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Magnetic design and method of a superconducting magnet for muon $g-2$/EDM precise measurements in a cylindrical volume with homogeneous magnetic field

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ABSTRACT

A magnetic field design method of magneto-motive force (coil block (CB) and iron yoke) placements for $g-2$/EDM measurements has been developed and a candidate placements were designed under superconducting limitations of current density 125 A/mm^2 and maximum magnetic field on CBs less than 5.5 T. Placements of CBs and an iron yoke with poles were determined by tuning SVD (singular value decomposition) eigenmode strengths. The SVD was applied on a response matrix from magneto-motive forces to the magnetic fields in the muon storage region and two-dimensional (2D) placements of magneto-motive forces were designed by tuning the magnetic field eigenmode strengths obtained by the magnetic field. The tuning was performed iteratively. Magnetic field ripples in the azimuthal direction were minimized for the design.

The candidate magnetic design had five CBs and an iron yoke with center iron poles. The magnet satisfied specifications of homogeneity (0.2 ppm peak-to-peak in 2D placements (the cylindrical coordinate of the radial position R and axial position Z) and less than 1.0 ppm ripples in the ring muon storage volume (0.318 m $< R <$ 0.348 m and -0.05 $< Z <$ 0.05 m) with 3.0 T strength and a slightly negative B_R (magnetic field radial component) at $Z >$ 0.0 m) for the spiral muon injection from the iron yoke at top.

1. Introduction

At the J-PARC muon facility, preparations are being made for a new measurement experiment on the anomalous magnetic moment of the muon ($g-2$) and its electric dipole moment (EDM). In the experiment, the difference between two angular frequencies, the spin precession frequency and the orbital cyclotron precession frequency, will be measured in a homogeneous magnetic field and hence $g-2$ will be determined.

Previous experiments were done at high momentum ($\gamma = 29.3$, magic momentum) at CERN [1] and BNL [2] facilities, and their reported $g-2$ measurement results were not consistent with the Standard Model of Particle Physics, with a $\sim 3\sigma$ deviation, which suggested the need for physics beyond the Standard Model. The J-PARC experiment will use low momentum ($\gamma = 3$) and a very low emittance muon beam, which requires only weak magnetic focusing to maintain the beam storage ring; these conditions set the J-PARC experiment apart from these other experiments. New research and development work for the source of the low emittance beam (ultra-cold muons) has achieved significant results [3,4].

A 3.0 T compact magnet will be used for the muon storage by a spatially and time dependently very homogeneous magnetic field in the cylindrical storage area of 30 mm radial width and 100 mm axial height, at 0.666 m diameter, which refers to the orbital cyclotron motion. We expect the smaller storage ring and the compact fiducial volume inside it will offer a great advantage in field precision. Since the conventional injection scheme is not applicable, we have discussed a three-dimensional (3D) spiral injection scheme and determined that the new injection scheme is suitable for the precise beam control in such a compact ring [5,6].

We expect such homogeneous magnetic field can be realized by a superconducting magnet using MRI technologies [7,8], which are

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the determination method of magneto-motive force placements (coil block (CB) placements [9,10] and iron pole optimizations [11]) in MRI magnet design, and the shimming calculation method to obtain iron piece placements for magnetic field shimming [12,13], using use SVD (singular value decomposition) regularization [14,15], as well as superconducting aspects of MRI magnets including the persistent current operation. Using the compact magnet with these technologies, we expect residual and error fields to be much reduced from those of previous measurements.

The magnet needs a homogeneous axial magnetic field B_Z at the beam storage cylindrical volume and a radial field B_R suitable for the spiral injection under limitations of a current density and an allowable magnetic field strength on a conductor which are roughly equal to those of the MRI magnets. Using the MRI technologies, it is expected to obtain a much better homogeneous magnetic field in the J-PARC measurements than prior measurements, especially for the 3D distribution. However, the geometry for the magnet of the planned experiment is different from that of the MRI magnet and we have had to modify the design method. Moreover, to get a suitable B_R condition, we have introduced a new concept for the magnetic field distribution and the design method. This paper describes a magnetic design study of the superconducting magnet for the J-PARC $g-2$/EDM measurements experiment. We discuss the design method and one magnetic design candidate of the magneto-motive force placements.

2. Specifications and design baselines

Concepts of $g-2$/EDM measurements have been described in the literature [1–6]. From these studies, we understood that the magnet should have the following concept and specifications of the magnetic field for precise $g-2$/EDM measurement in the J-PARC experiment.

2.1. Beam orbit concept and main magnet specifications

Fig. 1 shows a conceptual drawing of a muon orbit in the measurements with a solenoid type magnet [6]. The orbit is schematically plotted in the upper area as a solid line. Muons are injected from the top and the radial field B_R of the magnet deflects the muon momentum to reduce axial speeds as they come down. When they reach the storage region a kicker generates a short (0.2 μs) and weak (1 G) radial field ${B_R}^{KC}$ to stop their axial motions. The measurements are done in the very homogeneous magnetic field of the storage region, which has a cylindrical shape volume.

