Excitation and Magnetic Field Performances of a Prototype REBCO Sextupole Magnet at 4.2 K

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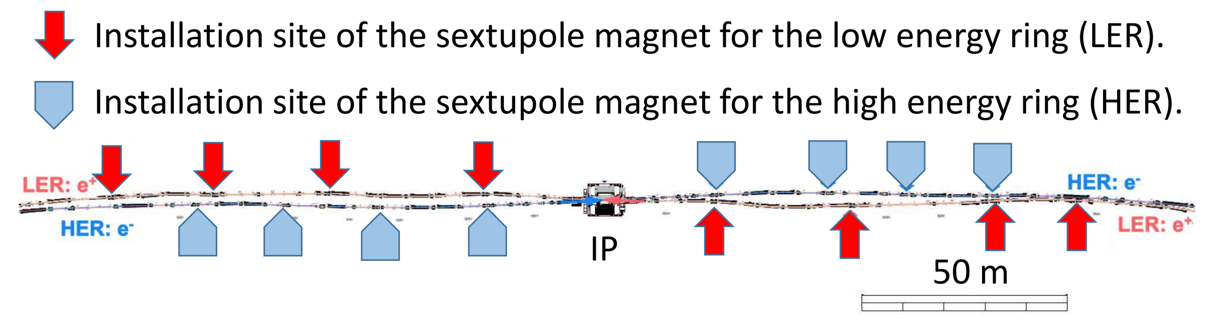
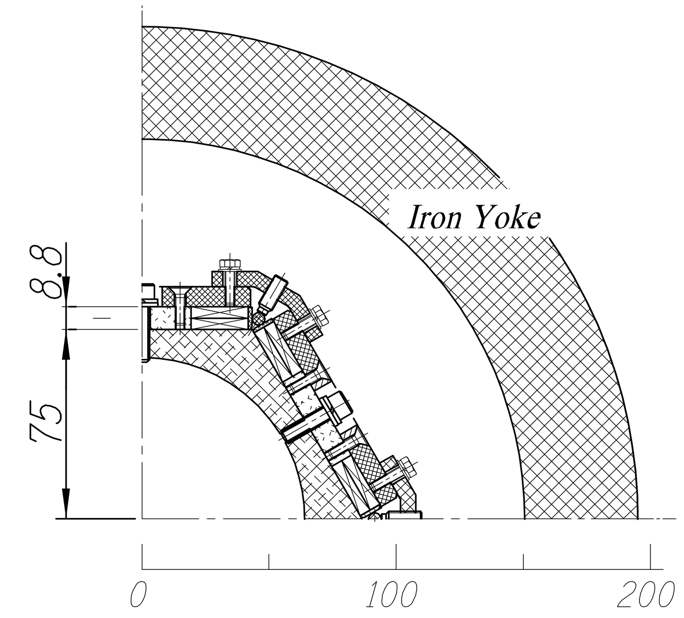
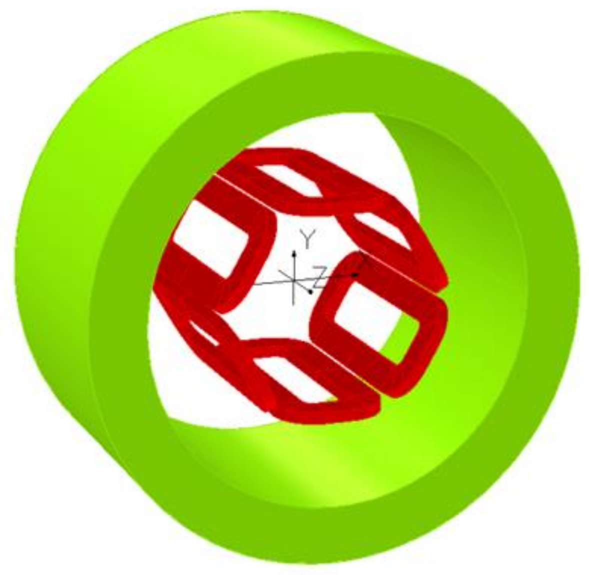
I. INTRODUCTION



