SUPERCONDUCTING MULTIPOLE WIGGLERS: STATE OF ART

Khrushchev S., Mezentsev N., Lev V., Shkaruba V., Syrovatin V., Tsukanov V.
Budker Institute of Nuclear Physics, Novosibirsk, Russia

Abstract

Superconducting multipole wigglers installed on synchrotron radiation sources are the powerful tools for researches in various areas of science and technics. SuperConducting Multipole Wigglers (SCMWs) represent sign-alternating sequence of magnets with lateral magnetic field. Relativistic electrons, passing through such set of magnetic elements, create radiation with properties of synchrotron radiations depending on maximum field, its period and poles number. SCMWs are installed on Synchrotron Radiation (SR) sources to increase brightness and rigidity of the radiation.

The first superconducting wiggler has been made and installed on the VEPP-3 electron storage ring as a generator of synchrotron radiation in 1979. Nowadays tens of the wigglers are successfully working in the various synchrotron radiation centers and more than 10 of them were developed and made in Budker INP. These wigglers may be divided into 3 groups:

1- Long period 14.5-20 cm with field 7-7.5Tesla.
2- Medium period 4.8-6 cm with field ~ 3.5-4.5 Tesla
3- Short period 3-3.5 cm with field ~2-2.5 Tesla.

The description of magnetic properties of the wigglers, parameters of both the cryogenic and vacuum systems and their technical decisions are presented in the report.

INTRODUCTION

Superconducting magnetic systems with sign-alternating lateral magnetic field (superconducting wigglers) have received wide enough application as generators of synchrotron radiations (SR). In comparison with the wigglers made on basis of permanent magnets and on the basis of ordinary electromagnets the superconducting (SC) wigglers have essential advantage as higher magnetic field level at smaller period. This advantage gives a chance to create a higher photon flux from the same space of a straight section. Such insertion devices considerably improve consumer characteristics in hard X-ray range of SR sources which have the critical photon energy of 5 keV or less. In addition under certain conditions the SC wiggler can reduce horizontal beam emittance and thus improve the consumer properties of SR. More than ten of SC wigglers were designed and fabricated by Budker INP over the last 10 years which are successfully used as SR sources. The cryogenic system also has undergone considerable changes during last 10 years and now the cryogenic system of the SC wigglers is reliable system with the zero liquid helium consumption, working in the conditions of the limited access round-o-clock.

MAGNETIC SYSTEM

The magnetic system of a SC multipole wiggler consists of two halves which are mirror symmetrical relative to the median plane. A pole number can be even or odd but the basic requirement to magnetic system is equality to zero of the first and second field integrals along a beam trajectory in the wiggler with a length ***L***:

$$I_1 \quad \int_{-L/2}^{L/2} B_z(s)ds\,,\quad I_2 \quad \int_{-L/2}^{L/2} ds' \int_{-L/2}^{s'} B_z(s'')ds'' \qquad (1)$$

In order to satisfy to the conditions of equality to zero of the integrals above at the wiggler ends the special side poles are used. The most universal variant of the side poles applicable for even and odd pole number is the variant with use of four side poles (two at each end of the wiggler) with the field integrals of ¼ and ¾ of the main pole.

The main magnetic element of the SC wigglers is the separate pole with horizontal racetrack type of the coils (see Figure 1). The pole coil consists of one or two sections which have been reeled up by a SC wire with the same diameter. In case of two-section coil the currents in the different sections are different in accordance with behaviour of a superconducting wire critical curve. Optimal current ratio in the sections gives about 15% field increasing.

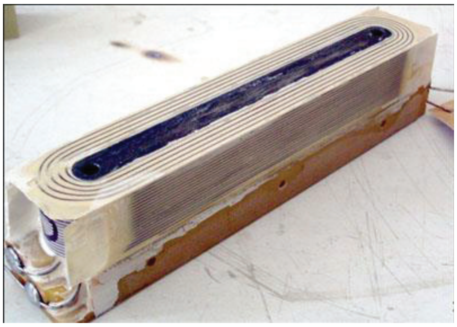

Figure 1: Two sections magnetic pole of a SC wiggler magnet with period of 24 mm.

Each half of the multipole magnets consists of a number of separate poles which assemble on an iron yoke and are controllably pressed together by special bronze rods for creation of a necessary pressure between poles (Figure 2). All poles in the pole array are connecting in series so that the magnetic field changed a sign from pole to pole.

The SC connections of the poles are connecting with use of a cold welding method which provides the resistance of the connection of 10^{-10} - 10^{-12} Ohm. Between welded ends and the coil terminals the SC wires in addition are soldering for reliability.

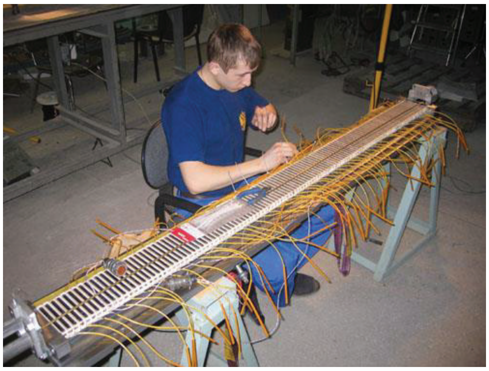

Figure 2 Half of the wiggler magnetic system under assembling procedure. The wiggler length is 1.8 m, period – 30 mm, magnetic field – 2.2T.

