Influence of neutron irradiation on conduction cooling superconducting magnets

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Abstract. The conduction-cooled superconducting magnets are now widely used in various applications due to their minimum usage of helium. In the accelerator science, they also play an increasingly important role in particle detector solenoids because they can minimize the materials needed for the magnet such that they can be more transparent against irradiated particles. For the same reason they are currently used in high radiation environments because they can reduce the heat load from the irradiation. However, the hadronic reactions, such as neutron or proton irradiation, can create degradation on the thermal conductivity of pure aluminum which is used as a cooling path. It leads to a poor cooling condition of the magnets. In Japan, there are two conduction-cooled superconducting magnets for muon production; one is already constructed and under operation, the other is now under construction. This paper briefly reports the influence of the irradiation on those magnets and discusses the possibilities of HTS based conduction-cooled magnets under high irradiation environments.

1. Introduction
Conduction-cooled superconducting magnets are now widely used for various applications. The magnets are utilized on various muon beam lines on which the magnet may be subjected to high irradiation. In Japan there are two conduction-cooled superconducting magnet systems for muon production; one is the system for COMET\textsuperscript{[1]} which is under construction at J-PARC, and the other is under operation at Osaka University RCNP.

The magnet system for COMET contains a 4 m long solenoids with a diameter of 1.3 m which surround a production target (figure 1). A high intensity proton beam with a beam power of 56 kW will be injected to the target and estimated maximum irradiation to the solenoid is about 30 mW/kg and $10^{16}$ neutrons/m$^2$/sec. Since the target is placed under the solenoid field, secondary charged particles such as muons and pions (that decay to muons) can be efficiently captured by the magnetic field. Such solenoids are called either pion capture solenoid or muon production solenoid. In the COMET muon production solenoid, the overall heat input from the irradiation is estimated to exceed 60 W such that the magnet must be cooled by a large helium refrigerator.

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The other muon production solenoid at Osaka University, called MuSIC [2], contains a target that receives 0.4 kW proton beam (figure 2). The maximum irradiation heat density is estimated to about 1 mW/kg and total heat deposit in the coil is 1 W. The solenoid is cooled by 3 GM refrigerators with the total cooling power of 4 W at 4 K.

Both magnets are designed with NbTi superconductor and must be cooled to around 4.2 K. The conduction cooling technology is employed because it can eliminate the helium vessel, such that
minimize the amount of weight of the cold mass structure. Since the total heat load to the cold mass can be proportional to its weight, less cold mass has obvious advantage. Another merit of the conduction-cooled magnet is that it can minimize an amount of helium that is irradiated by neutron. Neutron irradiation to helium can create tritium, which creates non-trivial complications for refrigerator maintenances. Both muon production solenoids are designed with a large aperture to accommodate a thick radiation shield inside the bore to reduce the radiation as well as the heat input to the coils.

1.1. Influence of irradiation on LTS based conduction cooled superconducting magnets

Despite the fact that the conduction-cooled superconducting magnet has apparent merits to use under high radiation condition, there are some disadvantageous influences by irradiation especially on LTS(NbTi) based conduction-cooled magnet. Many of the conduction-cooled magnets utilize very high purity aluminum with RRR higher than 2000 as thermal conductors. In figure 3 thermal conductivity of pure aluminum with various RRR is plotted as a function of temperature for a magnetic field of 3.5 T, taking into account magnetoresistivity at a magnet field of 3.5 T. An LTS magnet should be cooled to around 4 K because its current sharing temperature is around 6 K. On the other hand, the thermal conductivity of the aluminum is reduced significantly compared to its peak around 20 K. These facts require a good RRR on thermal conductor aluminum. It is known that irradiation of hadron such as neutron introduces a degradation of electrical conductivity. Ref. [7] shows the electrical resistivity measurements with an fast neutron irradiation by a reactor with a flux of $1.4 \times 10^{11}$ neutron/m$^2$/sec at a temperature around 15 K. Increase of the electrical resistance of aluminum is about 0.03 nΩ·m for $10^{20}$ neutrons/m$^2$ irradiation. The effect may introduce a serious consequence in a conduction-cooled magnet. For instance, in the COMET muon production solenoid after 280 days of operation, some part of the pure aluminum thermal conductor can degrade to RRR of 40 resulting an insufficient cooling condition. Fortunately, in case of aluminum the electrical conductance, as well as thermal conductance will be recovered perfectly after a thermal cycle to the room temperature. For the COMET muon production solenoid, the magnet is designed to withstand the degradation down to RRR of about 200 and planned to be thermal cycled by every 1-2 months. The COMET cryogenics are designed such that thermal cycle may be done within 20 days.