- ✓ 16 special sextupole magnets, which are distributed in a 100-m-long straight section on either side of the interaction point (IP), are installed in SuperKEKB for the chromaticity correction.
- ✓ To achieve the tartget luminosity of SuperKEKB, which is extremely high at 8 × 10^{35} $cm^{-2}s^{-1}$, the sextupole magnet is required to simultaneously produce the precise normal and skew sextupole fields. For this reason, the superconducting magnet would be appropriate for these sextupole magnets than the normal conducting magnet in the future operation.
- ✓ To cool the superconducting magnet, it is not economical and feasible to transfer the liquid helium to all sextupole magnets along the 100-m-long straight section from a refrigerator in-stalled near the IP. Therefore, each sextupole would preferably have to be cooled by a stand-alone cryocooler. However, the cryocooler system requires a long time to recovery from the beam-induced quenching that may occur during accelerator operation. This long recovery time would degrade the integrated luminosity. To reduce the beam-induced quench, we proposed a magnet design by using a high temperature superconducting (HTS) conductor as the winding of the sextupole magnet.
- ✓ We fabricated a prototype REBCO normal sextupole magnet on the basis of the original design. After the fabrication, we carried out the excitation and field measurement tests at 77 K to confirm that the magnet did not degraded by the manufacturing process. In this study, we performed the excitation and field measurement tests at 4.2 K to clarify the electromagnetic properties of the magnet.

