Superconducting wigglers and undulators: technical aspects

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Superconductivity phenomena - 100 years

The phenomenon of superconductivity was discovered in 1911 by the Dutch physicist H. Kamerlingh Onnes and his assistant Gilles Holst in Leiden. They found that dc resistivity of mercury suddenly drops to zero below 4.2 K.

In 1933, W. Meiser and R. Ochsenfeld discovered in Berlin one of the most fundamental properties of superconductors: perfect diamagnetism.

The first microscopic theory of superconductivity in metals was formulated by J. Bardeen, L. Cooper and R. Schrieffer in 1957, which is now known as the BCS theory.

Introduction

Superconducting (SC) wigglers (SCWs) and undulators (SCUs) are high performance IDs suitable for extending the spectral range of SR storage rings towards shorter wavelengths and harder x-rays, increase brightness of photon sources. The SCWs can be either wave length shifters (WLS) with a few magnet poles with very high magnetic field or multipole wigglers (MPW) with a large number of poles with high magnetic field. The maximum magnetic field in SCWs and SCUs is defined by the critical curve of the SC wire. SC MPWs fabricated with use of Nb-Ti/Cu wire provide magnetic fields that are 2-3 times higher than what can be obtained using permanent magnets for the same pole gap and period length. SCWs and SCUs, as a rule, have zero first and second magnetic field integrals along electron orbit and their operation does not affect the working reliability of the storage ring.

There is no any basic difference between wiggler and undulator. Phase errors in a magnetic field are more important for undulators as spectrum-angular properties of radiation are formed by all undulator length.

The main parameter of alternating-sign magnetic field which defines radiation property is K-value:

\[ K = 0.934 \cdot \lambda_c [\text{cm}] B_0 [\text{T}] \]

K<1 - undulator
K>1 - wiggler
History

The history of SC IDs used for generation of SR started more than 30 years ago in Budker INP where the first SC MPW was designed and fabricated in 1979. The first SC MPW was installed on the 2 GeV storage ring VEPP-3 to increase photon flux density with higher energy. The cross section of the vacuum chamber of the SCW was like a keyhole where a wide vertical area was used for injection (30 mm), and narrow area (8 mm) was used for creation of magnetic field by the wiggler. These two areas were connected by narrow 5.5 mm slit for electron beam moving from injection area to area with high magnetic field. In order to move the electron orbit from the injection area to the working area, 4 steering magnets were used.

First superconducting multipole wiggler, BINP, Russia

Cross section of the magnet with vacuum chamber
The wiggler cryostat was built in the traditional scheme of those times with use of liquid nitrogen and liquid helium with a consumption of approximately 4 l/hr. Main benefit of the wiggler installation on VEPP-3 storage ring was a 200 times increase of the photon flux in the photon energy range 15–20 keV.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole number</td>
<td>20</td>
</tr>
<tr>
<td>Pole gap, mm</td>
<td>15</td>
</tr>
<tr>
<td>Period, mm</td>
<td>90</td>
</tr>
<tr>
<td>Magnetic field amplitude, T</td>
<td>3.5</td>
</tr>
<tr>
<td>Vertical beam aperture, mm</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Abstract. A superconducting undulator has been fixed on the ACO storage ring. It has been observed that the electron beam is stable in the small gap of the vacuum chamber and unperturbed by the magnetic field of the undulator. Light emission has been observed at 140 and 240 MeV in the visible and ultra-violet. First results indicate that its geometrical as well as spectral distribution agree with theoretical predictions; small disagreements very probably arise from the fact that the electrons are not travelling exactly on the axis of the undulator.
Superconducting materials

Period 40 mm
Number of periods 23
Effective length 0.96 m
Maximum field $B_0$ 0.45 T ($K = 1.68$).

