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# Influence of neutron irradiation on conduction cooling superconducting magnets

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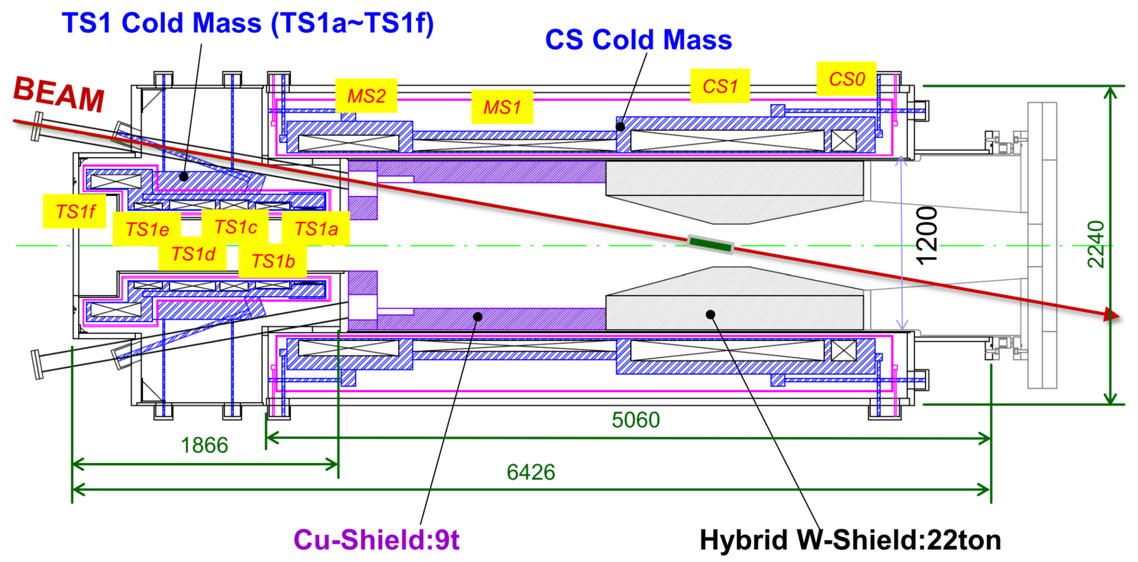
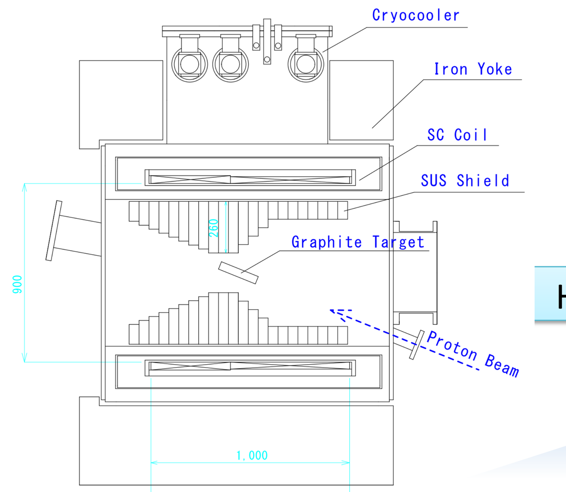
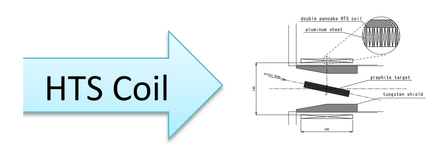
**Abstract.** The conduction cooling superconducting magnets are now widely used in various application because of their minimum usage of helium. In the accelerator science field, they are also widely used for particle detector solenoids because they can minimize the materials needed for the magnet such that they can be more transparent against irradiated particles. For the same reason they are now used at irradiation environments because they can reduce the heat load due to the irradiation. However, the hadronic irradiation, such as neutron irradiation, can degrade thermal conductivity of pure aluminum that are used as thermal conductor. This leads to a pure cooling condition of the magnets. In Japan, there are two conduction cooling superconducting magnets used as muon production solenoid; one is already built and under operation, the other is now under construction. The paper briefly introduces the influence of the neutron irradiation on those magnets. And then it discusses the possibilities of HTS based conduction cooling magnets under high irradiation environments.