II. MAGNET DESIGN AND FABRICATION



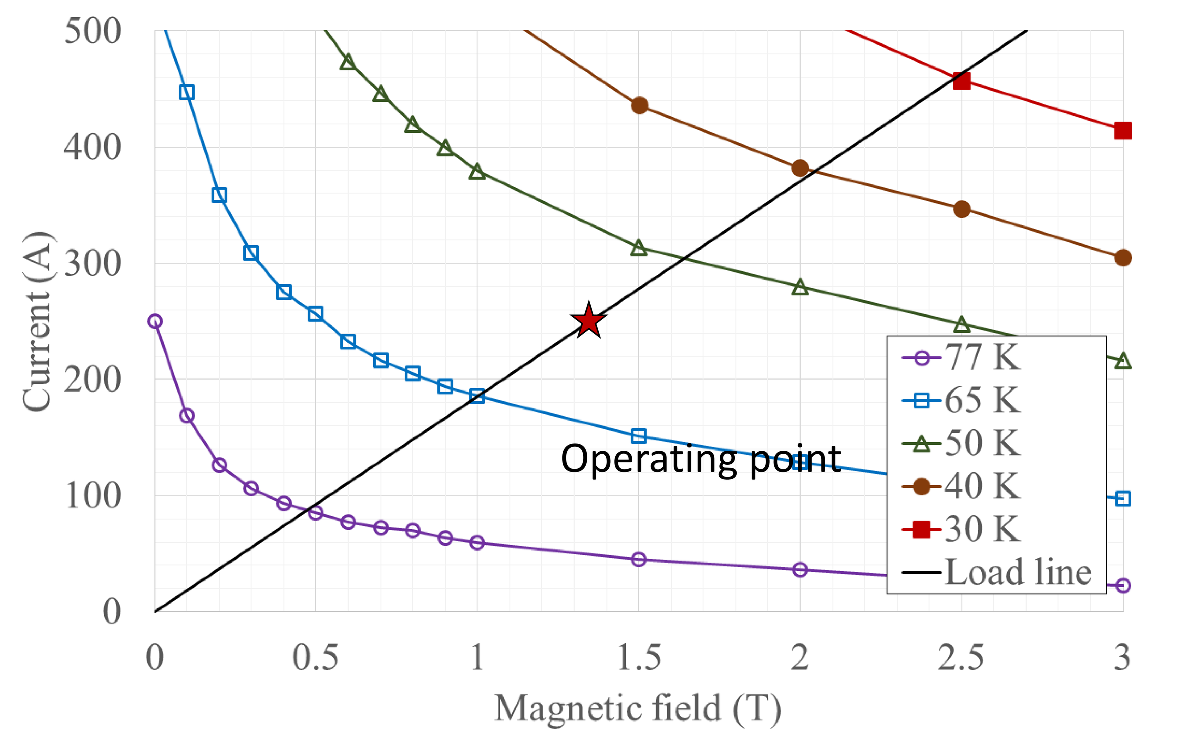


- ✓ The final design of the REBCO sextupole magnet was carried out using Opera-2D and Opera-3D on the basis of the original design.
  K. Tsuchiya, et al., "Development of HTS sextupole magnet for SuperKEKB interaction region," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, 4100904 (2016)
- ✓ The magnet consists of six rectangular coils and a cylindrical iron yoke, which functions as a magnetic shield to reduce the outer leakage field.

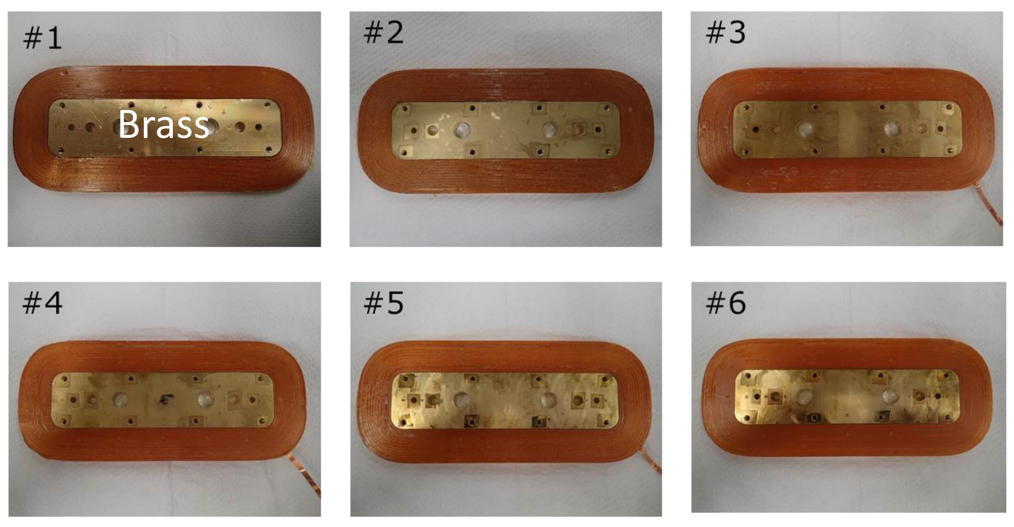
Main Parameters of Prototype Sextupole Magnet

Parameter	Value
Sextupole magnet	
Inner bore radius	75 mm
Yoke radius (inner, outer)	150.5, 195 mm
Yoke length	200 mm
Design current	250 A
Normal sextupole field gradient	211.7 T/m²
Inductance	74 mH
Stored energy	2.32 kJ
REBCO coil	
Width (inner, outer)	38.6, 83.6 mm
Height	8.8 mm
Length	200 mm
Number of turns	121 x 2 turns
Conductor length per one coil	110 m
Maximum field parallel to c-axis	1.38 T