Fig. 4: Spectral distribution of the emitted light ($\epsilon = 150$ MeV, $K = 1.2$) through a very small hole in the horizontal plane. Experiment: full lines; Theory: dashed lines.
**Main properties of SC materials**

The greatest interest from the point of view of creation of superconducting magnets represents such properties of superconductors, as critical temperature $T_c$, density of current $J_c$ and field $B_c$. These parameters define position of critical surface in space with coordinates $T$, $J$ and $B$ and, hence, limiting characteristics of a magnet. Therefore it is desirable, that the specified critical parameters had higher values.

The critical surface of niobium titanium: superconductivity prevails everywhere below the surface and normal resistivity everywhere above it.

B-T (critical field-critical temperature) and B-J (critical field – critical current) diagrams are shown in the figures below for best low temperature superconductors. Most of them exceed superconductors NbTi and Nb$_3$Sn by maximal magnetic field. However they, as a rule, essentially are more complex in manufacturing, and only two materials V$_3$Ga and Nb$_3$Al are possible to receive in the comprehensible form and the sufficient length for winding.
**Nb-Ti/Cu SC wire**

NbTi/Cu superconductor began one of the first to be used as a material suitable for magnet manufacturing. Owing to reliability and simplicity of windings manufacturing it still is the basic superconducting material for various magnets with field up to 8T.

Bottura’s formula

\[
B_{C2}(T) = \frac{B_{C2}}{T_{C0}} \left[ 1 - \left( \frac{T}{T_{C0}} \right)^{1/2} \right]^2
\]

\[C_0, \alpha, \beta, \gamma - \text{empirical parameters}\]

Typical values: \[C_0 = 0.005, \alpha = 0.6, \beta = 1, \gamma = 2\]

There are two basic processes for Nb-Ti/Cu which are used for manufacturing of windings:

- Wet winding – epoxy coating is used during winding with special fillers for alignment of contraction coefficients between superconducting wire and epoxy coating, for increasing of heat capacity (Al₂O₃, Gd₂O₂S etc)

- Dry winding - vacuum impregnation or impregnation under pressure with hot (120°C) hardening epoxy coating with corresponding fillers.

There is a technology of dry winding at which each coil layer is covering by the glass tape impregnated by silic-on-organic varnish which hardens at low temperature, but at room temperature again becomes viscous.
**Nb₃Sn/Cu SC wire**

Magnet manufacturing with use of superconductors on base of Nb₃Sn/Cu demands much more complex technology connected with baking out of a ready magnet at high temperature in vacuum or inert gas.

Three main processes of fabricating Nb₃Sn wires:
- Bronze process
- Internal Sn process
- Powder in tube (PIT) process

![Diagram of NbTi and Nb₃Sn comparison](image)

Comparison of NbTi and Nb₃Sn

\[
\frac{R_{c}(T)_{Sn}}{R_{c}(T)_{Ti}} = \left[1 - \frac{0.31}{T/T_{c,Sn}} \right] \left[1 - \frac{1.77}{T/T_{c,Sn}} \right] \left[1 - \frac{b}{T/T_{c,Sn}} \right]
\]

\[R_{c,Sn} = 30 \text{T}
\]

Critical field at T=0K

\[T_{c,Sn} = 18 \text{K}
\]

Critical temperature at B=0T

\[a = 900 \text{ for compressive deformation}
\]

\[a = 1250 \text{ for tensile deformation}
\]

\[\varepsilon = \text{deformation}
\]

Most technically comprehensible process of manufacturing of superconducting windings from Nb₃Sn is “Wind and react”. At this process the winding is made of a “crude” wire which has comprehensible properties for winding, and then the winding is baked out and as a result the wire possesses superconducting properties at low temperature.

**Process of baking out of Nb₃Sn/Cu coil**

![Process of baking out of Nb₃Sn/Cu coil](image)

**Nb₃Sn/Cu SC wire**

The Nb₃Sn wire will have superconducting properties at low temperature after baking out in vacuum or in inert gas at temperature 600-750°C. But after this process the wire becomes very fragile as glass and there are technological restrictions at manufacturing windings with use such wire during bend.

