MEASUREMENT OF FIELD INACCURACY AND SHIM SIMULATION OF A 130-POLE SUPERCONDUCTING UNDULATOR

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Abstract

A superconducting undulator (length 975.2 mm, with 130 poles) was wound and trained, and its field measured, at National Synchrotron Radiation Research Center. The NbTi wires were excited to 1.36 T at 497 A after 28 cycles. A Hall probe (length 2.50 m) was used to characterize the distribution of the magnetic field of arrays in the magnetic gap (width 5.6 mm). The measurement region of the Hall probe in the vertical dewar is greater than 1 m. The shrinkage or expansion of the Hall probe depends on the thermal variation at both its ends. The length of the Hall probe must be evaluated in the long region. The reproducibility of the measurement system was verified in the same experiment. A shim method involving a trim pole piece was developed to correct for deviations of the magnetic field. This paper discusses the source of measurement inaccuracy with the Hall probe and present results of the simulation of shimming the trim poles.

INTRODUCTION

The superconducting undulator (SU) was developed in the accelerator field because of its possessing a large field and large photon brilliance. Many workers studied the prototype fabrication and performance of the magnetic field of a SU [1-3]. The field qualities of a SU are influenced by the mechanical accuracy of the iron pole, the position of the coil winding and systematic errors of measurements. The coil winding method were discusses in previously studies [4]. The systematic errors of measurements include the reproducibility of the position and field amplitude of the Hall probe, its shrinkage or expansion during field measurements, and deviations of the field when calibration of the Hall sensor near 300 K is applied at 4.2 K [5]. In early work many methods of field shimming were investigated to compensate the field errors and these were successful within 2% [6, 7]. The field shimming strength affects not only the shimmed pole but also several nearby iron poles, because the length of a period in a SU is short [7]. The field shimming of a SU is thus more complicated than of a traditional undulator.

MECHANICAL INACCURACY OF A SU OF LENGTH 1 M

The magnetic arrays of a SU with 130 poles and 55 turns per groove, thus designated 130P55T, were manufactured by CNC through machining in a single block (whole machining) and wound with NbTi wires. The machining accuracy of the iron poles directly influences the space of the coil winding. Figures 1(a) and (b) display the machined dimension from measurement of the groove depth and width with a 3D-coordinate-measuring machine. Marker 1A denotes array No.1 and its A side. The measured (design) depth of grooves is 6.03±0.1 mm (6.03 mm), and the width of grooves is 4.63±0.02 mm (4.65 mm). The entire machining of the iron poles of length 1 m was therefore not seriously deficient with regard to the dimensions. The entire coil was arranged straight in the groove. The surface of the iron pole protrudes above the surface of the wound coil approximately 0.1 mm when the coil winding is perfect. This gap 0.1 mm directly obstructs thermal conduction from the beam duct to the superconducting coils. In the winding, the gap dimension is between 0 and 0.1 mm and some surface of the wound coil is level with the surface of the iron pole.

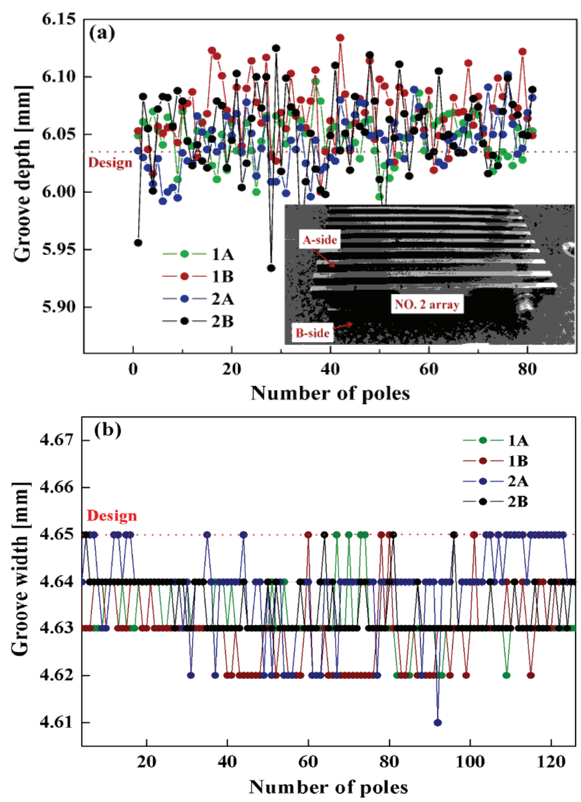

Figure 1: (a) and (b) are plot the dimension of groove depth and groove width, respectively.

