Radiation study on the Superconducting Solenoid Magnet for $\mu^- \to e^-$ Conversion Experiment

ミューオン電子転換実験による放射線環境下における超伝導ソレノイドに関する研究

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I Introduction

The physics beyond the Standard Model (BSM) can be explored via a charged lepton violation (cLFV). Latest upper limit of $\mu \to e\gamma$ is 5.7×10^{-13} (90% C.L.), which is updated by MEG experiment for searching $\mu^+ \to e^+\gamma$.The upper limit for $\mu \to e$ conversion is 7×10^{-13} (90% C.L.) measured by SINDRUM-II experiment with Ti target.

A coherent muon to electron transition (COMET) experiment is aiming to achieve the sensitivity of $< 3\times10^{-17}$ to search for the cLFV with two steps. COMET experiment intends to search for $\mu \to e$ conversion with aluminium stopping target. COMET phase-I is aiming to measure the backgrounds and search for $\mu \to e$ conversion with sensitivity of 3.1×10^{-15}. Phase-II is to search for it with $< 3\times10^{-17}$. Thus, 10^{11} μ^-/sec muons with low momentum are required.It can be obtained by using high intense pulsed proton beam and superconducting magnet system.

II Design

The COMET superconducting magnet system consists of pion capture solenoid, muon transport solenoid and detector solenoid for phase-I experiment. Phase-II experiment utilizes the capture and transport solenoid, but the detector solenoid will be replaced by a long curved transport solenoid and spectrometer solenoid. The pion capture solenoid provides 5 Tesla to capture the pions produced from production target, muon transport solenoid and detector solenoid transport muons from pion decay to stopping target and track the signal of 105 MeV electron from $\mu^- \to e^-$ conversion with 3 Tesla and 1 Tesla. These magnetic field must be smooth to eliminate the trapping of charged particle.

To reduce the costs and stored energy, the two coils of pion capture solenoid, CS0 and CS1, are designed close to the production target with radius of 672 mm, which works under high radiation. As for the radiation issue, the conduction cooling is employed to minimize the ^{3}H production due to the reaction ^{3}He(n,p)^{3}H. Conductor is stabilized by Al to reduce the energy deposition from nuclear heating and mass in pion capture solenoid.

2.5×10^{12} pps proton beam with graphite target and 4.4×10^{13} pps proton beam with tungsten target is employed in phase-I and phase-II experiment. Therefore, a radiation shield will be installed inside the capture solenoid to protect the superconducting magnet.

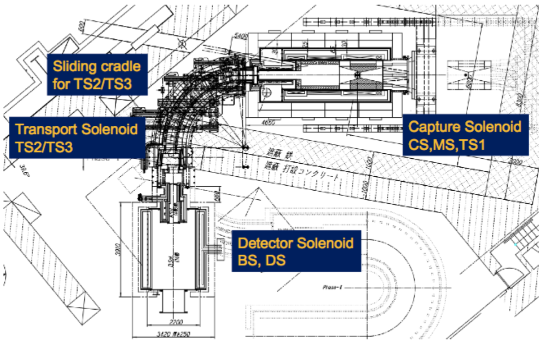

Figure 1: Concept of current superconducting magnet system for COMET experiment.

III Radiation estimation

The prompt radiation of phase-II is investigated by Monte Carlo code (GEANT4[2], PHITS and FLUKA[1]) with different physics model. The magnetic field map for simulation is calculated by finite element method (FEM) with iron yoke. As a result shown in figure 2, about 2.4×10^{21} n/m^2 ($E_n > 0.1$ MeV) at peak deposits in CS1 coil for 280-day operation. In addition, over 2×10^7 n/cm^2/sec neutrons with low energy will leak into detector room.

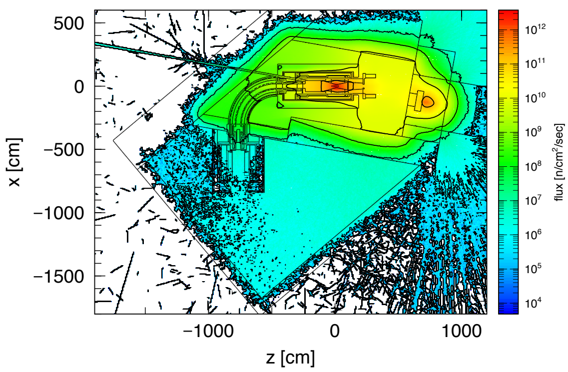

Figure 2: Neutron distribution of COMET phase-II experiment. It calculated by PHITS code with detector solenoid.

The residual radiation for phase-I is estimated to 3.7 mSv/h at target and 1 mSv/h behind to the CS0 after 30-day operation and 300-day cooling, which indicates it is difficult to take maintenance at the end of phase-I experiment. In practice, the phase-I experiment is currently planning to have over 7-month running.

