DEVELOPMENT OF A SHORT-PERIOD SUPERCONDUCTING UNDULATOR AT 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 intended users require a photon energy that can be tuned from 19 to 28 keV for inelastic x-ray scattering studies. The SCU design consists of two low-carbon-steel cores that are positioned above and below the beam chamber. There are 20 turns of NbTi/Cu superconducting (SC) wire within a coil cross section of 4.3 x 4.0 (w x h) mm^2. At a pole gap of 8 mm, the necessary average current density in the coil will be about 1 kA/mm^2 to achieve a peak field of 0.8 T on the beam axis. The design and fabrication progress of a 12-period prototype SCU are presented, and some challenging requirements are discussed.

INTRODUCTION

Demands for undulators with shorter periods and/or higher peak fields than those available from permanent magnet (PM) undulators are emerging for the storage-ring-based synchrotron radiation facilities and for future free-electron lasers. Superconducting undulators (SCUs) with high current densities in the coils have the potential to overcome these limitations. In the past, there has been considerable progress in developing short-period SCUs at Brookhaven National Laboratory and ANKA/ACCEL [1, 2]; here we report on recent developments at APS.

The goal of the SCU program at APS is to develop, fabricate and install an undulator tunable over a photon energy range from 19 to 28 keV in the first harmonic. Further extensions to this energy range can be achieved by using the third harmonic of the radiation, which would require a high field quality in the SCU. The intended users at the 7-GeV APS storage ring (SR) require this tuning range for inelastic x-ray scattering studies in condensed-matter physics. The possibility of shorter period SCUs (~ 12 mm) with acceptable pole gaps will also be investigated. This is of interest for future programs in applied materials research and geological studies. The lowest reachable energy of the first harmonic depends on the highest magnetic field achieved. Using a 15-mm period at 0.8 T, 19 keV can be achieved, and at 1.0 T, 16 keV. Figure 1 compares the on-axis brilliances calculated for the PM Undulator A (33-mm period), which is the mainstream undulator at the APS and the 15 mm SCU described here. This paper reports on the progress of a 12-period prototype SCU.

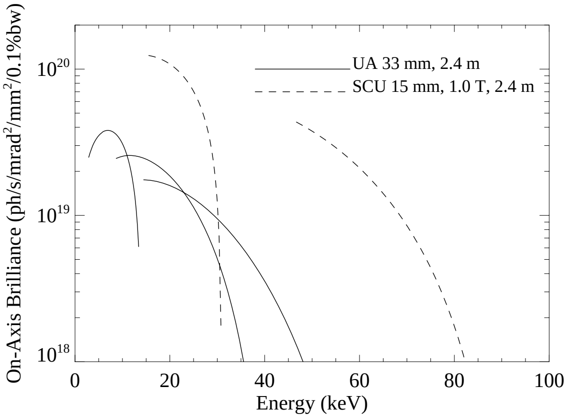

Figure 1: On-axis brilliances calculated for the permanent magnet Undulator A with 33-mm period (harmonics 1, 3, 5) and a SCU with 15-mm period (harmonics 1, 3) for the APS storage ring (7.0 GeV, 100 mA, 2.5 nm-rad). The on-axis brilliance is six times higher for the SCU at 25 keV, an energy of interest for selected experiments.

SCU DESIGN

Figure 2 depicts a 3-D model of one period of the SCU with a period length of 15 mm. It 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 gap 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 liquid helium. The core has grooves for 20 turn coils with cross sections of 4.3 x 4.0 (w x h) mm^2.

Plotted in Fig. 3 are the vertical peak field B_o in the SCU midplane (*top*) and the maximum field B(coil) in the SC coil (*bottom*) as a function of the average current density in the coil. Also plotted in the same figure are the critical current densities measured for three selected NbTi/Cu SC wires as a function of applied magnetic field (*bottom*) at 4.2K. The rectangular wire Jc(#2), which has a Cu/SC ratio of 1.25 and dimension of 1.05 x 0.8 mm^2, has been chosen for the fabrication of this prototype. By choosing a rectangular wire instead of a round wire, a packing factor over 90% can be achieved and better control of the wire positioning in the grooves can be made. To achieve a peak field of 0.8 T for the rectangular wire, we find that the required current density of 1 kA/mm^2 will be less than 70% of the critical current density at a B(coil)

