Superconducting Insertion Devices for Light Sources at Budker INP

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Abstract. The first superconducting insertion devices were designed, fabricated and installed on electron storage rings more than 25 years ago, and used for generation of synchrotron radiation in Budker INP. Since then, a wide experience of manufacturing and use of such superconducting (SC) insertion devices as SC wave length shifters, multipole wigglers, and superbend is accumulated .A review of various types of Superconducting Insertion Devices for Light Sources is given in the report. Their basic characteristics as SR sources are discussed.

Keywords: Superconducting magnet, insertion device, synchrotron radiation
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INTRODUCTION

Spectral characteristics of Synchrotron Radiation (SR) from bending magnet are determined by two parameters: electron energy E and magnetic field B, $\varepsilon_c \sim E^2 B$, and, hence, there are two ways how to make a spectrum harder: to increase energy or to increase magnetic field at the radiation point. The first way has many advantages, but demands serious material and manpower resources, while the second way is cheap enough and rather simple: we can use insertion devices like a superconducting wiggler or wavelength shifter or replace one or more bends by a superconducting high field bending magnet (superbend).

Insertion Devices are intended to improve quality of SR of light source and, basically, represent magnetic structures with the transverse magnetic field, placed in a straight section of a storage ring. The main goals of three poles shifters and a multipole wigglers are shift of SR spectrum to X-ray rigid area and increase of photon flux.

SUPERCONDUCTING WAVE LENGTH SHIFTERS

In three-pole magnets only the central magnet with high field is used as a source of radiation. Two others are used for compensation of orbit distortion by the central pole. The compensation puts two conditions: vanishing first and second field integrals over the magnetic system:

$$I_1 = \frac{1}{H\rho}\int_{-L/2}^{L/2} B_z(s)ds = 0 \qquad I_2 = \int_{-L/2}^{L/2} ds' \int_{-L/2}^{s'} \frac{B_z(s'')}{H\rho} ds'' = 0 \tag{1}$$

Traditional variant of shifter with magnetic structure (-1/2, 1, -1/2) has an undesirable second radiation source from the side poles (see FIGURE 11). To suppress the brightness of the second source, the side poles should have magnetic field as low as possible. Thus the brightness of the second source can be considerably suppressed, but the horizontal orbit displacement inside the shifter is increased (see FIGURE 12). On one hand, this imposes some restrictions on the vacuum chamber dimension, and on another this improves conditions to filter out the second source with a diaphragm.

There is a variant of 3 pole shifter (shifter with fixed radiation point) with superconducting part of magnet has non-zero field integrals and requirements of zero field integrals are performed by normally conducting correcting magnets which are outside of shifter cryostat (FIGURE 3). This variant of shifter allows to compensate for the first

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and second field integrals over each ½ shifter parts so that in the central pole the radiation point will be always on an straight section axis at any field level of the shifter (see FIGURE 3, FIGURE 4). The magnetic gap in WLSs is high enough and this fact allows to make the beam vacuum chamber of room temperature.

NbTi wire is the main superconducting material which is used for fabrication of WLSs, although Nb3Sn is used also for fabrication of WLS with fields about 10 Tesla [4].

A list of superconducting 3-pole WLS fabricated for light sources is shown in TABLE 1.

