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STATUS OF DEVELOPMENT OF SUPERCONDUCTING INSERTION DEVICES FOR GENERATION OF SYNCHROTRON RADIATION AT BUDKER INP

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Abstract

The installation of superconducting insertion devices on storage ring gives an opportunity to increase the photon flux in the required range of synchrotron radiation spectrum and shift the photon spectrum to hard X-ray region. During more than 35 years BINP developed the superconducting insertion devices for generation of synchrotron radiation. More than 20 superconducting wigglers which were produced by BINP are used on many storage rings around the world. Each of them was optimized for the individual requirements of the experiments and taking into account the characteristics of the storage rings. However all the device can be conditionally divided into several groups with similar features: high field wigglers (up to 7.5 T) with long period (140 - 200 mm), middle field (2.5 - 4.2 T) with middle period (46 - 64 mm) and low field (2 - 2.5 T) with short period (30 - 34 mm). The superconducting wiggler cryostats which are developed in BINP are operated not only with zero liquid helium consumption but even with a lower relative to the atmosphere pressure despite of additional heat load from the electron beam and from the current of ~1000 A for supplying of superconducting magnet. This allows not only to avoid a helium loss but also to increase the level of the magnetic field due to the shifting of the critical parameters of superconducting wire. The features of magnetic and cryogenics systems of the superconducting wigglers produced in BINP are presented in this report.

INTRODUCTION

The superconducting insertion devices (ID) being installed on storage ring gives an opportunity to increase the photon flux of synchrotron radiation (SR) spectrum in the required range and shift the photon spectrum to hard X-ray region. Budker INP develops superconducting insertion devices technology during more than 35 years. The world's first superconducting 20-pole wiggler with magnetic field of 3.5 T and the period of 90 mm was created in BINP and installed on the 2 GeV VEPP-3 storage ring in 1979 [1]. Since 1995 Budker INP has created more than 20 superconducting insertion devices which operate on many SR sources. The features of magnetic and cryogenics systems of the superconducting insertion devices produced in BINP are presented in this report.

WAVELENGTH SHIFTERS

The insertion device is installed in a free straight section and is not an element of main magnetic lattice of storage ring. Therefore the main requirement for ID being installed on a storage ring is not to reduce the reliability of the machine. Such effect as tune shifts, beam dynamic reduction etc. should be compensated with use of external magnetic elements. One of the main demands for ID field distributions is not to disturb of beam orbit in any place except of the straight section. The condition for closed orbit is zeroing of first and second field integrals along of beam trajectory inside of the inserting device.

The simplest ID with magnetic structure that satisfies these conditions is a three-pole Wave Length Shifters (WLS) which consists of one main dipole with high magnetic field for generation of SR and two side poles with low field for compensation of orbit deviation [2]. The main parameters of high field superconducting WLS with the maximum field from 7 T to 10 T produced in BINP are presented in Table 1.

Table 1: The Main Parameters of Three-Pole High Field SC WLS Produced in BINP

SR source, year	**B_{max}/B, T**	**Pole gap, /beam gap, mm**	**SR power, kW (E,GeV; I,A)**
PLS, Korea, '95	7.68/ 7.5	48/26	3.6 (2; 0.1)
LSU-CAMD, USA, '98	7.55/7.0	51/32	5.3 (1.5; 0.3)
SPring-8, Japan, '00	10.3/10.0	40/20	100 (8; 0.1)
BESSY-II, Germany, '00	7.5/7.0	52/32	13 (1.9; 0.5)
BESSY-II, Germany, '01	7.5/7.0	52/32	13 (1.9; 0.5)

The field in the side dipoles should be minimized to reduce the contribution of radiation of the so-called "second source" from the side poles to the spectral flux of photons of the main pole. Three-pole WLS has a disadvantage in a shift of the radiation point in horizontal plane due to the displacement of the beam orbit for different field values in the main dipole. To fix the radiation point in the center of the shifter at any field level on the main pole two additional steering magnets can be used as presented in Fig.1.

