DESIGN OF THE COMET PION CAPTURE SOLENOID

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Abstract

An intense muon beam is mandatory for the next-generation experiments to search for lepton flavor violating processes in the muon sector. The COMET experiment, J-PARC E21, aims to search for muon to electron conversion with an unprecedented sensitivity. The muon beam is produced from pion decays in a strong magnetic field generated by superconducting solenoid coils. The large-bore superconducting coils enclose the pion-production target to capture pions with a large solid angle. The magnetic field is designed to have a peak of 5T at the target. To avoid severe radiation from the target, thick shielding is inserted in the warm bore of the pion capture solenoid magnet. The proton beam is injected through the gap between the pion capture solenoid and the subsequent transport solenoid magnets. For this purpose, the bore of the pion capture solenoid has to be larger than 1 m. This paper describes the design of the pion capture solenoid magnet for the COMET experiment.

INTRODUCTION

The COMET experiment [1], J-PARC E21, aims to search for muon to electron conversion in a muonic atom with a sensitivity of 10^{-16}. Negative charged muon beam with quite high intensity of 10^{11} μ^-/sec at the stopping target is required. Thus novel method to generate such a muon beam is adopted in the COMET experiment. The pions, which are produced using an 8 GeV proton beam from the J-PARC Main Ring, are captured with high efficiency using a superconducting solenoid magnet surrounding the pion-production target. The muons, which are produced by pion decays, are captured and transported through subsequent solenoids and are brought to stopping targets. All the equipments from the pion production target to the detector to identify conversion signal are enclosed in a series of solenoid magnets as shown in Fig. 1. Since higher magnetic field is preferred in the pion capture solenoid and the other section also require high magnetic field, superconducting solenoid magnets are employed.

There exist several technical challenges for the construction of the superconducting solenoid magnets. The main challenges are 1) a high magnetic field (of about 5 T) and radiation-hardness for the pion capture solenoid that surrounds the pion production target, 2) construction of curved solenoids with a compensating dipole field, 3) precise control of the magnetic field from pion capture to the detector, and 4) quench protection for a large-stored energy solenoid system in which all solenoids are magnetically coupled to each other. Additionally, it would be beneficial to reduce the cost the of superconducting solenoids as they are a major part of the cost of COMET.

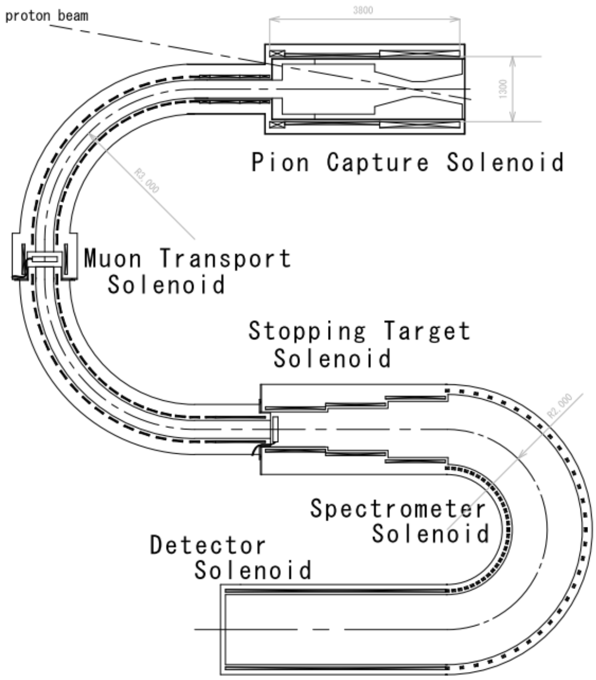

Figure 1: Layout of the muon beamline in the COMET experiment, which consists of a proton target, pion capture solenoid, muon transport solenoid, stopping targets, the spectrometer solenoid and detector solenoid.

In the following sections describe the pion capture solenoid magnet in detail.