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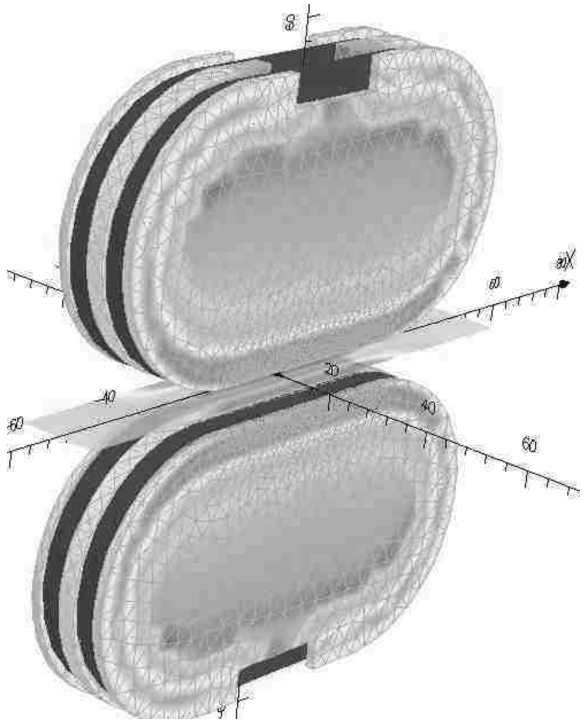

Figure 2: One 15-mm-period, 3-D model of the SCU was used for the magnetic field calculations. Two steel cores (*gray*) are positioned to form a central gap of 8 mm to accept the beam chamber. The core has grooves 4.3 x 4.0 (w x h) mm^2 for 20 turns of SC coil windings (*black*).

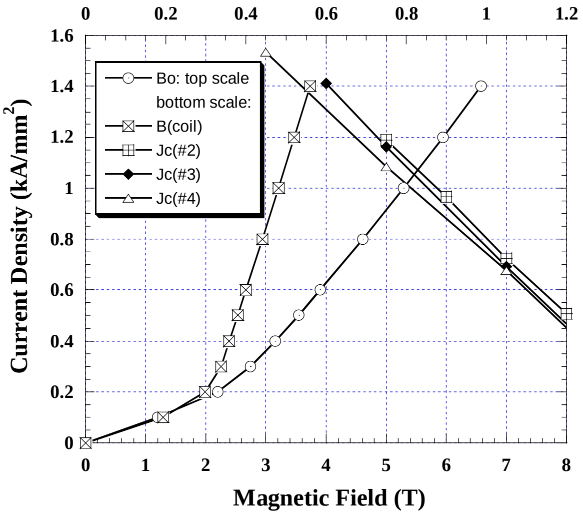

Figure 3: The vertical peak field B_o (*top scale*) and the maximum field in the coil B(coil) (*bottom*) for a period of 15 mm and gap of 8 mm are plotted as a function of the average current density. The critical current densities under applied magnetic field (*bottom*) at 4.2K are plotted for three SC wires, Jc(#2): rectangular cross section (1.05 x 0.8) used for this work, Jc(#3): dia = 0.896 and Jc(#4): dia = 0.753; all in mm units.

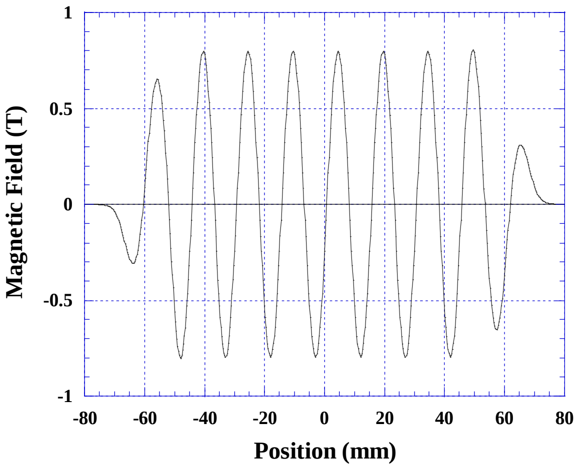

Figure 4: The vertical magnetic field was calculated at a current density of 1 kA/mm^2 along the beam trajectory in a short-section undulator. The end fields were adjusted by reducing the number of turns from the nominal 20 to 17, 10 and 3 turns for the three end coils.

of 3.2 T. This relative low ratio of the current density will however not guarantee that the coil will be cryogenically stable because of the high value of the current density and the low Cu/SC ratio. The required current with 20 turns of the wire will be 860 A.

