DEFLECTOR DESIGN FOR SPIN ROTATOR IN MUON LINEAR ACCELERATOR

S. Artikova*, Y. Kondo, Japan Atomic Energy Agency (JAEA), Tokai-mura, Japan
T. Mibe, M. Otani, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

A muon g-2/EDM experiment based on muon linear accelerator was proposed for the J-PARC muon facility [1]. In this experiment, the ultra-slow muons created in muonium target region will be accelerated to 210 MeV kinetic energy then will be injected into the muon storage magnet to measure the decay products depending on the muon spin. Therefore, a spin rotator (device) is a key component of the muon linac. Spin rotator consists of a pair of combined electrostatic and magnetic deflectors and a pair of solenoids which will be placed in between these two deflectors. In this paper, we report the design of these two dispersionless deflectors and the simulation results of the device performance will be discussed.

INTRODUCTION

A new experiment to measure the muon's anomalous magnetic moment $a_\mu=(g-2)/2$ is one of the ongoing research along the construction of the muon linear accelerator at J-PARC(Japan Proton Accelerator Research Complex) [2]. In this experiment, the ultra-slow muons created in muonium target region [3] will be accelerated to 210 MeV kinetic energy. To measure $(g-2)$, longitudinally polarized muons will be injected into 3 T MRI(Magnetic Resonance Imaging)-type solenoid magnet [4] and the decay products depending on the muon spin will be detected. Parity violation in the weak decay of the muon then serves as the spin analyzer. The higher-energy positrons in the muon decay chain $\mu^+ \to e^+ + \nu_e + \bar{\nu_\mu}$ will be emitted preferentially in the direction of the muon spin at the time of decay. Muons are spin polarized opposite to their momenta or spin and momentum are aligned. In both cases, muons are longitudinally polarized but in an opposite direction. Motivation of developing the spin rotation technique for $(g-2)$ experiment is to provide 180 degrees spin rotation during the transport of muon beam in a linear accelerator. An advantage of using the spin rotator is: muons can be injected into storage magnet either spin and momenta aligned or spin polarized opposite to their momenta. The quoted result for $(g-2)$ is determined by measuring the difference between the angular frequencies of spin precession the magnetic field and orbital cyclotron motion. The characteristic anomalous precession frequency is clearly visible in a wiggle plot of positron counting rate from the previous experiments [5]. If muons are spin rotated by 180 degrees, as a result, this wiggle will be shifted in time by a half period. Spin rotator is designed to be installed after the RFQ where muons will be accelerated up to 0.34 MeV.

* sayyora@post.j-parc.jp

Structure and Working Principle of the Spin Rotator

The schematic view of the spin rotator is shown in Fig. 1. It composed of a pair of deflectors and a pair of identical solenoid magnets situated in between the deflectors. Each deflector is designed to combine the magnetic and the electrostatic fields at the same position simultaneously in order to satisfy the requirements of device. An electrostatic deflector

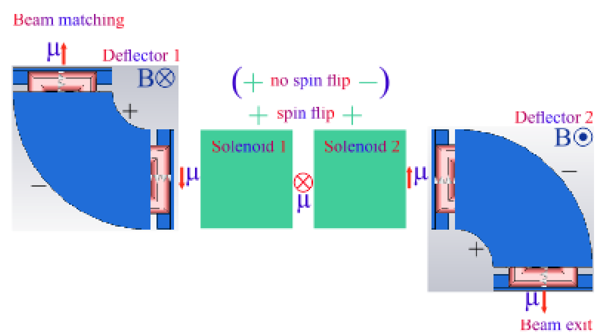

Figure 1: Schematic view of spin rotator. Dipole fields are transverse and the direction of electric fields are radially outward. The red arrows of μ^+ represents the muon spin orientation during the beam transport through the device. Plus signs on solenoids show that the magnetic fields of solenoids oriented in the same direction. Opposite signs show the magnetic field directions are opposite.

consists of two cylindrical electrodes is designed to bend the muon beam by 90° without changing the spin direction. To rotate the spin in a magnetic field generated by a cylindrical dipole an angle between the muon spin and the magnetic field should not be 0 or 180 degrees. After deflection in a normal dipole magnet, the muon spin has the same direction as the muon velocity because g factor is very close to 2. It is also possible to to make 90° deflection with double of the normal dipole magnetic field value, thus the muon spin will rotate 180°. We can use this advantage, then muons are transverse polarized after 90° deflection and perpendicular to the velocity. When beam enters the solenoid the magnetic momentum is perpendicular to the magnetic field. If solenoids' magnetic fields are in the same direction the muon spin rotates by 180°. If magnetic fields are opposite muon spin orientation will not change. Second deflector is an identical but has an opposite field direction regarding to the first one. At the exit of the second deflector muon beam polarization is still longitudinal but an opposite to its initial polarization. B_y using a pair of solenoids (depend on their field directions), the spin rotator can operate in two modes: either spin flip(rotation) or no spin flip.