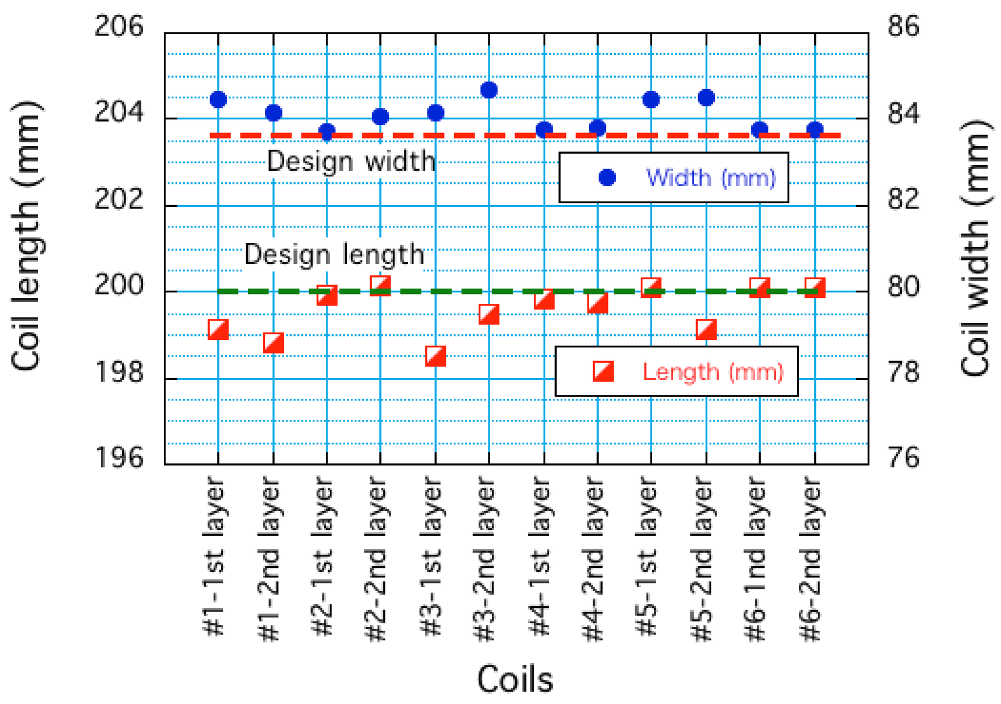
Fujikura Ltd. FYSC-SCH04 : 4.1 mm wide and 0.13 mm thick
Hastelloy® : 75 um, REBCO : 2 um, copper plating : 20 um



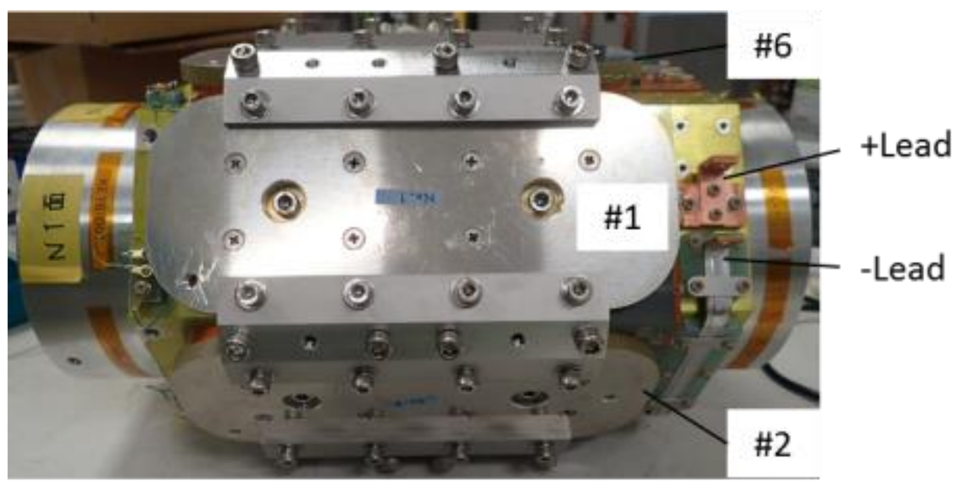
The critical currents in a magnetic field parallel to the c-axis of the REBCO conductor, and the load line of the REBCO sextupole magnet.



- ✓ The corner radius of the center post was designed to be 8.5 mm in order to enhance the field quality around the magnet end.
- ✓ A special winding scheme was employed to ensure that the safety margin of the bending radius was sufficient, because the corner radius is very close to the limit of the allowable bending radius of the REBCO conductor.
- ✓ The inner 100 turns were wound with the Hastelloy® substrate facing outward, where the compressive stress is applied to the REBCO layer at the corner. The remaining outer turns were wound with the REBCO layer facing outward in order to reduce the joint resistance at the coil end. There are three joints per one REBCO coil for this winding scheme.
- ✓ The REBCO coil was impregnated with epoxy resin after the winding process.