Figure 4 shows the calculated vertical field along the beam axis of the SCU. The calculation has not yet been fine-tuned, but it demonstrates that the end fields may be 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 fields will also depend on the wire positions within the coil grooves. Small correction coils may be required at both ends to adjust for proper field integrals through the device. However, one way to avoid the correction coils may be to reduce the thickness of the end poles to match the permeability variation with the nominal poles.

Current Status

One core for a 12-period device was machined from “1006~1008 low-carbon” steel. The cross section of the core is approximately 76 mm x 40 mm. Figure 5, (*a*) and (*b*), shows the bottom and top sides of the core, respectively. The transverse width of the poles is approximately 50 mm, and the core has coil grooves with a cross section of 4.3 x 4.0 (w x h) mm^2. The choice of the groove dimensions make the pole thickness 3.2 mm. The flat bottom side of the core shows the coil grooves with windings for the first two periods. The top side has additional grooves for the transitions of the SC wire to the adjacent periods. The coil is designed to be first wound in one direction into every other groove for the full length. The alternate coil grooves are then similarly wound in the opposite direction.

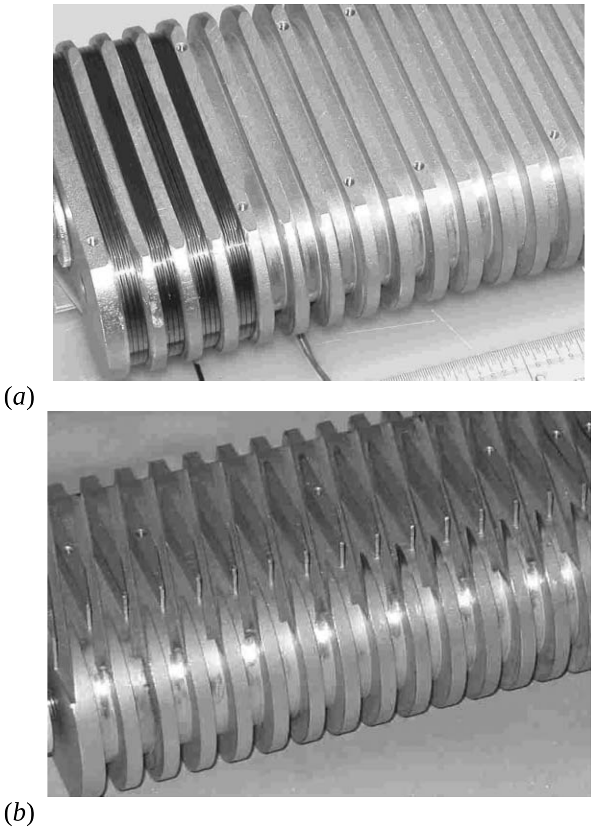

Figure 5: One core for the 12-period prototype was machined from “1006~1008 low-carbon” steel. The cross section of the core is approximately 76 mm x 40 mm. (*a*): Bottom flat side of the core shows coil grooves and windings for two periods. (*b*): Top side shows additional cross-over slots connecting every other coil groove for the SC wire transition to the next period after complete winding of the 20 turns in one groove.

DISCUSSION

The coil cross section for the present prototype was not designed to achieve the highest peak field B_o. Rather it was adjusted to use a readily available SC wire. Increasing the total current by increasing the coil cross section, but keeping the current density constant, at 1 kA/mm^2 for example, increases the peak field B_o by only a small fraction for the prototype SCU. Also, a reduced pole thickness will result in the field quality being more sensitive to wire position errors. And overall increasing the total current would also reduce the cryogenic stability of the device. Thus, the chosen design is expected to be a good prototype for further studies.

One of the challenging requirements for the SCU is the high current density in the coil. This demands a low Cu/SC ratio and a high packing factor of the coil. Because of the high current density and the low Cu/SC ratio, the minimum quench propagation length is estimated to be less than 2 mm. Moreover, the minimum quench energy is not expected to be larger than 1 mJ. This is a typical value for SC dipoles used in high-energy accelerators. Commonly, this small amount of the energy can be released by small wire displacements in the coil during energizing. The first excitation of the coil will therefore be done by slowly cycling the current to higher values. Future studies will involve the stability of the coils and magnetic measurement of the field quality to identify the sources of the field errors.

The peak field is limited by the average critical current density for the selected SC wire (0.98 T at 1.4 kA/mm^2 under ideal conditions--no energy release due to the conductor displacements, no eddy current and hysteresis losses due to operating current ripples, and no direct heating of the coils by effects of the electron beams, etc.; see Fig. 3). Thus, to achieve a 1.0-T, 8-mm-gap SCU, one may need to cool below the lambda point for stable operations.

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