EXPERIMENTAL STUDY OF THE STABILITY MARGIN WITH BEAM HEATING IN A SHORT-PERIOD SUPERCONDUCTING UNDULATOR FOR THE APS*

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Abstract

A 15-mm-period superconducting undulator (SCU) is under development at the Advanced Photon Source (APS) to achieve a peak field of 0.8 T with an 8 mm pole gap. A 12-period SCU was fabricated and charged up to its critical current. An experiment was conducted to measure the stability margin of the SCU under external heat loads. Steady-state heat loads were deposited into the SCU coil/pole face using thin-film heaters attached to the inner surface of a vacuum chamber wall. The heat-load tests performed in pool-boiling LHe indicate that the stability margin was much larger than the expected minimum quench energy. This was attributed to the latent heat of vaporization of the LHe at the SCU/chamber interface.

INTRODUCTION

A planar superconducting undulator (SCU) with a period of 15 mm was designed to achieve a peak field of 0.8 T on the beam axis with an 8 mm pole gap and a current density of 1 kA/mm^2 in the NbTi superconducting (SC) coil at the Advanced Photon Source (APS) [1]. The undulator tunable range of the photon energy in the APS 7-GeV storage ring would be from 19 to 28 keV for the first harmonic.

For short-period SCUs the maximum field in the coil is less than 5 T, relatively low compared to SC dipole magnets for high-energy particle accelerators. However, the required average current density in the coil is over 1 kA/mm^2 to meet the design peak field B_o and deflection parameter K. Therefore, for the coil design, we are forced to use a low Cu/SC ratio and high packing factor for the coil winding, which results in a poorly cooled device. It is essentially an adiabatic SC coil, which is susceptible to premature quenches, mainly due to conductor motion, at current densities well below the intended design current or below the critical current density. When the coil is fully "trained" by means of quenches during the charging process, the stability margin of the coil will mainly depend on the enthalpy, the heat capacity integral of the coil from the operating temperature to the current-sharing temperature at which the coil quenches. Because of the high current density in the coil, the 15-mm-period SCU is designed to operate at a current density ratio of about 70 to 75% of the short sample limit at 4.2 K. Heat loads to the coil, mainly due to the image currents in the beam chamber walls and synchrotron radiation from the electron beam in the storage ring, will reduce the stability margin. An experiment was conducted to measure the stability margin with steady-state heat loads deposited into a 12-period SCU coil/pole face using thin-film heaters.

This paper describes the design, fabrication of a steel core and SC coil winding on it, as well as test results of a 12-period upper-half SCU up to its critical current density. Initial test results of the thermal stability margins under pool boiling are reported.

SCU DESIGN AND FABRICATION

Plotted in Fig. 1 are the calculations of the vertical peak field B_o on the beam axis in the midplane of the SCU and the coil maximum field B_m(coil) as a function of the average current density in the coil. Also plotted in Fig. 1 is the critical current density J_c(coil) as a function of applied magnetic field B for the NbTi SC wire measured at 4.2 K. The critical current density limits operation beyond 1.4 kA/mm^2 and 3.8 T, indicated by the point at which the curves for the coil maximum field and critical current intersect. At this point, the highest attainable B_o

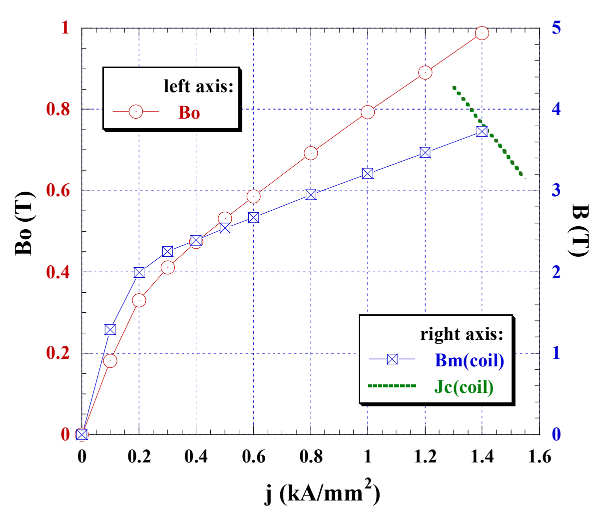

Figure 1: Calculated vertical peak field B_o at undulator midplane (*left axis*) and the coil maximum field B_m(coil) (*right axis*) for the SCU are plotted as a function of the coil average current density j. Also plotted are the critical current density J_c(coil) (*bottom axis*) of the SC coil under applied magnetic field B (*right axis*) at 4.2 K

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on the beam axis would be 1.0 T as indicated by the curve for B_o. The formvar-insulated NbTi SC wire has an approximate Cu/SC ratio of 1.3 and dimensions of 1.05 x 0.77 mm^2. The rectangular grooves in the core for winding the SC coils are 4.32 mm wide and 3.89 mm deep. A 20-turn coil, 4 wide by 5 deep, is wound in this groove. A packing factor of 95% is achieved, which helps reduce conductor positioning errors within the winding grooves. The design peak field of 0.8 T is achieved with a current density of 1 kA/mm^2 as shown in Fig. 1.