DISPERSIONLESS DEFLECTOR DESIGN

To maintain the beam, it is known that the effect of the bending shear due to the linear dispersion has to be avoided. A beam deflector designed by a magnetic field combined with an electrostatic field can eliminate the linear dispersion of the beam orbit. When the electric field **E** and the magnetic field **B** and the central velocity **v** of the beam satisfies the following equation:

$$\vec{E} = -\frac{\vec{v} \times \vec{B}}{2} \tag{1}$$

this deflector can eliminate the effect of the linear dispersion. Such dispersionless deflector can be realized by inserting a cylindrical electrostatic deflector in the gap of the bending dipole magnet. As shown in Fig. 2 the dipole is H-type magnet driven by two stranded coils is designed. Dipole magnet

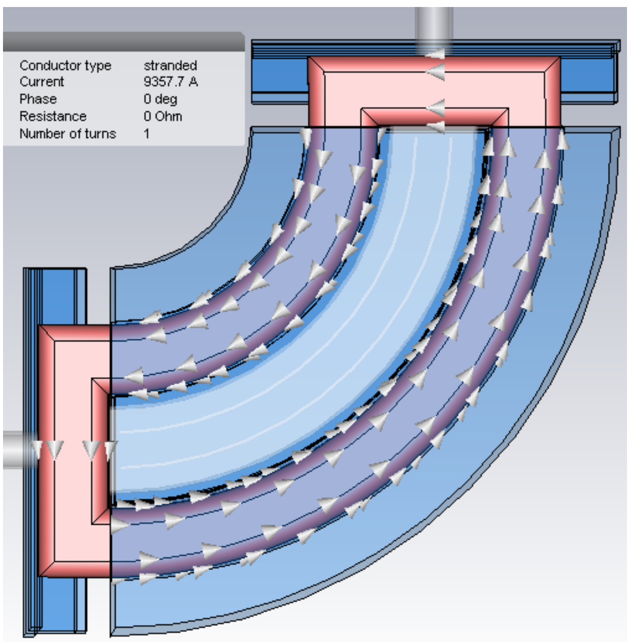

Figure 2: Schematic view of dispersionless deflector. In the simulation, the excitation current of each coil is 9357.7 A, the number of turns is 1. Magnetic field shielding in the beam region is 2.5 cm away from the yoke.

and cylindrical electrodes are modeled by using the electromagnetic simulation software CST STUDIO SUITE [6]. Bending radius of dipole is 30 cm and arc length of the sector is 73.79 cm with the central angle of 90°. Height, width and total length of the dipole magnet are 38 cm, 34 cm and 47 cm relatively. Dipole magnet is equipped with two identical, cylindrical coils each has an excitation current of 9357.7 A, where number of turns is 1.

Magnetic Field Calculation

The magnetic field to bend the 0.34 MeV muons into 90° is realized by dipole magnet, the yoke is made of a pure iron (non-linear) such that the $B(H)$ curve of the material can be taken into account by the Magnetostatic Solver in CST. For a detailed investigation the field along the particle trajectory has been evaluated. Figure 3 shows the H-field which mainly occurs in the gap, while the B-field concentration will be in the iron yoke. Magnitude of magnetic flux density B_y on central trajectory curve along z-axis in the dipole gap is shown in Fig. 4. Obtained result B_y=0.1886 T is consistent with required value of magnetic field. Simulation then revealed adjustment of the magnetic field shielding is sufficient to optimize the particle orbit tracking results.

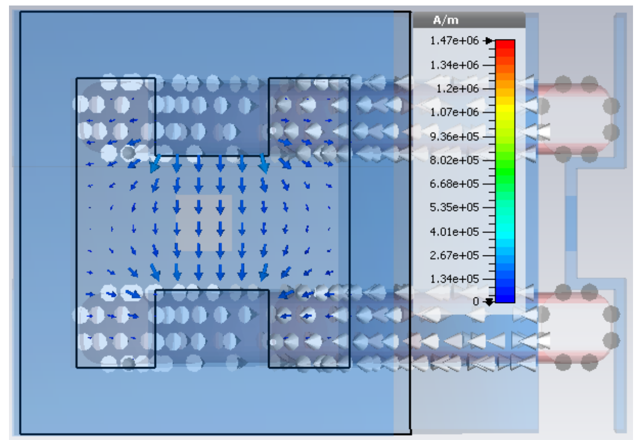

Figure 3: H field of the dipole magnet. Cutplane is shown in transverse plane. The direction of the arrows indicates the field direction. Gap height=12 cm, width=10 cm.

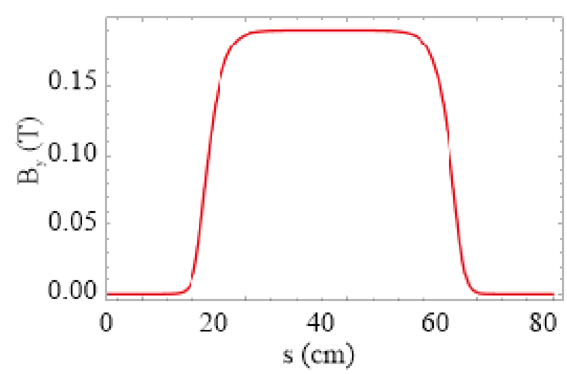

Figure 4: Magnitude of magnetic flux density B_y on central trajectory curve along z-axis in the dipole gap.

