Commission of the Superconducting Insertion Devices

The demand for intense hard X-rays up to 33 keV has been increasing in recent years from users in protein crystallography, material science, and scattering experiments. To meet this demand from users of NSRRC, two superconducting insertion devices, the superconducting wavelength shifter (SWLS) and the superconducting wiggler (SW6), have been constructed, installed, and commissioned with electron beam. Three more superconducting wigglers will be constructed in the near future. The article describes the performance of SWLS and SW6.

We began to design and contruct the SWLS in 1999 and completed the installation in 2002. The SW6 project started in 2002 and was completed in April 2004. Table 1 lists the specifications of SWLS and SW6. Fig. 1 shows the spectra of the X-ray source in NSRRC.

Since cryogenic plant was not available until early 2004, a compact cryogen-free SWLS with a magnetic field of 5 T was designed. The SWLS can operate in the liquid helium mode to meet the requirement of high magnetic flux density. The flange-to-flange distance of the SWLS, including the beam duct taper, the cooling water pipes, and BPM, is only 835 mm. This magnet is conduction-cooled by a 1.5 W GM-type cryo-cooler, and the surface contact between the conduction parts is carefully joined by soft solder. A flexible S-shape 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. Mechanisms for damping the cold head support are also considered. Trim correctors located upstream and downstream of the SWLS are used to compensate for the multipole components and the first integral field strength, thus supporting the magnetic multipole field shimming of SWLS. The integral field distribution was measured along the transverse axis using a stretch wire measurement system following multipole and trajectory shimming. The field distribution was analyzed to give multipole components; the resulting normal (skew) multipole components, –20 (-20) G-cm, 40 (13) G, -70 (-40) G/cm, -4 (0.5) G/cm^2 are all close to the specified values. The field homogeneity of the central pole was measured using a Hall probe mapping system, and the roll-off range of $\Delta B/B$ was within 0.06%, at ±10 mm. The maximum electron deviation is 7.3 mm at the magnet's center at magnetic flux density of 5.0 T. The radiation angle is very large (Table 1) and the electron orbit at the center pole is offset by 7.3 mm. Thus the ceramic chamber of kicker 4 downstream of the SWLS should be wide enough to avoid the huge heat load resulting from SWLS radiation. Fig. 2 shows the power distribution of the SWLS radiation 0.532m downstream from the magnet center at 400 mA beam current, which also serves to define the aperture of the ceramic chamber of kicker 4 to avoid damage of the ceramic chamber.

The SWLS was installed in the injection section between kickers 3 and 4 of the storage ring in

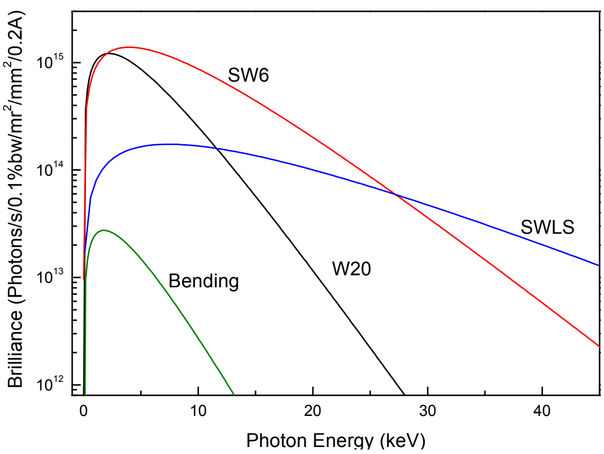

Fig. 1: Spectra of the X-ray sources from insertion devices and bending magnet. SW6 is a superconducting wiggler with 28 effective poles (and a periodic length 6 cm) and a magnetic field of 3.2 T, installed in January 2004.

Table 1: Parameters of the superconducting insertion devices of SWLS and SW6.