One 12-period upper-half SCU was machined from “1008 low-carbon” steel. The cross section of the core is approximately 75 x 40 mm^2. One side of the core is flat and the rest more rounded with additional grooves opposite the flat face to allow winding transitions between periods. The flat side is immediately above the beam plane. Two of these cores, above and below the beam, form the full SCU. 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.

HIGH CURRENT DENSITY TESTS

The 12-period upper-half SCU was tested at 4.2 K in LHe. In the first test, the coil was not epoxy impregnated. The design current density of 1.0 kA/mm^2 was reached after 10 training quenches. A second test was performed after the coil was epoxy impregnated. This time, the coil reached the critical current density limit of 1.4 kA/mm^2 after only two training quenches as shown in Fig. 2. Magnetic field measurements were made using a Hall probe at a distance of 3.6 mm from the magnetic pole face

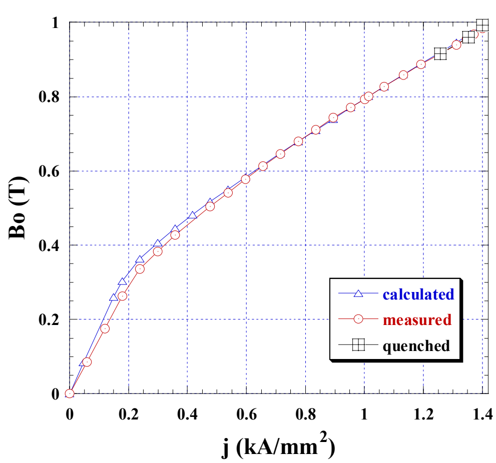

Figure 2: The measured peak field B_o for the upper-half SCU at a fixed distance from a magnetic pole and the quenched fields are plotted. The calculated B_o used the permeability data for 1008 steel.

and adjusted to measure the field component perpendicular to the pole face. Since this measurement is made with only one of the two cores in place, measured values are multiplied by a factor of (2 * 0.8349) to get the undulator field, B_o plotted in Fig. 2 [2]. Figure 2 also shows that the measured fields at low current densities are slightly lower than the calculations. This indicates that the core has a slightly lower permeability than that of the 1008 steel used for the calculation.

In order to assure that these measurements were reproducible and representative of expected performance, the coil and epoxy were removed from the core and another coil was wound and epoxy impregnated. It also reached 1.4 kA/mm^2 with very little training.

THERMAL STABILITY TESTS

In Fig. 3 the two test setups for the heat loads are schematically shown in planes perpendicular to the beam axis. In test setup (a), a thin-film heater (Heater #1) is attached directly to the coil/pole face of the SCU, and, in test setup (b), another thin-film heater (Heater #2) is attached the inner wall of a vacuum chamber that presses against the coil pole face. A photograph of the latter is shown in Fig. 4. The two heaters are identical. They have a cross section of 121 x 11 mm^2 and a thickness of about 0.2 mm including thin insulation on both sides. The stainless-steel vacuum chamber is 0.61 mm thick.

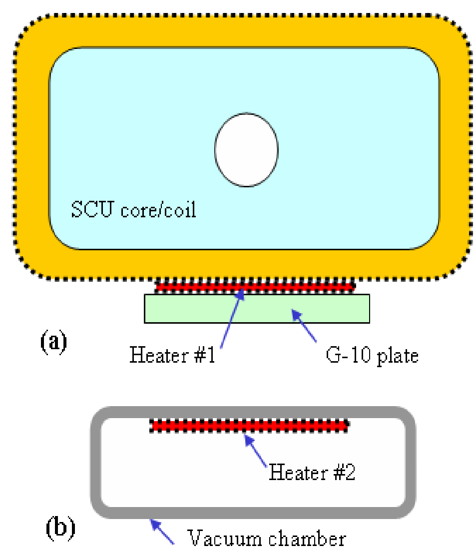

Figure 3: 2-D schematics of the setup for the heat-load tests. (a): Heater #1 was attached to the core/coil flat face of the upper unit of an SCU and was supported by a thick G-10 plate. (b): Heater #2 was attached to the inner wall of a vacuum chamber. Then, the chamber was attached to the SCU core/coil flat face as shown in Fig. 4.

