Development of a Superconducting Undulator Prototype at the SSRF

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***Abstract*—Development of a 50-period superconducting undulator prototype is underway at the Shanghai Synchrotron Radiation Facility. The prototype is composed of magnetic system, cooling system, and cryostat. The SCU magnet system has a period length of 16 mm and a magnetic gap of 9.5 mm. The coils are wound with NbTi/Cu conductors. The design operation current is 400 A to produce a peak field on axis of 0.67 T. The cooling system includes four cryocoolers and independent cooling circuits for magnet and the beam vacuum chamber. The manufacturing of the magnet and beam vacuum chamber is in progress. The cooling test of the cryostat was performed using a dummy load. Stand-alone test of the prototype is planned in December 2016. Installation into the storage ring is scheduled in July 2017.**

***Index Terms*—Synchrotron radiation, undulators, cryogenics, superconducting magnets.**

I. Introduction

SUPERCONDUCTING technology has been successfully employed in insertion devices such as wiggler and undulator for synchrotron light sources [1]–[4]. At given period length and vacuum gap, superconducting undulator may produce higher magnetic fields than conventional permanent magnet and hybrid undulators, thus may increase photon energies and fluxes [5].

A superconducting planar undulator (SCU) is being developed at the Shanghai Synchrotron Radiation Facility (SSRF) to accommodate the increasing demand of light source users [6]. Short magnets were built and tested for feasibility study as reported in [7], [8]. Based on results of the short magnets, design of the SCU was modified and improved. Then a prototype with 50 periods will be built and tested in the storage ring. The 50-period SCU is composed of magnet system, cooling system and cryostat. Superconducting coils of the SCU magnet are wound with NbTi/Cu conductors. The period length is 16 mm and the magnetic gap is 9.5 mm. Design operation current of 400 A produces a peak field on axis of 0.67 T. Cooling system includes 4 cryocoolers and independent cooling circuits for magnet and the beam vacuum chamber. Specifications of the SCU prototype are presented in Table I. Design for each component of the 50-period prototype is described in this paper in detail. Cooling test results of the cryostat are also presented.

TABLE I
SPECIFICATIONS OF THE 50-PERIOD SCU PROTOTYPE

Parameter	Value
Electron energy (GeV)	3.5
Peak field on axis (T)	0.67
Number of periods	50
Period length (mm)	16
Magnetic gap (mm)	9.5
Vacuum gap (mm)	7.5
Winding	NbTi/Cu
Length of cryostat (m)	1.8

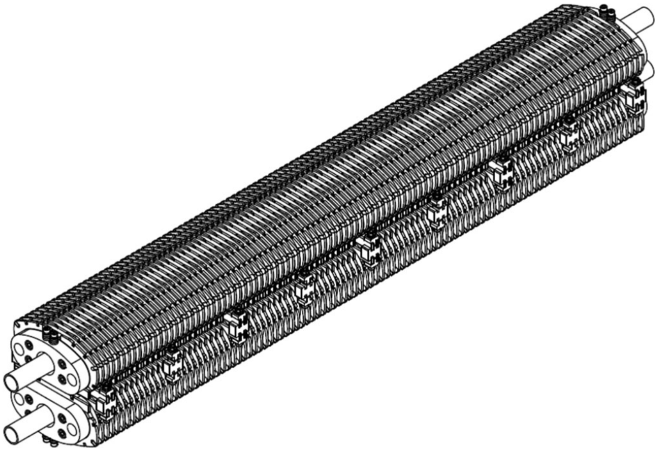

Fig. 1. Design model of the 50-period SCU magnet.

II. SCU Magnet

The SCU magnet is composed of a top and a bottom part with a vertical gap in between to accept the beam vacuum chamber. The top and the bottom parts have identical structure. The magnetic core was ground, polished and precisely machined with slots on it. Then magnetic poles manufactured with high precision were inserted in slots to form a series of grooves, which is similar to the design of Advanced Photon Source (APS) of Argonne National Laboratory. Fig. 1 shows the design model of the 50-period SCU magnet. The material of core and pole is electrical pure iron (DT4C). Superconducting coils were wound into the grooves with opposite current flow direction in adjacent coil packs.