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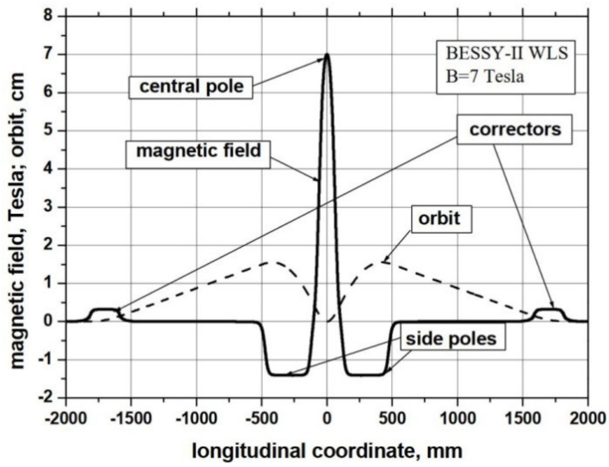

Figure 1: Magnetic field distribution and beam orbit of three-pole SC WLS with fixed radiation point.

MULTIPOLE WIGGLERS

In different from three-pole WLS with only one high field pole the multipole wigglers have essential advantage as higher photon flux which is proportional to number of poles. The using of superconductivity gives advantage to create a higher photon flux from the same space of a straight section due to high magnetic field level and smaller period. Such ID considerably improves consumer characteristics in hard X-ray range for storage rings which have the critical photon energy of 5 keV or less. The magnetic structure of Superconducting Multi-Pole Wiggler (SCMPW) consists of two halves with sign-alternating sequence of magnets which are located upper and lower of beam chamber. To obtain the maximum possible photon flux in the required spectral range it is necessary to optimize such parameters of the wiggler magnetic structure as the period, the magnetic field at the pole and magnetic gap considering given beam energy, photon energy and the accessible length of the straight section. In the process of optimizing the magnetic structure it is also necessary to take into account such additional limitations as the limited power of the photon absorbers.

The feature of the superconducting coils of SCMPW produced by BINP is the using of two sections in the windings. It gives a possibility to increase maximum field on the pole up to ~15% due to the addition of current to the outer section where the field level is lower. All the coils are fabricated with using of superconducting NbTi/Cu wire.

The coils are a horizontal racetrack type. All the coils are winded to iron core separately and connected in series as shown in Fig. 2. Two pair of side poles with the field level of ¼ and ¾ of the main pole is used to close orbit. Two power supplies are used for feeding of the wiggler coils. The current of the first power supply feed all inner and outer sections which are connected in series and two side poles with the field level of ¼ of main pole field. The second power supply adds current only into outer sections and into two side poles with the field level of ¾ of main pole field. The feeding of coils by two independent power supplies gives an opportunity to zeroing of field integrals by redistributing of currents.

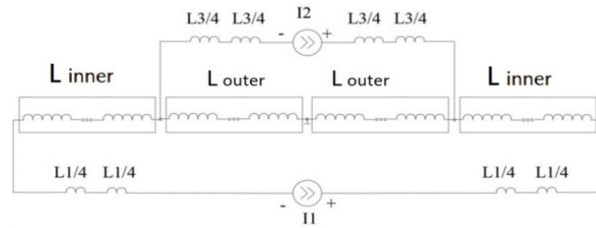

Figure 2: The simplified circuit of wiggler coils supply.

Each of SCMPW was optimized for the individual requirements of the experiments and taking into account the characteristics of the storage rings. However all the devices can be conditionally divided into several groups with similar features [3].

High Field Wigglers (up to 7.5 T) with Long Period (140 - 200 mm)

High field SCMPW is advantageously installed on SR sources with low and middle beam energy at the level of 1-2 GeV. This allows increasing the photon flux at hard X-ray range and prolonging of life cycle for storage rings with low critical photon energy from bending magnets. Moreover it is the possibility to install together up to three beamlines on one high field SCMPW due to wide horizontal fan angle of the orbit deflection at high field and low beam energy. Due to large stored magnetic energy of such wigglers (up to 0.4-0.8 MJ) it is important task to protect coil from damage in a case of a quench. In Fig. 3 is presented overall view of high field magnet of wiggler for DELTA storage ring with installed quench protecting system which consists of cold diodes and dump resistors. The main parameters of high field SCMPW produced by BINP are presented it Table 2.