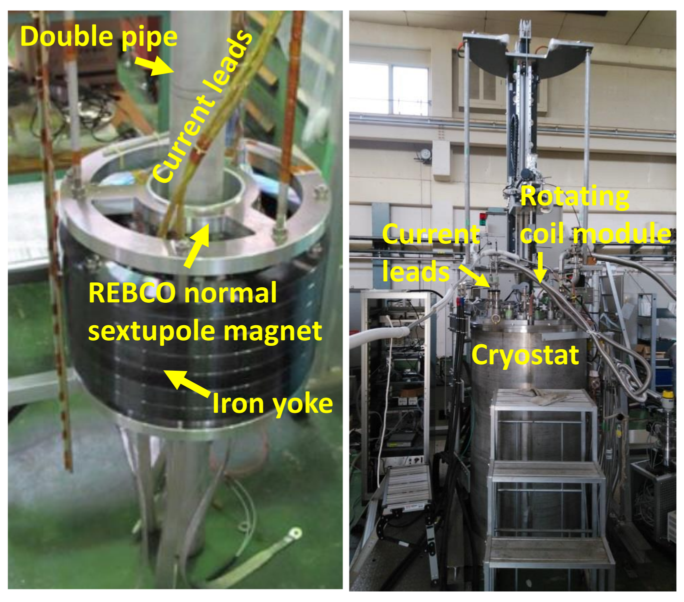


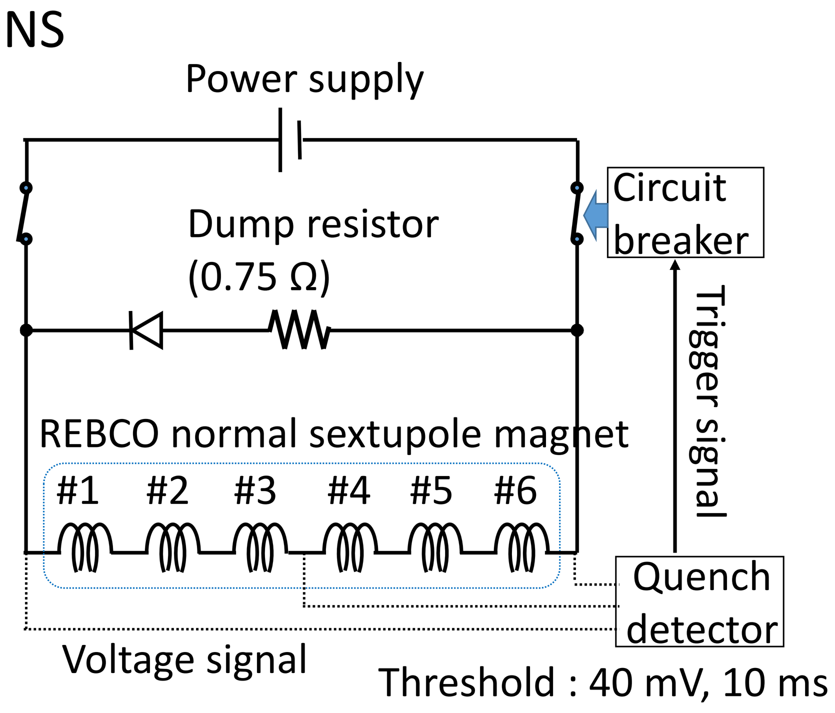
The widths and lengths of the six REBCO coils deviated approximately 1.5 mm and 1.2 mm at the maximum from the design values, respectively.