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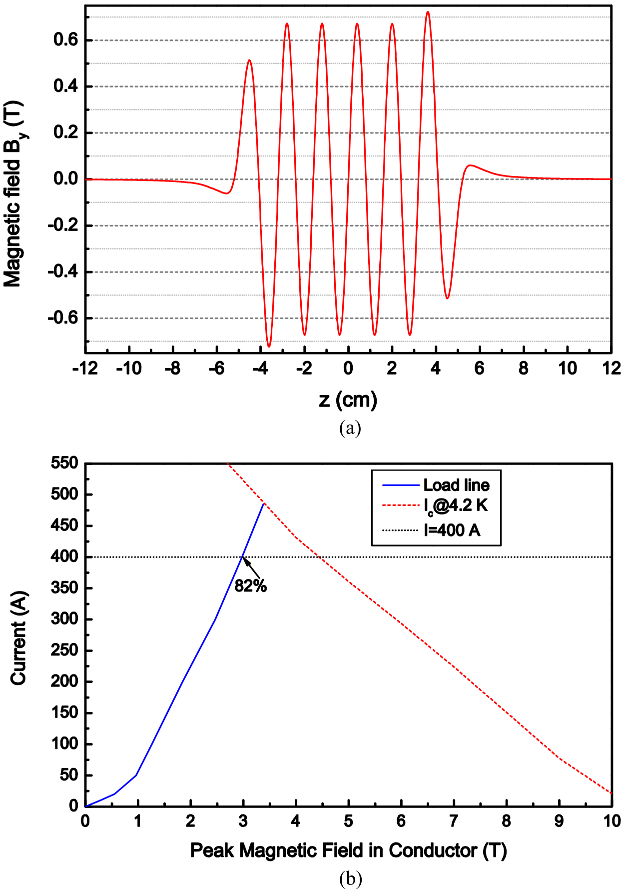

(a)

(b)

Fig. 2. (a) Calculated field profile of a short 3-D model. The magnet current is 400 A. (b) Load line of the superconducting magnet for the 50-period SCU prototype.

Round NbTi/Cu wire with the diameter of 0.6 mm (including insulation) from Western Superconducting Technologies Co., Ltd. (WST) was chosen for winding. The specifications of the NbTi/Cu wires can be found in [7]. The magnetic design is based on simulation results using the OPERA software package. The design was modified from previous report [7], [8], i.e. the magnetic gap was increased from 8 mm to 9.5 mm to accommodate the beam vacuum chamber. Thus the operating current was increased from 387 A to 400 A in order to generate a peak field on axis of 0.67 T. The SC wires are at 82% of the critical current value at 4.2 K. The calculated field profile of a short model is shown in Fig. 2(a) and the load line is presented in Fig. 2(b). The calculated temperature margin is about 0.8 K. The minimum quench energy (MQE) was estimated to be about 5 μJ.

The grooves for winding have a cross section of $5.2 \times 6.5\,\text{mm}^2$. A continuous winding scheme with a single strand and no splices was adopted. Instead of winding odd grooves first then back to even grooves as described in early papers [7], [8], the winding direction altered for adjacent grooves through reversing rods on sides of the iron core. The regular (full) grooves have 83 turns and the coil cross section of $4.98 \times 5.8\,\text{mm}^2$. The filling factor is 69%. Parameters of the SC coils are shown in Table II. Electrical insulation was a critical issue encountered during the development. Ceramic coating and thin G10 sheets were applied to short magnets, which were investigated by voltage test. For the 50-period prototype, Kapton films are placed on bottom of grooves and G10 sheets are used on sides of the grooves. The insulation can withstand 500 V with a leakage current less than 1 mA.

TABLE II
SPECIFICATIONS OF THE SUPERCONDUCTING COILS

Parameter	Value
Width of coil section (mm)	4.98
Height of coil section (mm)	5.80
Number of layers	11
Turns per layer	7/8
Total turns	83
Rated current (A)	400
Peak field in coils (T)	2.93

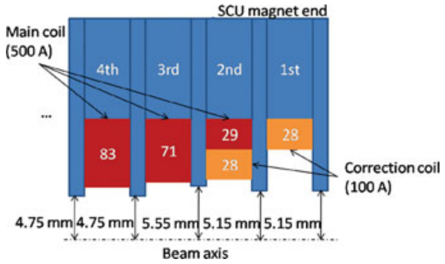

Fig. 3. End design of the superconducting magnet for the 50-period SCU prototype. The turn numbers of the end grooves are presented. The first, second and third end poles are vertically reduced by 0.4, 0.4, and 0.8 mm, respectively. The main coil is powered by a power supply of 500 A. Two sets of correction coils are powered by two power supplies of 100 A separately.

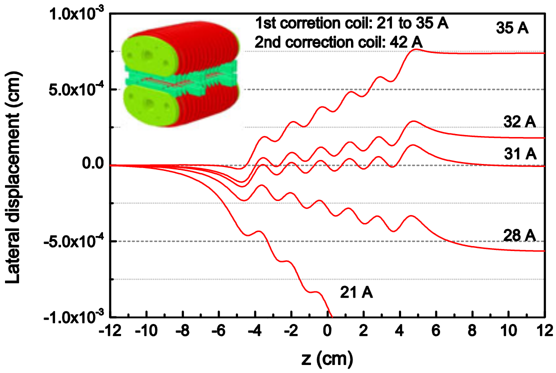

Fig. 4. Election trajectories of the 6-period model with end design. Current of the second correction coil was set to 42 A. Current of the 1st correction coil varies from 21 to 35 A. Inset shows the 3D numerical model.