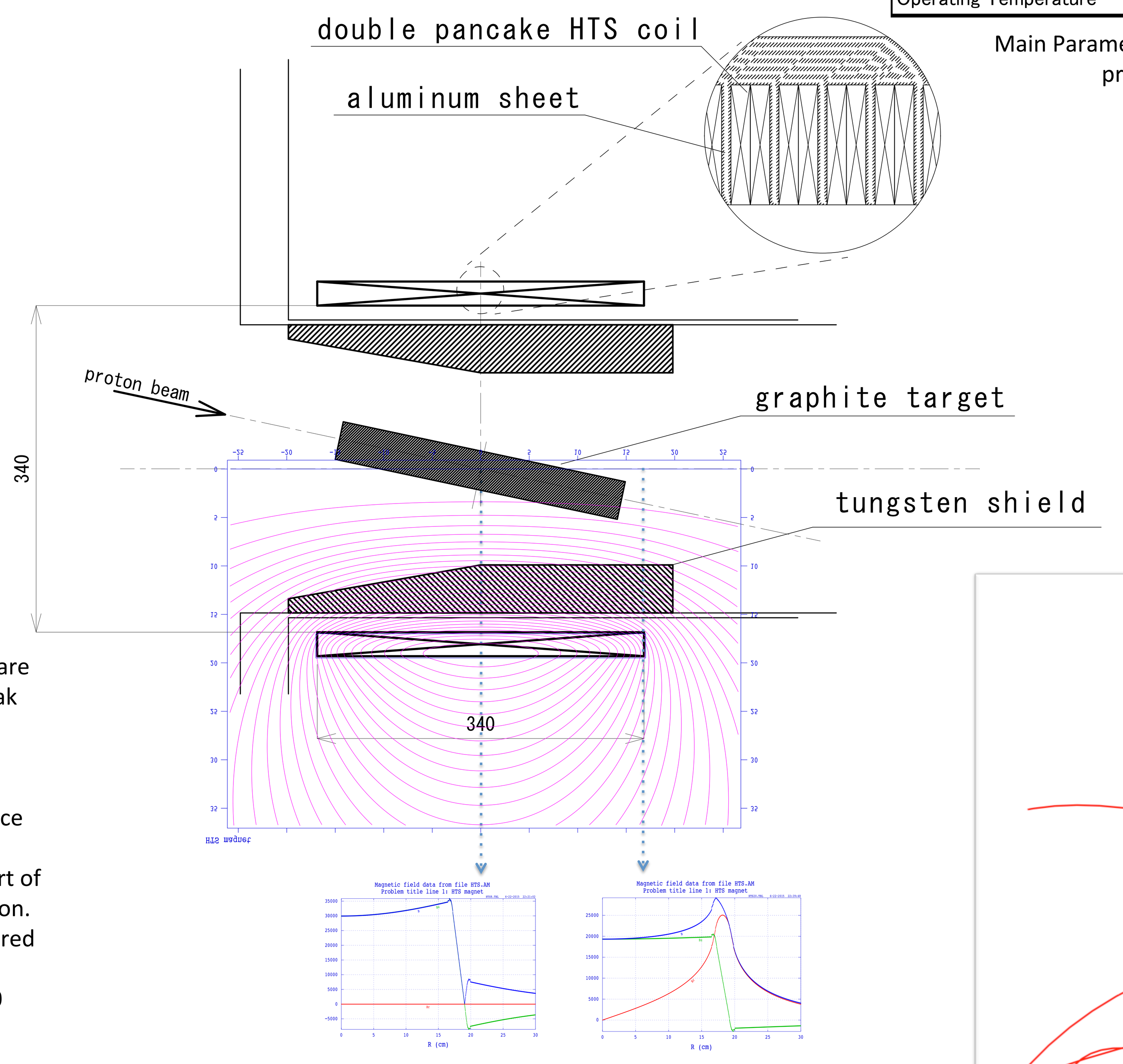
LTS based muon production solenoids are designed with a large aperture that can accommodate a thick irradiation shield inside of the bore. They are needed to reduce the irradiation as well as the heat input to the SC coils.