Due to the cost issue, a radiation shield is optimized to replace the pure tungsten shield to protect the superconducting coils. New radiation shield consists of stainless steel, copper and tungsten alloy with polygonal shape. The maximum energy deposition, neutron fluence and DPA for 280-day operation are estimated to 0.8 MGy, 2.4×10^{21} n/m^2 and 1.1×10^{-5} DPA, respectively.

IV Irradiation test

Since the superconducting magnet is exposed under high radiation, it may cause the degradation of superconducting coils, which has risk in thermal and mechanical property. To investigate the degradation of pure aluminium which used as stabilizer and cooling strips, the aluminium and copper is irradiated with 2×10^{20} n/m^2 reactor neutrons. As a result, the resistivity of aluminium and copper increase about 0.03 nΩ·m and 0.01 nΩ·m. It will also recover totally after the temperature returns to room temperature.

The polyimide tape covers the conductor as ground insulation. It is reinforced by boron free glass cross on polyimide film with BT and epoxy resin to enhance the radiation resistance and mechanical property. Its mechanical property is tested with and without irradiation. The maximum shear stress is about 9 MPa, and its tensile strength will not reduce after 10 MGy irradiation with cobalt.

GFRPs are employed as the spacer in superconducting solenoid. 4 kinds of candidates, G10, CE, BMI and BT, are irradiated with electron with energy of 1 MeV and 34 MeV until 200 MGy and 4500 MGy, respectively. BT has best radiation resistance and mechanical property among these samples, which shows its tensile strength is 350 MPa without irradiation, and almost keep it until 200 MGy irradiation.

Quench protection diode for transport solenoid is a switch of the quench protection circuit. It irradiation test is taken by using secondary neutrons produced from reaction of (d,xn). The neutron flux is measured by activation of Au, Al and Ni, which is estimated for 10^{12} n/cm^2 totally until the end of experiment. However, its turn-on voltage has no big change before and after irradiation. Its cryogenic property is also investigated on the liquid nitrogen temperature. The turn-on voltage increases from 0.6 V to 1.1 V at 77 K. In the real case, its voltage will increase up to 1.5 V at 210 A, 4.2 K under 10^{12} n/cm^2 fast neutron irradiation by fitting the V-I curve. As for the worst case, the temperature will rise upto 70 K during the operation.

V Thermal stability and quench

As for the original design of CS1, 1 mm thick Al strip are inserted into each layer from single side. Al strip is connected to the cooling pipe where is flowed in liquid helium. The resistivity of Al and Cu grow up in terms of the irradiation test. Its thermal conductivity will degrade owing to the increasing resistivity, thus the temperature during the operation is possible to exceed to the current sharing temperature after irradiation. Figure 3 shows the temperature will rise to the current sharing temperature, 6.5 K, after 20-day operation. To solve this issue, the design is optimized by inserting the Al strips from two sides, shortening the Al strip from edge to cooling pipe and enlarging the thickness of inner Al strip to 3 mm. The 60-day operation becomes available after the optimization.

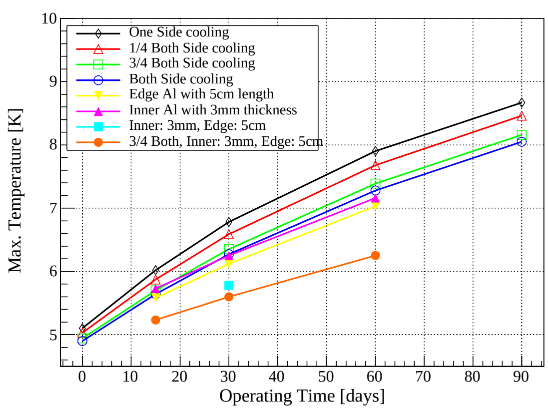

Figure 3: The maximum temperature during the operation. Black line: original design, orange line: optimized design.

The maximum temperature after quench is estimated by MIITs calculation. Electrical resistivity and specific heat of copper, aluminium and NbTi are fitted in terms of the experimental data. Dump resistor and inductance are supposed to 0.185 Ω and 12.69 H, respectively. As a result, the MIITs is estimated to 250 MA^2·sec, which corresponds to 270 K after quench when the RRR of aluminium drops to 100. It's too high for the superconducting solenoid, thus the temperature after quench will be discussed in future.

VI Conclusion and Discussion

In this study, the radiation and the radiation induced degradation of pion capture solenoid are estimated. As for current design, the superconducting solenoid is able to work for 60 days continuously. In COMET phase-II experiment, the superconducting solenoid is able to be operated until quench. Because Al and Cu can recover from the thermal cycling, the operation will be stopped after quench and wait the recovery of Al and Cu.

References

(1) T.T. B$\ddot{o}$hlen, et al.: Nucl. Data Sheets, 120 (2014), 211-214.

(2) S. Agostinelli, et al.: Nucl. Instrum. Methods Phys. Res. A, 506 (2003), 250-303.