The end design for tuning field integrals is as follows. The first, second and third end grooves contain 0, 29 and 71 turns, respectively. Meanwhile, as shown in Fig. 3, the first, second and third end poles are vertically reduced by 0.4, 0.4 and 0.8 mm, respectively. Two sets of correction coils with 28 turns each were wound in the first and second end grooves on top of the existing winding and separately powered. Identical type of NbTi wires are used for the correction coils and the main coil. Feasibility of the end design was investigated by numerical simulation. The electron trajectories of a 6-period model are shown in Fig. 4. Current of the 2nd correction coil was set to 42 A. Current of the 1st correction coil varied from 21 to 35 A. the lateral displacement of the electron beam can be limited to

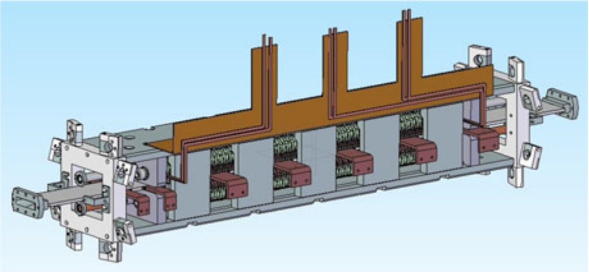

Fig. 5. Design model of the 50-period SCU magnet with frame and power leads.

less than 60 nm and may be further adjusted by varying current of the 2nd correction coil.

After winding, the assembly will be impregnated with epoxy resins. The magnet frame is made of aluminum. One pair of 500 A power leads for the main coil and two pair of 100 A power leads for correction coils are installed on the copper plate connected with the frame. Fig. 5 shows the design model of the magnet with frame and power leads.

Quench protection scheme was developed to limit hot-spot temperature to less than 150 K and internal voltage to less than 500 V in the coil. The quench protection circuit includes two pair of cold diodes, subdivisions and a Multi-quench detector (DANFYSIK, P-83826). Details will be reported elsewhere.

III. Cryostat and Cooling System

The design of SCU cryostat is similar to that of the Advanced Photon Source [4] and the Budker Institute of Nuclear Physics (BINP) [9]. The cryostat is a stainless-steel vacuum vessel with a length of 1.8 m, and contains a copper thermal shield and a cold mass. The cold mass is composed of the superconducting magnet, power leads for the magnet, a beam vacuum chamber, a 30-liter liquid helium tank, cold mass supports and instrumentations. The binary power leads consist of copper parts from room temperature to 60 K and high temperature superconducting (HTS) parts from 60 K to 4.2 K. The beam vacuum chamber is fabricated using extruded aluminum alloy 6063 with two stainless-steel transitions on both ends. The LHe tank has piping to form a closed 4-K circuit. The cold mass support system is designed to support the magnet, 60 K thermal shield and the beam chamber. The authors point out that there were two thermal shields in previous design [10]. In the latest design, the 20 K thermal shield is eliminated. The self-centering structure is adopted for magnet support to maintain magnet axis stable after cool down. Eight strap assemblies (four at each end of the magnet) hold the weight of about 140 kg and the thermal stress. The beam vacuum chamber inserted in the magnetic gap is supported by twelve G10 spacers distributed symmetrically along the beam axis at both sides. Thus the beam chamber is thermally isolated from the magnet, and the heat load from the beam on the magnet is substantially reduced. The 60 K thermal shield of 165 kg is supported by eight G10 rods (4 horizontal and 4 vertical) with diameter of 5 mm. Details of the cold mass support are reported in [11].

The SCU cooling system includes four 2-stage cryocoolers (type KDE-415 from Nanjing 724 Pridetech Co., Ltd.), which are divided into two groups. The superconducting magnet is cooled indirectly by LHe flowing through cooling channels inside the magnet cores. Pressure test using Helium gas shows that the cooling channel can withstand 1.2 MPa at 77 K. Evaporated Helium gas is recondensed by second stages of two cryocoolers in group one. Each cyrocooler has a cooling capacity of 1.5 W at 4.2 K. The LHe flow is driven by thermosiphon cooling loops between the condenser and the magnet. The low-temperature end of copper and HTS parts of the power leads are cooled by the first and second stages of two cryocoolers in group one, respectively. The beam vacuum chamber is cooled by second stages of two cryocoolers in group two. Each cryocooler has a cooling capacity of 21 W at 20 K. The beam heat load is estimated to be 24.4 W [12]. The 60 K thermal shields are cooled by first stages of four cryocoolers. Table III lists the design heat loads on the system and available cooling capacities at 4.2 K, 20 K and 60 K.