Figure 3: The overall view of 22-pole 7 T magnet of DELTA wiggler with quench protecting system.

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Table 2: The Main Parameters of High Field and Long Period SCMPW Produced in BINP

SR source, year	B_{max}/ B, T (Period, mm)	Pole gap/beam gap, mm, (N_{pole})	SR power, kW (E,GeV; I,A)
BESSY-II, Germany,'02	7.0/ 7.67 (148)	19/13 (17)	56 (1.9; 0.5)
KSRS, Moscow,'07	7.5/ 7.7 (164)	19/14 (21)	36 (2.5; 0.1)
CAMD-LSU, USA,'13	7.5/ 7.75 (193)	25/15 (15)	17 (1.3; 0.2)
DELTA, Germany,'18	7.0/ 7.25 (128)	16.5/10 (22)	17 (1.3; 0.13)

Middle Field Wigglers (2.5 - 4.2 T) with Middle Period (46 - 64 mm)

Middle field SCMPW became the most in demand due to generation of SR in the most used in experiments photon energy range. Due to the small period such wigglers can contain an array of 50 and more superconducting magnets. The stored magnetic energy in such type of wigglers is only ~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. In Table 3 is presented the main parameters of middle field SCMPW produced by BINP.

Table 3: The Main Parameters of Middle Field and Period SCMPW Produced in BINP

SR source, year	B_{max}/ B, T (Period, mm)	Pole gap/beam gap, mm, (N_{pole})	SR power, kW (E,GeV; I,A)
ELETTRA, Italy,'02	3.5/3.7 (64)	16.5/11 (49)	8.8 (2.0; 0.2)
DLS, UK,'06	3.5/ 3.8 (60)	16.4/10 (49)	60 (3.0; 0.5)
CLS, Canada,'07	4.0/ 4.3 (48)	13.9/9.5 (27)	12 (2.9; 0.2)
LNLS, Brazil,'09	4.1/ 4.2 (60)	18.2/14 (35)	4.45 (1.37; 0.3)
DLS, UK,'09	4.2/ 4.3 (48)	14.4/10 (49)	55 (3.0; 0.5)
AS, Australia,'12	4.2/ 4.4 (52)	15.2/10 (63)	37.5 (3.0; 0.2)

The main task of SCMPW designing is to increase the magnetic field at the minimal period length because it takes the opportunity to place more periods at an accessible place in straight section and increase the photon flux in required energy range. For increasing of magnetic field at the pole it was used several different approaches.

The thickness of elements inside of magnetic gap and the gaps between them were reduced down to technological and mechanical limits ~0.5 mm at the length of ~ 2m.

The superconducting wire with very high critical current (up to ~700 A for NbTi/Cu wire with diameter of 0.9 mm) is used for coil production. In Fig. 4 it is presented the location of field-current critical points relatively of critical current curves of used Nb-Ti wire for several SCMPW. The real currents in the wiggler coils were reached up to 90-95% from critical current. It is very high values for racetrack type coils with flat winding areas.

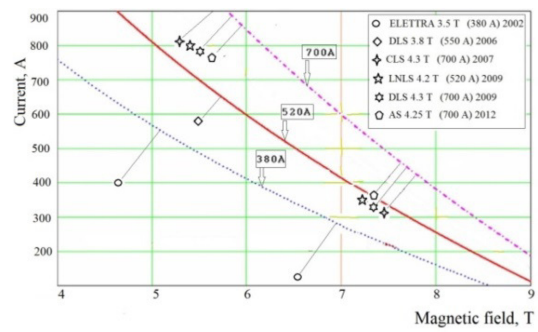

Figure 4: The location of field-current critical points inside of coils relatively of critical current curves of used Nb-Ti wire for several SCMPW.

