SUPERCONDUCTING MULTIPOLE WIGGLERS FOR GENERATION OF SYNCHROTRON RADIATION

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Abstract

Superconducting (SC) multipole wigglers are very powerful instruments for generation of synchrotron radiation of high intensity. Use of a superconducting wire for creation of a sign alternating lateral magnetic field has the big advantages in comparison of permanent magnets and conventional electromagnets. Superconductivity use allows to create much higher magnetic field at the same field period and the vertical aperture for a beam. The high magnetic field allows not only to increase intensity, but also to expand spectrum of synchrotron radiations.

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.

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

INTRODUCTION

Multipole superconducting wigglers are installing on synchrotron radiation (SR) sources to improve user properties of radiation by increasing of rigidity and intensity of SR. The magnetic system of multipole wiggler represents an array of superconducting dipole magnets creating sign alternate lateral magnetic field. Electron beam passing through this array generates SR in each magnet which the radiation intensity is summarised from all magnets practically in the same solid angle. Use of such magnetic systems is rather effective and cheap enough way of increase in intensity and rigidity of radiation. Spectral properties of radiation from such magnetic structure depend on parameter $K = 0.934 \cdot B[T] \cdot \lambda[cм]$, where B and λ - amplitude and magnetic field period. For K~1 - the radiation spectrum has undulator property, for K>> 1 - the radiation spectrum transits to spectrum of synchrotron radiation. To expand opportunities for carrying out of experimental works and thus to prolong a life, expensive installations as electron storage rings superconducting insertion devices (SC ID) may be installed into straight sections of the storage rings to change spectral, angular, and polarizing properties of SR. These devices, as a rule, have zero first and second magnetic field integrals along electron orbit, and, therefore, they are not basic elements of the electron storage rings, and their status does not affect working reliability of all ring.

The magnetic system using superconducting magnets with NbTi/Cu or Nb_3Sn/Cu wires creates much higher field in comparison with use of conventional or permanent magnets. However use of superconductors demands use of a cryostat for maintenance of low temperatures of magnetic system.

MAGNETIC SYSTEM OF SC WIGGLERS

Magnetic Field Distribution and Field Integrals

Magnetic field of a superconducting multipole wiggler represents a periodic, sign-variable field (1) which begins and ends by special compensating end magnets.

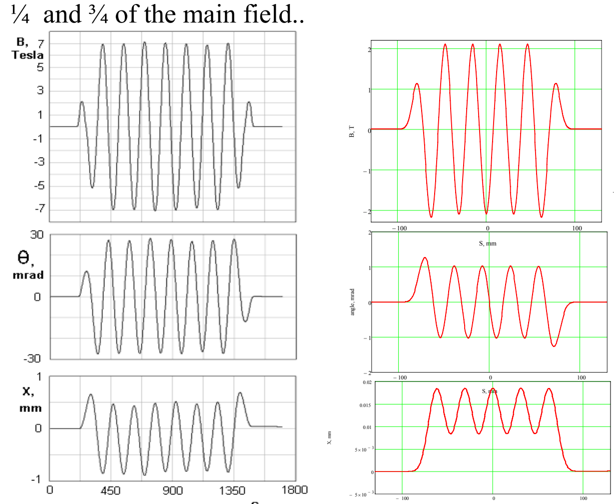
$$\begin{aligned} B_z &= B_0 \cos(k_0\sigma)\cos(k_x\chi)\cosh(k_z z) \\ B_\chi &= -\frac{k_x}{k_z} B_0 \cos(k_0\sigma)\sin(k_x\chi)\sinh(k_z z) \\ B_\sigma &= -\frac{k_0}{k_z} B_0 \sin(k_0\sigma)\cos(k_x\chi)\sinh(k_z z) \end{aligned} \quad (1)$$

Where: $k_0 = 2\pi/\lambda_0$, $k_x = 2\pi/\lambda_x$, $k_z = 2\pi/\lambda_z$ - characteristic magnetic field variation in longitudinal and lateral directions.