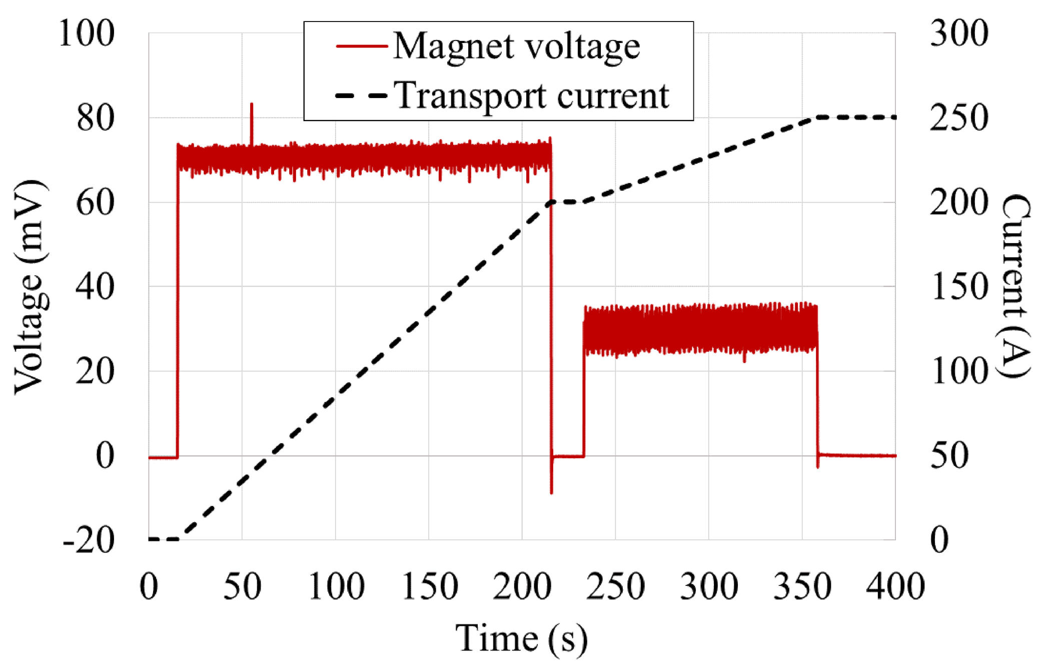
- ✓ The six coils were assembled on a hexagonal support tube manufactured from a single piece of aluminum alloy, A5052.
- ✓ These coils were connected with copper connection plates, onto which 3-mm-wide REBCO tapes were soldered to reduce the resistance of the splices between the coils.
- ✓ Aluminum alloy plates were attached to the rectangular coils, and a support structure against the electromagnetic bursting force, which works on the coil, was mounted between the coils.