The using of Sumitomo SRDK-415 cryocoolers with 1.5W cooling power at 4.2K and simultaneous upgrade of cryogenic system gives a possibility to overcool liquid helium down to ~3 K and achieve low pressure inside of helium vessel compared to the atmosphere. So low temperature lead to shifting of field-current parameters of used superconducting Nb-Ti wire for tens of amperes and allows increasing of magnetic field.

Low Field Wigglers (2 - 2.5 T) with Short Period (30 - 34 mm)

The spectrum of short period SCMPW in the low photon energy range has undulator characteristics whereas at the higher photon energy the spectrum is the wiggler spectrum. In Fig. 5 is presented the spectrum of 2.1 T SCMPW for ALBA storage ring with the period of 30 mm and K-parameter of ~6.

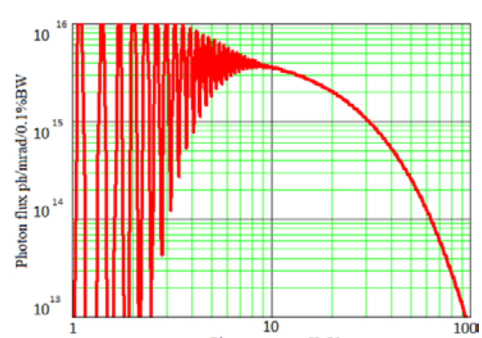

Figure 5: The spectrum of 2.1 T ALBA SCMPW.

Common approach is to use the vertical racetrack type of coils for the creation of short period magnetic struc-

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ture. The feature of the short period SCMPW produced by BINP is the using of horizontal racetrack coils as for wigglers with long period. The advantage of this approach is in 3-4 time smaller wire length, stored energy and inductance. The disadvantage is large number of splices between coils which is produced individual. The decision is cold welding method for wires connection with residual resistance of 10^{-12} Ohm which is used in BINP. In this case even for several hundred of connections and the current going through these contacts of ~1000 A the total power does not exceed 1 mW. In Table 4 is presented the main parameters of short period and low field SCMPW produced by BINP.

Table 4: The Main Parameters of Short Period and Low Field SCMPW Produced in BINP

SR source, year	**B_{max}/ B, T (Period, mm)**	**Pole gap/beam gap, mm, (N_{pole})**	**SR power, kW (E,GeV; I,A)**
CLS, Canada,'05	2.0/ 2.2 (34)	13.5/9.5 (63)	12 (2.9; 0.5)
ALBA, Spain,'10	2.1/ 2.27 (30)	12.64/8.5 (119)	20 (3.0; 0.4)
ANKA, Germany,'13	2.50/ 2.85 (47)	19/15 (40)	4.5 (2.5; 0.4)

CRYOGENIC SYSTEM

The feature of the cryostat for SCMPW which is operates at SR source is additional heat load from electron beam and synchrotron radiation which can reach several tens of watts. So there is a compromise between reduction of the magnetic gap to obtain higher magnetic field and increasing one to reduce heat load to vacuum chamber. The main concept of the cryostat is full interception of heat inleaks into liquid helium vessel onto cryocooler cool-heads to prevent heat penetration into cryostat and evaporation of helium [4].

In Fig. 6 is presented the design of the cryostat for SCMPW with zero liquid helium consumption. The helium vessel with superconducting magnet is surrounded by two copper heat screens with the temperature of 60K and 20K. Four stages of all four cool-heads with total cool power of ~180 W are used for cooling of outer 60K.