The wigglers made in Budker INP may be divided into three groups according to their applicability and the user requirements for the various purposes:

- the wigglers with a high field 7-7.5T and the period of 150 - 200 mm;
- the wigglers with a field 2.5-4.5 T and the period of 48-60 mm;
- the wigglers with a field 2-2.2 T and with the period of 30-35 mm.

All these wigglers were fabricated with use of SC NbTi/Cu wire.

The magnetic field in the median plane for such periodic systems depends on two parameters: period λ and pole gap g. The estimation of the maximum magnetic field in the median plane depending on these two parameters for superconducting multipole wigglers can be made, using the formula below:

$$B(Tesla) \quad 12.5\cdot\exp\left[-\pi\frac{g}{\lambda}-2.2\left(\frac{g}{\lambda}\right)^2\right] \qquad (2)$$

The pole gap ***g*** is defined by requirements for a vertical aperture for a beam at the wiggler location and by required space for the vacuum chamber with a copper liner. The vacuum chamber of the wiggler is a part of the liquid helium vessel and it has a temperature of the liquid helium. The copper liner plays a role of the thermal shield screen protecting the vacuum chamber from heat generated by an electron beam in an accelerator (synchrotron radiation, image currents etc.).

The Table 1-Table 3 list the data of the superconducting wigglers used for the various purposes. Table 1 presents parameters of the high field wigglers. The primary goal of these wigglers is essential increasing of the SR rigidity for experiments. Due to a wide horizontal fan angle of the radiation several beamlines (2-3 beamlines) can be used independently for experiments. A feature of such wigglers is a large stored magnetic energy (~ 0.4-0.8 MJ) and in case of a quench the cryostats may lose much of liquid helium. Table 2 shows the information of the most called-for wigglers at which radiation possesses sufficient rigidity and intensity in comparison with the radiation from the bending magnets. Owing to the small period such wigglers can contain an array of 50 and more SC magnets. The stored magnetic energy in such wigglers is about 30-60 kJ and liquid helium losses during a quench are insignificantly and even is equal to zero if the pressure in the liquid helium tank was below of an atmospheric pressure.

Table 1: List of the High Field Wigglers

	Magnetic field, normal	Poles number (main + side)	Pole gap, mm	Period mm
7Twiggler BESSY-II	7.0	13 + 4	19	148
7.5Twiggler SIBERIA	7.5	19 + 2	19	164
7.5Twiggler CAMD LSU	7.5	11+4	25.2	193.4

Table 2: List of the Medium Magnetic Field SC Wigglers

	Magnetic field, normal	Poles number (main + side)	Pole gap, mm	Period mm
3.5T wiggler ELETTRA,	3.5	45 + 4	16.5	64
3.5 T wiggler DLS	3.5	45 + 4	16.5	60
4.2 T wiggler CLS	4.2	25 + 2	14.5	48
4.2 T wiggler DLS	4.2	45 + 4	13.8	48
4.1 T wiggler LNLS	4.1	31 + 4	18.4	60
4.2 T wiggler ASHo,	4.2	59+4	15.2	50.5
2.5 T wiggler KIT	2.5	36+4	19	46.88

Table 3: List of SC Wigglers with Small Period

	Magnetic field, normal	Poles number (main + side)	Pole gap, mm	Period mm
2 T wiggler CLS	2.0	61 + 2	13.5	<34>
2.1T wiggler ALBA-CELLS	2.1	117+ 2	12.6	30

Table 3 shows the information about short period wigglers. It is interesting to notice that these two wigglers with approximately equal period are made of the SC wire with the different diameters, but with the same ratio NbTi/Cu. The wiggler for CLS made by the wire in the diameter of 0.9 mm, and the ALBA-CELLS wiggler made of the wire of 0.5mm. These wigglers are very close to the SC undulators with a large K-value (K~6) and the spectrum in the low photon energy range has undulator characteristics whereas at the higher photon energy the spectrum is the SR spectrum. The experience acquired with the short period superconducting multipole wigglers on the base of the racetrack type coils gives the assurance that such technology can be successful for creation of superconducting undulators with the period down to 16 mm.

CRYOGENIC SYSTEM OF THE WIGGLERS

The primary goal of the cryostat design is to create reliable safe systems with the possibility of long term independent work with close to zero liquid helium consumption. The cryostat is a horizontal cylinder consisting of the vacuum housing, thermal shield screens and the liquid helium volume with the superconducting magnetic system inside (Figure 3).

