CONSTRUCTION AND PERFORMANCE OF SUPERCONDUCTING MAGNETS FOR SYNCHROTRON RADIATION*

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Abstract

Two superconducting magnets, one wavelength shifter with a field of 6 T and one wiggler with a field of 3.2 T, were constructed and routinely operated at Taiwan Light Source to generate synchrotron X-rays. Additionally, three short multipole wigglers with the same field of 3.1 T are under construction and will be installed in the three achromatic short straight sections. A warm beam duct with an inner gap of 20 mm and a 1.5 W GM type cryo-cooler were used in the wavelength shifter to achieve cryogen-free operation. For the 3.2 T wiggler, a cold beam duct with an inner gap of 11 mm was kept at 100 K temperature and no trim coil compensation is necessary for its operation. Meanwhile, no beam loss was observed when it was quenched. The design concept, magnetic field quality, and the commissioning results of these magnets will be presented.

INTRODUCTION

The demand for intense hard X-rays up to 33 keV has been increasing in recent years from the users of Taiwan Light Source (TLS) in the areas of protein crystallography and advanced material research. A 6 T superconducting wavelength shifter (SWLS) [1,2] and a 3.2 T superconducting wiggler with a period of 6 cm (SW6) [3,4] were installed in the TLS storage ring in May 2002 and Jan 2004, respectively. The SWLS is a cryogen-free design and was installed in an 83.5 cm long free space between the third and fourth kicker magnets in the injection section. The magnet length includes the cryostat vessel is 61 cm and the magnet provides three X-ray beamlines with photon energies between 5 and 33 keV. The SW6 has 32 poles with a total length of 140.5 cm and is located at the down-stream of the superconducting RF cavity in the fourth straight section. The SW6 provided X-rays for three protein crystallography beamlines with energies between 5 and 20 keV. Nowadays, these two superconducting insertion devices are operated routinely and the beamlines have been open to general users. In addition, three short In-Achromate superconducting wigglers (IASW) with a period of 6 cm and a total length of 96 cm are to be constructed. Each IASW will provide X-rays for two beamlines for high energy photonemission, small angle scattering, and liquid spectroscopy. The magnet will be installed in the short straight section between the arcs of the bending magnet.

Table 1 lists the main parameters of the superconducting insertion devices. The flux of the IASW at 15 keV is 15 times larger than that from W20 at TLS. A independent cryoplant [5] will be built to provide LHe for the five superconducting magnets. The cryoplant can also be switched to provide LHe for the superconducting RF (SRF) cavity, to help backup in case of imergency or maintenance of the SRF cryoplant.

Table 1: The Design Parameters of the Various Superconducting Insertion Devices at NSRRC

	SWLS	SW6	IASW
Magnet length (cm)	83.5	140.5	96
Periodic length (cm)	---	6.1	6.1
Periodic number	---	16	8
Superconductor size (mm)	1 x 1.9	0.52 x 0.78	0.65
Superconductor Cu/SC	3	1.34	1.33
Peak field at coil Bm (T)	6	4.9	5
Critical current at Bm (A)	566	380	356
Operation current (A)	215	285	260
Magnet gap (cm)	5.5	1.8	1.9
Clear Horizontal (vertical) aperture of beam duct (cm)	10 (2.0)	8 (1.1)	10 (1.1)
LHe boiling off (l/h)	0	$\leq$ 3	$\leq$ 3
Beam duct temperature (K)	300	100~300	90~300
Peak filed [T]	$\geq$ 5.0	3.2	3.1
Average excitation rate [A/s]	$\geq$ 0.5	$\geq$ 1	$\geq$ 1
Critical energy [keV]	$\geq$ 7.5	$\geq$ 4.8	$\geq$ 4.64
Radiation cone (mrad)	69	6	5.9
Total power (kW) @ 500 mA	6.8	6.4	3.0

MAGNET DESIGN, CONSTRUCTION AND COMMISSIONING RESULTS

The SWLS was designed as a compact cryogen-free magnet with a magnetic field of 6 T [1]. In contrast, the SW6 is designed in a liquid helium bath, consuming 2.5 L/h with a gaseous helium warm return. Finally, the three IASWs are also designed in a liquid helium bath and with helium gas cold return.

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SWLS Superconducting Wavelength Shifter

The flange-to-flange distance of the SWLS, including the length of beam duct taper, the cooling water pipes, and BPM, is only 83.5 cm. This magnet is conduction-cooled by a 1.5 W GM-type cryo-cooler, and the surfaces of the contact between the conduction parts are carefully joined by soft solder. Flexible S-shaped OFHC copper was used to connect the 4.2 k mass and the second stage of cold head, to reduce the vibration of the cryo-cooler. A cold head damping support was designed and constructed to reduce the effect of cryocooler vibration on the magnet. The SWLS can also be operated in the liquid helium mode in order to provide higher magnetic flux density.