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FIELD MEASUREMENT OF THE SU OF LENGTH 1 M

The 130P55T arrays were trained and the field measured in a vertical dewar; an illustration and a photograph appear in Fig. 2(a) and (b), respectively. The magnetic arrays were mounted on the test frame and immersed in liquid helium. Figure 2(a) left (right) displays the measurement start-end (stop-end) at the magnetic array bottom (top). The total distance of measurement is approximately 1 m with 0.1 mm interval. The total duration of measurement is approximately 4.5 h. A Hall probe driven with a stepping motor is mounted on the top of the vertical dewar. The training current in the coil is up to 497 A to achieve 1.36 T after 28 cycles, with the training current not saturated [8]. With excitation at 458 A the measured field spectra, angle and trajectory are displayed in Fig. 3 (a), (b) and (c), respectively. The average field strength excluding six end poles is 1.2928 T at 458 A. The maximum field deviation ($\Delta B/B$) excluding the end poles is 3.1%. The lengths of the half periods of 130P55T are 7.52±0.1 mm, with average 7.51 mm. The deviation of the trajectory along the axis is approximately 30 μm after correction.

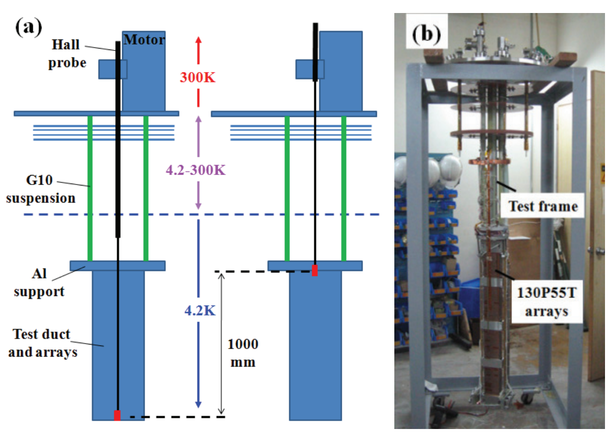

Figure 2: (a) and (b) display the assembly of arrays and measurement system in the vertical dewar.

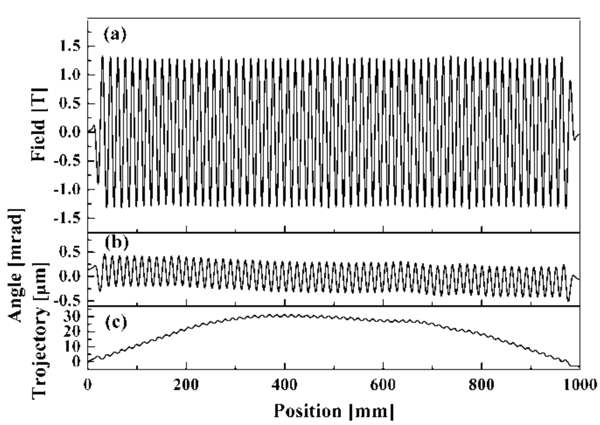

Figure 3: (a), (b) and (c) are plot the measured field spectra, angle and trajectory at 458 A, respectively.

Tests of the reproducibility of position and amplitude of the Hall probe are displayed in Fig. 4 (a) and (b), respectively. Figure 4 (a) displays two scans with the Hall probe from 500 mm to 600 mm. A shift 0.1 mm was observed on the maximum, as shown in Fig. 4 (a) inset. The reproducibility of the field amplitude between measurements is within 20 G at the field maxima as shown in Fig. 4(b). The maximum difference of the amplitude in the low-field region exceeds that in the peak-field region, because the spectral slope in the low-field region is larger than in the peak-field region.

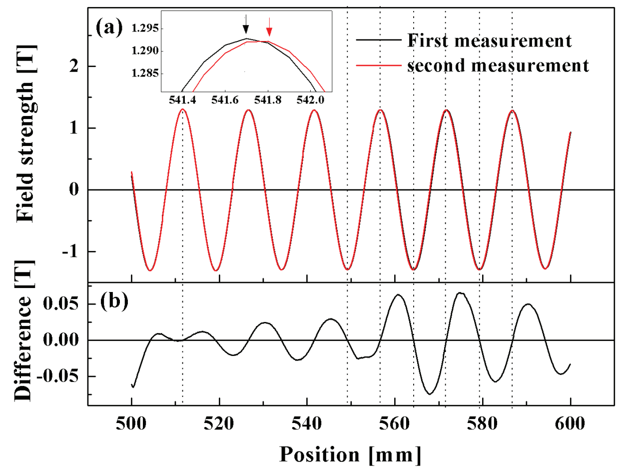

Figure 4: (a) plots the tests of the reproducibility of position and amplitude of the Hall probe. Figure 4(b) plots the difference spectrum of both scans.

