IMPROVED WINDING OF A SUPERCONDUCTING UNDULATOR AND MEASUREMENT OF THE QUENCHING TOLERANCE*

J. C. Jan#, C. S. Hwang, C. H. Chang and F. Y. Lin
NSRRC, 101 Hsin-Ann Road, Hsinchu Science Park, Hsinchu 30076, Taiwan

Abstract

The performance of the superconducting (SC) wire windings of the mini-pole superconducting undulator at National Synchrotron Radiation Research Center (NSRRC) has improved. A precise measurement of the magnetic field was undertaken to examine the quality of the wire winding. We improved the insulation between the wires and the iron pole to avoid degradation of the SC wire when the coil was trained to a large current. A coating (Teflon, layer thickness 0.045±0.02 mm) on the iron pole is capable of providing insulation to 0.5 kV. We pasted extra tape (Teflon, thickness 0.12 mm) on the coating layer; this tape serves as a buffer that prevents the SC wires scraping the coating layer during adjustment of the position of the SC wire during winding. A quenching experiment was performed to measure the tolerance of the coil during extra heating of the beam duct; a heater ($Ni_{80}Cr_{20}$) simulated the heating of that duct with synchrotron radiation. The coil and heater were separated with tape (Kapton, thickness 0.3mm), stainless steel (SS, 316L), beam duct (thickness 0.3 mm), Al foil (thickness 0.1 mm) and an epoxy layer. This result is an important issue for the design of the cryostat and operation of the magnet.

Introduction

The superconducting undulator is a powerful insertion device for which some issues to be clarified include the quality of the magnetic field and the heat-load budget. The quality of the magnetic field depends on the wire winding, including selection of the SC wire and the method of insulation. In previous work, a NbTi wire (diameter 0.44 mm) was wound but exhibited poor quality of the field due to the irregular position of the coil along the pole [1]. Effective insulation between the coil and the iron pole can avoid degradation of the coil when quenching occurs. The heat-load budget directly influences the operation of a magnet when it is installed in the storage ring [2]. In the design of the cryostat, the magnetic array is directly soaked in liquid helium, which introduces an increased heat load on the coil; we therefore measured the heat tolerance of the coil.

Wire winding and experimental setup

A prototype with 40 poles each with 55 turns (40P55T) was wound with NbTi SC wires (0.77×0.51 mm^2), and the quality of the field from non-insulated and Teflon-coated arrays was tested. The insulation layer (Teflon, thickness 0.045±0.02 mm) was constructed of fluorinated ethylene propylene (FEP) and perfluoroalkoxy (PFA) coating with sintering at 350 °C. The insulation layer provided a voltage-resistance to quenching about 0.5 kV between the coil and the iron pole when quenching occurred. A beam-duct prototype (length 576 mm) was manufactured for training and measurement of the 40P55T arrays. The magnetic unit was constructed with the beam duct, a gap block (thickness 5 mm), Hall sensor guides and heater units. The beam duct was assembled from sheets (SS316L thickness 0.3 mm) and frames using laser welding. Fig. 1 (a), (b) and (c) display the profile of beam duct, the assembly of the beam duct and a sketch of the cross-sectional view of the beam duct, respectively.

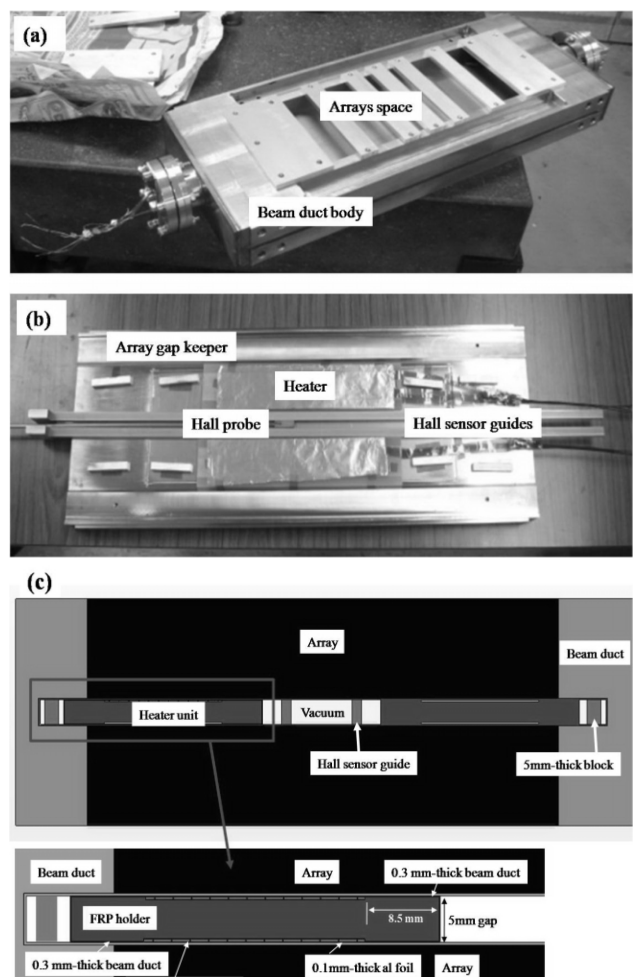

Figure 1: (a), (b) and (c) display the profile of the beam duct, the assembly of the beam duct and a sketch of the cross-sectional view of the beam duct, respectively.