Another issue associated with an LTS based conduction-cooled magnet is a quench. For the muon production magnet irregular beam can be induced to the target that may cause a larger heat deposit. In case of COMET, there is a possibility to have about 180 KJ beam to the target instantaneously. This may result in instant heat deposit of about 100 mJ/kg. This may cause an instant temperature rise of about 0.5 K in the coil because of the low specific heat of conductor at low temperature. This is not critical for COMET operation without the thermal conductivity degradation but may cause quench after degradation.

![Figure 3. Thermal conductivity of pure aluminum.](image-url)
To accommodate those two effects, both solenoids must have large aperture to implement a thick radiation shield. This may be significantly eased if HTS conductor can be used and operated in a higher temperature such as 20 K. An HTS based compact muon production solenoid is considered and its advantages are reviewed.

2. Conceptual design of the compact HTS base pion capture solenoid

The design overview of an HTS based muon production solenoid is shown in figure 4. The HTS coil, of which overall length is about 340 mm, are made from 34 double pancake coils with an inner diameter of 340 mm. Each pancake coil is wound from ReBCO coated conductor of which size is 0.1 mm thick and 4 mm wide with 25 μm polyimide insulation wrapped around the conductor. The number of turns in each coil is 166 turns resulting to about 25 mm thick coil. In between each double pancake thermal conductor of a 1.9 mm thick pure aluminium sheet, which is thermally linked to an aluminum shell of 10 mm, is installed. An operation current of the coil is 105 A resulting to a central field of about 3 T. The maximum field parallel to the conductor surface is about 3.5 T and that vertical to the conductor surface is about 2.5 T. A critical temperature of the coil is estimated to a temperature higher than 50 K [8]. The outer shell of the coil is directly cooled to 20 K by a cryocooler, which provides a refrigeration power of about 10 W at 20 K.

The muon production target is made of graphite with a length of 300 mm and a diameter of 40 mm. Between target and the HTS coil a tungsten alloy radiation shield with an outer diameter of 300 mm and maximum thickness of 50 mm is installed. The other magnet system will be connected to the muon production solenoid to extract a muon beam. Proton beam should be tilted by 12° to be injected from a gap of the magnet system. The tilted injection has a benefit to result in more muon yield by around 10 %, while the radiation particles and effect of the irradiation have asymmetric distributions in the muon production solenoid.

3. Normal Operation mode

To estimate the irradiation effects, assuming the production target is hit by 8 GeV 3 kW proton beam, energy deposition and displacement per atom (DPA) are calculated by using Monte Carlo code, PHITS[9] without magnetic field. DPA is a coefficient that indicates the displacement degradation of material by reactions with particles (neutron, proton, etc.). All following results are simulated with
JAM_INCL4.6 hadronic cascade model and nuclear library of JENDL4.0 is included for the neutron interaction below 20 MeV. Furthermore, the cut off energy of all particles are setup below 0.1 MeV.

3.1. Irradiation estimation

In the PHITS simulation to estimate the irradiation superconducting coils are considered as a stainless steel cylinder with an inner diameter of 340 mm and with a thickness of 25 mm. The cylinder is divided into 4 pieces along the solenoid axis. Aluminium sheets with a thickness of 2 mm are inserted in between each cylinder and attached to the both ends to calculate DPA in aluminium cooling path. The simulation is made assuming the proton beam hitting the target center. Simulation results are shown in figure 5 as a heat deposition distribution in the coil. The coil is divided into 4 segments in azimuth, and the results are shown for each azimuthal segment. The origin of the azimuth angle is defined at the coil location close to the exiting proton beam, where the irradiation is most severe in the coil. The peak energy deposition is estimated about 0.43 W/kg and the overall heat deposition to the coil is about 7.1 W. The maximum DPA on the aluminum is estimated to about $1.3 \times 10^{-11}$ DPA/sec. An increase of electrical resistivity is proportional to DPA that is about $0.07 \, \text{n}\Omega \cdot \text{m}$ for $10^{-5}$ DPA[10]. For 5000 hours operation the integrated DPA is $2.3 \times 10^{-5}$ that results in degradation of RRR from 2000 to about 130.

![Deposit energy distributions in HTS coil in the unit of Gy/sec (=W/kg).](image)

**Figure 5.** Deposit energy distributions in HTS coil in the unit of Gy/sec (=W/kg). Horizontal axis indicates the axis of HTS solenoid, and vertical is the radius from the solenoid axis. Each plot corresponds to the distributions in a coil region segmented by 90° in azimuthal angle.