After attaching the heater or the vacuum chamber with heater to the SCU, the setup was firmly wrapped with glass-filament tape so that the contact pressure would not change during the tests. The tape wrapping did not stop the passage of LHe or He vapor to and from the heated interface and other pool-boiling areas. The SCU axis was in the vertical direction during the tests in a vertical dewar.

When there is a thermal disturbance in an adiabatic coil, like a conductor motion or external heat load, the stability margin would depend only on the enthalpy between the operating temperature T_{op} and the current sharing temperature T_{cs}. The calculated T_{cs} at 1 kA/mm^2 is 5.3 K, which gives a temperature safety margin of 1 K from the T_{op} of 4.2 K.

Figure 4: A photo of the vacuum chamber depicted in Fig. 3 (b), attached to the coil/pole face of the SCU before wrapping glass-filament tape around it.

In Fig. 5, enthalpy was calculated for the SC wire between T_{op} and T_{cs}. It was assumed that T_{cs} is a linear function of the operating-to-the-critical current density ratio [3]. When any section of the SC wire in the coil has no direct contact with LHe, the enthalpy may be equivalent to the minimum quench energy of the coil without taking into account the heat transfer or heat diffusion [4].

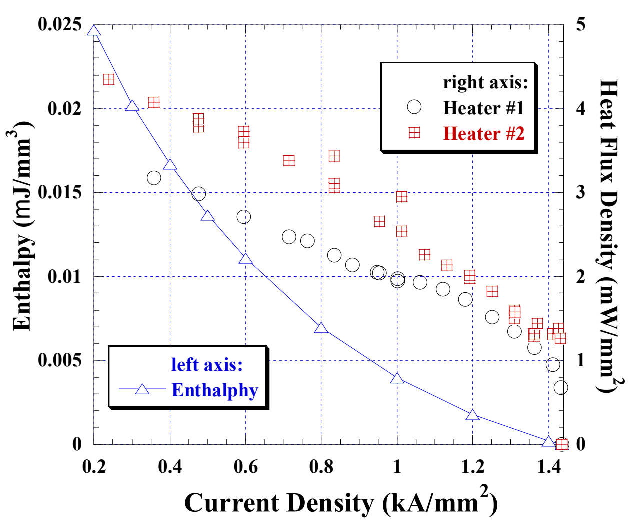

Figure 5: The enthalpy (*left axis*) for the coil is plotted as a function of the current density. For the two heaters in Fig. 3, the steady-state heat-flux densities (*right axis*) to quench the coil are measured in pool boiling

Also plotted in Fig. 5 are the steady-state heat flux densities under test setups shown in Fig. 3, (a) and (b) (described above) that were measured when the coil quenched. During the measurements, the SCU was cooled in pool boiling so that the coil/pole face, Heater #1 and the vacuum chamber were all directly cooled with LHe. The data show that the heat flux density from Heater #2 is somewhat larger than that from Heater #1. This may be due to the fact that, because of the low thermal diffusivity in LHe, the heat flux spreads much faster in the SS vacuum chamber than in the LHe. When the coil is charged with a current density very close to the J_c (~ 1.43 kA/mm^2), the coil should quench without any heat loads. The data in Fig. 5 show that, at a current density of 0.998J_c, the coil did not quench until the heat flux of Heater #2 was increased to 1.3 mW/mm^2. This implies that the heat flux is intercepted by the LHe near the coil/pole and chamber interface area. This is consistent with the large latent heat of vaporization (2.6 mJ/mm^3) for LHe. It is also consistent with earlier studies that, when the SC wire is in direct contact with LHe, the quench energy density increased by an order of magnitude compared to the enthalpy [4]. At a lower current density, where the current-sharing temperature must be higher, higher heat flux may be intercepted.

CONCLUSION

After the design, fabrication and successful tests of a short-section upper-half SCU up to its critical current density, the SCU was stable enough near the design current density to study the impact of external heat loads. Using thin-film heaters, heat-load tests performed in pool boiling indicate that the stability margins were much larger than the expected minimum quench energy density. This was attributed to the large latent heat of vaporization of the LHe in the SCU/chamber interface area and is consistent with earlier studies. Additional tests using aluminum vacuum chambers and analysis with thermal modeling for the test setups are planned.

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