LAYOUT OF THE PION CAPTURE SOLENOID

To collect as many pions (and cloud muons) of low energy as possible, the pions are captured using a high solenoidal magnetic field with a large solid angle. Figure 2 shows a schematic layout of the system of pion production and capture and the field distributions in the solenoid magnet. It consists of a proton target, a surrounding radiation shield, a superconducting solenoid magnet for pion-capture with a 5 Tesla magnetic field. Backward-scattered pions are captured in the magnetic field and focused toward the transport solenoids in a degrading magnetic field. In this case, pions emitted into a half hemisphere can be captured within

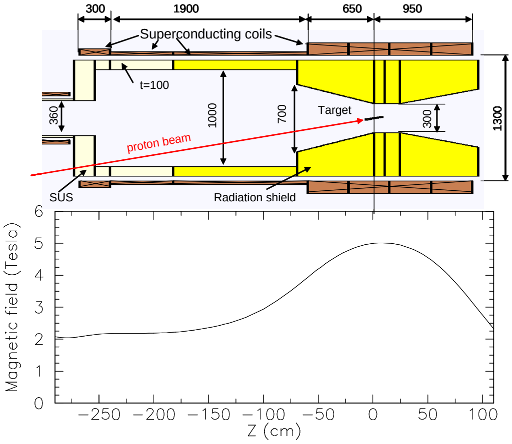

Figure 2: (Upper) Schematic layout of the pion capture solenoid system, which consists of the proton target, the superconducting coils and the radiation shielding in magnet warm bore. (Lower) Magnetic field profile along the pion capture solenoid axis. Pion production target is located at $z = 0$.

the transverse momentum threshold ($p_T^{\max}$). This $p_T^{\max}$ is given by the magnetic field strength (B) and the radius of the inner bore of solenoid magnet (R) as $p_T^{\max}[\mathrm{GeV}/c] = 0.3B[\mathrm{T}]R[\mathrm{m}]/2$. The optimization of the magnetic field of the capture solenoid was performed and it was observed that the higher the pion capture magnetic field, the better the muon yield at the exit of the pion decay system. In the current design, we employ conservative design values, namely of $B = 5$ T, $R = 15$ cm. It can accept most of the pions with P_T^{max} = 112.5 MeV/c.

The radiation shield is inserted between the pion production target and the coil which generates 5-Tesla magnetic field. The shield is made of tungsten and the maximum thickness of the radiation shielding is about 45 cm. Thickness of the shield is tapered so that pion absorption is minimized. There is a gap between the coil of pion capture section and the coil of transport section in order to inject a proton beam into the bore of the solenoids. The valley of magnetic field at the coil gap can lose pions and also trap unwanted particles. To correct the field distribution, a series of matching coils with large aperture is necessary. The injection angle of the proton beam is adjusted to 10 degrees from the solenoid axis in order to keep the coil diameter as small as possible. The injection angle is determined from the balance between the coil size and the radiation dose. A larger coil would be needed for shallower injection. With a larger injection angle, the coil would be irradiated with a harder radiation dose. In the current design, the first coil, which generates 5 T field, has dimensions of 1300 mm in diameter and 1600 mm in length. The target is located 150 mm off the magnet center to focus trapped pions to the directions to subsequent transport section.

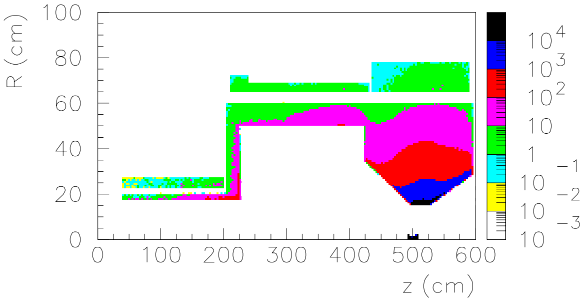

Figure 3: Heat deposit distribution by radiation from the pion production target at $z = 500$ cm in the pion capture solenoid. Color chart represents deposit energy density in the unit of μW/g.

RADIATION DOSE

Radiation dose from proton bombardment on the pion production target was estimated by MARS15 [2]. The radiation heat comes mostly from neutrons. The deposited energy distribution is presented in Fig. 3. It was found that an averaged heat deposition in the pion capture coil generating 5 T field is about 8 W for a proton beam of 8 GeV and 7 μA. The maximum deposited energy density is about 10 μW/g, corresponding to a radiation dose of about 0.1 MGy in the experiment life time (10^{21} protons on target).

The neutron flux can degrade the RRR (Residual Resistance Ratio) of aluminum stabilizer. The maximum flux of neutrons with the energy larger than 0.1 MeV at the pion capture coil is estimated to be 6×10^{21} n/m^2 for 10^{21} protons. Since the degradation of a stabilizer is not negligible to keep adequate quench protection, it will be important to measure resistance during the beam exposure. If the degradation is observed, a thermal cycle to room temperature would be necessary to recover the resistance.

