

The six-cell FFAG ring has been constructed at Research Center for Nuclear Physics at Osaka University. Alignment has been done with the theodrite and the autolevel. The vacuum pressure in the beam duct is less than 2×10^3 Pa with two turbo molecular pump system. The measurement of magnetic field has been done. The individual difference of the D magnets is 0.2% in root-mean-square and that of the F magnets is 0.1%. The multi-pole components are obtained at F magnet center. These multi-pole shows a good consistency with TOSCA calculation until sectapole.

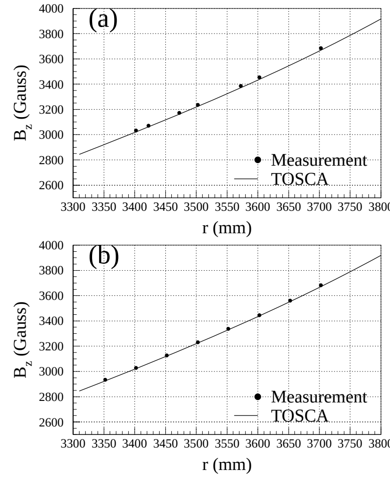

Figure 5: Profiles of magnetic field along F pole axis. (a):Profile for the magnet at Cell 2. (b):Profile for the magnet at cell 5.

Table 3: Multi-pole coefficients of the PRISM-FFAG magnets, where the multi-poles are expanded at r=3500 mm.

Components	Measurement Cell 2	TOSCA
Dipole [Gauss]	3230.7	3218.6
Quadrupole [Gauss/mm]	2.109	2.0724
Sectapole [Gauss/mm^2]	1.146e-3	1.1948e-3
Octapole [Gauss/mm^3]	-0.8612e-5	2.7802e-5
	Cell 5	
Dipole [Gauss]	3225.3	3219.8
Quadrupole [Gauss/mm]	2.093	2.0803
Sectapole [Gauss/mm^2]	1.257e-3	1.1880e-3
Octapole [Gauss/mm^3]	-1.597e-6	2.7878e-6

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