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High Temperature SuperConductors (HTSC)

1G BSCCO-2223 Tape (AMSC)

2G YBCO Wire (SuperPower, Inc.)

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Critical current versus magnetic field for different orientation of tape and for various temperature.
SC coil design types for multipole wigglers and undulators

\[ \text{Nb}_3\text{Sn} \text{ wire may increase field by another 1.5 times} \]
Planar coils:

- Horizontal racetrack coils
- Vertical racetrack coils

Comparison of horizontal and vertical racetrack coils

<table>
<thead>
<tr>
<th>Horizontal racetrack</th>
<th>Vertical racetrack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short SC wire is required</td>
<td>Long SC wire is required</td>
</tr>
<tr>
<td>Large number of splices for large number of poles.</td>
<td>Less number of splices.</td>
</tr>
<tr>
<td>Total SC wire length is minimal</td>
<td>Total SC wire length is 3-4 time more.</td>
</tr>
<tr>
<td>There is a possibility to make multi sections coils</td>
<td>There is no possibility to make multi section coils</td>
</tr>
<tr>
<td>The coils are stressed by bronze rods to compensate magnetic pressure in coils.</td>
<td>There is no possibility to stress coils by external compression</td>
</tr>
<tr>
<td>Minimal stored magnetic energy and inductance</td>
<td>Stored energy and inductance is more by 3 times</td>
</tr>
<tr>
<td>The coils have good thermo contacts with iron yoke after cooling down due to external compression</td>
<td>The thermo contacts became worth after cooling down. This is important disadvantage for indirect cooling magnets</td>
</tr>
</tbody>
</table>
Horizontal racetrack type (SC wiggles)

Budker Institute of Nuclear Physics

Magnet array of horizontal racetrack type poles (example of 30 mm period SC 2.1T wiggler)

Horizontal racetrack coils assembly allows:
• to pre-stress all coils together for compensation of magnetic pressure
• to use 2 or more sections coils, which gives a possibility to obtain higher field for the same SC wire.

Cold welding method of wires connection gives resistance of the connection $10^{-10}$, $10^{-13}$ Ohm

Vertical racetrack coils (SC undulators)

42 pole undulator APS prototype, period -16 mm
Vertical racetrack coils (SC undulators)

Under development in collaboration with ANKA

Period length, mm 15
Number of full periods - 100.5
Max field on axis with 8 mm magnetic gap, T 0.77
Max field in the coils, T 2.4
Minimum magnetic gap, mm 5.4
Operating magnetic gap, mm 8
Gap at beam injection, mm 16
K value at 5 mm gap - >2
Design beam heat load, W 4

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Vertical racetrack coils (SC undulators)

Jim Clarke
ASTeC, STFC Daresbury Laboratory

Magnetic length: 2 m
Period: 15 mm
Field on axis: 1.4 T
K: 2.0
Beam stay clear: 5 mm (Vert.) x 50 mm (Horiz.)
rms phase error: < 3 degrees
Trajectory straightness: ±/− 0.5 micron

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Vertical racetrack coils (SC wigglers)