The end magnets are used for creation of the first and second field integrals of the wigglers equal to zero for indemnification of a beam orbit distortion which is created by the basic wiggler field.

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

Field integrals of the wiggler with odd pole number can be compensated by two end magnets with a field of ½ of the main field or four end magnets with the fields, equal ¼ and ¾ of the main field..



a) b)

Figure 1: Magnetic field distribution and behaviour of the first and second field integrals with the end magnets of a) ¼ and ¾ and the end magnets of ½ of the main field.

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The second field integral is equal to zero automatically (if the first field integral is zero) for a wiggler with odd number of poles. The first field integral is provided with a separate power feeding of the end poles. Contrariwise for a wiggler with even pole number the first field integral is automatically equal to zero, and the second integral is controlled by separate power supply connected to the end poles.

Focusing Properties and Nonlinear Field Components

High field SC ID is a focusing element in magnetic structure of the storage ring and creates betatron tune shifts and structural functions changes. Horizontal and vertical betatron motion inside SC ID may be described by the following equations:

$$x'' + K_x \cdot x = 0 \qquad (3)$$
$$z'' + K_z \cdot z = 0$$

where the where coefficients of magnetic strength K_x, K_z are equal to:

$$K_x = \frac{B_z^2}{(B\rho)^2} + \frac{1}{B\rho}\left(x'\frac{\partial B_z}{\partial s} - \frac{\partial B_z}{\partial x}\right), K_z = -\frac{1}{B\rho}\left(x'\frac{\partial B_z}{\partial s} - \frac{\partial B_z}{\partial x}\right) \quad , \qquad (4)$$

where: $B\rho$ –electron beam rigidity.

Edge focusing completely compensates focusing by magnetic field in horizontal direction and the main focusing action of SC wiggler occurs in vertical direction.

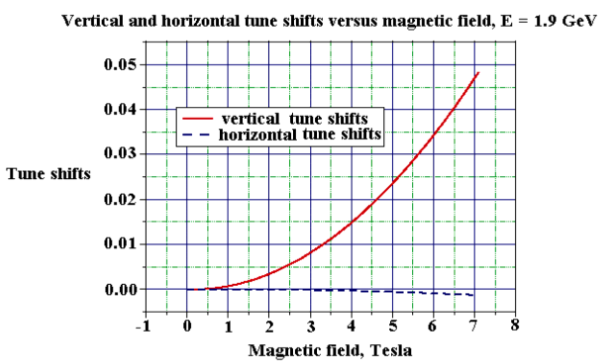

Figure 2: Example of tunes behaviour versus magnetic field in the 7 Tesla SC wiggler of BESSY ring.

Integral values of nonlinear components of the magnetic field of multipole wigglers with length *L*, at conditions that orbit distortion is much less than characteristic pole sizes and assuming $k_x/k_0 << 1$ may be written as:

$$\int_L B(s)ds = \frac{B_0^2 \cdot k_x^2}{2B\rho \cdot k_0^2} \cdot \delta \cdot L \qquad (5)$$
$$\int_L G(s)ds = \left(\frac{B_0^2}{2B\rho} + \frac{B_0^2 \cdot k_x^2}{2B\rho \cdot k_0^2}\right) \cdot L$$
$$\int_L S(s)ds = -\left(\frac{B_0^2}{B\rho} + \frac{B_0^2 \cdot k_x^2}{2B\rho \cdot k_0^2}\right) \cdot k_x^2 \cdot \delta \cdot L$$
$$\int_L O(s)ds = -\left(\frac{3B_0^4}{8B\rho^3} + \frac{3B_0^2 \cdot k_x^2}{2B\rho} + \frac{3B_0^4 \cdot k_x^2}{8B\rho^3 \cdot k_0^2}\right) \cdot L$$

where: δ – horizontal orbit displacement relative SC wiggler axis.

