STATUS OF SHORT-PERIOD SUPERCONDUCTING UNDULATOR R&D AT THE APS*

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Abstract

A planar superconducting undulator (SCU) with a period of 15 mm is under development at the Advanced Photon Source (APS). The design, fabrication and test results of a 12-period upper-half SCU are described. The SCU is designed to achieve a peak field of 0.8 T on the beam axis for a pole-gap height of 8 mm at a coilpack current density of 1.0 kA/mm^2. The SCU was tested in 4.2K liquid He pool-boiling to reach the critical current density J_c of 1.4 kA/mm^2 after three quenches near the J_c.

INTRODUCTION

The goal of the superconducting undulator (SCU) program at the Advanced Photon Source (APS) is to develop, fabricate and install an undulator tunable over a photon energy range from 19 to 28 keV in the first harmonic [1]. The intended users at the 7-GeV APS storage ring require this tuning range for inelastic x-ray scattering studies in condensed-matter physics. The SCU under development has the following parameters: magnetic period = 15 mm, pole gap height = 8 mm, peak magnetic field on the beam axis = 9.8 T and K = 1.12.

There are important R&D issues to resolve besides the high current density of 1.0 kA/mm^2 in the NbTi/Cu coilpack. At the operating current density, the SCU must have adequate stability margins to accept the electron-beam-induced heat loads in the coilpack. Also, field-quality correction may be required to achieve high-photon beam brilliance at higher harmonics. This paper reports the design concept, fabrication of a steel core and superconducting (SC) coil winding on it, and test of a 12-period upper-half SCU to its critical current density.

SCU DESIGN

Figure 1 shows a 3-D model of one period for the SCU with a period length of 15 mm. The SCU consists of two low-carbon-steel cores with SC coils. The two halves of the core are placed symmetrically with respect to the SCU midplane. The flat sides of the cores adjacent to the midplane are the top and bottom undulator poles. The beam chamber with an elliptical cross section will be inserted in between the poles providing a pole-gap height of 8 mm. The design concept assumes that the cooling of the device is "pool boiling" by immersing both the SCU and the beam chamber in 4.2K liquid helium (LHe).

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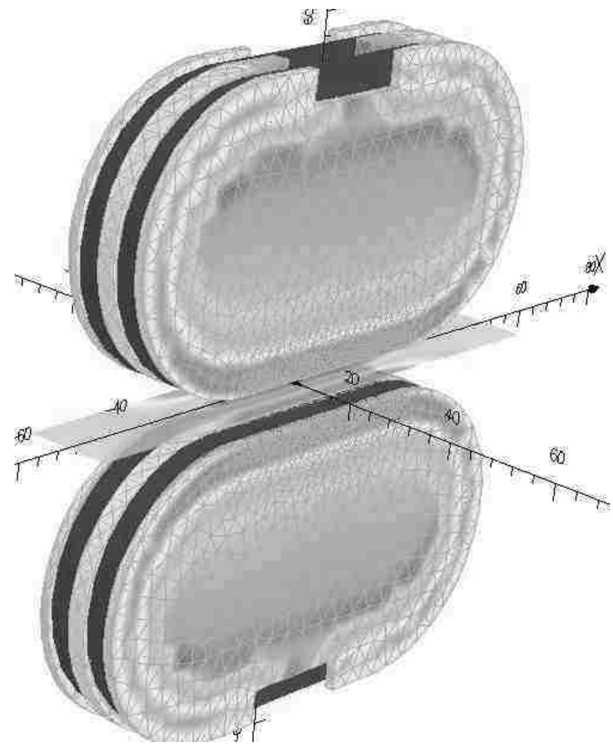


Figure 1: One 15-mm-period, 3-D model of the SCU used for the magnetic field calculations. Two steel cores (gray) are positioned to form a pole-gap height of 8 mm to accept the beam chamber. The core has grooves for 20-turn SC coils (*black*).