Two cool-heads SRDK-415 produced by Sumitomo are the main elements of current leads units. Each the unit consists of outer brass current leads (optimized for current of 300 A) which are connected with HTSC current leads permanently connected with magnet coils through electrical inputs with ceramic insulator on the helium vessel. The 60 K stage of cool-head cools the connection between brass and HTSC current leads and intercepts heat transfer from outside through thermal conductivity and Joule heat from current. The 4 K stage with cool power of 1.5 W intercepts the residual heat from lower ends of HTSC current leads and cools liquid helium by special gilded heat exchanger inside of helium vessel. The heat inleak into helium through thermal conductivity of current leads is equal to ~0.3 W and Joule heat from current adds another ~0.3 W. If necessary it is possible to use four pairs of current leads simultaneously and feed to the magnet a total current of ~1200 A.

For increasing of the magnetic field level by reducing the magnetic gap there is no used a room temperature vacuum chamber inside of the magnetic gap but the helium vessel chamber is used as beam duct. Special copper liner which is cooled by the 20 K stages of SRDK-408 cryocoolers is used for protection of liquid helium from the heating generated by beam and synchrotron radiation.

In Table 5 is presented a heat budget of the SCMPW cryostat. One can see that the cool capacity exceeds the corresponding heat influxes at all cryocooler stages. Moreover the cooling power of 4 K stages exceeds the heat inleak by ~ 3 times and the excess power is used for overcooling the helium vessel with magnet and reduction of pressure relative outside. This makes it possible to increase the level of the magnetic field and to keep helum during a quench.

Table 5: The Heat Budget of SCMPW Cryostat

	60 K, W	**20 K, W**	**4 K, W**
Thermal radiation	8	0.05	0.0002
Central throat	2.5	0.3	0.06
Vacuum chamber bellows	5.3	0.25	0.04
Suspension system	0.5	0.1	0.01
Current leads (conductivity)	50	0	0.3
Current leads (Joule heating)	50	0	0.3
Diagnostic wires	5	0.1	0.01
Liner	10	10	0.2
Total	131.3	10.8	0.92
Cooling power	180 (at 50K)	15 (at 20K)	3 (at 4.2K)

INDIRECT COOLING WIGGLERS

The next step for increasing of magnetic field level by reducing of magnetic gap is the removing one more element from magnetic gap - vacuum chamber of helium vessel. In this case there is the only beam vacuum chamber inside of magnetic gap which protects the superconducting coils from heating generated by beam. So the magnet is located in a vacuum and cooling of superconducting coils is provided by using only heat conductivity of applied materials. The indirect cooled magnet with 72 poles and the field of ~3 T was created by BINP as a prototype for damping wiggler for CLIC project [5]. In Fig. 7 a view of assembled indirect cooling magnet for CLIC prototype is presented.

One of the expected problems of indirect cooling cryostat is how to speed up the primary cooling of the cold mass weighing about 700 kg by only cryocoolers power without using of cryogenic liquids.