Orbit displacement δ leads to occurrence of nonzero first field integrals and nonzero integral of a sextupole field component. In case $k_x = 0$ (two-dimensional field at infinitely wide poles of magnets) field integrals and sextupole field component are equal to zero, but gradient and octupole field components are nonzero values:

$$\int_L G(s)ds = \left(\frac{B_0^2}{2B\rho}\right) \cdot L \qquad (6)$$
$$\int_L O(s)ds = -\left(\frac{3B_0^4}{8B\rho^3}\right) \cdot L$$

WIGGLERS USED AS GENERATORS OF SYNCHROTRON RADIATION

The Budker INP has fabricated more than one dozen of different wigglers, which may be divided into three groups: high field wigglers, medium field wigglers and short period wigglers (see Tables 1,2,3).

High Field Superconducting Multipole Wigglers

This type of the wigglers are installing on SR sources with relative low electron energy on purpose to expand a photon energy range to more hard X-ray. As a rule one wiggler may give a SR beam for 3 or more independent beamlines (Figure 3). This kind of the wiggler to be installed on a storage ring with electron energy of 6-8 GeV can give the chance to development of new researches, including possibility of creation of bright sources of positrons and neutrons. (On SR sources with electron energy 1-2 GeV it also can be used as a source of terahertz undulator radiations).

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

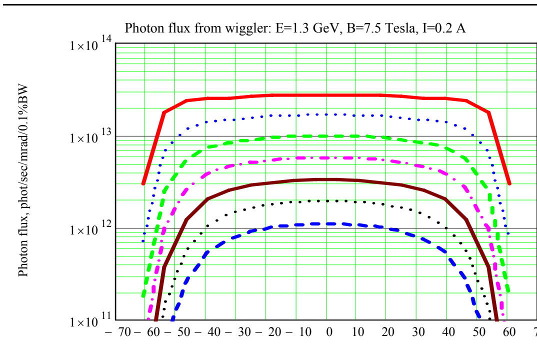

Figure 3: Spectral – angle photon flux distribution from 7.5 Tesla 15 pole SC wiggler for CAMD LSU.

In spite of the fact that undulation parameter

$$K = 0.934 * B_0(T) \cdot \lambda(cm) \quad (7)$$

takes on values 100-140 for this group of the wigglers, the photon spectrum has an undulator properties in low photon energy range (Figure 4).

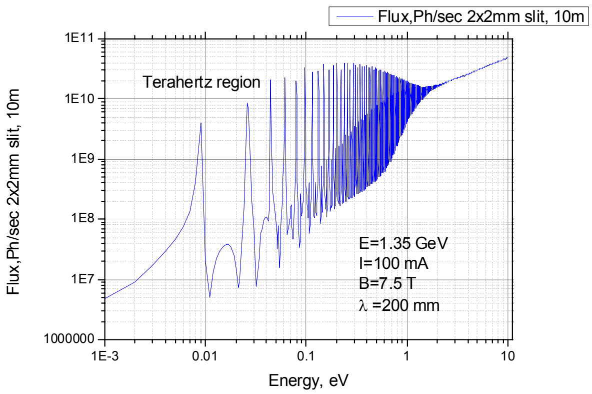

Figure 4: Low photon energy spectrum of radiation from 7.5T wiggler CAMD LSU .

Medium Field and Medium Period Wigglers

This type of the wigglers is most popular for installing on SR sources with 2-3 GeV electron energy on purpose to create very high photon flux of hard X-ray in range 10-100 keV. As a rule one wiggler may give a SR beam for 1 beamline which is equipped by many techniques and can be used in different investigations.

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

As a rule beamlines of this type wiggler are very long (more than 100 m). For example, beamlines of the SC wigglers in CLS (Canada) and ASHo (Australia) are used for biomedical imaging and therapy. The SC wigglers in DLS (England) are used for investigation of extreme conditions of materials and for Joint engineering, environmental and processing.

Main magnetic element of the superconducting wigglers with medium period is a magnetic pole with 2-sections horizontal racetrack coil (Figure 5). Superconducting NbTi/Cu wire with diameter of 0.9mm and critical current 650A at 7 Tesla magnetic field was used. Two section coil with optimal currents in the sections gives 15% increasing maximum field in comparison with an one section coil with the same sizes.

Figure 5: Main element of the medium field SC wigglers.

