# DEVELOPMENTS OF HTS MAGNETS AT RCNP

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*Abstract*

At RCNP, we have been developing magnets utilizing high-temperature superconducting (HTS) wires for this decade. We built three model magnets, a mirror coil for an ECR ion source, a set of coils for a scanning magnet and a super-ferric dipole magnet to generate magnetic field of 3 T. They were excited with AC/pulse currents as well as DC currents. Recently we fabricated a cylindrical magnet for a practical use which polarizes ultracold neutrons. It consists of 10 double pancakes and the field strength at the center is larger than 3.5 T which is required to fully polarize 210 neV neutrons. It was successfully cooled and excited. One dipole magnet is under fabrication which is used as a switching magnet after the ring cyclotron and is excited by pulse currents. It becomes possible to deliver beams to two experimental halls by time sharing.

## INTRODUCTION

High-temperature superconductor (HTS) materials were discovered in 1986 [1]. Significant efforts went into the development of new and improved conductor materials [2] and it became possible to manufacture relatively long HTS wires of the first generation [3]. Although many prototype devices using HTS wires have been developed, so far these applications have been rather limited in accelerators and beam line facilities [4].

At the Research Center for Nuclear Physics (RCNP) of Osaka University, we started to investigate the performance of HTS wires applied for magnets excited by alternating (AC) and pulsed currents as well as direct current (DC) more than ten years ago. We have fabricated three types of prototype magnets. They are a cylindrical magnet [5], a scanning magnet with race-track shape coils [6] and a super-ferric dipole magnet [7]. The coil of the dipole magnet has a negative curvature and the magnet successfully generated the field higher than 3 T at operating temperature of 20 K. Recently, we fabricated a cylindrical magnet for a practical use which polarizes ultracold neutrons. At RCNP, we have been developing a superthermal ultracold neutron (UCN) source to search for the neutron electric dipole moment (nEDM) [8,9]. The critical energy of UCN from the RCNP source is 210 neV which is determined by the Fermi potential of the He-II bottle. The neutron magnetic potential is 60 neV/T. Then the magnetic field is required to be larger than 3.5 T in order to fully polarize UCNs from the source. We decided to apply HTS wires for a practical use after our developments on HTS magnets. One dipole magnet is under fabrication now. The magnet is used as a switching magnet after the ring cyclotron and is excited by pulse currents. It becomes possible to deliver beams to two experimental halls by time sharing.

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## 3 T DIPOLE MAGNET

In order to investigate feasibilities of synchrotron magnets using HTS wire, we have built a super-ferric dipole magnet to be operated by lumping currents. The specification of the magnet is summarized in Table 1.

Table 1: Design Parameters of the HTS Dipole Magnet

| | | |
|---|---|---|
| Magnet | Bending radius | 400 mm |
| | Bending angle | 60 deg. |
| | Pole gap | 30 mm |
| Coils | Number of turns | 600 x 2 |
| | Winding | 3 Double pancakes/coil |
| | Temperature | 20 K |
| | Rated current | 300 A |

The HTS wire consists of a flexible composite of Bi-2223 filaments in a silver alloy matrix with a thin stainless steel lamination that provides mechanical stability and transient thermal conductivity. The wire, DI-BSCCO Type HT-SS, was supplied by Sumitomo Electric Industries, Ltd. [10]. The wire is 4.5 mm wide and 0.3 mm high in average. Upper and lower coils consist of 3 double pancakes of 200 turns. Critical current Ic of wire measured at 77 K and self-field was higher than 160 A. Ic values of double pancakes were 60-70 A at 77 K. After stacking, they were 47 A and 51 A for the upper and lower coil, respectively. There were no damages in wire during winding process. Stacked pancakes are sandwiched by ion plates to reduce magnetic fields on the wire surface, since the Ic is lowered by fields on surface. Figure 1 shows the lower coil which has a negative curvature inside.

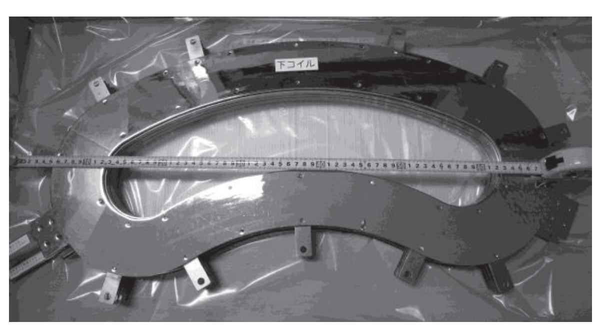


Figure1: Lower coil of the dipole magnet.