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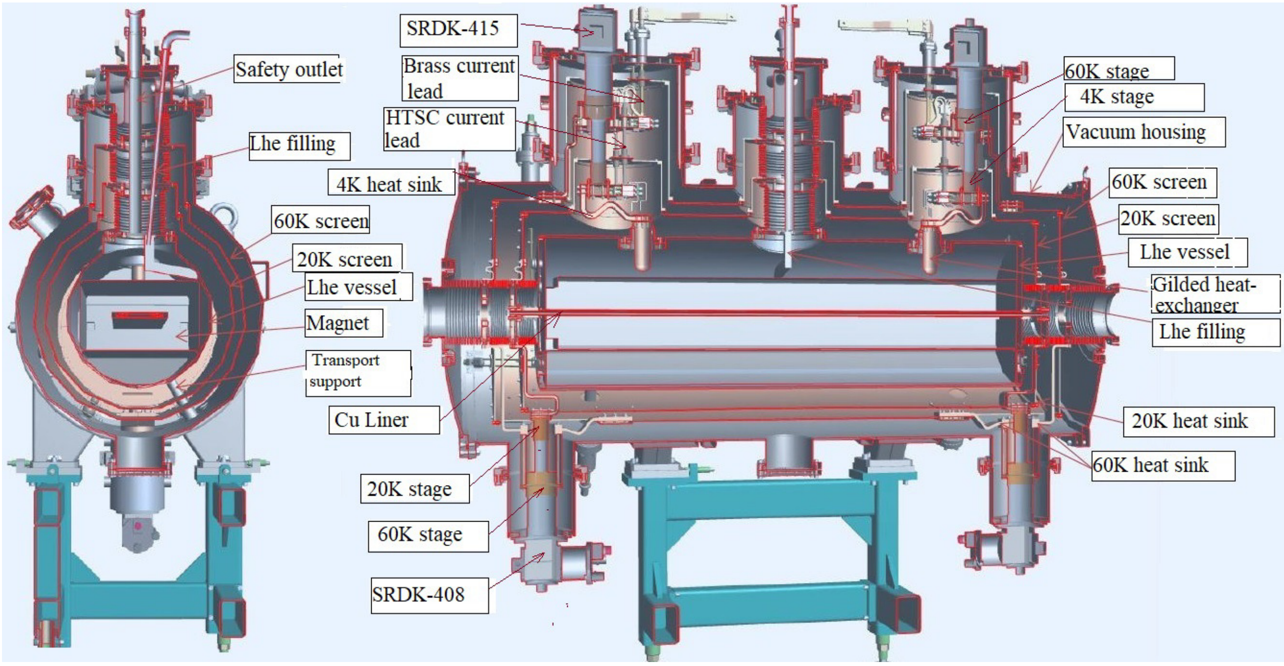

Figure 6: The design of SCMPW cryostat with zero liquid helium consumption.

To speed up the cooling it used two-phase nitrogen thermo-siphon heat pipes connected with 60 K stages of all four crycoolers with a total power of ~200 W. The heat tube is operated as a thermal switch which automatically cut off the thermal connection with the magnet body after cooling down to the temperature of ~64 K when the nitrogen will be frozen. Maximal extracted power for each pipe reaches a value of ~100 W [6].

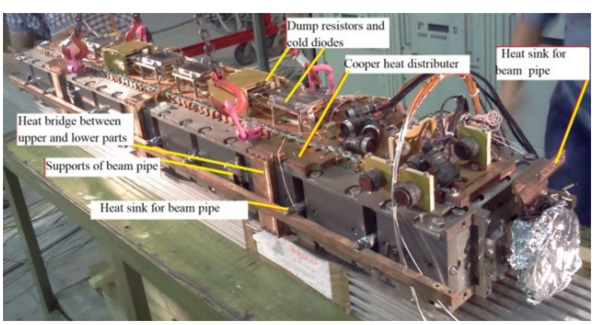

Figure 7: View of indirect cooling magnet for CLIC prototype.

The CLIC damping wiggler prototype with indirect cooling was successfully installed and commissioned in ANKA storage ring at 2016. Now wiggler is under study of effects on the beam dynamics. The wiggler will be used in parallel as synchrotron radiation source with photon energy of 20-50 keV for MIQA hard X-ray microscope on ANKA image beamline and for testing as damping wiggler prototype for CERN.

SUPERCONDUCTING UNDULATORS

A prototype of superconducting undulator magnet using active and neutral poles with a period of 15.6 mm and an operational field of ~1.2 T was tested by BINP at 2017. A pole gap of 8 mm provides a vertical aperture of 6 mm for an electron beam. In contrast to the traditional type of undulator with vertical racetrack coils in this type of undulator the coils are of the horizontal racetrack type. The magnet design consists of the aluminium-alloy frame, into which individual poles are inserted. The coils are made of NbTi/Cu superconducting wires with the diameter of 0.55 mm. In Fig. 8 the view of two halves of superconducting undulator during assembling is presented [7].


Figure 8: View of two halves of superconducting undulator during assembling processes.

CONCLISION

The family of the superconducting insertion devices produced by BINP is used in many synchrotron radiation sources for generation of photon spectrum covered a wide range of research tasks. Each of these devices was optimized for the individual requirements of the experiments and taking into account the characteristics of the storage rings.

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