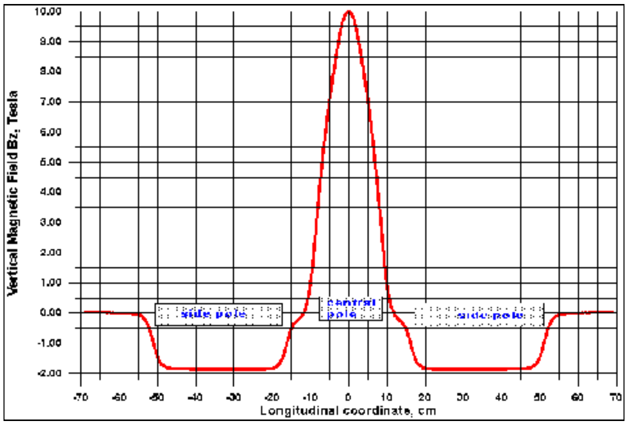

FIGURE 1. Magnetic field distribution inside the 10 Tesla WLS for SPring-8

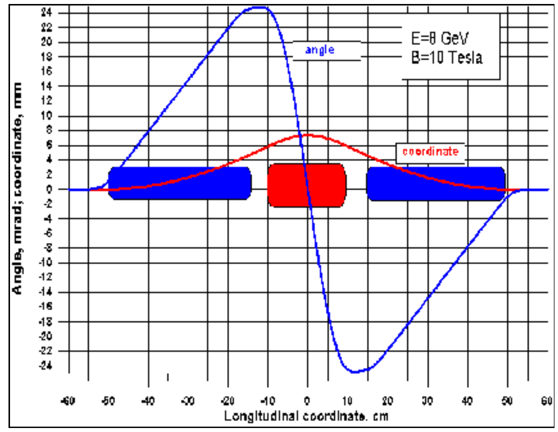

FIGURE 2. Angle deviation and orbit distortion inside the 10 Tesla SC WLS for Spring-8

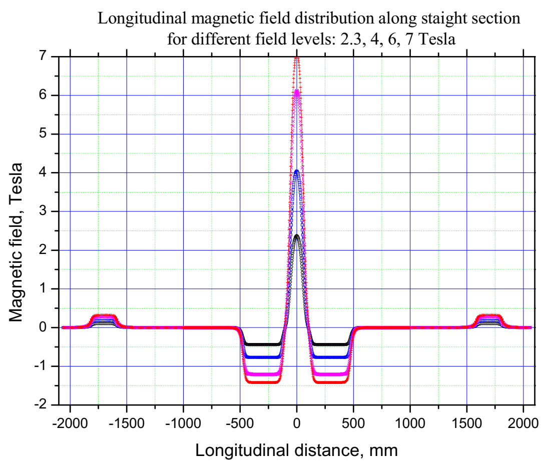

FIGURE 3. Magnetic field distribution of a wiggler with fixed radiation point.

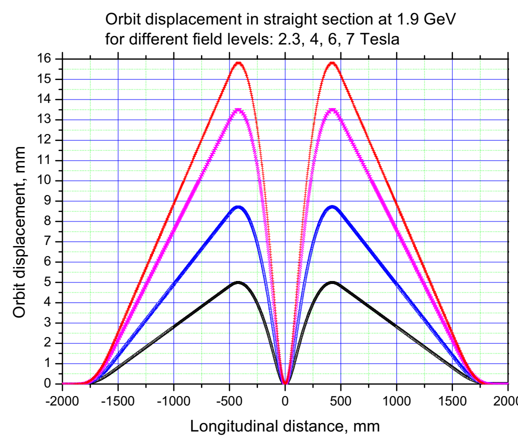

FIGURE 4. Orbit distortion inside the wiggler with fixed radiation point.

TABLE 1. List of Superconducting WLSs fabricated in Budker INP

	Year	Magnetic field, Max/normal	Magnetic gap, mm	Magnetic length, mm	Vertical aperture, mm	Electron energy, GeV
Siberia-1 (Moscow)	1985	5.8(4.5)	32	350	22	0.45
PLS (Korea)	1995	7.68 (7.5)	48	800	26	2
LSU-CAMD (USA)	1998	7.55 (7.0)	51	972	32	1.5
SPring-8 (Japan)	2000	10.3 (10.0)	40	1042	20	8
BESSY-II (Gernany)	2000	7.5 (7.0)	52	972	32	1.9
PSF-WLS (BESSY-II, Germany)	2001	7.5 (7.0)	52	972	32	1.9

The WLS cryostats are immersed types working at liquid helium temperature. For shield screens cooling cryocoolers fabricated by SUMITOMO HI and Leybold Companies are used (see FIGURE 5, FIGURE 6). The dimensions of WLS magnetic pole gap allows to use room temperature vacuum chamber.

FIGURE 5. Photo of the 10 Tesla WLS for SPring-8.