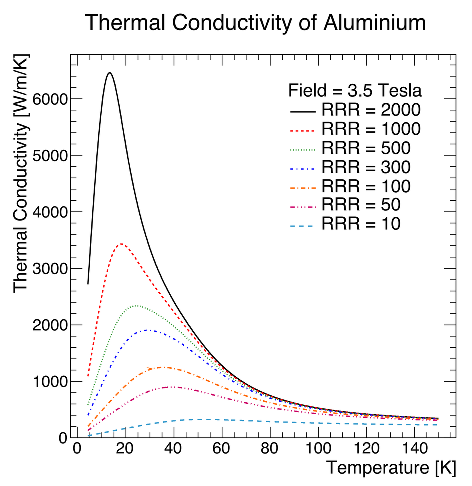

HTS based compact muon production solenoid

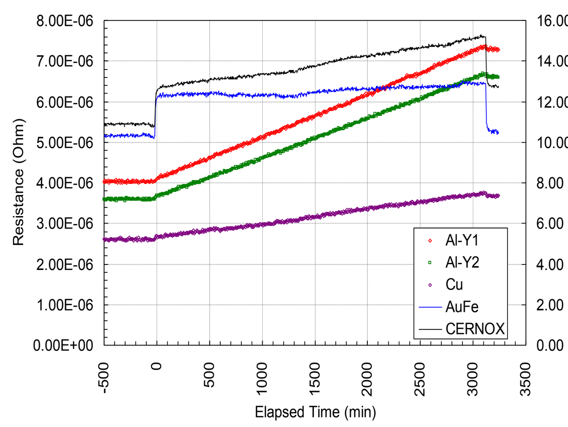



| | |
|---|---|
| Conductor | ReBCO coated conductor |
| Coil inner diameter | 340 mm |
| Coil length | 340 mm |
| Coil length (double pancake) | 10 mm (including Al sheet) |
| Num. of pancake coils | 68 (34 double pancake coils) |
| Avg. current density | 140 A/mm2 |
| Max. field on axis | 3T |
| Max. field on conductor | 3.5T |
| Operating Temperature | 20K |