Plotted in Fig. 2 are the vertical peak field B_o on the beam axis in the midplane of the SCU (*left axix*) and the maximum field B(coil) in the SC coil (*right axis*) as a function of the average current density in the coilpack. Also plotted in Fig. 2 are the critical current density J_c(cond) measured for a rectangular NbTi SC wire as a function of applied magnetic field B (*right axis*) at 4.2K. The formvar-insulated rectangular wire, which has a Cu/SC ratio of 1.35 and dimension of 1.05×0.77 mm^2, has been chosen for the 12-period prototype SCU. The core grooves for the 20-turn SC coils (4 turns $\times$ 5 layers) have cross sections (width $\times$ depth) of 4.32×3.89 mm^2. The packing factor of over 90% for the coil winding would reduce the conductor positioning error within the coil grooves. Figure 2 also shows that the design peak field of 0.8 T is calculated at a current density of 1.0 kA/mm^2, which is approximately 72% of the critical current density J_c(cond) = 1.4 kA/mm^2 at the maximum field in the coil B (coil) of 3.78 T. Increasing the coil cross section, to make a 24-turn or 25-turn coil, for example, increases the peak field less than 0.02 T at 1.0 kA/mm^2.

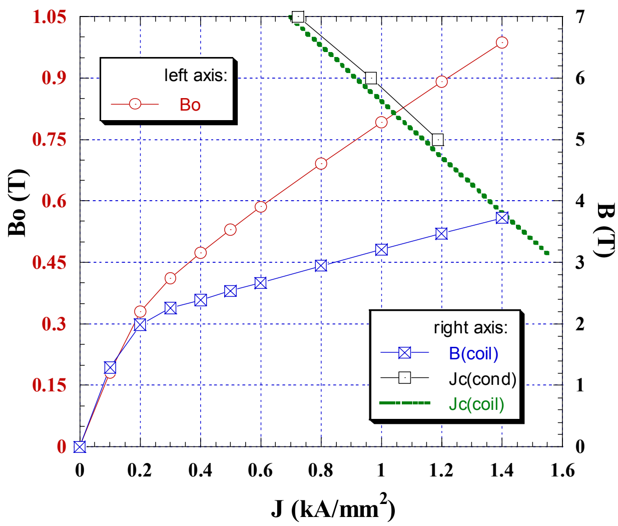
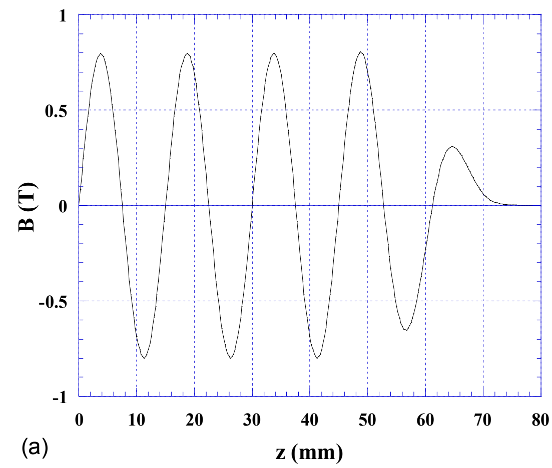


Figure 2: The vertical peak field B_o (*left axis*) and the maximum field in the coil B(coil) (*right axis*) for a period of 15 mm and pole-gap height of 8 mm are plotted as a function of the coil average current density J. Also plotted are the critical current density J_c(cond) under applied magnetic field B (*right axis*) at 4.2K for the rectangular conductor (1.05 $\times$ 0.77 mm^2) used for this work and the average critical current density J_c(coil) in the coil groove.

