IRRADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS AT LOW TEMPERATURE

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Abstract

Superconducting magnets for high intensity accelerators and particle sources are exposed to severe radiation from beam collisions and other beam losses. Neutron fluence on the superconducting magnets for the near future projects of high energy particle physics, such as LHC upgrades and the COMET experiment at J-PARC, is expected to exceed 10^{21} n/m^2, which is close to the requirements on the fusion reactor magnets. Irradiation effects at low temperature in superconducting magnet materials should be reviewed to estimate the stability of the superconducting magnet system in operation and its life. The pion capture superconducting solenoids for the COMET experiment are designed with aluminum stabilized superconducting cable to reduce the nuclear heating by neutrons. Also, the heat is designed to be transferred in pure aluminum strips. Irradiation effects on the electrical conductance of aluminum stabilizer and other materials are tested at cryogenic temperature using the reactor neutrons. This paper describes the study on the irradiation effects for the magnet developments.

INTRODUCTION

Superconducting magnets are commonly used in the high energy physics experiments. The magnets near the proton target or the interaction point are exposed to the severe radiation. It is expected that neutron fluence on the magnets exceeds 10^{21} n/m2 and the dose reaches 1 MGy or higher in the operation life time of the next generation projects, such as a high luminosity upgrade of the LHC accelerator at CERN [1] and the muon source for the COMET experiment at J-PARC [2]. To estimate the irradiation effects in magnet materials in such a high radiation environment, R&D programs were started at KEK in cooperation with various institutes to develop radiation-hard superconducting magnets. This work is a part of the R&D programs for radiation-hard superconducting magnets.

A superconducting magnet consists of not only superconductor, but also stabilizer, insulator, glue, thermal conductor, thermosensor and other materials. Each component should be reviewed in the development of the radiation-hard superconducting magnet. First in this paper the conceptual design of the COMET pion capture solenoid magnet is shown to introduce the radiation environment of the superconducting magnet, then described are concerns on each magnet component. In the last section, preliminary results on the irradiation tests with reactor neutrons on stabilizer materials and other metals are reported.

COMET PION CAPTURE SOLENOID

Figure 1 shows the conceptual layout of the solenoid magnet systems of the COMET experiment, in which muon-to-electron conversion processes beyond the standard model are searched for. The experiment requires unprecedented intense muon beam on the stopping target made of aluminum foils. All the components are included in a series of superconducting solenoid magnets to keep the best transmission of muons and signal electrons. To produce the intense muon beam, the production target is embedded in a superconducting solenoid magnet, the Pion Capture Solenoid, to trap the pions in the strong magnetic field. The proton beam with the energy of 8 GeV is injected into the magnet bore from a space of solenoid coils with tilted by 10 degrees. To avoid the severe radiation particles from the production target, the target is surrounded by thick shielding of tungsten with the maximum thickness of 45 cm. The superconducting coil generates 5 T on the target and needs a large diameter of 130 cm to hold the shielding in its bore.

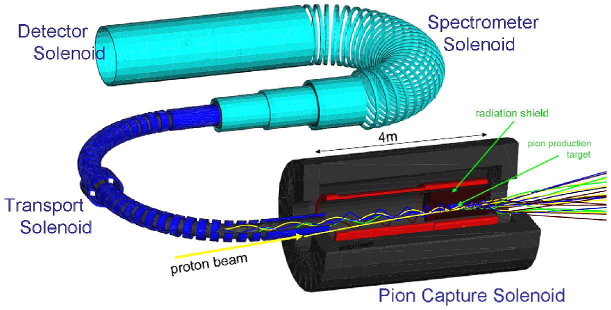

Figure 1: Layout of superconducting solenoid magnets for the COMET experiment.

To reduce the heating by radiation particles from the target, the aluminum stabilized superconductor is used for the Pion Capture Solenoid. The conductor has less mass keeping the mechanical strength against the electromagnetic forces, compared to the copper stabilized conductors. The solenoid magnets with aluminum stabilized superconductor are so far realized in the detector magnets, such as the ATLAS Central Solenoid [3]. The design parameters of the conductor for the COMET Pion Capture Solenoid are listed in Table 1.

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Table 1: Design Parameters of the Aluminum Stabilized Superconductor for the COMET Pion Capture Solenoid

Item	Value
Strand diameter	1.15 mm
Number of strands	14
Al/Cu/NbTi	7.3/0.9/1.0
Aluminum Residual Resistance Ratio	500 (B=0)
Copper Residual Resistance Ratio	50 (B=0)
Critical Current	15000 A (4.2 K, 5 T)
Yield Strength of aluminum stabilizer	85 MPa (4.2 K)

The irradiation on the coil is estimated by using the simulation codes, MARS [MARS]. The neutron fluence at the superconducting coil of the Pion Capture Solenoid exceeds 10^{21} n/m^2 for the experiment life time (10^{21} protons on the target). The maximum heat deposit in the coil is 0.02 mW/g. Total heat load by radiation particles is estimated to be 60 W in the magnet system. Irradiation effects in the magnet materials are discussed below.

IRRADIATION EFFECTS IN MAGNET MATERIALS

Superconductor

Irradiation effects in superconductor were investigated in the literatures, e.g. [4, 5]. Critical current density was measured after the neutron irradiation at room temperature or cryogenic temperature. They indicate the performance of superconductivity is kept up to the neutron fluence of 10^{22} n/m^2. Thus the superconductor in the COMET experiment does not affected by the radiation.

Stabilizer

Superconductor needs to be accompanied to metal with good conductance to achieve the stability in operation and to protect the coil against quench. Pure metals attached to superconductor as a stabilizer may show a degradation in electric conductance by neutron irradiation. The degradation of electric/thermal conductance is caused by Frenkel defects produced by the irradiation and possible defect concentrations by subsequent interactions. At low temperature, the defects are stable and the damage can be accumulated. Therefore it is important to investigate the irradiation effect on stabilizer at low temperature.

