SURVEY OF SUPERCONDUCTING INSERTION DEVICES FOR LIGHT SOURCES

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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 [11]. Since then, a wide experience of manufacturing and use of such superconducting (SC) insertion devices as SC wave length shifters, multipole wigglers, and undulators 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.

INTRODUCTION

Spectral characteristics of Synchrotron Radiation (SR) from bending magnet are determined by two parameters: electron energy E and magnetic field B, ε_c~E^2B, 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 to increase hardness 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 as a 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.

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:

$$K = 0.934 \cdot \lambda_0[cm]B[Tesla] \le 1 \qquad (1)$$

where K is the undulator parameter, λ is the undulator period, B_0 is the magnetic field amplitude in median plane. Spectral peaks of undulator radiation result from interference of certain wavelengths satisfying the condition:

$$\lambda_n = \frac{\lambda_0}{n \cdot 2 \cdot \gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad (2)$$

where n is the harmonic number, γ is the relativistic factor.

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.

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:

$$I_1 = \frac{1}{H\rho}\int_{-L/2}^{L/2} B_z(s)ds = 0 \qquad (3)$$

$$I_2 = \int_{-L/2}^{L/2} ds' \int_{-L/2}^{s'} \frac{B_z(s'')}{H\rho} ds'' = 0 \qquad (4)$$

A traditional variant to satisfy these conditions is to build the side poles with the longitudinal dimensions same as the central pole, but with twice less amplitude of the opposite polarity magnetic field. The traditional variant of shifter has an undesirable second radiation source from the side poles. To suppress the brightness of the second source, the side poles should have magnetic field as low as possible (Figure 1). Thus the brightness of the second source can be considerably suppressed, but the horizontal orbit displacement inside the shifter is increased (Figure 2). 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.

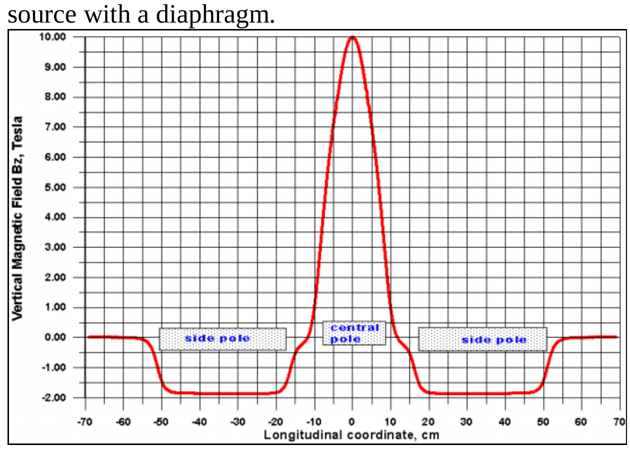

Figure 1: Magnetic field distribution inside the 10 Tesla WLS for SPring-8

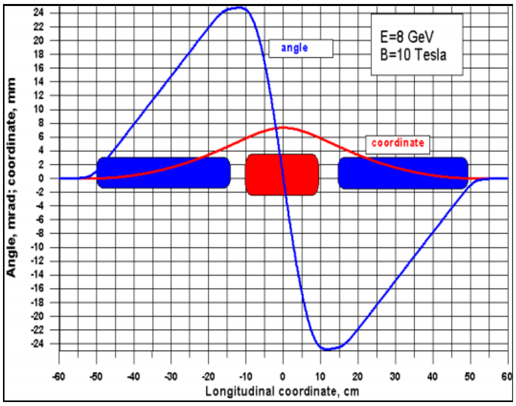

Figure 2: Angle deviation and orbit distortion inside the 10 Tesla SC WLS for Spring-8

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 (Fig. 3). This variant of shifter allows to compensate for the first 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 (Fig. 4).

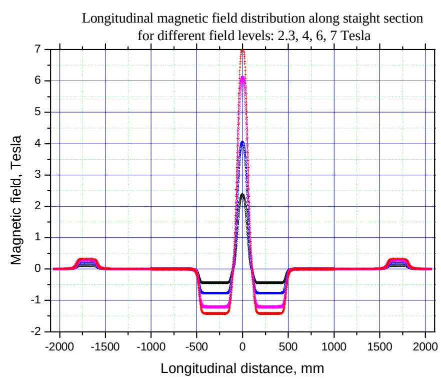

Figure 3: Magnetic field distribution of the 7 Tesla WLS for BESSY-2.