Special multipole correctors with finger poles in upstream and downstream of the SWLS are employed to shim the multipole components, especially for the intrinsic quadrupole strength shimming. Since the electron orbit at the center pole was offset by 7.3 mm, there exists quadrupole strength if the field was integrated along the true orbit (see Fig. 1). Although, the calculated integral quadrupole strength along the straight orbit is quite small. Its value along the true orbit is 565 G which is much larger than 20 G of the specification value. Figure 1 also reveals the integral field distribution measured on the transverse axis using a Hall probe and stretch wire measurement systems [2]. The normal and skew multipole components have been compensated by the multipole correctors to meet the specified values [6]. The on-axis field measurement and the transverse roll-off were measured by Hall probe. The ΔB/B was within 0.06%, at ±10 mm [2] and the first and second integral fields are corrected by the dipole corrector magnets. The radiation angle is very large (Table 1) and the electron orbit at the center pole was offset by 7.3 mm. Therefore the ceramic chamber of 4th kicker downstream of the SWLS had to be wide enough to prevent SWLS radiation from hitting the ceramic chamber.

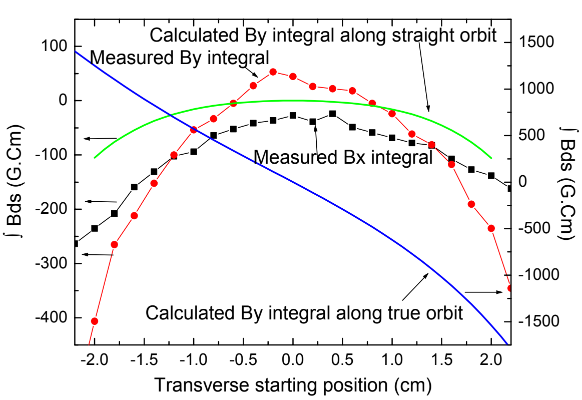

Figure 1: Field integral along the true and straight orbit starting from different transverse positions. Solid and dashed lines are the calculated and measured field integral, respectively.

After the SWLS was cooled down, the SWLS was charged and tested using a low electron current. A look-forward table for field compensation was then obtained by incrementally increasing the SWLS field-strength from zero to 6 T. Finally, electrons were injected after the magnet was charged to the nominal field. The tune-shift effect of SWLS was also measured as a reference for adjusting the working tune [6,7]. Injection with fully charged SWLS was accomplished without difficulty. The measured tune shifts and the path-length compensation (RF was increased by 1.7 kHz at 6 Tesla), are consistent with the values predicted by modeling. In the top-up injection, quadrupoles Q2 and Q3 were used to compensate for the tune-shift effect of SWLS at 6, 5.3 and 5.0 T, while the working tune of the TLS storage ring was fixed at (7.304, 4.16).

3.2 T Superconducting Wiggler

The key issues concerning this magnet are the construction quality of the magnet array, i.e. coil and iron pole, and the cryogenic heat intersect of the beam duct. The magnet array has been designed and constructed [3,4] successfully. The beam duct aperture design is discussed herein.

A magnet gap separator made of aluminum bars maintains a precise magnet gap of 18 mm into which the 4.2 K aperture beam duct is inserted. Figure 2 shows the aperture cross-section of the aluminum UHV beam duct and the 4.2 K stainless steel aperture duct. A thermally shielded, specially shaped aluminum beam duct was used to prevent the heat load from heating the magnet coil. Thus, the magnet gap of 18 mm can insert the aluminum beam duct and 4.2 K aperture duct. The aluminum beam duct has 11 mm inner vertical aperture and a thickness of 1.2 mm in the central region. A 1.2 mm gap between the Al beam duct and the 4.2 K duct prevents the beam duct from touching the 4.2 K aperture duct. Sixteen 5.1 mm-long G10 rod bumpers with a diameter of 1 mm were fixed to the UHV beam duct. The gap between the bumper and the 4.2 K aperture duct was approximately 0.6 mm, ensuring that the only contact between the beam duct and the 4.2 K duct was the G10 rods that reduce the conducted heat load. The aluminum beam duct was supported and fixed at both ends of the 4.2 K aperture duct using a G10 with a thickness of exactly 1.2 mm. The Al beam duct was thermally intersected at 100 K by two copper plates connected to the liquid nitrogen (LN_2) vessel plate, on both of the outer ends of the 4.2 K vessel.

Thirteen training events of SW6 yielded a nominal current of 285 A and a field of 3.2 T. The UHV pressure of the beam duct is maintained at an almost constant value (0.5-0.8 nTorr), regardless of whether the beam duct is warm or cold, and of whether a stored beam (of up to 200 mA) is present. The boil-off rates of LHe and LN2 are around 2.5 L/h and 1.6 L/h at magnet excitation current of 285 A, respectively.