Electrostatic Deflector Field Calculation

Due to the size limitation to be installed in the dipole magnet gap of 12 cm, the height of electrostatic deflector electrodes is 7.8 cm. The gap region between two electrodes is 3 cm in which the radially uniform electric field of the deflector is generated. As shown in Fig. 5 electrodes are placed within the vacuum chamber which has been installed in the dipole gap. The space from electrodes to the vacuum chamber is 15 mm in all directions. Central angle of the electrodes 87.574° is determined from particle tracking simulation in which the total deflection angle 90° was achieved.

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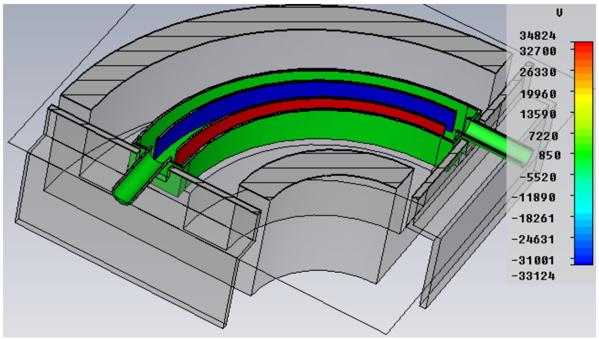

Figure 5: Cutview of the dispersionless deflector. Coils are not shown for better visibility of electrostatic deflector which is placed in the gap of H-type dipole magnet. Electric potential distribution of the inner and outer electrodes are 34.823 kV, −33.124 kV relatively for 0.34 MeV muons. Vacuum chamber is on ground potential.

Orbit Tracking Simulation

An orbit tracking simulation in magnetic field and electrostatic field were performed in CST PARTICLE STUDIO. The particle tracking solver can model the behavior of particles through static fields and perform a fully consistent simulation of particles and electromagnetic fields. As shown in Fig. 6, two point source particles are defined in the center of electrodes. The reference particles are traced in both directions in the electrostatic field. Results show that, both particles has 45° deflection precisely, which means the total deflection angle is 90°. In addition, orbit tracking simulation in magnetic field using particle solver is performed separately. Point source reference particles are traced from the orbit center in the magnetic field in both directions. Result is shown in Fig. 7 where it can be seen that the total deflection angle is 90°.

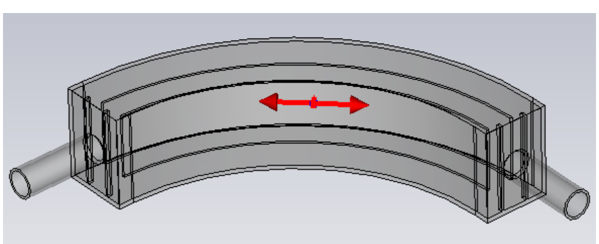

Figure 6: Particle point sources are used in orbit tracking simulation to achieve 90° deflection.

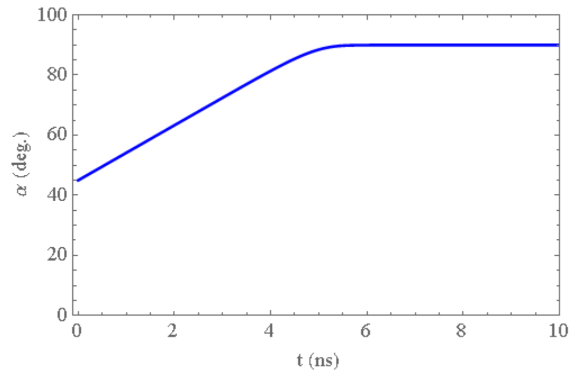

Figure 7: Particle orbit tracking simulation shows 90° deflection by dipole magnetic field.

CONCLUSION AND OUTLOOK

Dispersionless deflector is designed for spin rotator applications. Spin rotator will be used after the RFQ in a linear accelerator, in lower energies. Otherwise the required electric fields become too large for particle beams in the accelerator. Design studies, magnetic and electrostatic field calculations for dispersionless deflector were optimized. Particle tracking simulations show that design value for deflection is achieved. Ongoing studies involve spin tracking through the complete structure and evaluation of parameters.

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REFERENCES

[1] J-PARC website, `http://g-2.kek.jp/index.html`

[2] J-PARC website, `http://j-parc.jp/MatLife/en/`

[3] J-PARC website, `https://j-parc.jp/hypermail/news-1.2016/0002.html`

[4] H. Inuma *et al.*, “Three-dimensional spiral injection scheme for the g-2/EDM experiment at J-PARC”, *Nucl. Instr. Meth.*, vol. 832, pp. 51–62, 2016.

[5] G. Bunce, “Final results from the muon g-2 experiment”, in *Fundamental Interactions, Proc. 9th Lake Louise Winter Institute*, Alberta, Canada, Feb. 2004, pp.135–139.

[6] CST, `https://www.cst.com/products/csts2`