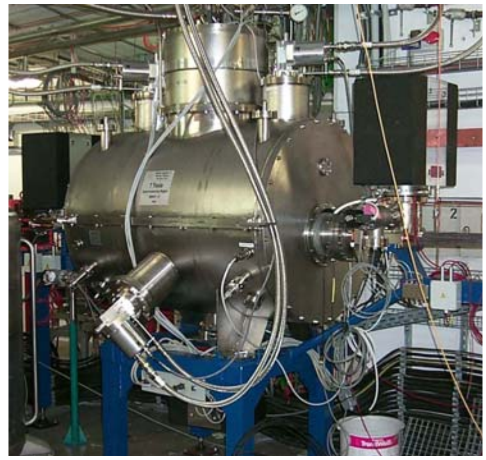

FIGURE 6. Photo of the 7 Tesla WLS with fixed radiation point for BESSY-2.

For performance of conditions (1) the windings of the central pole and side poles are fed on a miscellaneous from 2 power supplies. For each magnetic field level there is a unique combination of currents of power supplies with field integrals close to zero.

SUPERCONDUCTING MULTIPOLE WIGGLERS

Multipole wigglers represent sign-alternating magnetic structure with many poles with high magnetic field. Electron beam passing through multipole wiggler concentrates SR from all poles into the same horizontal angle and increase photon flux.

Undulators are sign-alternating, periodic magnetic structures with the transverse magnetic field, satisfying a condition:

$$K = 0.934 \cdot \lambda_0[cm]B[Tesla] \approx 1 \tag{2}$$

With increasing parameter K so, that $K >> 1$, the spectrum of undulator radiation converts into the SR spectrum and an undulator transforms into a multipole wiggler.

To satisfy this condition (1) the field integral of side poles should be twice less than that of the main pole, having magnetic structure like ½,-1,1,-1 …..-1, ½ for symmetrical magnetic structure with an odd number of main poles, and ½,-1,1,-1 …..1, - ½ with an even main pole number. A symmetrical magnetic system with an odd pole number satisfies second part of condition (1) automatically, and does not disturb the orbit outside the wiggler, while an asymmetric magnetic structure with an even pole number has a non-zero second field integral and disturbs the electron orbit; hence it needs additional correctors. The electron orbit inside a wiggler with ½ side poles oscillates with respect to the axis line horizontally, with a shift equal to the oscillation amplitude. In order to avoid this orbital shift, the end poles may have a structure 1/4,- 3/4,1,-1,….1,-3/4, 1/4. As example of this structure, the magnetic field distribution of the 7 Tesla BESSY-2 wiggler and the orbit distortion inside the wiggler is shown in FIGURE 7, FIGURE 8.

The peak magnetic field in SC multipole wigglers is mainly defined by two parameters: period length λ, and magnetic gap g. Having fixed available longitudinal space for a wiggler magnet structure, it is possible to optimize these two parameters for the maximum SR flux over the needed photon spectrum range. The magnetic gap g is defined by the vertical aperture of the beam vacuum chamber and the space between vacuum chamber and iron pole.

To minimize a pole gap in wigglers a 4.2K cold bore vacuum chamber is used. Copper liner with temperature 20K is inserted inside of this vacuum chamber. The magnetic gap of a wiggler with the copper liner is 2 mm larger, but the liner fully shields the liquid helium vessel from heat induced by the electron beam.

Usually a wiggler is proposed as SR source under the specific target demanding the maximal photons flux in the set spectral range. Such parameters as the beam vertical aperture, allowed space for the wiggler, electron energy, the maximal radiated power from the wiggler are base for optimization of wiggler parameters, which are defined from other system requirements. Key parameters of optimization are length of the wiggler period and superconducting wire parameters. As an example of wiggler parameters optimization dependences of photon flux depending on the wiggler period for storage ring CELLS are shown in FIGURE 9 and FIGURE 10.

Parameters of some SC wigglers designed by Budker IP for light sources are listed in TABLE 2.