III. TEST RESULTS AND DISCUSSIONS

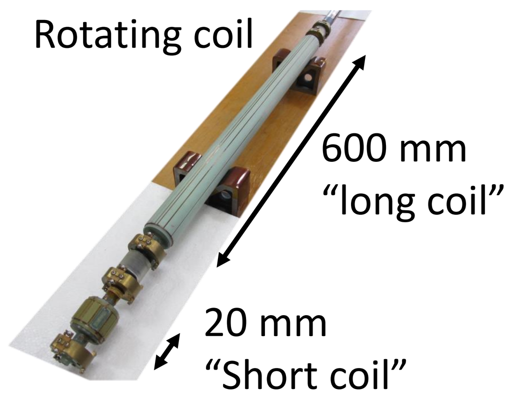




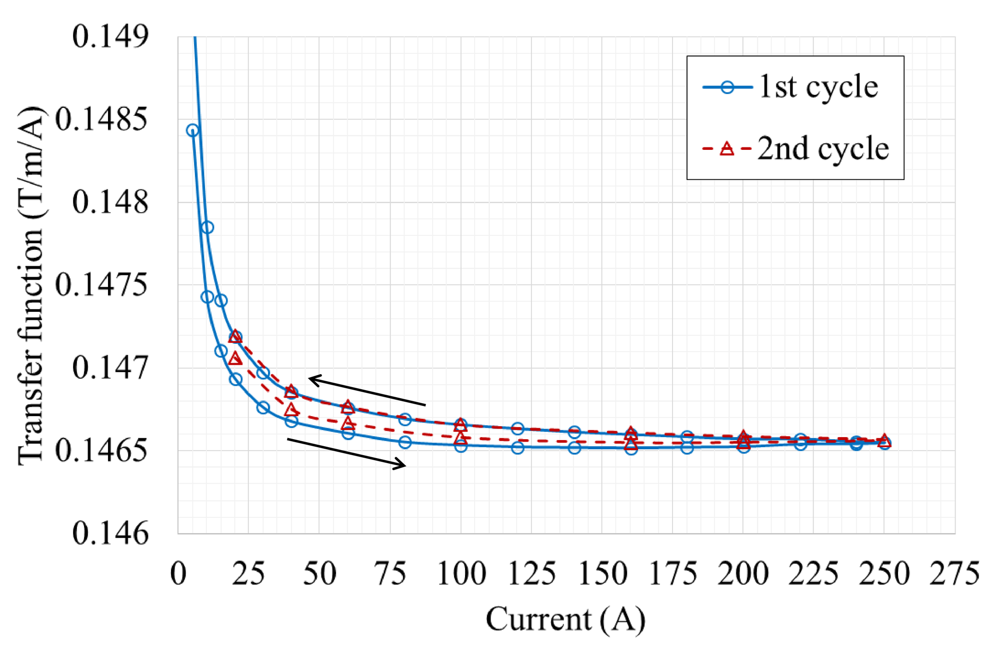
Threshold : 40 mV, 10 ms



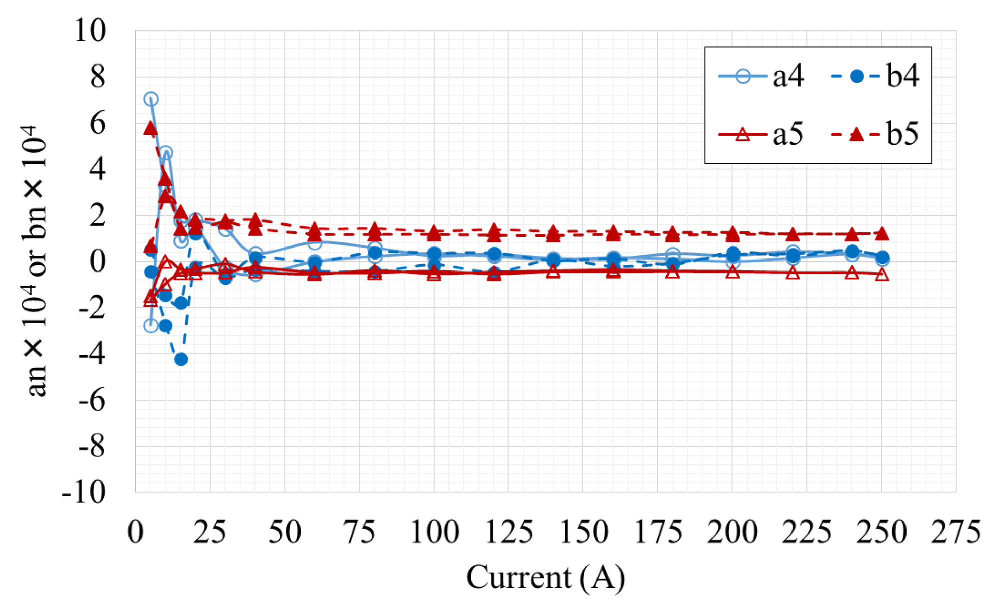
- ✓ The magnet was successfully ramped up to 250 A without quench.
- ✓ No degradation was observed after several excitations and thermal cycles.
- ✓ The magnet inductance, which is approximately 71 mH, agrees with the simulation result of the design within an accuracy of 5%.
- ✓ The total joint resistance including the eighteen splices in the coils and five joints between the coils is less than 0.4 μΩ at 4.2 K.
- ✓ Before the test at 4.2 K, we confirmed the magnet did not degraded by the manufacturing process at 77 K.