TABLE III
Design Heat Load at 4.2 K, 20 K and 60 K (Units: Watts)

Heat source		at 4.2 K	at 20 K	at 60 K
SCU magnet	Radiation heat	0.101		0
Vacuum chamber	Beam		24.4	
Cryostat	Radiation heat	0.268		8.097
	Conduction heat through piping and supports	0.170		6.496
	500 A HTS leads	0.130		46.008
	100 A HTS leads	0.096		13.803
	Instrument wires	0.050		0
Total		0.815	~ 24.4	74.404
Cooling capacity		3	42	171.1

IV. Cryogenci Test

The fabrication of the magnet and beam chamber is in progress. Therefore the cryostat was tested first with a dummy load, which simulates the magnet without the beam vacuum chamber. The cool-down test started on January 8, 2016. Fig. 6 shows the test site of the cryostat. Cooling of the system was performed using cryocoolers. The helium circuit was pressurized with pure helium gas to speed up the cooling process. No liquid Nitrogen or LHe was used. Cool-down was completed after 58 hours. It took 89 hours to accumulate LHe to fill 90% volume of the helium vessel. A heater of 0.8 W was placed on the LHe vessel to avoid subatmospheric operation. The temperature traces of the representative positions of the cryostat are shown in Fig. 7. Fig. 7(a) includes cool-down curves of the 1st stages of 4 cryocoolers, thermal shields, low-temperature end of the copper leads and high-temperature end of the HTS leads. Fig. 7(b) presents cool-down curves of the 2nd stages of cryocoolers in group one, Helium vessel and low-temperature end

Fig. 6. The 50-period SCU cryostat and the test site.

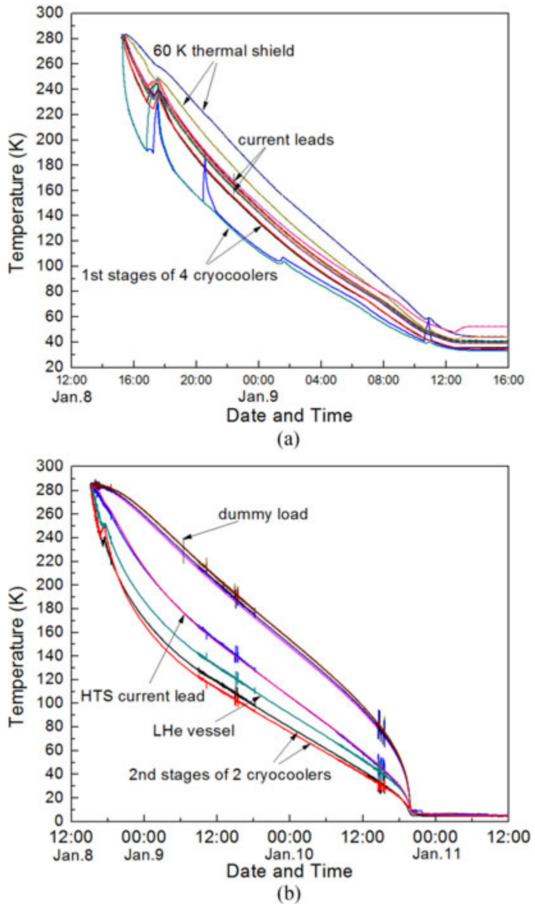

Fig. 7. Temperatures in the SCU cryostat during cool-down. (a) Cool-down curves of the 1st stages of 4 cryocoolers, thermal shields, low-temperature end of the copper leads and high-temperature end of the HTS leads. (b) Cool-down curves of the 2nd stages of cryocoolers in group one, Helium vessel, dummy load and low-temperature end of the HTS leads.

of the HTS leads. The spikes on the temperature curves are due to temporary shutoff of the cryocoolers. The measured average temperature of the cold mass is 4.5 K, higher than the design value of 4.2 K. The test heat load at 4.2 K is 1.8 W, including static heat load of 1 W and the heater of 0.8 W mentioned above. The measured temperature of the 60 K thermal shield is 38 ∼ 45 K. The test heat load at the thermal shield is about 100 W. The design of SCU cryostat and cooling system will be further verified by stand-alone test with real magnet and beam vacuum chamber.

V. SUMMARY

A 50-period superconducting undulator prototype is being developed at the SSRF. Short magnets were designed, built and tested for feasibility study. The magnet system and beam vacuum chamber are being manufactured. The cryostat and cooling system were designed and fabricated. The cool-down of the cryostat was successfully performed with a dummy load simulating the magnet without beam vacuum chamber. The beam chamber will be included in the off-line test planned in December 2016. Installation into the storage ring is scheduled in July 2017.

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