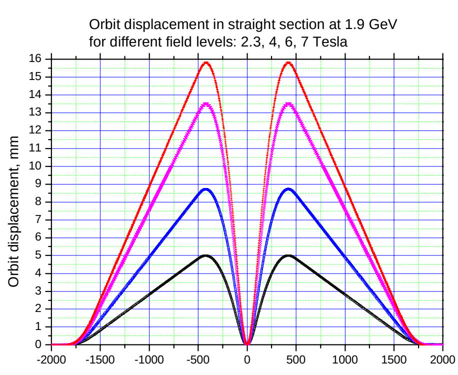

Figure 4: Orbit distortion inside the 7 Tesla SC WLS for BESSY-2.

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 Nb_3Sn is used also for fabrication of WLS with fields about 10 Tesla [4].

The WLS cryostats are immersed types, use is made of cooling machines fabricated by SUMITOMO HI and Leybold Companies (see Fig. 5).

Figure 5: Photo of the 7 Tesla 3-pole WLS for BESSY-2.

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

Table 1 Examples of Superconducting WLSs

	Year	Fabricated by	Magnetic field, T Max/normal	Magnetic gap, mm	Magnetic length, mm	Vertical aperture, mm	Electron energy, GeV
WLS for Siberia-1 (Moscow)	19 85	Budker INP	5.8 (4.5)	32	350	22	0.45
WLS for PLS (Korea)	19 95	Budker INP	7.68 (7.5)	48	800	26	2
WLS for LSU-CAMD (USA)	19 98	Budker INP	7.55 (7.0)	51	972	32	1.5
WLS for SPring-8 (Japan)	20 00	Budker INP	10.3 (10.0)	40	1042	20	8
WLS for (BESSY-II, Gernany)	20 00	Budker INP	7.5 (7.0)	52	972	32	1.9
SWS for TLS	20 00	NSRRC Taiwan	6	47	514	18	1.5
PSF-WLS (BESSY-II, Germany)	20 01	Budker INP	7.5 (7.0)	52	972	32	1.9

SUPERCONDUCTING MULTIPOLE WIGGLERS

As was mentioned above, a superconducting wiggler presents a sign-alternating magnetic structure satisfying condition (3). To satisfy this condition, 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 condition (4) 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 (see Fig. 6), 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 Figs. 7 and 8.

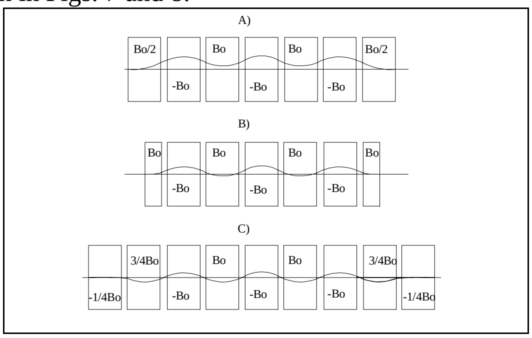

Figure 6: Orbit distortion inside wigglers with different magnetic structures.

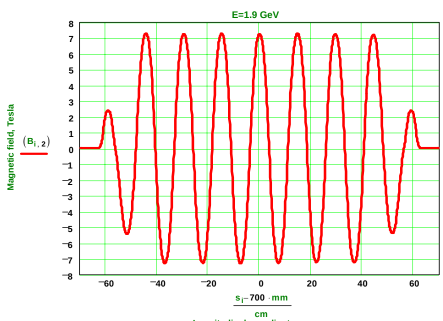

Figure 7: Magnetic field distribution of the 7 Tesla wiggler for BESSY-2

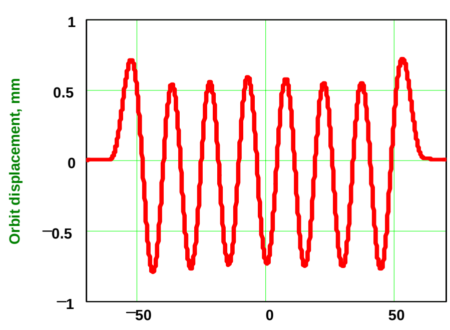

Figure 8: Orbit distortion inside the 7 Tesla wiggler for BESSY-2

The peak magnetic field in SC multipole wigglers is mainly defined by two parameters: period length λ, and magnetic gap g. These parameters are bound with some relation shown in Fig. 9.