COIL LAYOUT

The solenoid is designed to use aluminum stabilized conductor to reduce the heat load due to the secondary beam heat load. The parameters of the conductor considered are summarized in Table 1. The conductor uses a Rutherford type cable with 14 copper stabilized strands. The cable is encased in the aluminum stabilizer by a conforming technology.

The pion capture solenoid consists of 3 parts. The first part, namely CS, is the coil closest to the target. The second one, namely MS1, is the coil to provide matching field from the proton target to the transport solenoid. The third one, namely MS2, is the coil to compensate the valley of magntic field at the gap between the pion capture solenoid and the muon transport solenoids. The coils of CS and MS2 are wound from the cable with edgewise solenoid winding with a 8-layer structure. The coil of MS1 are wound from the same cable with the same winding method as CS, but

Table 1: Main Parameters of Aluminum Stabilized Conductor

Item	Value
Cable Dimension (without insulation)	15×4.7 mm^2
Cable Dimension (with insulation)	15.3×5.0 mm^2
Strand Diameter	1.15 mm
Strand Number	14
Al/Cu/NbTi	7.3/0.9/1.0
Aluminum RRR	500
Copper RRR	50
NbTi Jc at 5 T 4.22 K	2700 A/mm^2
Al yield strength	55 MPa
Overall yield strength	150 MPa

Table 2: Main Parameters of the Coils in the Pion Capture Solenoid Magnet

	CS	MS1	MS2
Length (mm)	1600	1900	300
Diameter (mm)	1300	1300	1300
Layer	8 layers	4 layers	8 layers
Thickness (mm)	120	60	120
Current density (A/mm^2)	42	42	42
Maximum field (T)	5.8	4.8	4.2
Hoop stress (MPa)	73	100	38

have a 4-layer structure. The parameters of these coils are listed in Table 2.

The coils are structurally connected to each other making a single ridged cold mass. The cold mass is encased in the cryostat that provides the thermal insulation vacuum. The cryostat is then covered by an iron return yoke. The electromagnetic force on the cold mass is strongly depend the layout of the yoke. The support structure will be designed such that the cold mass does not move with respect to the iron yoke. A maximum magnetic field on the coils is about 5.8 T at CS with an operation current of about 3 kA. The load line ratio of the CS coil is about 0.5 and the critical temperature at the operating point is about 6.5 K.

As shown in Table 2, the hoop stress in the coils exeeds the allowable stress of 33 MPa. Therefore, these coils should need surrouding support rings. The compressive stress is also calculated in the case all coils are connected each others, and the maximum stress is found to be 39 MPa at the edge of MS1. To reduce the compressive strees, the support plates should be inserted among the coils. In the case, the stress in MS1 is reduced to be 18 MPa. Since the compressive stress in the CS coil is 33 MPa, which is just near the allowable stress, it is better to divide the CS coil to keep enough margin. The maximum stress can be reduced to 18 MPa by dividing the coil into 2 parts of 200 mm and 1400 mm.

COOLING

Although the solenoid is protected by a tungsten shield, the coil is still subjected to a large amount of radiation. The heat load to the coil is estimated to be about 30 W overall and this must be removed. The heat removal is performed by aluminum strips installed in between coil layers that carry heat to cooling pipes attached to the coil ends and outer support cylinder. The temperature bias along radial axis from heat deposit by the radiation penetrating from the proton target is estimated to be less than 1 K with aluminum strips between coil layers. Details of the cooling scheme must be examined carefully.

The solenoids are cooled by a helium refrigerator that provides two-phase liquid helium. The helium is supplied to the solenoid using a thermo-siphon system. The refrigerator system should be designed such that the thermal cycle to 10 K and the cycle to room temperature can be achieved in 6 hours and in one week respectively. The system also should be designed such that capture solenoid can be warmed up without warming up the other solenoids.

PROSPECTS

The conceptual design of the pion capture solenoid has been performed to overcome the severe radiation environment. The specific design study on the coil structure is underway to show the feasibility of the system construction. One of the critical issue is the degradation of RRR of the aluminum stabilizer caused by neutron irradiation. The COMET collaboration plan to test the sample of aluminum stabilizer at the reacter neutron irradiation facility and to reveal the properties.

REFERENCES

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