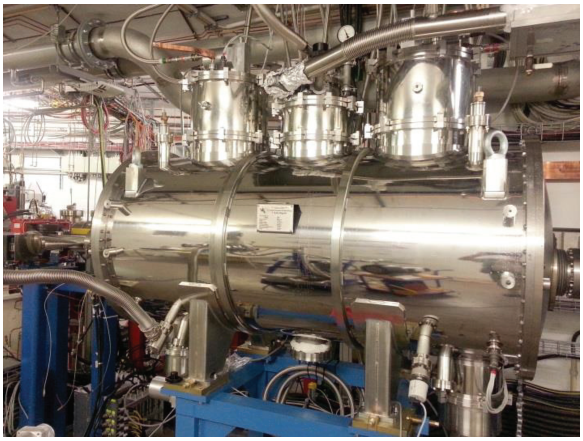

Figure 3; Photo of the cryostat for the superconducting wiggler.

In order to provide zero liquid helium consumption, four 2-stage cryocoolers are used symmetrically situated relatively of the wiggler ends. The main aim of the cryostat is to prevent any heat penetration into the liquid helium tank by intercepting it by heat sinks connected to the cryocoolers stages. Two cryocoolers with stages of 4K and 50K (type 1) and two cryocoolers with stages of 10K and 50K (type 2) are used for this aim. The cryocooler stages with temperature ~50K are used for cooling the external 50K shield screen. Type 1 cryocoolers are assembled together with the current leads block, consisting of a normal conducting part and high-temperature superconductors (HTSC). The second stages of the type 2 cryocoolers are used for cooling down of the 20K shield screen and for interception of a released heat in the copper liner when the electron beam is passing through the liner. The copper liner represents a copper tube by length of about 2 m which is inserted into the electron beam vacuum chamber. The gap between the liner and the vacuum chamber is kept with use of special supports made of a material with low heat conductivity. Released heat in the copper liner generated by an electron beam (image current, electron clouds, synchrotron radiation etc.) is withdrawing to the second stages of the type 2 cryocoolers with use of the high heat conductivity of the copper links. The primary goal of the liner is to intercept the heat created by an electron beam. In the case of the bath cryostat, the liner has heat sinks just on its ends, the material used for the liner should have a high heat conductivity at the liquid helium temperature to remove the heat efficiently. Almost all body of the liner is situated inside the wiggler magnet and is inaccessible. Heat conductivity and electrical conductivity for metal are linked by Wiedemann-Franz-Lorentz law: $\kappa/\sigma = L \cdot T$, where κ - heat conductivity, σ - electrical conductivity, L – Lorentz constant, T - the temperature. That means the higher heat conductivity, the higher electrical conductivity. As the liner is situated inside the wiggler magnet, so during a quench fast decreasing of the magnetic field creates the eddy current in the liner walls and the higher electrical conductivity, the higher the currents.

The eddy currents created on the top and the bottom of the liner walls interacting with each other and with coils currents may deform the liner. In order to avoid the liner deformation during a quench, the purity of the copper intended for the liner should be correctly chosen. The choice of thickness of the top and the bottom of the liner walls is also essential for the liner stability from deformations during a quench, the thinner wall, the smaller eddy currents deforming the liner. But the walls thickness should be also chosen correctly taking into account manufacturing problems. The liner problems considerably become simpler in case of use of the cryostat with indirect cooling of the wiggler magnet. Unlike the bath cryostat where the magnet is immersed into liquid helium, in the cryostat with indirect cooling, the wiggler magnet is situated in an insulating vacuum and in this case the beam vacuum chamber and the liner can be combined. In this case the heat created by an electron beam may be removed from the chamber by moving aside, considerably reducing requirements of heat conductivity of the chamber (Figure 4).

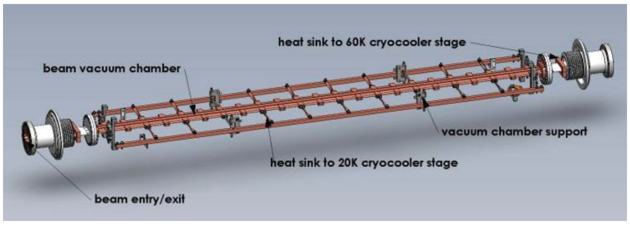

Figure 4: Vacuum chamber for the superconducting wiggler with indirect cooling system.

The cryostat with the indirect cooling system for the SC wiggler for KIT light source is under commissioning and will be installed on the ring this year.

CONCLUSION

The superconducting wigglers and the cryostats described above have proved to be so reliable and effective that it is possible to ensure a reliable and independent operation for a long time in a mode of limited access. Depending on the overall performance change of the cryocoolers with time the magnet temperature can change within 3.2-4.2K. Above 10 superconducting wigglers with this kind of cryostats are successfully working in various centres of synchrotron radiations (CLS (Canada), DLS (England), LNLS (Brazil), ELETTRA (Italy), BESSY (Germany), CAMD (USA), Siberia (Russia), ASHo (Australia), ALBA-CELLS (Spain), KIT (Germany).

As a plan for the next step of the superconducting magnet developing is further improvement of the superconducting magnets quality used as light sources, design and fabrication of the SC undulators with a short period (16-25 mm) and further upgrading of the cryogenic systems to the systems with indirect cooling of magnets.

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