Main Parameters of the HTS based muon production solenoid



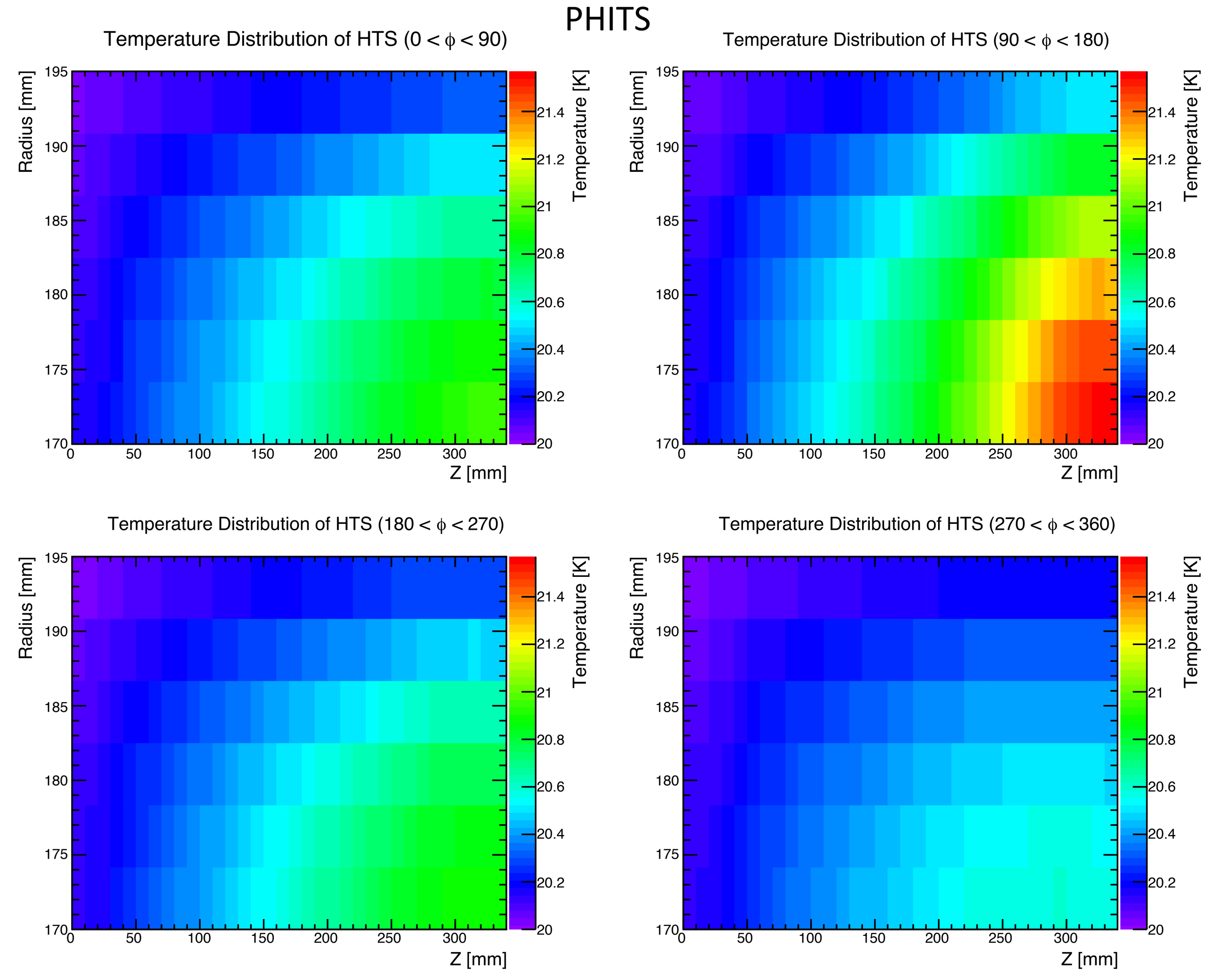



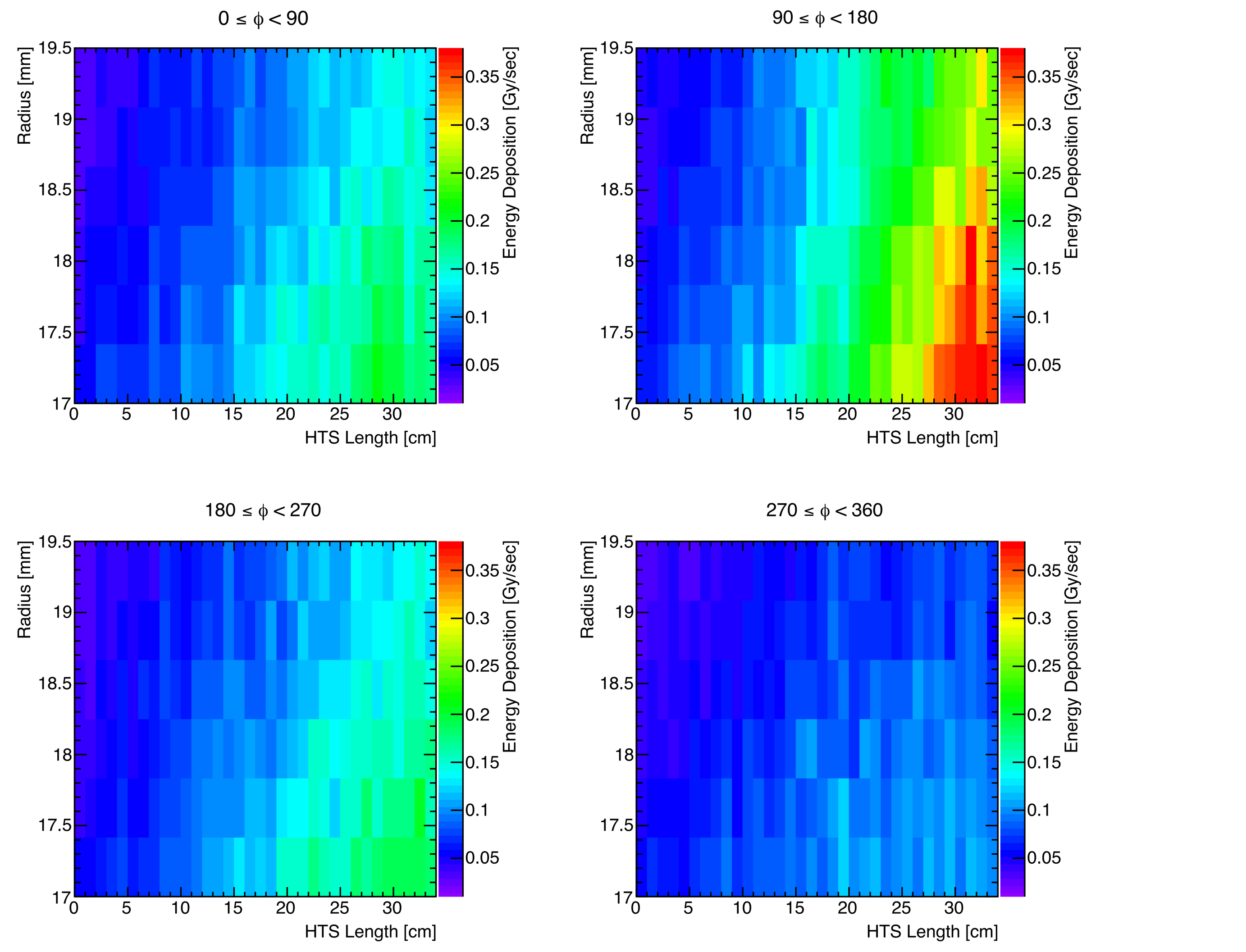

Many of the conduction cooling magnets utilize very high purity aluminum with RRR better than 2000 as thermal conductors. Thermal conductivity of pure aluminum with various RRR is plotted as a function of temperature (above left). LTS magnets should be cooled to around 4 K because their critical temperatures are around 6 K. On the other hand, thermal conductivity of the aluminum is reduced signify compare to its peak values 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. An electrical resistivity measurement with a irradiation of reactor base fast neutron of $1.4\times10^{11}$ neutron/m2/sec at a temperature around 15 K is shown (above right). The plot clearly shows a increase of the electrical resistance and the value is about 0.03 nΩ•m for $10^{20}$ n/m$^2$ neutron irradiation. The effect may introduce a serious consequence. For instance for the COMET muon production solenoid, after 280 days of operation some part of the pure aluminum thermal conductor can be degraded to RRR of 40 resulting a insufficient cooling condition. Fortunately, in case of aluminum the electrical conductance, as well as