Study of Radiation Influence on Thermal Characteristics of Superconducting Magnets for High Intense Muon Beam Line

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論 文 名 ： Study of Radiation Influence on Thermal Characteristics of Superconducting Magnets for High Intense Muon Beam Line
(大強度ミューオンビームラインのための超伝導磁石の熱特性に対する放射線の影響に関する研究)

区　　分 ：甲

論 文 内 容 の 要 旨

Recently, a superconducting magnet that can be operated under a high radiation environment is required for high intense beam lines and accelerators. A conduction-cooled superconducting magnet system, where the aluminum-stabilized NbTi superconducting coil is conductively cooled by using pure aluminum strips as a thermal path, is desirable to minimize tritium production in helium loop and energy deposition due to the radiation by reducing the cold mass of the magnet. A Pion Capture Solenoid (PCS) for the COherent Muon to Electron Transition (COMET) muon beam line, which will be a conduction-cooled superconducting magnet in the high radiation environment is now under construction at J-PARC. The superconducting coil will be exposed by neutron flux of 10^{14} n/m^2/sec with a peak dose of 1 MGy and a total energy deposition in magnets will be more than 200 W. This means that the temperature distribution in the conduction-cooled coil is determined not only by the thermal design using pure aluminum strips but also by the energy deposition distribution due to the radiation. In addition, it is well known that thermal and electrical conductivities of aluminum used as a stabilizer and a thermal path in the coil can be degraded by neutrons at low temperature below 10 K. For this reason, it is seriously concerned that the coil temperature will be increased as the beam operation and that the quench protection scheme will be compromised. Consequently, the magnet system would have to be warmed up to room temperature so that thermal and electrical conductivities of aluminum can be fully recovered by the anneal effect.

In this thesis, a feasibility study on the stable operation of the conduction-cooled superconducting magnet for high intense muon beam line (COMET-PCS) regarding the coil temperature and the quench protection is performed by using a novel design method with a consideration of energy deposition in the magnet and degradation of the material properties due to the radiation.

Chapter 1 gives a motivation of this study. The coil structure of PCS and the radiation degradation effects on the materials utilized in the magnet are introduced.

In chapter 2, the neutron flux and the energy deposition in PCS is estimated by performing a Monte Carlo simulation for the studies in chapter 3 and 5. A detailed geometry of PCS and a magnetic field map calculated by a finite element method are implemented into the simulation.

Eventually, the total heat load and the peak of the neutron flux in the coil are estimated to be more than 200 W and 1.2×10^{14} n/m^2/sec, respectively. Spatial distributions of the neutron flux and heat load are found to be asymmetrical in the coil due to the tilted incident proton beam, thus the three-dimensional thermal and quench analysis are essential for the studies in chapter 3 and 5.

In chapter 3, a three-dimensional thermal analysis is performed to investigate the coil temperature rise during the beam operation. Firstly, spatial distribution of thermal conductivity in the coil degraded by the neutrons is estimated. Then, the coil temperature is calculated with the heat load profile due to the radiation. It is found that COMET-PCS can be operated for three months at most in view of the temperature margin decrease during the beam operation.

In chapter 4, radiation tolerance on thermal conductivity of a newly developed insulation tape is experimentally determined. A new insulation, bismaleimide-triazine prepreg tape, is employed to enhance the radiation resistance for PCS. To investigate the irradiation effect on the thermal conductivity, a measurement system is developed with a Gifford-McMahon cryocooler. The thermal conductivity is measured before and after the gamma ray irradiation. A heat-scan method is utilized to improve the measurement accuracy. With a detailed data analysis, no significant degradation on the thermal conductivity of the insulation tape is observed after the gamma-ray irradiation with a total dose up to 5 MGy.

In chapter 5, influence of the radiation on the magnet quench is analyzed. Firstly, a quench protection circuit is designed with a by-pass dump resistor to extract the stored energy. Then, a three-dimensional quench analysis implementing the radiation degradation of the thermal conductivity of the cooling paths as well as the electrical conductivity of aluminum stabilizer is performed. It is found that the magnet is capable of being protected even after a long-term operation. Additionally, it is shown that the novel method to insert the thermal path between the coil layers for enhancing the cooling performance also helps to reduce the coil temperature by accelerating the normal zone propagation.

In chapter 6, a conceptual design of a compact coil using a high temperature superconductor (HTS) is proposed as the first step for future high intense muon beam line. The conduction-cooled HTS coil is designed for operating at the same radiation environment as the COMET-PCS magnet but the operation temperature will be set around 20 K where very large thermal conductivity and heat capacity can be expected. It is shown that the HTS coil has a good thermal stability at operation temperature of 20 K and can be applied to the PCS in future high intense muon beam line with the large temperature margin.

Chapter 7 gives a conclusion of this thesis.