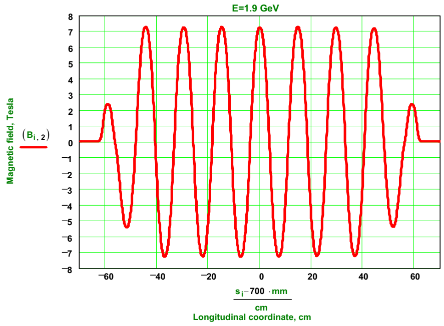

FIGURE 7. Magnetic field distribution of the 7 Tesla wiggler for BESSY-2

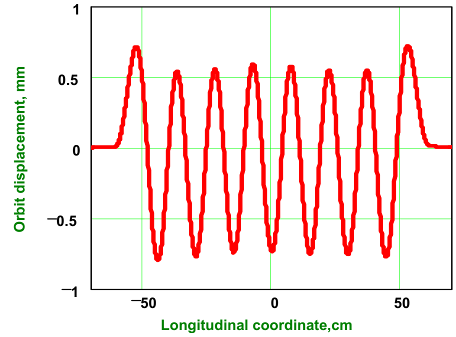

FIGURE 8. Orbit distortion inside the 7 Tesla wiggler for BESSY-2

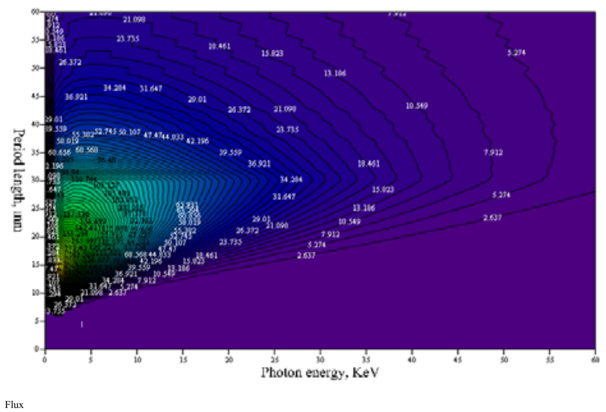

FIGURE 9. 2-D map of photon flux (a.u.) in axis: x- period length, y- photon energy (Electron energy -3 GeV, magnet length 2 m, Vertical beam aperture – 8 mm, maximum radiated power 20 kWatt for beam current 0.4 A (CELLS project)

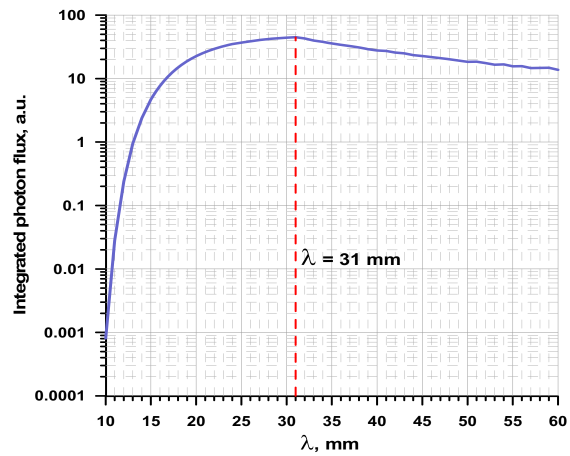

FIGURE 10. Photon flux with energy range 10-40 keV versus wiggler period for CELLS (magnet length – 2m, vertical aperture 8 mm, electron energy- 3 GeV)

TABLE 2. List of Superconducting wigglers fabricated in Budker INP

	Year	Magnetic field, T (Max)/ normal	Number of poles (Main + side)	Magnetic gap, mm	Period, mm	Vertical aperture, mm/ (temperature K)
Multipole wiggler for VEPP-3 (Novosibirsk, Russia)	1979	(3.6) /3.5	20	15	90	8 (78)
Multipole wiggler for BESSY-II, (Germany)	2002	(7.67)/ 7	13+4	19	148	14(20)
Multipole wiggler for ELETTRA (Italy)	2002	(3.7) /3.5	45+4	16.5	64	11(20)
Multipole wiggler for CLS (Canada)	2005	(2.2)/2	61+2	13.5	34	9.5(20)
Multipole wiggler for DLS (Engaland)	2006	(3.77) /3.5	45+4	16	60	10(20)
Multipole wiggler for Siberia-2 (Moscow, Russia)	2006	(7.7)/7.5	19+2	20.2	164	14(20)
Multipole wiggler-2 for CLS (Canada)	2007	(?)/4	25+2	14.	48	10(20)

Non-uniformity of the photon spectrum from wigglers with short period lengths may raise some problems for experimental study having requirements for smooth spectrum. To avoid the interference, the wiggler periodicity should be broken using special spacers between wiggler poles with random thickness. Such a randomized wiggler was designed, produced and successfully commissioned at Canadian Light Source in January 2005 with zero liquid helium consumption using Leybold cooling machines.