thermal conductance will be recovered 100 % after room temperature thermal cycle. For the COMET muon production solenoid the magnet is designed to withstand the degradation upto RRR of about 200 and planed to be thermal cycled by every 30 days. The COMET cryogenics are designed such that thermal cycle maybe done within 20 days.

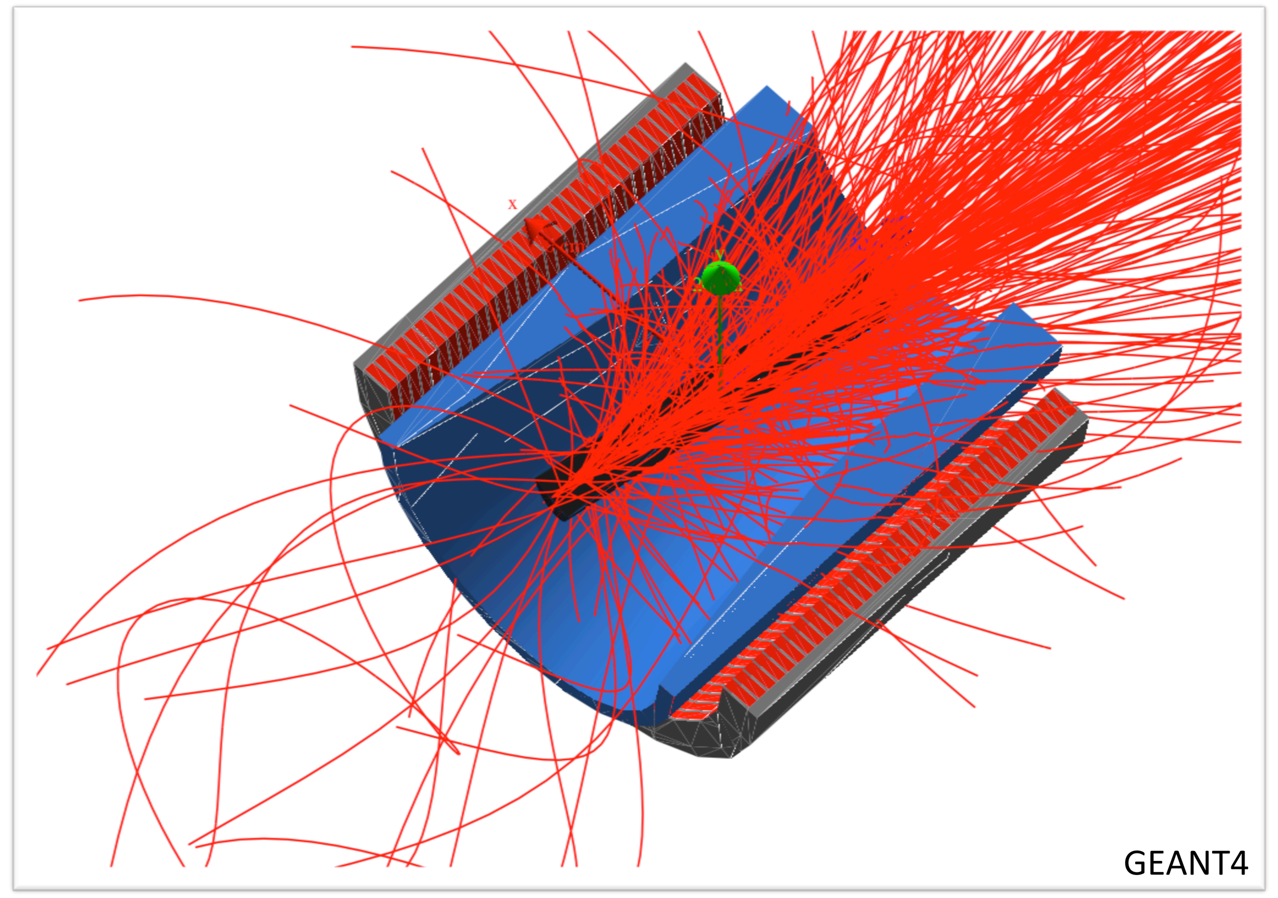
The HTS coil, of which overall length is about 340 mm, are made from 34 double pancake coil with an inner diameter of 340 mm. Each pancake coil is wound from ReBCO coated conductor of which size is 0.1 mm thick and 4 mm wide with 25 μm polyimide insulation wrapped around the conductor. The number of turns of the coil is 166 turns resulting to about 25 mm thick coil. In between each double pancake a 1.9 mm pure aluminium thermal conductor, which are thermally link to a aluminium 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. The outer shell of the coil is directly cooled to 20 K by a cryocooler, which provides about a refrigeration power of 10 W at 20 K.
The muon production target is made from carbon and is 300 mm long and 40 mm diameter. In between target and the HTS coil a tungsten radiation shield with a outer diameter of 250 mm and a maximum thickness of 50 mm is installed.