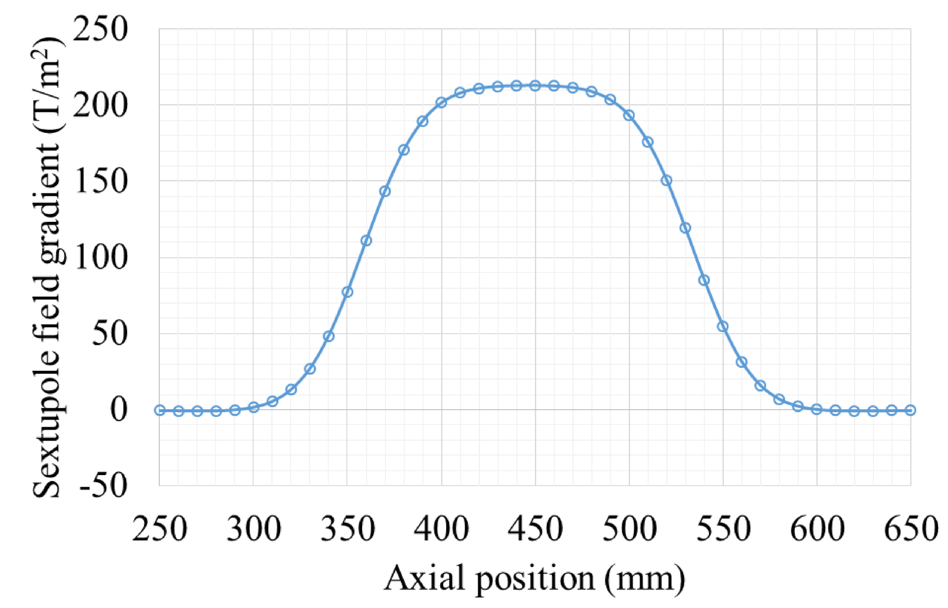
Radius : 20 mm (reference radius)
A tangential coil, two dipole coils, and two quadrupole coils were assembled in each coil.
The dipole and quadrupole coils were used for the bucking scheme.



Current dependence of the integrated transfer function measured by the long coil.



Current dependence of the integrated octupole and decapole components. an = An/B3, bn = Bn/B3



Distribution of the normal sextupole gradient measured by the short coil at 250 A.

- ✓ The transfer function of the normal sextupole is approximately 0.14656 T/m/A at 250 A. Although the hysteretic behavior is observed in the transfer function, it is less than 0.1% when the current is higher than 100 A. Therefore, the magnetic influence is small enough to be neglected for the practical operation.
- ✓ The higher multipoles are considered to be mainly induced by the non-uniform coil size between the six REBCO coils. The multipole components, which are less than 2 × 10^{-4} with respect to the normal sextupole, are in an acceptable range. The hysteretic behavior is not observed in the multipole components.
- ✓ The strength of the normal sextupole gradient is approximately 213 T/m². The effective length is approximately 174.6 mm. The measured results are in a good agreement with the design, 211.7 T/m² and 173.3 mm. The slight difference between the measurement and design is considered to be mainly caused by the winding error of the coils. Therefore, the improvement of the winding technology is necessary in order to fabricate a high precision coil for the practical REBCO sextupole magnet.

IV. SUMMARY

- ✓ A prototype REBCO normal sextupole magnet was tested at 4.2 K. The magnet was successfully excited up to a design current of 250 A without quench. The magnet performance was not degraded after several excitations and thermal cycles.
- ✓ The magnet inductance was agreeed well with the design, and the joint resistance was small enough to apply to a practical magnet cooled by the cryocooler.
- ✓ The normal sextupole field of the magnet was in a good agreement with the design. Although the hysteretic behavior was observed on the normal sextupole field, it is small enough to be neglected for the practical operation. The octupole and decapole components were less than 2 × 10^{-4} with respect to the normal sextupole.