Figure 2 shows the assembled cold mass consisting of poles and coils. Coils are fixed to poles to withstand the radial electro-magnetic expansion force of 100,000 N/m. Poles are fabricated by stacking 2.3 mm thick carbon steel plates. Plates were bent before stacking, welded to form a pole and finally annealed to remove the stress. The weight of coils, poles and the total cold mass is 56, 90 and 250 kg, respectively. The magnet was successfully excited with the DC current of 300 A. The magnetic fields were measured in the median plane and were consistent with design values. It was also excited with pulsed current with the rising speed of 100 A/s which corresponds to 1 T/s.

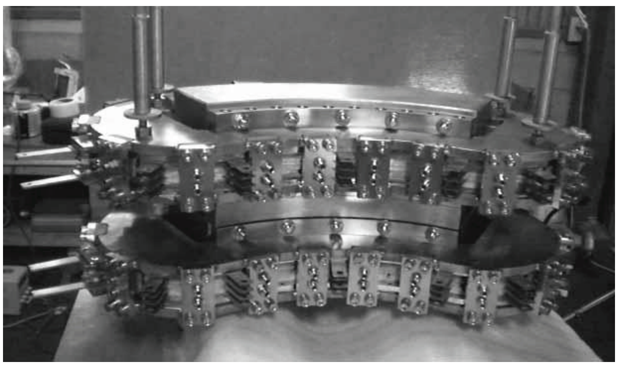

Figure 2: Assembled 3 T dipole magnet.

## CYLINDRICAL MAGNET

Design parameters of the cylindrical magnet are summarized in Table 2. The HTS wire is DI-BSCCO Type H of SEI. It has no stainless steel laminations and is 0.23 mm thick. The magnet is built by stacking ten double pancakes and fixing them on a bobbin made of stainless steel. The total length of HTS wire is 1530 m. Figure 3 shows a cross sectional structure of the upper half of the magnet. The operating temperature is expected to be 20 K and the magnetic field should be higher than 3.5 T.

Table 2: Design Parameters of the HTS Cylindrical Magnet

| | | |
|---|---|---|
| Coil | Inner diameter | 131.5 mm |
| | Outer diameter | 213 mm |
| | Length | 105 mm |
| | Number of DP | 10 |
| | Number of turns | 2800 |
| | Total length of wire | 1530 m |
| | Inductance | 1 H |
| | Weight | 30 kg |
| Magnet | Operating Temperature | 20 K |
| | Rated current | 200 A |
| | Field at the center | 3.5 T |
| Cryostat | Cooling power | 35 W at 45 K<br>0.9 W at 4 K |
| | Temperature of the shield | 60 K |

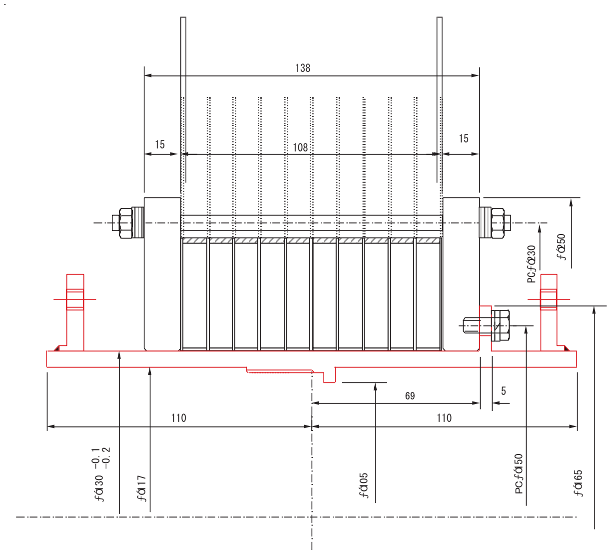


Figure 3: A cross sectional structure of the upper half of the cylindrical magnet. Each double pancake is sandwiched by 1 mm thick cooling plates made of copper.

The Ic of the HTS conductor depends on the operating temperature and the magnetic field at its surface. The magnetic field $B_{\perp}$ perpendicular to the conductor has larger effects on Ic than the horizontal field component. Before winding, the Ic of the wire over the full length was measured at 77 K in a 10 m pitch and found to be about 147 A corresponding to an electric field amplitude of 0.1 μV/cm. The Ic values of the coils were estimated from the Ic ( $B_{\perp}$ ) characteristics of the tape conductor and a magnetic field analysis using the finite element code TOSCA. In the present design, the maximum field is 3.5 T at the center and the maximum field perpendicular to the tape surface is estimated to be 2.8 T. From the temperature dependence of the I( $B_{\perp}$ ) characteristics, the Ic value was estimated to be 256 A at 20 K. The Ic of wounded coil was measured at 77 K and was 25 A. It is higher than the design value 20 K. Figure 4 show the result of the Ic measurement at 77K. Figure 5 shows the coil fixed to the stainless steel bobbin

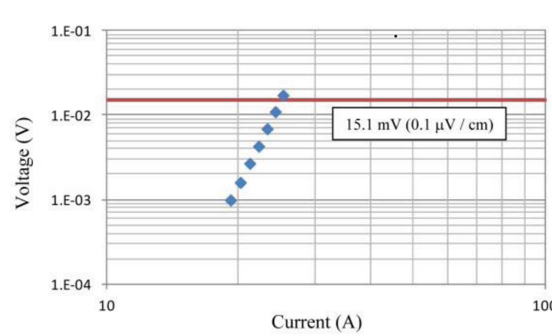


Figure 4: Results of Ic measurement at 77 K. The total length of wire is 1530 m.