The maximum of radiation intensity from wiggler corresponds to harmonic number:

$$N_{\max} \approx 3/8K^3$$

K is the undulator parameter defined by (2)

For CLS wiggler the above parameters are: K~6.3, Nmax~ 95 and photon energy of the basic harmonic is equal 0.11 keV. In real situation, the spectrum of radiation is continuous due to final number of the wiggler periods, existence of energy and angular spread in electron beam. Effects of electron beam energy spread and final number of wiggler poles are not enough for spectrum smoothness in photon energy area 5-10 keV. To provide of required spectrum smoothness in low energy range it was required to bring in casual disorder in period length of the wiggler, increasing average period up to 34 mm (see FIGURE 11).

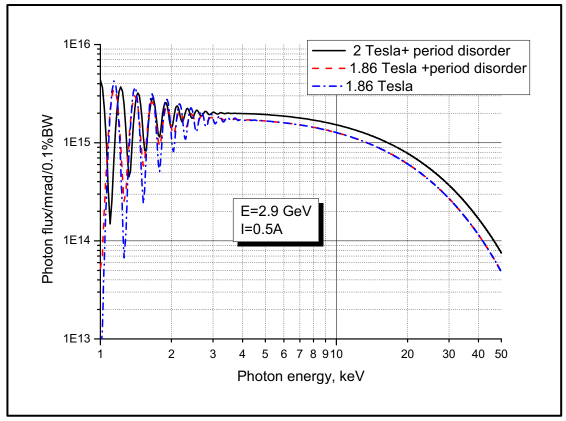

FIGURE 11. Spectrum of radiation from SC CLS wiggler.

WIGGLER CRYOGENIC SYSTEM

Some cryostat concepts in which cryocoolers (Leybold and SUMITOMO companies) for refrigerating of evaporated He were used for WLS and wigglers. Cryocooler heat exchangers were placed inside liquid helium vessel. Recondensing efficiency in such scheme is low and liquid helium consumption was about 0.5 liter per hour.

More effective cryostat concept is a cryostat where cryocoolers are used for interception of heat inleak into liquid helium vessel. This concept of cryostat gives zero liquid helium consumption for normal cryocooler operation. Cryocooler efficiency of work degrades with time and liquid helium consumption became not zero. Average liquid helium consumption during an year is estimated as 0.05 litres per hour under condition of annual technical service of the coolers.

Current leads feeding the magnet with current about 400A are the main source of heat in-leak into liquid helium vessel due to both heat conductivity and Joule heat. Each current lead consists of two parts: normal conducting brass cylinder and high-temperature superconducting ceramics.

One pair of current leads assembled into one block together with 2 stage cooler 4.2GM (see FIGURE 14) which is placed in insulating vacuum of the cryostat. The junctions of normally conducting and superconducting parts of current leads are supported at temperature 50-65K by first stage of coolers.

The lower part of a superconducting part of the current lead is connected with superconducting Nb-Ti cable and

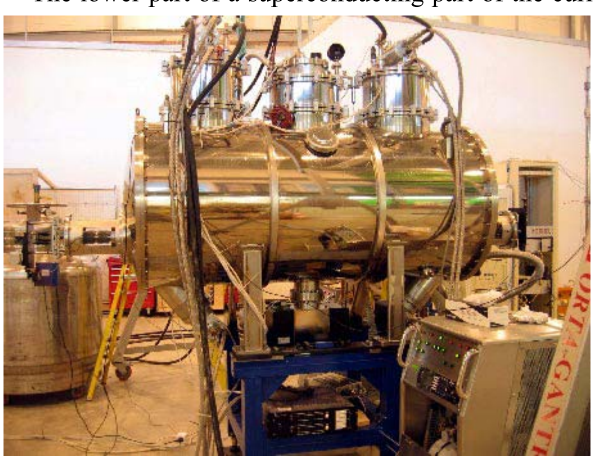

FIGURE 12. 49 pole SC wiggler For Diamond Light Source under Site Acceptance Test