Irradiation effects in pure fcc metal at low temperature was investigated in past studies, e.g. [6, 7], where annealed pure metals were tested. It is shown that pure metals degrade in electric conductance by neutron irradiation with the fluence of 10^{20} n/m2 or higher. Although aluminum stabilizer material has internal transitions by cold work for high strength and is doped with additives to optimize the residual resistance at low temperature, it may have same tendencies for neutron irradiations. The effects are being investigated in our R&D program measuring the irradiation effects in practical metals for the actual stabilizers. The preliminary results of the irradiation tests are described in the following section.

Thermosensor

Temperature monitor in a superconducting magnet is important to find possible trouble in the cryogenic system and also investigating the possible instability or causes of quench. The CERNOX sensor is commonly utilized in the superconducting magnets. The irradiation effects in various thermosensors are checked for the LHC project [8]. In the report, they observed no significant drifts of the CERNOX sensor readouts at 1.6K with the neutron irradiation up to 10^{19} n/m^2. Further investigation is necessary for higher neutron fluence in the COMET experiment and other applications. Some hints are also indicated in our irradiation tests.

Insulator, Diode

Superconducting cables should be insulated and glued using organic materials. Usual insulator consists of polyimide film with epoxy resin. Irradiation can break the cross-linking in the polymer material, and then the sheer strength and other properties may degrade. Expoxy resins can be used in the radiation environment below 1 MGy. In severer radiation environment, radiation-hard resins, such as cynate ester and bismaleimide-triazine resin, should be employed.

As a thermal insulator, aluminum-coated polyimide film is proposed instead of polyethylene super insulator.

A diode for quench protection is one of the most sensitive parts in the radiation environment since it is a semiconductor product. Diodes easily degrades at a level of 1 kGy, thus they have to be placed apart from the cryostat.

IRRADIATION TESTS AT KUR

Irradiation effects in metal materials of stabilizer and thermal conductor are being investigated in our program. The samples are irradiated by the reactor neutrons at Low Temperature Lab. [9] of Kyoto University Research Reactor Institute (KURRI). A cryostat is attached to the reactor and the samples can be cooled down to 12 K during reactor operation by circulating cooled helium gas. The aluminum stabilizers cut from the prototype superconductor for the COMET experiment were tested [10]. The results indicate the degradation in electric conductance can be accumulated at cryogenic temperature and can recover from irradiation damage by thermal cycling to the room temperature. The observed neutron-induced resistivity in the stabilizer aluminum sample is 0.027 nΩm for the fast neutron fluence of 10^{20} n/m^2, which can be comparable to the original residual resistance. Therefore thermal cycling could be needed to recover the damages in operation life time of the COMET experiment.

Figure 2 shows the resistance changes in pure aluminum and copper samples during irradiation by the reactor neutrons, taken in Sep. 2011. The copper data indicates less sensitivity to the irradiation damages by a factor of 3, although the recovery by annealing at room temperature could not be perfect. Effects of iterative irradiation will be investigated in the coming experiments.

The temperature readout of the CERNOX sensor is also checked in the irradiation tests. A drift of the readout is observed during irradiation as shown in Figure 3, taken in Nov. 2011. By comparing the stable temperature at 12 K measured by thermocouple of Au(Fe)+Chromel, the CERNOX readout drifts by 2 K after irradiation of 2.6x10^{20} n/m^2. It corresponds to the resistance change of the sensor from 1.6 kΩ to 1.4 kΩ. It indicates that we cannot ignore the degradation of CERNOX sensors in the radiation with neutrons of 10^{20} n/m^2 or higher.

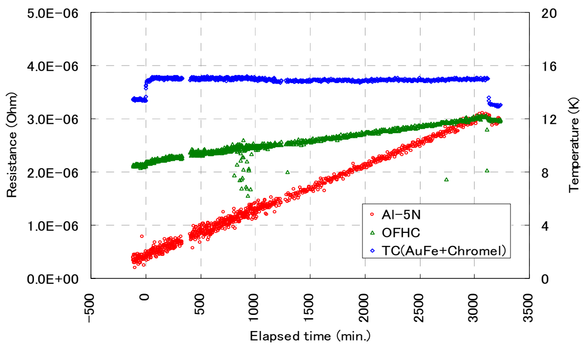

Figure 2: Resistance changes in pure aluminum and copper as a function of irradiation time.

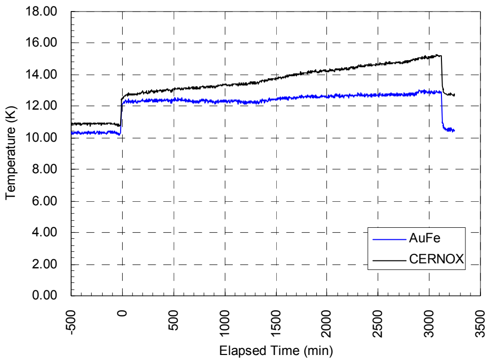

Figure 3: Temperature readout of the CERNOX sensor and thermocouple(AuFe) during neutron irradiation.

SUMMARY

As an R&D on the radiation-resistant superconducting magnet in KEK, irradiation effects in the magnet materials are being investigated in cooperation with various institutes. Especially degradation of the electrical and thermal conductance in stabilizer attached to the superconductor is concerned. Neutron irradiation tests are carried out using the research reactor at KURRI, and measured the degradation of aluminum, copper and the CERNOX temperature sensors. Effects of the iterative irradiation will be checked soon, and also irradiation tests on organic materials are planned in the near future.

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