	SWLS	SW6
Flange to flange of magnet (cm)	83.5	140.6
Magnet gap (cm)	5.5	1.8
Clear Horizontal (vertical) aperture of beam duct (cm)	10 (2.0)	8 (11)
LHe boiling off	0	≤4
Beam duct temperature (K)	300	100~300
Peak filed (T)	≥5.0	≥3.2
Average excitation rate (A/s)	≥0.5	≥0.8
Critical energy (keV)	≥7.5	≥4.8
Total radiation angle (mrad.) [70% of flux @ 0 mrad & 20 keV]	± 65 [± 22]	±6 [±3]
Photon beam size and divergence σ_r (σ'_r)(μm),(mrad)@20 keV	0.03(0.17)	0.04 (0.17)
Total power (kW) @ 500 mA	6.8	6.4

April 2002 (see Fig. 3). Commissioning such a superconducting insertion device in the injection section was a challenging task. In May 2002, the electron injection was pre-tested successfully before the SWLS was cooled and charged, indicating that the reduced aperture of the modified ceramic chamber of kicker 4 was acceptable. After the SWLS was cooled, the SWLS was charged and tested using a small stored beam. A look-forward table for field compensation was then measured by incrementally increasing the SWLS field-strength from zero to 6 T . This procedure prevents damage caused by any field error, including the power-supply polar error of SWLS. Finally, electrons were injected after the magnet was charged to the nominal field. The tune-shift effect of SWLS was also measured (Fig. 4) as a reference for adjusting the working tune.

The first stored beam with 6 Tesla SWLS was observed on May 21, 2002. Injection with SWLS fully charged was accomplished without difficulty. The measured tune shifts and the path-length compensation (RF increased by 1.7 kHz at 6 Tesla), were consistent with the values predicted by modeling. In top-up mode, 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). During operation at 5.0 T, the beam stability is good and the beam current lifetime is approximately 6.5 hours at 200 mA. Now the SWLS was routinely operated at 5.0 T without filling liquid He and liquid N_2 to test of the three X-ray beamlines.

When the magnet was charged without the electron beam current, the temperature (T7) of the magnet increased by 0.25 K above that without an excitation current. When the magnet is charged to 215 A (5 T) and the electron beam current at 200 mA, the temperature of the magnet increases by 0.35 K. During long-term operation, the temperatures of the magnet (T7) and the HTS current leads (T6) were maintained at 4.55 K and 86 K at 200 mA, respectively. However, the temperatures of the first (T3) and second stage (T2) of the cryocooler were at 59 K and 4.2 K, respectively. When the magnet is operated at 6 T, liquid He is required but

Fig. 3: SWLS was installed in the injection section between kicker 3 and 4. A pair of multipole shimming magnets is mounted on the magnet flange. The cold head of the cryocooler was mounted on the bottom of the magnet.

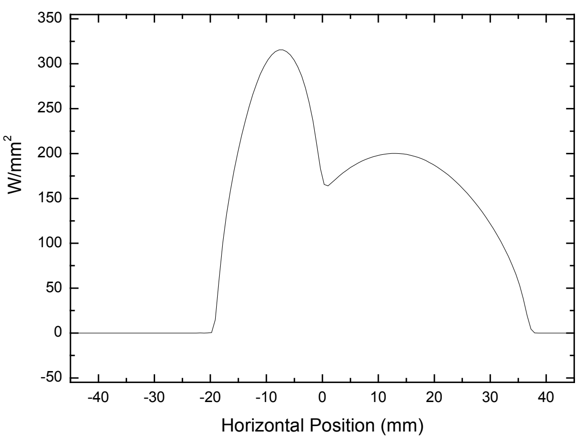

Fig. 2: The power density distribution on the transverse x-axis was calculated at the kicker entrance, 0.532 m from the center of the magnet, at an electron current of 400 mA.

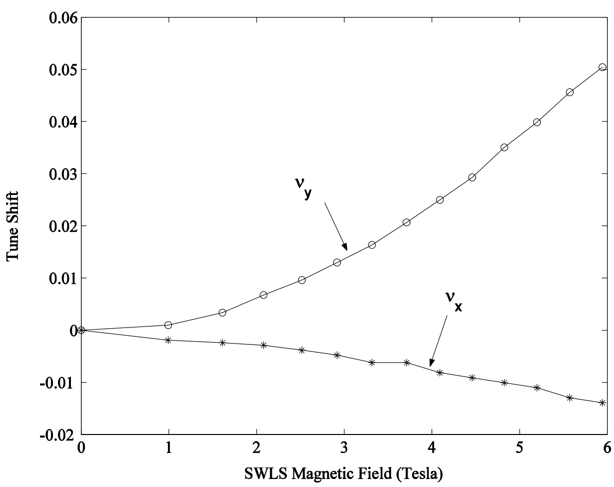

Fig. 4: Tune shift as a function of SWLS magnetic flux density.