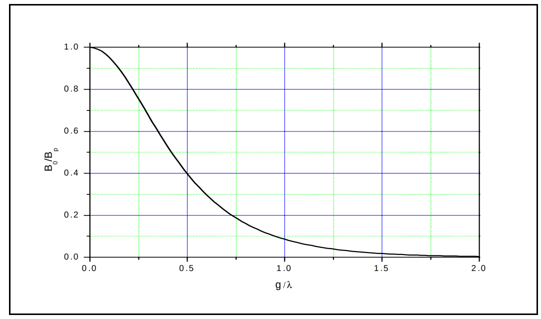

Figure 9: Behaviour of peak field in median plane vs. the ratio g/λ for the same type of superconducting wire.

Having available longitudinal space for a wiggler, it is possible to optimise 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. There is an experience of 4.2K cold-bore vacuum chamber [8] to minimise this space. But as a result of this design solution, there is an additional heat load from the electron current to places close to the SC windings, and hence an additional liquid helium consumption and a risk to make a quench.

An alternative design of vacuum chamber is the design using a copper liner at 20K which shields the 4.2K vacuum chamber from heating by electron beams [9,10]. The magnetic gap of a wiggler with a copper liner is 2 mm larger, but the liner fully shields the liquid helium vessel from heat induced by the electron beam.

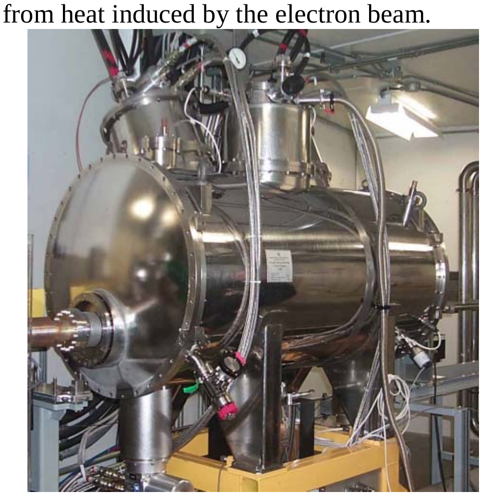

Figure 10 2 Tesla 63-pole superconducting wiggler with zero liquid helium boil off for Canadian Light Source.

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 (See Fig. 10).

Parameters of some SC wigglers used at light sources are listed in Table 2.

Table 2. Examples of superconducting wigglers

	Year	Fabricated by	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	1979	Budker INP	(3.6) 3.5	20	15	90	8 (78)
VEPP-2 (Budker INP)	1984	Budker INP	(8.5) 8	5	26.5	240	15 (78)
Multipole wiggler for (BESSY-II, Germany)	2002	Budker INP	(7.67) 7	13+4	19	148	14 (20)
MAX-Lab wiggler	2001	MAX-Lab	(4.3) 3.5	47+2	12.2	61	10.2 (4.2)
Multipole wiggler for ELETTRA (Italy)	2002	Budker INP	(3.7) 3.5	45+4	16.5	64	11 (20)
Multipole wiggler for CLS (Canada)	2005	Budker INP	(2.2) 2	61+2	13.5	34	9.5 (20)

SUPERCONDUCTING UNDULATORS

Significant progress was achieved over the last several years in building of superconducting undulators. Some undulator prototypes are under fabrication, some are already tested and installed on the rings. The main problem which is under consideration for short-period undulators is how to protect superconducting coils from heat load induced by the electron beam.

The basic tendencies in undulator designing are reduced to using more high-temperature superconducting materials, using cooling machines and heat conductivity to keep coils superconductive.

Superconducting in-vacuo undulators with parameters $\lambda = 15$ mm, g = 5 mm, Bo = 1.4 T, K = 1.8 were fabricated and successfully tested in collaboration ACCEL, ANKA (Germany), SSLS (Singapore) (Fig. 11).