The vertical field including the end field, calculated at a current density of 1.0 kA/mm^2 along the longitudinal beam direction z of the SCU, is plotted in Fig. 3 (a). The end field was adjusted by reducing the number of coil windings from the nominal 20 to 17, 10 and 3 turns for the three end coils. The end field also depends on the wire positions within the coil grooves and the current density. The end fields for J = 0.4 and 1.4 were calculated, and the deviations of the normalized fields $\delta B/B_o$ to that for J = 1.0 are plotted in Fig. 3 (b). Since the magnetic poles for the end fields saturate differently from those for the "main body fields," the period and the normalized fields for the end depend on the current. The field integrals and periods for the three current densities vary approximately by 10% and 0.2 mm, respectively. This suggests that small correction coils may be required at both ends of the SCU for beam steering.

FABRICATION

One core for a 12-period upper-half SCU was machined from "1008 low-carbon" steel. The cross section of the core is approximately 75$\times$40 mm^2. Figure 4, (*a*) and (*b*), shows the bottom and top sides of the core, respectively, after the coil winding. The flat-bottom side has coil grooves with a cross section (width$\times$depth) of 4.3 $\times$ 3.89 mm^2 and a pole thickness of 3.18 mm. The transverse width of the poles is approximately 50 mm. The top side has additional grooves for the transitions of the SC wire to the adjacent periods. The core is designed to wind the coil first in one direction into every other groove for the full length. The alternate coil grooves are then similarly wound in the opposite direction.



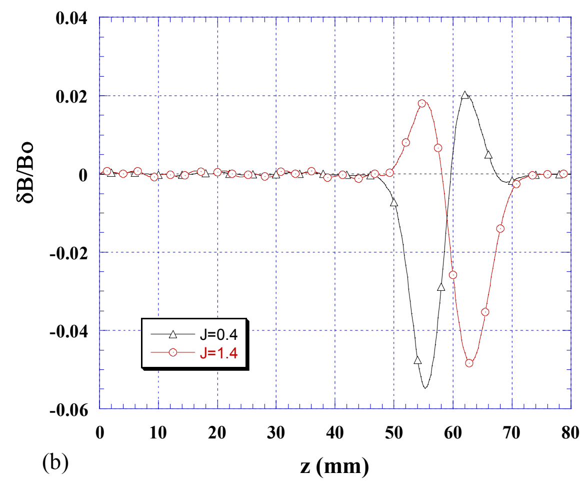
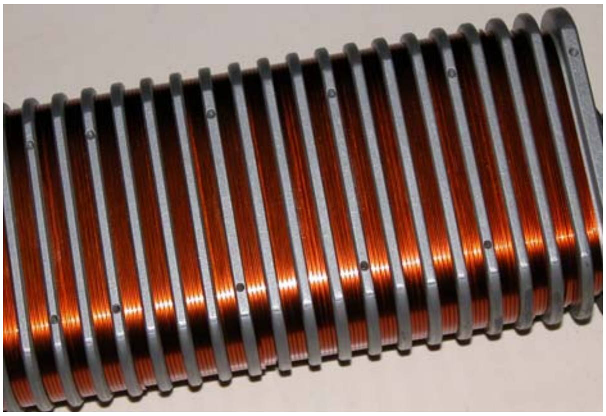


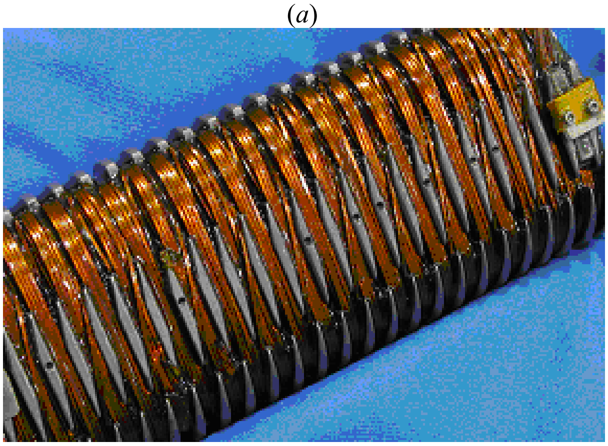
Figure 3: (a): The vertical fields, including the end, were calculated at a current density of 1.0 kA/mm^2 along the beam direction z of the SCU. The three end coils have 17, 10 and 3 turns instead of the nominal 20 turns. (b): At J = 0.4 and 1.4 the normalized field deviations from J = 1.0 are plotted.