The option of using trim coils on the SW6 magnet to compensate for the first and second field integrals is available, but this option is not needed because the field quality is very close to the designed value. The commissioning results show that the tune shift effect of SW6 is highly consistent with the value predicted by the

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model calculation [6,7], and no unexpected horizontal tune shift is caused by the potential misalignment of the magnet structure. When the magnet quenches or the powers supply is tripped suddenly, the electron beam current survives without beam loss, as shown in Fig. 3. The commissioning with electron beam was found to be smooth and successful.

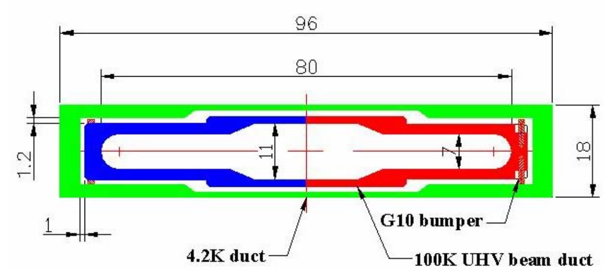

Figure 2: Coss-section of aluminum UHV beam duct and 4.2 K vessel aperture duct (unit: mm).

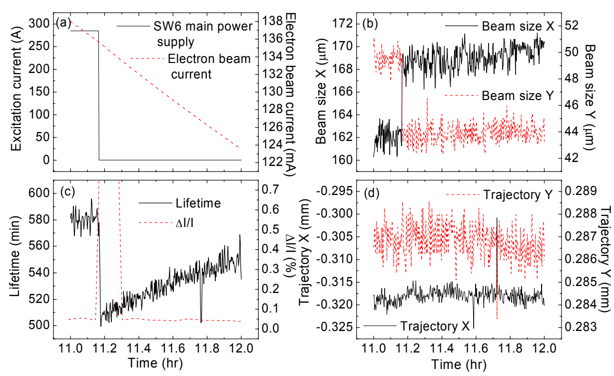

Figure 3: The variation of (a) electron beam current, (b) electron beam size, (c) lifetime and photon flux, and (d) electron orbit before and after SW6 quenching.

IASW Superconducting Wiggler

The design of the IASW is similar to that of the SW6. However, the design of the cold return helium gas is adopted for the IASW. In the cold return design, a liquid nitrogen reservoir is in direct contact with the HTS current lead via the thermal-intersect to maintain the temperature at 80 K. An additional liquid nitrogen reservoir is needed to keep the UHV beam duct at 90 K. Furthermore, the IASW is close to the down stream of the bending magnet. The inner horizontal and vertical aperture of the UHV beam duct is 100 x 11 mm to prevent the synchrotron radiation from heating the beam duct. Hence, the magnet gap is maintained at 19 mm to accommodate the thickening of UHV beam duct.

The NbTi superconducting wire with a diameter of 0.64 mm was selected for the coil design. A five-pole prototype magnet was constructed and tested in the vertical test dewar. A nominal field strength of 3.1 T was obtained at an excitation current of 260 A after quenching eight times (The design current was 266 A). The maximum excitation current achieved on the five-pole was 284 A. A complete 16-pole magnet was completed and trained in the same test dewar. Figure 4 depicts the magnetic field and the second integral field of the 16-pole magnet measured in the vertical test dewar. No trim coil was needed to correct the magnetic field. The electron trajectory was quite straight.

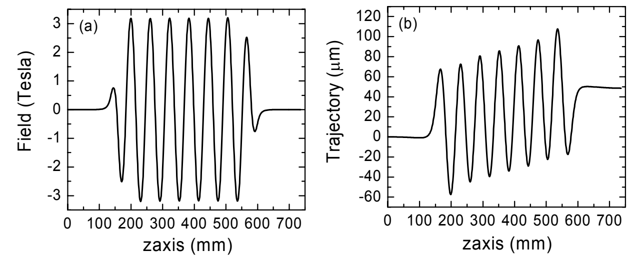

Figure 4: Field measurement in the vertical tests dewar (a) magnetic field distribution and (b) second field integral distribution.

CONCLUSION

The operation of the cryogen-free SWLS using a cryocooler is found to be easy. However, the maintenance of the cryocooler should be carefully conducted to ensure normal operation. The cryogenic interface with the cryogenic plant and the operation of the magnet inside the LHe bath is quite complicated. The magnet can be operated quite reliable if the cryogenic plant is reliable. Additionally, an aluminum beam duct with a temperature at 90 K was designed for use in IASWs, and represents good solution to the vacuum problem. The magnet testing results verify that the magnet performance is close to the design. Even pole design is the favorable choice for a superconducting wiggler or undulator.

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