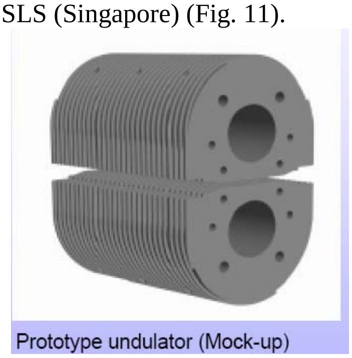

Figure 11 The metallic body of the short undulator

A planar superconducting undulator (SCU) is under development at APS. The goal of the SCU program is to develop, fabricate and install a device tunable over a photon energy range from 19 to 28 keV for the first harmonic. Undulator parameters:

$\lambda = 15$ mm, g = 8 mm, Bo = 0.8 T, K = 1.12

SUPERBENDS

All mentioned above devices are intended to be installed into straight sections of storage rings. For storage rings with energy up to 2 GeV the spectrum from bending magnet is limited to energy of photons up to 25 keV and it strongly limits possibilities of realization of experiments. Besides the superconducting insertion devices like shifters and multipole wigglers there is a problem of the 'second source' which may limit the spatial and energy resolutions in experiments if these are required. From this point of view Superbend is free of these problems and it is a rather cheap approach allowing to considerably expand possibilities for experiments of already existing and expensive experimental stations, needing expanded spectrum in its hard end [14,15]. A disadvantage of the Superbend is that in comparison with a superconducting high-field insertion devices it is a basic element of the storage ring and all its systems should be not less reliable than conventional magnetic elements forminf the storage ring.

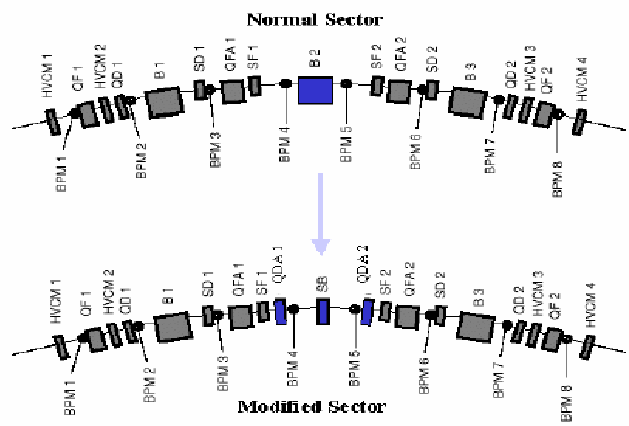

Figure 12 Magnetic layout of a normal (top) and modified (bottom) sector.

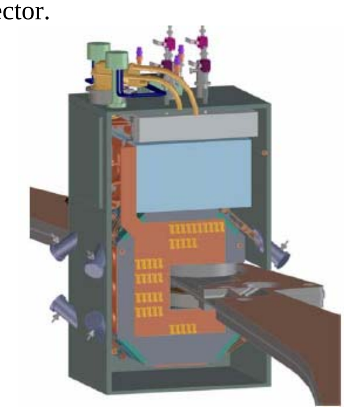

Figure 13 Schematics of an ALS Superbend magnet.

First realization of superbend idea was done in USA in 2001: several superconducting bending magnets

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(Superbends) with a field above 5 Tesla [12] were made and installed at the ALS storage ring. (See Figs. 12,13).

Following the idea to change normal conducting magnet by superbends, Budker INP in collaboration with BESSY-2 designed, fabricated and tested in 2003 a prototype superconducting bending magnet with the magnetic field above 9 Tesla using combined Nb-Ti and Nb-Sn superconducting wire. The photos of the 9 Tesla superbend magnet and the cryostat assembled with the magnet are shown in Figs. 14 and 15, respectively.

Figure 14 Cold part of Superbend for BESSY-2

Figure 15 Assembled BESSY-2 Superbend.

CONCLUSION

In the last 7 years, a significant progress in building high field (up to 10 Tesla) superconducting magnetic systems such as superconducting wave length shifters and multipole wigglers for generation of synchrotron radiation in the hard spectral range was achieved, with use of traditional Nb-Ti and Nb-Sn superconducting materials.

Activities on creation superconducting undulators with the periods less than 15 mm and magnetic field more than 1 Тесла have begun.

The working temperature of magnetic systems basically is the temperature of liquid helium with use of cooling machines; and also works on creation of helium-free systems with use of cooling machines, and using materials with high heat conductivity are in progress.

There is a successful experience of replacement of traditional bending magnets by superconducting magnets at already operating light sources, this strongly expands experimental possibilities of the light sources.

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