3.2. Thermal computation

The thermal computation are made with a thermal conduction model that solve the equation below.

$$\gamma C \frac{dT}{dt} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + W$$  (1)

where $\gamma$, $C$, $k$, and $W$ are density, specific heat, thermal conductivity, and heat deposit. Longitudinally the model is divided in each double pancake coil that is thermally connected to the 1.9mm thick aluminium thermal conductor through the 25 μm polyimide insulation. Each pancake coil is divided into 6 cells radially and is assumed to have a thermal conductivity equivalent to a series of stainless steel, copper and polyimide with the thickness ratio of 6:4:5. For the longitudinal and azimuthal thermal conductivity the stainless steel thermal conductivity is used. For faster computation all the conductivity is fixed for 18 K value. For the aluminium thermal conductor, taking into account the degradation by irradiation estimated above and an uncertainty of the estimation, the RRR of 40 is used for the thermal computation.
The heat deposition distribution shown in figure 5 is used for heat input to each cell. For the boundary condition the coil outer shell temperature is fixed to 20 K. The computation is made starting from the base temperature of 20 K and then continuously input the heat deposit until the model becomes thermal equilibrium. This coil is expected to reach the thermal equilibrium after 5 minutes beam operation. The temperature profile after the equilibrium is shown in figure 6. The maximum temperature is about 21.6 K well below the critical temperature of the coil.

![Temperature distributions in the HTS coil.](image)

**Figure 6.** Temperature distributions in the HTS coil. Each plot corresponds to the distributions in a coil region segmented by 90° in azimuthal angle.

4. Accidental Fast Extraction Beam
As discussed in Chapter 1, there are some possibilities of irregular beam extraction that may cause a large heat deposit to the coil instantaneously. Even if the synchrotron is used with slow extraction beam there are always some risks of having irregular time structure in the beam extraction. The worst case is the beam extraction similar to the fast extraction, i.e. all the beam stored in the synchrotron ring is extracted at once. In such case the instant beam power can be as large as average beam power multiplied by synchrotron operation cycle. For instance if the operation cycle is 10 sec with the average beam power of 3 kW, the instant beam power is 30 kJ. In such case heat deposit to the coil can be the 10 times of the heat deposit described in Chapter 3, and the maximum heat deposit is about 4.3 J/kg. Taking into account the copper specific heat of about 7 J/kg/K at 20 K the temperature rise is only 0.8 K. (Stainless steel, which is a half content of conductor, has higher specific heat than copper.) Since the coil critical temperature is excessively high, around 50 K, such beam extraction will not cause quench to the coil.

5. Discussion
The results reported in Chapter 4 indicate that HTS based muon production solenoid has great advantage on thermal performance. For the normal operation condition even though the RRR of the thermal conductor aluminum is 40 and the maximum heat deposit is 0.43 W/kg that is more than ten times higher than that of COMET the temperature rise is only about 1.6 K. This is mostly due to the fact that thermal conductance at 20 K is much higher than that at 4 K as shown in figure 3. For the accidental beam it was confirmed that temperature rise of the coil is only about 0.8 K because of higher specific heat at 20 K. Combining the very large temperature margin of the HTS coil, above results indicate that the coil has very little risk of a quench or a thermal runaway.

The design parameter of the coil may be optimized, for example higher operation current for shorter conductor length (i.e. less expensive) or for a higher magnetic field (i.e. higher muon yield) may be considered. On the other hand one should consider more severe accidental beam such at beam...
directly hit the radiation shield should be considered depending on the beam operation condition. Since a quench protection of the HTS coil is difficult especially with higher current density, the optimization should be made deliberately. The other optimization may be made for the radiation shield that is currently 50 mm thick tungsten alloy. Thinner tungsten or use of copper instead of tungsten may be considered. This consideration may be allowable in terms of the thermal design. However, even with the current design accumulated radiation dose after 5000 hour operation corresponds to 10 MGy. The number is already marginal for many of the organic materials. Even if the organic materials which has good performance against radiation, such as polyimide or cyanate ester, are used it may withstand up to around 50 MGy. The margin is not large in any case, and it indicates that organic material degradation is more severe than the thermal design for HTS based coil with high operation temperature. One should consider the structure without organic materials, since the muon production solenoid can be used for DC operation, stainless steel insulation design [11] may be a choice.

6. Conclusion
An HTS based conduction-cooled compact muon production solenoid with 3 T central field and 20 K operation temperature was designed and evaluated for the influence of neutron irradiation as well as irradiation by other particles. The evaluation indicated that the thermal design is very robust for 20 K design because of higher thermal conductivity of thermal conductor aluminum as well as higher specific heat of coil materials. Degradation of organic materials used as insulator may be the biggest issue and non-organic material structure should be considered for such magnets.

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