TEST RESULTS

The 12-period upper-half SCU was tested at 4.2K in LHe. In the first test, it reached the design current density of 1.0 kA/mm^2 only after several quenches. After epoxy impregnation of the coil, it quenched twice approximately at J = 1.26 and 1.35 before the quench at J_c = 1.4 kA/mm^2. The vertical field B, measured using a Hall probe fixed at an approximate distance 3.6 mm from a magnetic pole, is plotted in Fig. 5. Since the measured field is only for the upper half at a distance less than the half-gap, the peak field B_o in Fig. 2 is obtained by multiplying a factor of (2$*$0.8349) by the vertical field B of Fig. 5. Figure 5 also shows that the measured fields at low current densities are slightly lower than the calculations. This indicates that the core has slightly lower permeability than that of the 1008 low-carbon steel used for the calculation.



(*a*)



(*b*)

Figure 4: One core for the 12-period upper-half SCU was machined from low-carbon steel. (*a*): Bottom flat side of the core shows coilpacks and magnetic poles. (*b*): Top side shows additional cross-over windings, connecting every other coilpack by the conductor transition to the next period after complete winding of the 20 turns in one groove.

The current ramping rate is mainly limited by the hysteretic losses in the SC filaments. The estimated losses for a slow cycle between 3.2 T to 3.8 T (J from 1.0 to 1.4) are less than 5 μJ/mm^3. The estimated enthalpy from 4.2K to 7.6K, which is the transition temperature at the maximum field in the coilpack, is not larger than the energy density for the hysteretic losses. This implies that, if we assume the local adiabaticity of the coilpack, the ramping rate must be low enough to avoid quenches near the critical current density.

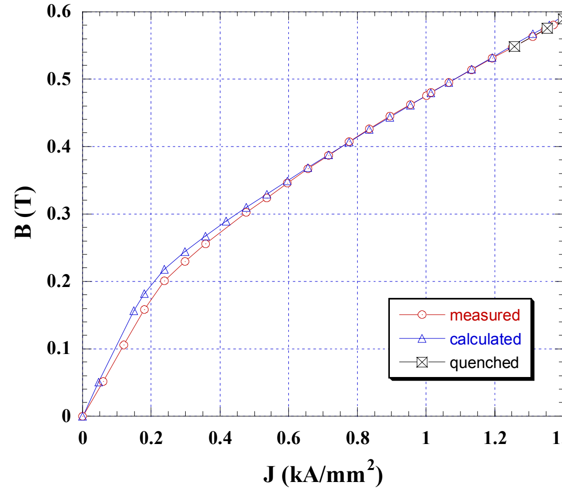


Figure 5: The vertical field for the upper-half SCU was measured at an approximate distance 3.6 mm from a magnetic pole. The calculated data, using the permeability data for the1008 low-carbon steel, gives slightly higher field values at low current densities.

CONCLUSION AND FUTURE PLAN

From the design and fabrication of a short-period prototype and successful tests of a short-section upper-half SCU up to its critical current density, the stability at the design current density of 1.0 kA/mm^2 (72% of J_c) has been demonstrated. Experimental studies for additional stability margins at the operating current densities will be conducted by depositing heat loads on the vacuum-chamber walls adjacent to the coilpacks.

ACKNOWLEDGMENTS

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REFERENCES

[1] S.H. Kim, R.J. Dejus, C. Doose, R.L. Kustom, E.R. Moog, M. Petra, K.M. Thompson, “Development of a Short-Period Superconducting Undulator at APS,” Proc. 2003 PAC, p. 1020, IEEE Catalog Number: 03CH374.