Table 1 lists parameters for the $g-2$/EDM measurements [1–6]. The table includes information for the BNL-E821 measurement, the FNAL measurement which used the same magnet as in the BNL-E821 measurement and had improved accuracy, and the planned measurement at J-PARC. Comparing the three, the measurement in J-PARC will be done at low energy (roughly 1/10 that of BNL and FNAL measurements), and then, with a small magnet, the radius of the storage ring will be about 1/20 that of the other two. Then, we can expect a much better homogeneous magnetic field in the J-PARC measurement. The BNL measurement had 0.46 ppm (parts per million) statistic accuracy and the FNAL measurement had an improved accuracy of 0.1 ppm due to the increased number of μ^+ and better magnetic field homogeneity.

The magnetic field specifications for the J-PARC measurement are given in Table 2. These specifications ensure that the injection and the measurement with the intended accuracy are possible. The magnetic field strength should be homogeneous at the storage volume for precise measurement and the radial field B_R should not be a large negative value for the spiral injection [5,6].

We discuss the magnet design, which optimizes placements of the CBs and the iron yoke with poles. They are tuned so that the homogeneous magnetic field is obtained in two-dimensional (2D) geometry. The target homogeneity of the residual magnetic field ${B^{RE}}_{2D}$ in 2D geometry

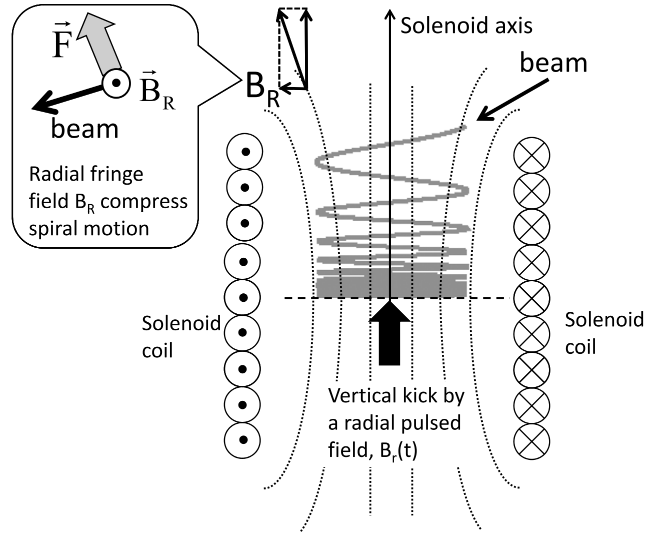

Fig. 1. Schematic magnetic force lines, muon orbit and radial magnetic field component.

is 0.2 ppm PP (peak-to-peak) amplitude in the muon storage volume specified in Table 2; that is,

$$-0.3\ \mu T < {B^{RE}}_{2D} < +0.3\ \mu T. \tag{1}$$

While the optimizations are done in 2D geometry, the magnetic field in the storage volume is in a 3D configuration. Then, the target homogeneity in the 3D azimuthal direction is less than 1.0 ppm PP in the design and it will be shimmed when installed at the site. Hereafter, the homogeneity is discussed using peak-to-peak values and PP is not indicated.

The muons are expected to be injected and stored with these specifications. In the spiral injection area, which is located above the storage area, the muons go down and axial speeds are lowered. The orbits are compressed axially as the muons go down (Fig. 1). Since a negative B_R may accelerate the axial motions, the fringe magnetic field with no negative B_R is preferable. We plan to use the weak focus magnetic field for stabilization of the stored muon beam orbit and it will be supplied by a gradient field coil, which is not discussed here; we focus our discussion on the homogeneous static magnetic field.

The magnets for these measurements are superconducting magnets. For the J-PARC measurements, the magnet is operated by the persistent current, while the others are driven by a power supply. The J-PARC magnet uses MRI technologies. The typical guaranteed field decay in MRI magnets is less than 0.1 ppm/hour. Due to the facts that our system has more than 5 times magnetic energy comparing with 1.5 T typical MRI magnets and reduced number of superconducting joints, we can expect that the decay rate is less than 0.01 ppm/hour. This rate is smaller than the other experiments [16,17]. The homogeneous magnetic field in the fiducial volume is possible through the developed method discussed in this paper.

2.2. Magnetic design baselines

We show that a magnetic design with the specifications of Table 2 is possible and can be designed by extending the MRI design technologies. The design is done on 2D geometry. However, error fields can have 3D distributions. We design the magneto-motive force placements, making the error fields as small as possible, but slight residuals can exist even without the error fields. The following considerations are made for the magnetic design.

(1) The magnetic design is done in 2D geometry.