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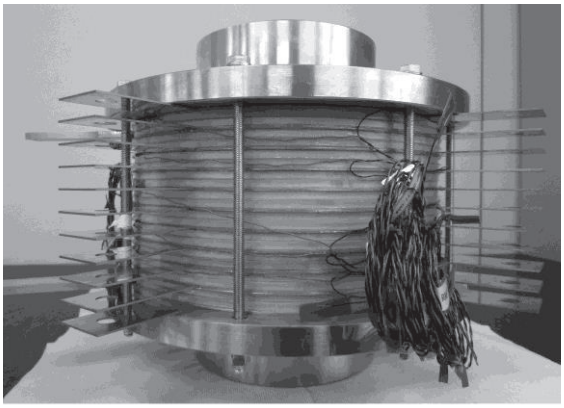

Figure 5: Stacked coils fixed to the bobbin.

The coil is installed in a cryostat which is covered by a magnetic shield made of 25 mm thick soft steel plates. The coil is covered by a thermal shield and 10 layers of super-insulation. The coil is cooled by a pulse tube cryocooler, RP-082B2S from Sumitomo Heavy Industries, Ltd. [11]. The shield and power leads are connected to the first stage whose cooling power is 35 W at 45 K. The coil is connected to the second stage whose cooling power is 0.9 W at 4 K. The coil is cooled down to 13 K in 36 hours from the room temperature, which is lower than designed value of 20 K. The equilibrium temperature of the shield is about 60 K. The energy deposit form two power leads is estimated to be 14 W and is consistent with measurements.

Magnetic fields on axis were measured using Hall probe. A warm bore was installed for the measurement. Figure 6 shows the excitation results. At 200 A, the field was about 3.75 T which is higher than the expected strength 3.5 T. Figure 7 shows the field distribution along the axis. The calculated values are normalized to the measured field at the center. The measured value is larger than the calculation by 3.5%.

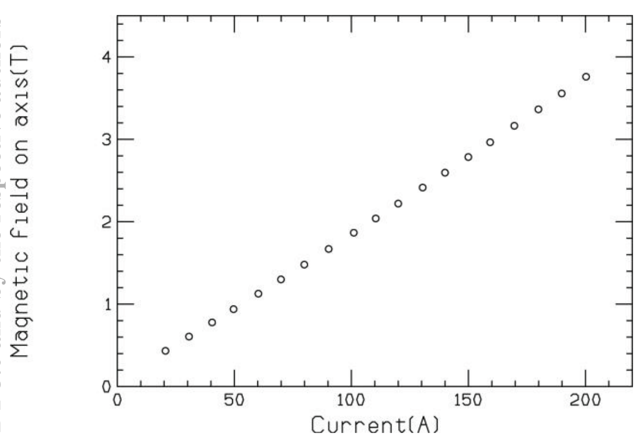


Figure 6: Excitation results of the fabricated magnet.

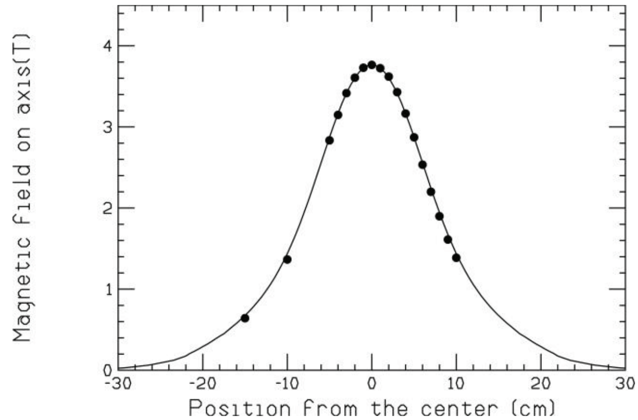


Figure 7: Field distribution along the axis. the solid line shows results of the numerical simulation by TOSCA.

## SUMMARY

At RCNP, we have developed HTS magnets for this decade. Recently we fabricated a cylindrical magnet for a practical use which polarizes 210 neV ultracold neutrons. The coil cooled by a pulse tube cryocooler to 13 K in 36 hours. The field strength was measured to be 3.75 T at the center which is larger than the requirement, 3.5 T. One dipole magnet is under fabrication now. It will be used as a switching magnet after the ring cyclotron and enable to deliver beams to two target positions by time sharing.

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