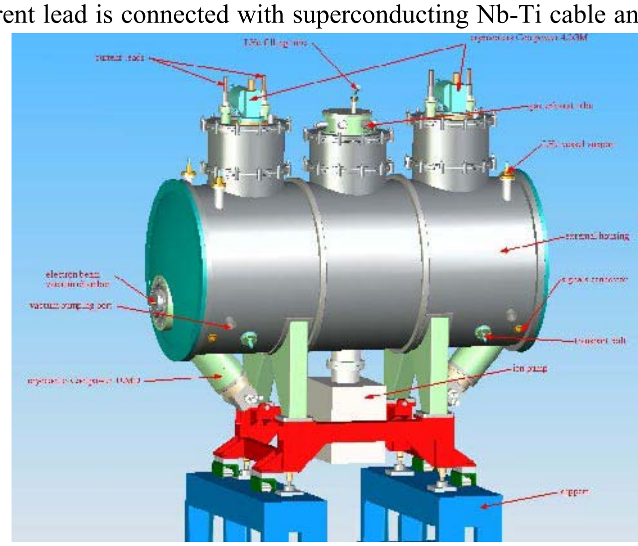

FIGURE 13. Main view of wiggler cryostat

supported at temperature below 4.2K with the help of the second stage of the coolers (see FIGURE 15).

Power of 2-nd stage of the coolers is approximately twice more than heat in-leak power at lower end of superconducting current leads and the rest cooler power is used for cooling liquid helium vessel.

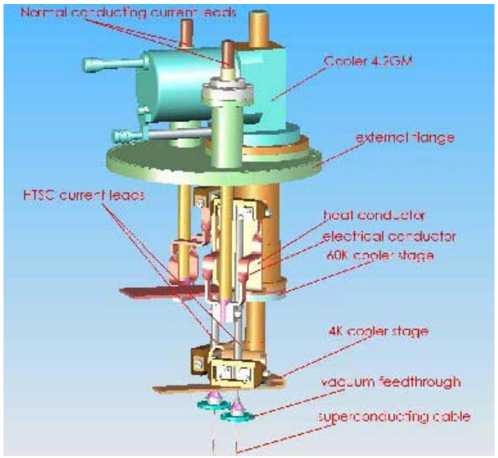

FIGURE 14. Current leads block assembled with cryocooler.

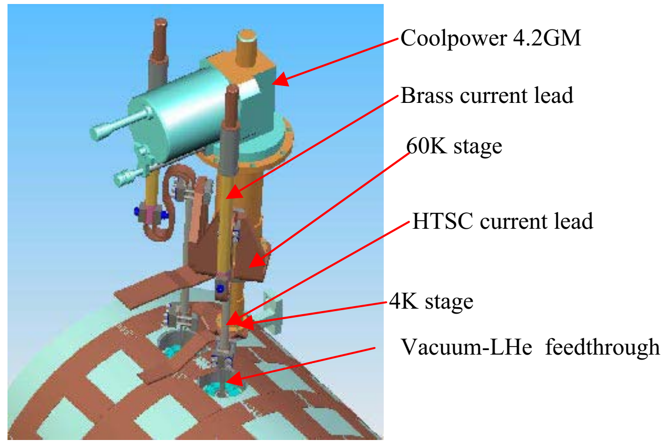

FIGURE 15. Schematic view of current leads block with vacuum feedthrough into liquid helium vessel.

CONCLUSION

The main progress in Budker INP concerning superconducting insertion devices is as follow:

- The manufacturing techniques of superconducting bending magnets (superbends) with magnetic field up to 9 Tesla is developed
- The manufacturing techniques of multipole superconducting wigglers with the optimum period (> 26 mm) for the given spectral range is developed
- Cryostat design for superconducting multipole wigglers and WLS with the zero liquid helium consumption with use of 2-stage cryocoolers is developed
- For reduction of heat inleak into liquid helium high temperature superconducting current leads are used
- For reduction of heat inleak into liquid helium due to electron beam the copper liners cooled by 2-stage coolers down to temperature 20K are used

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