Short Period Wigglers

This type of the wigglers has a K-value about 5-7 and its spectrum properties are very close to undulators. The wiggler installed on SR sources with 2-3 GeV electron energy creates photon flux of very high brightness of X-ray in range of 6--50 keV.

Table 3: List of SC wigglers with short 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

Figure 6: Assembling of 2 Tesla SC multipole wiggler for ALBA-CELLS (Spain).

Table 3 shows the information about short period wigglers. The wiggler for CLS made by the SC 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 (see Figure **8**). Achievement of such advanced parameters of wire is caused by reduction of copper percentage in a conductor down to 30%. Thus the enhanced attention needs to be given for protection of windings since the using of such wire increases the risk of destroying of superconducting wire during a quench. Superconducting coils of the wiggler are protected from damaging during quench by shunts with resistance of 0.1 Ohm and cold diodes.

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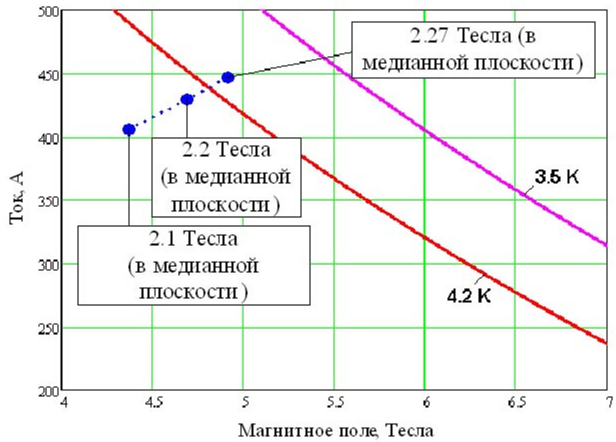

Figure 7: Load curves of the SC wire at different temperature and operation points.

Despite of rather small level of a magnetic field 2.1 T on median plane, the field on the coils reaches the value of 4.7 T and the superconducting wire is close to a critical condition (Figure 7). 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 and without any length limitation of the undulator.

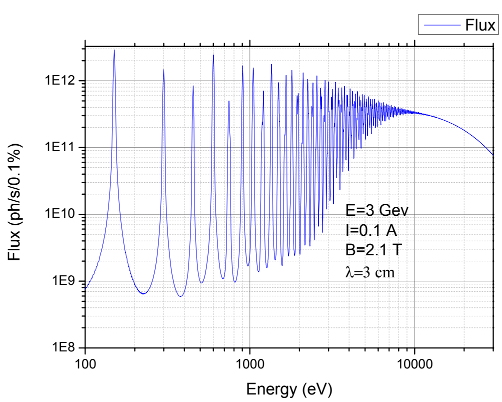

Figure 8: Spectrum photon flux through 1x1 mm^2 at 30m from 2T SC multipole wiggler ALBA CELLS.

CRYOGENIC SYSTEM OF THE WIGGLERS

The cryostat for the superconducting wigglers has been designed and made in Budker INP for continuous autonomic work in conditions of the limited access and raised radiation. The superconducting magnet is immersed into a vessel with liquid helium. The vacuum chamber for electron beam is passing through the magnet and it is a part of the vessel having liquid helium temperature. To provide zero liquid helium consumption, four 2-stage cryocoolers are used which intercept thermal load from thermal screens and current leads and from the copper liner passing inside the vacuum (Figure **9**).

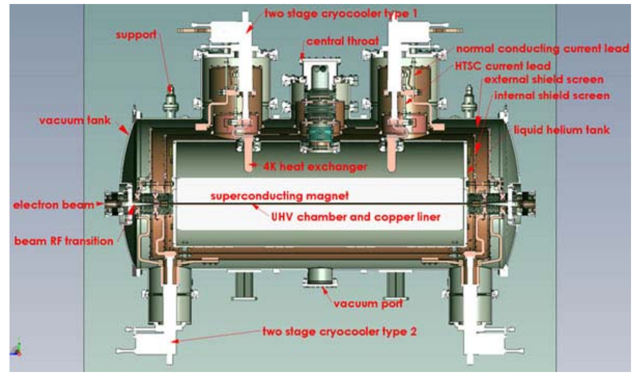

Figure 9: Sketch of the cryostat for SC wigglers.