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# janjc@nsrrc.org.tw

A heater unit was inserted between the arrays to simulate heating from synchrotron radiation, and a Hall sensor guide ensured that the Hall sensor moved in the center of the magnet. A block (thickness 5 mm) fixed the beam duct aperture at 5 mm; the array gap is 5.6 mm. The region between the sheet (thickness 0.3 mm) and the beam duct is ultra-high vacuum to guide the electron beam. In the arrays (with Teflon coating), a sheet (Kapton, thickness 0.07 mm) was inserted between the beam duct and the arrays to buffer the winding error caused by the non-uniform thickness of the coating. The sheet of the beam duct, the Kapton sheet and the magnetic arrays were glued together to resist the pressure difference of the sheet (thickness 0.3 mm) on both sides.

Measurement of the magnetic field

The 40P55T arrays with non-insulated and Teflon-coated arrays were mounted in a test Dewar and measured with a mini-Hall sensor (AREPOC Ltd., type HHP-MP). The training of non-insulated and Teflon-coated arrays and the I-B curve is displayed in Fig. 2 (a), (b) and (c), respectively. The non-insulated arrays were trained to 1.45T @ 510A in the first training but degradation of the SC wire occurred in the second and third trainings; in contrast, the Teflon-coated arrays were continuously trained to a field strength 1.42 T @ 527 A in the first training and the maximum current is excite to 548 A in the second training. Figure 2 (c) reveals that the field strength of non-insulated arrays is greater than Teflon-coated arrays because a sheet (Kapton thickness 0.07 mm) was inserted between the arrays and the beam duct. This sheet provided effective contact and insulation between the array and the beam duct because the wire-wound surface was irregular from the non-uniform Teflon coating. The gap of the coated arrays was larger than for the non-insulated arrays by 0.14 mm, for which reason the field strength of Teflon-coated arrays was less than for non-insulated arrays at the same excitation current. Figure 3 (a), (b) and (c) display the magnetic field of non-insulated arrays, Teflon-coated arrays and the field deviation, respectively. The parameters involved in measuring the magnetic field included the range, step and waiting time, which were 450 mm, 0.1 mm and 1 s, respectively. The deviations of the field strength of non-insulated and Teflon-coated cases were less than 1 % and 3 % at the 32-center poles, respectively. The larger deviation of the coated arrays was due to the non-uniform Teflon layer that decreased the precision of the wire winding.

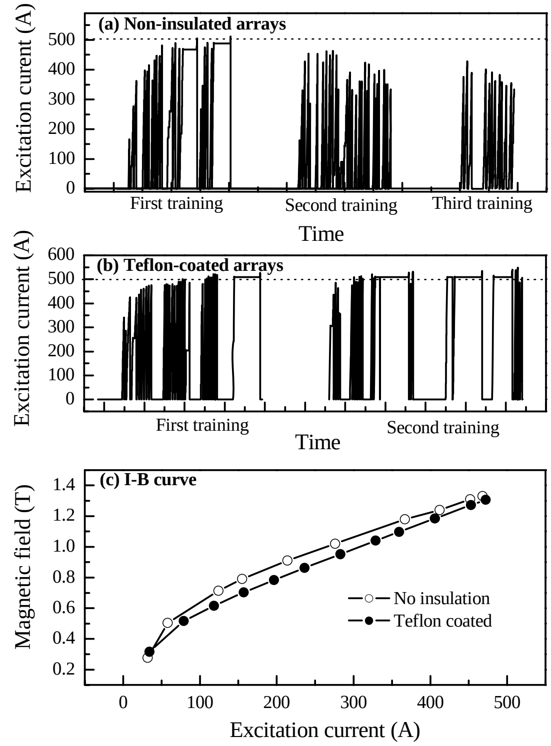

Figure 2: (a), (b) and (c) plot training of the non-insulated and the Teflon-coated arrays, and the I-B curve, respectively. Degradation of the SC wire in the non-insulated arrays occurred.