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, without magnetic field. DPA is a coefficient that indicates the displacement degradation of material by irradiation of particles (neutron, proton, etc.). All following results are simulated with JAM_INCL4.6 hadronic cascade model, and nuclear library (JENDL 4.0) is included for the neutron interaction under 20 MeV. Furthermore, the cut off energy of all particles are setup below 0.1 MeV.
For the PHITs simulation coil is considered as 25 mm thick 340 mm diameter copper ring. The coil is express as three 99 mm long ring and one 39 mm ring. In between each ring as well as the both ends, 2 mm thick aluminium is attached to simulate the DPA of the aluminium. The simulation is made assuming the proton beam hitting the target centre.

PHITS




Longitudinally the model is divided in each double pancake coil that are thermally connected to the 1.9 mm aluminium thermal conductor through the 25μm polyimide insulation. The pancake coil is divided into 6 cells radially and thermal conductivity equivalent the thickness ratio of 6:4:5 for stainless, copper, and polyimide is used. For the longitudinal and angular thermal conductivity the stainless steel thermal conductivity is used. For the faster computation all the conductivity is fixed for 18 K value. For the thermal conductor aluminium, taking into account the irradiation degradation discussed above, the RRR of 50 is used for the thermal computation.

**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 as bad as 40. This is mostly due to the fact that thermal conductance at 20 K is much higher than that of at 4 K. 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). On the other hand one should consider more severe accidental beam such as beam directly hit irradiation shield should be considered depending the beam operation condition. Since a quench protection of the HTS coil maybe very difficult especially with higher current density, the optimization should be made deliberately.
The other optimization may be made for the irradiation shield that is currently 50 mm thick tungsten. Thinner tungsten or use of copper instead of tungsten may be considered. These consideration maybe allowable in terms of the thermal design. However, even with the current design accumulated irradiation doze after 5000 hour operation corresponds to 10 MGy. The number is already marginal for many of the organic materials. If only radiation hard organic materials, such as polyimide or cyanate ester, are used it may withstand up to 50 MGy. The margin is not large in any case, and it indicates that for HTS based coil with high operation temperature organic material degradation is more severe than the thermal design. One should consider the structure without organic materials, such as mineral insulation scheme. Since the coil can be used for DC operation, non-insulation designs maybe the other choice.

**Conclusion**

An HTS based conduction cooling compact muon production solenoid with 3T central field and 20 K operation temperature was designed and evaluated for the influence of neutron irradiation as well as other irradiations. 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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