liquid N_2 is not. The SWLS can be easily excited up to 6.5 T in LHe operation mode. The nominal current slew rate is set to 0.2 A/s to reduce the eddy current. Hence, the charging time to generate 5.0 T at an excitation current of 215 A is around 18 minutes. However, the maximum slew rate can exceed 0.5A/s. The maximum magnetic flux density of 6.0 T can be obtained without training the magnet. The boiling-off rate of the SWLS at 6 T is about 0.06 L/h. If the second cryoplant is ready for supplying liquid helium for superconducting magnets at the end of 2005, the liquid helium transfer system will be planed for SWLS to promote the field strength up to 6 T, or up to 6.5 T to provide more photon flux in the energy range around 33 keV.

As mentioned above, after 2004 a cryogenic plant can supply liquid helium for superconducting RF cavity (SRF). This cryogenic plant can also supply SW6. As a consequence, the SW6 is designed as in liquid helium bath with consumption of 4 L/h. A magnet gap separator made of aluminum bars maintains a precise gap of 18 mm between the upper and lower magnets array. A thermally shielded, specially shaped aluminum beam duct was used to reduce heating of the cold mass at 4.2 K. Thus, the cold 11 mm vertical aperture of the aluminum beam duct that has 1.2 mm thickness at magnet center region was separated from the cold iron pole and coil by 18 mm. A 1.2 mm gap between the Al beam duct and 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 1mm diameter were affixed to the UHV beam duct. The gap between the bumper and the 4.2 K aperture duct was approximately 0.6 mm to ensure that the only point of 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 pieces of copper plates connected to the liquid nitrogen (LN_2) vessel, on both outer ends of the 4.2 K vessel.

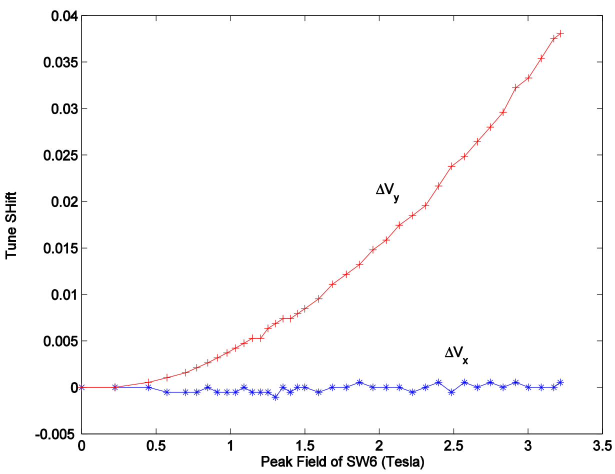

Fig. 5: Horizontal and vertical tune shift as a function of SW6 magnetic flux density.

Thirteen training events of SW6 yielded a nominal current of 285 A and a field of 3.2 T. When the magnet is quenched, the compressor can accommodate a large amount (since 10 liters liquid helium boils off within 15 seconds) of the recycled helium gas. The UHV pressure of the beam duct is always maintained at a fairly constant value, whether the beam duct is warm or cold, and whether there is stored beam (up to 200 mA) or not. The boil-off rates of LHe and LN_2 are around 2.5 L/h and 1.6 L/h at magnet excitation current of 285 A, respectively.

We also have the option of using trim coils on the SW6 magnet to compensate for the first and second field integral, but the option is not used because the field quality is already quite consistent with the design value. The SW6 was installed in January 2004, located downstream of the SRF in the fourth straight section of the storage ring. The commissioning results show that the tune shift effect (Fig. 5) of SW6 is in good agreement with the value predicted by model, and there is no unexpected horizontal tune shift caused by the roll-off of the magnetic field. Commissioning with beam was smooth and successful.

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PUBLICATIONS

- C. S. Hwang, *et al.*, IEEE Trans. on Apply Supercond. vol. 10 no. **1**, 503 (2000).
- C. S. Hwang, *et al.*, IEEE Trans. Appl. Supercond., vol. 12, no. **1**, 686 (2002).
- C. S. Hwang, *et al.*, SRRC, Activity Report 2001/2002, 56 (2002).
- P. Chang, *et al.*, SRRC Newsletter **53** (2003).

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