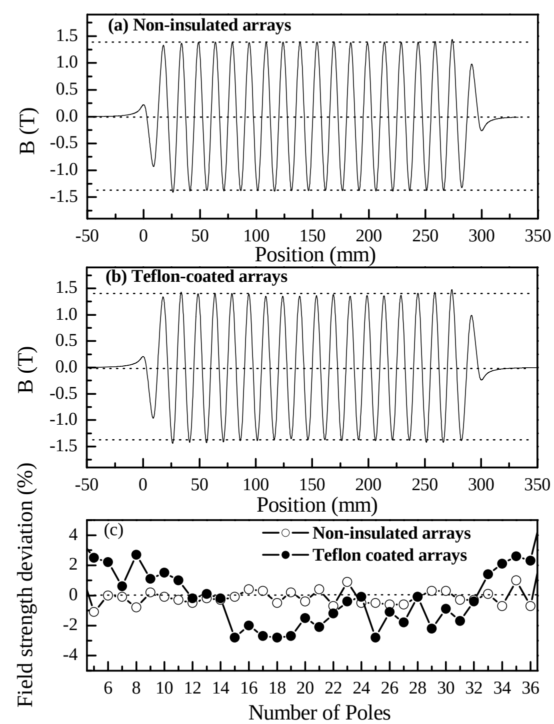

Figure 3: (a), (b) and (c) display the magnetic field of non-insulated and coated arrays, and their field deviations, respectively. The deviations of field strength for the non-insulated and coated arrays were less than 1 % and 3 % at the 32-center poles, respectively.

SC wire quench tolerate measurement

To simulate the heating of the beam duct from synchrotron radiation, a heater unit was inserted in the beam duct; the insert in Fig. 4 displays the cross section of the heater unit. The heater was wound with $Ni_{80}Cr_{20}$ wires (non-magnetic alloy, dimension 0.1 mm) and insulated with tape (Kapton, thickness 0.3 mm). The heated area of the beam duct was 4250 mm^2 (170 mm×25 mm); the total resistance was 302 Ω @ 300 K (294.4 Ω @ 4.2 K). A holder (Fiberglass-Reinforced Plastics, FRP) provided poor thermal conduction between liquid helium and the heater. Al foil (thickness 0.1 mm) was wrapped on the FRP and the heater to effect uniform heating. According to thermal analysis (Ansys softwave, data not shown here), the heat was uniformly conducted to the coil passing through the tape (Kapton, thickness 0.3 mm), Al foil (thickness 0.1 mm) and beam duct (thickness 0.3 mm). Most flux from the heater was conducted to the arrays; only about 3 % of the heat flux passed through the FRP (thickness 8.5 mm) leak to the liquid helium. A variable resistance fine-tuned the current passing through the heater; a precision multimeter (HP3458A) monitored the current. Figure 4 shows the tolerance of the heat load of the coil when coil quenching occurred in the liquid helium. This tolerance was inversely proportional to the strength of the magnetic field; for 0.79 mW/mm^2 on the coil, quenching occurred at 1.4 T. In estimating the heat load, the edge field of the bending magnet (BM) was considered and the total heat load of synchrotron radiation on the beam duct was 1.1 W [3]. To compare the quenching tolerance of the coil and the heat-load budget of the magnet, the local heating per mm^2 region was calculated. According to the distribution of synchrotron radiation at the BM, the maximum local heating on the beam duct occurred at the center with the end of beam duct; the local heat was 0.003 mW/mm^2. The heating from the image current was 0.223 mW/mm^2 when RRR=60 of copper coating, anomalous skin effect and TPS parameter was considered [4]. The thermal radiation between the vacuum at 300 K and the beam duct at 4.2 K was 0.009 mW/mm^2 when the emissivity of the copper coating within the beam duct was considered. The emissivity of copper coating was simulated with a copper foil tape, 0.02 $W/m^2 K^4$. The maximum local heating is thus 0.235 mW/mm^2 at the location of the center with the end of the beam duct, which implies that the mini-pole SC wire can withstand normal operation in the storage ring.

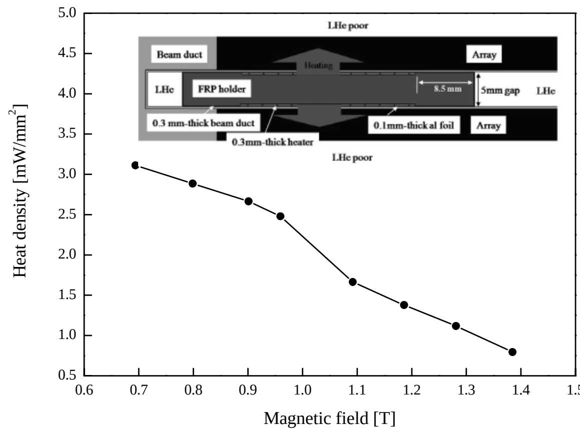

Figure 4: Measurement of the tolerance of the coil to a heat load when coil quenching occurred in liquid helium. The insert figure shows a sketch of the cross section of the heater unit.

Summary

A Teflon coating of thickness 0.045±0.02 mm can avoid coil degradation but diminishes the quality of the magnetic field. The magnetic field of the non-insulated and Teflon-coated arrays had 1 % and 3 % deviations, respectively, at the 32-center pole. A sheet (Kapton, thickness 0.07 mm) inserted between the arrays and the beam duct ensured effective contact and insulation. The gap of the coated arrays is larger than of the non-coated arrays by 0.14 mm and the field strength of the coated arrays is less than that of the non-insulated arrays. A measured heat tolerance 0.79 mW/mm^2 of the coil was compared with local heating calculated to be 0.235 mW/mm^2. The SC wire can thus withstand normal operation in the storage ring.

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