MEASUREMENT OF THE PERIOD OF THE SU OF LENGTH 1 M

In the ideal case, a measurement of the period length of the field yields the same result whether at 4.2 K or 300 K, when the measurement system and magnetic arrays are set at the same temperature, but in practice the measurement system is mounted between 300 K and 4.2 K, so different from the temperature of the magnetic array, 4.2 K. When the Hall probe is moved along the length, the thermal gradient of the Hall probe is altered, so altering the length. The shrinkage or expansion of the length of the Hall probe is an essential estimate to be acquired through a measurement of that length. The length of particular maxima is identical in Fig. 3(a), as listed in Table 1. The design length (measured length) between the 6th and 125th maxima is 892.5 mm (893.7 mm) at 300 K (4.2 K). This disparity 1.2 mm is caused by the expansion of the thermal gradient during measurement. A software package (COSMOS) was used to analyze the expansion of the Hall probe during a measurement. The thermal expansion of Hall probe is 1.215 mm (2.091 mm) when the Hall probe is at the array bottom (top) relative to 300 K in Fig. 2(a). The thermal expansion is thus 0.88 mm during the mapping of the field 1 m long. This estimate of expansion with COSMOS is near the difference between design and measurement. Moreover, the length between the 6th and 66th (20th and 30th) maxima is the same as between the 66th and 126th (101st and 111st) maxima. The symmetry of left-half and right-half iron poles implies that the thermal expansion, 1.2 mm, corresponds to a uniform distribution between the 6th and 125th poles. The error of length of a half period is 0.01 mm per pole caused by the variation of the thermal gradient of the Hall probe during a measurement.

Table 1: Distance Between Two Specified Maxima:

Number of poles	Design length at 300 K	Design length at 4.2 K
6th-125th	892.5	893.7
6th-66th	450	450.5
66th-126th	450	450.7
20th-30th	75	75
101st-111st	75	75.1

SIMULATION OF FIELD SHIMMING OF A SU 1 M LONG

The field shimming of the 130P55T arrays was simulated using an iron-piece method. Several iron pieces were directly added onto the iron pole, as in previous experiments [7]. The extra shimming field used in the simulation is listed in Table 2. In the first shimming by hand, four iron pieces were set at the 24th , 103rd, 108th and 109th poles with 5 mm, 5 mm, 15 mm and 5 mm, respectively. The maximum deviation of the peak improved from 3.1% to 2.3%. The trajectory deviation was diminished from 30 μm to 25 μm. The average half period length is maintained constant with shimming.

Table 2: Extra Shimming Field:

Neighbour poles	5 mm	15 mm	25 mm
0	-188.2	-325.9	-287.3
1	143.35	285	334.95
2	-125.8	-214.35	-170.55
3	68	190.05	175.45
4	-42.5	-59.5	-51.8
5	34.4	88.8	89.15
6	-35.9	-6	-28.6

SUMMARY

The iron poles of length 1 m were machined whole without observation of a serious defect of the groove dimensions. The measured depth and width of grooves are 6.03 ± 0.1 mm and 4.63 ± 0.02 mm, respectively. The reliability of the measurement system resulted from the performance in the test dewar. The reproducibility of the measurement position and amplitude are 0.1 mm and 20 G, respectively. The average field strength of 130P55T arrays excluding six end poles is 1.2928T at 458 A. The half-period length of the magnetic array is 7.52±0.1 mm and average 7.51 mm. The thermal expansion of the Hall probe is 1.2 mm during measurement as was confirmed with simulation (COSMOS). The deviations of the half-period length within 0.01 mm per pole result from thermal shrinkage of the Hall probe. The field error from thermal expansion is smaller than the error of iron-pole machining or coil winding. A method of shimming with iron pieces was simulated to decrease the maximum field deviation from 3.1% to 2.3%, and the trajectory deviation decreased from 30 μm to 25 μm. An elegant shimming program will be developed to implement automatic shimming of the magnetic field in future.

REFERENCES

[1] S. H. Kim, et. al., "Design and Development of a Short-Period Superconducting Undulator at the APS", IEEE Trans. Appl. Supercond. **15,** 1240 (2005).

[2] Y. Ivanyushenkovet. al., "Status of r&d on a superconducting undulator for the aps", in Proceedings of the Particle Accelerator Conference PAC09.

[3] S. Casalbuoni et. al., "Beam heat load in the ANKA superconducting undulaor", http://care-hhh.web.cern.ch/CARE-HHH/ECL2/Proceedings/Casalbuoni_ECL2_1.pdf.

[4] J. C. Jan et. al.," Improved winding of a superconducting undulator and measurement of the quenching tolerance", EPAC08, Genoa, Italy. (2008) 2270-2272.

[5] Y. Ivanyushenkov, et. al.,"Calibration of Hall Probes at Cryogenic Temperatures",16th International Magnetic Measurement Workshop (IMMW16), Bad Zurzach, Switzerland, 26-29 October 2009.

[6] D. Wollmann et. al., "Experimental demonstration of the induction shimming concept in superconductive undulators", PAC proceedings, pages 1–3, May 2009.

[7] J. C. Jan et. al., "Field trimming by iron pieces and coils in a superconducting undulator", IEEE T. APPL. SUPERCON. 19 , 1332 (2009).

[8] J. C. Jan et. al.," Development and testing of a prototype superconducting undulator", in Proceedings of the Synchrotron Radiation Instrumentation Conference, Australia, 2009.