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. Stages with temperature ~50K of all cryocoolers are used for cooling external shield screen intercepting of heat coming through electron vacuum chamber, radiation from warm walls of housing and heat coming from normal conducting current leads due to its heat conductivity and Joule heat. Type 1 cryocoolers are assembled together with current leads block, consisting of normal conducting part and high-temperature superconductors (HTSC) (Figure 10).

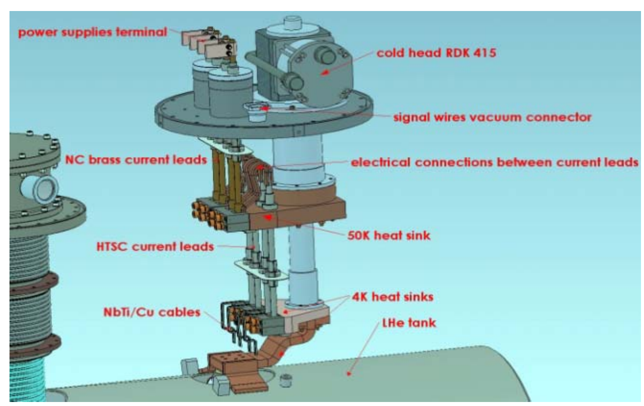

Figure 10: Current leads assembling with cryocooler type 1.

The second stages of type 2 cryocoolers are used for cooling down of 20K shield screen and for interception of released heat in the copper liner when electron beam is passing through the liner. The copper liner represents a copper tube in length 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 small heat conductivity (Figure 11). Released heat in copper liner stimulated by electron beam (image current, electron clouds, synchrotron radiation etc.), is withdraw to type 2 cryocoolers using high heat conductivity of copper. Cooling time of the all system is about 24-36 hours and depends on magnet weight. Insulating vacuum at steady state of the magnet at liquid helium temperature corresponds to 10^{-7} - 10^{-8} Torr. The second stages of cryocoolers type 1 are equipped with copper heat

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exchangers which are situated in gas helium inside liquid helium tank.

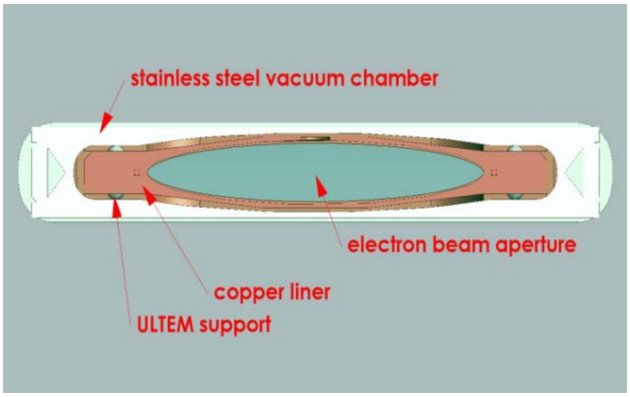

Figure 11: Cross section of UHV chamber and copper liner.

These heat exchangers liquify helium gas effectively reducing the magnet temperature and pressure in the helium tank. The equilibrium temperature can be decreased down to 3.0-3.6K and, accordingly, pressure in a tank can decrease till 0.3-0.5 bar under condition of isolation the helium tank from environment. Isolation should be reliable enough to prevent danger of air leak into helium tank from environment and creation of ice blockade during long term work with the lowered pressure in the helium tank. Temperature of HTSC current leads is in a range of 40-50K at different operating modes with or without currents in the wiggler coils. Protection of HTSC current leads from overheat and combustion is based on the temperature sensors located in junctions of normal conducting current leads with HTSC current leads. If temperature rise to higher level than 60K in these parts wiggler control system send a command to go slowly magnetic field down. If the temperature is above 65K then hard ware interlock sends a signal for switching-off of the power supplies.

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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