LBNL

S. Freytag, D. Dietelrich, S. Marks, R. Sch"{u}cter

<table>
<thead>
<tr>
<th>Coil Geometric Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J ) [mA]</td>
<td>30</td>
</tr>
<tr>
<td>( r_a ) [mm]</td>
<td>4.8</td>
</tr>
<tr>
<td>( c_1 ) [mm]</td>
<td>10.2</td>
</tr>
<tr>
<td>( c_2 ) [mm]</td>
<td>7.4</td>
</tr>
<tr>
<td>( \lambda_a ) [mm]</td>
<td>28</td>
</tr>
<tr>
<td>Average iron length [mm]</td>
<td>24.9</td>
</tr>
<tr>
<td>Transitions</td>
<td>5</td>
</tr>
<tr>
<td>Number of layers</td>
<td>5</td>
</tr>
<tr>
<td>Conductor</td>
<td></td>
</tr>
<tr>
<td>Round diameter [mm]</td>
<td>0.88</td>
</tr>
<tr>
<td>Number of strands in coil</td>
<td>6</td>
</tr>
<tr>
<td>Cable width (inner) [mm]</td>
<td>1.75</td>
</tr>
<tr>
<td>cable height (outer) [mm]</td>
<td>0.90</td>
</tr>
<tr>
<td>Insulation thickness [mm]</td>
<td>0.060</td>
</tr>
<tr>
<td>C/CC</td>
<td>1.04</td>
</tr>
<tr>
<td>RRR</td>
<td>21</td>
</tr>
<tr>
<td>Cooling packing factor</td>
<td>0.52</td>
</tr>
<tr>
<td>Overall N. turnons</td>
<td>0.24</td>
</tr>
<tr>
<td>( J_{(0,5)} ) [A/cm²]</td>
<td>4075</td>
</tr>
<tr>
<td>( J_{(0,5, 4.3K)} ) [A/cm²]</td>
<td>4075</td>
</tr>
</tbody>
</table>

Anticipated performance (april 2011):

\[ A_{(T)} \] | 3.2 |
\[ \lambda_{max} \] | 5.5 |
\[ \lambda_{min} \] | 200 |
\[ E \] stuck energy [GeV] | 200 |

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SCU Helical constructed from NbTi (0.86T @ 11.5mm)

Nb3Sn short prototypes will be constructed soon (1.5T @ 11.5mm?)

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Double helical coils

Field distribution on the conductors

2D design (proposed by R. Maccaferr)
SC ID field calculations

1-section coils (example, SC wiggler)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period, mm</td>
<td>30</td>
</tr>
<tr>
<td>Pole gap, mm</td>
<td>12.6</td>
</tr>
<tr>
<td>Pole number</td>
<td>119</td>
</tr>
<tr>
<td>Nominal field, T</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Magnetic field distribution at the inner radius of the coil along vertical coordinate (B, kGs; z, cm).

Critical current curve of used superconducting Nb-Ti and field-current critical points inside coil correspond to magnetic field in median plane. Temperature decreasing gives a possibility to increase field.

Wire parameters:

- Wire diameter with/without insulation, mm: 0.55/0.5
- NbTi/Cu ration: 1.4
- Number of filaments: 312
- Diameter of filament, micron: 37
- Critical current at 7 Tesla, A: 236
**Comparison of one and two sections coils**

Figure shows a comparison of one and two section coils with identical layer numbers in the coils. The one-section coil reaches a critical current at 450 A and field of 4.5 T at internal layer. The two-section coil has different currents in sections which simultaneously reach critical values. The external section reaches a current of 649 A and field of 3.2 T at internal layer of the section. The internal section reaches a current of 380 A and field of 5.2 T at internal layer of the section. Due to splitting the coil into two sections with equal layer numbers and feeding section with different currents the field value increases by 15% (5.2 T and 4.5 T) in comparison with one-section coil. Maximal field may be increased by 30% in comparison with one section coil with use of independent current feedings of each coil layer. This approach requires a lot of independent power supplies and it is technical complication. Two-section coil is a reasonable compromise.

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**2-sections coils (example, SC wiggler)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period, mm</td>
<td>48</td>
</tr>
<tr>
<td>Pole gap, mm</td>
<td>14.4</td>
</tr>
<tr>
<td>Pole number</td>
<td>49</td>
</tr>
<tr>
<td>Nominal field, T</td>
<td>4.1</td>
</tr>
</tbody>
</table>

**Wire parameters:**

- Wire diameter with/without insulation, mm: 0.91/0.85
- Number of filaments: 312
- Diameter of filament, micron: 37
- Critical current at 7 Tesla, A: 700
- Critical current curve of used superconducting Nb-Ti wire (red line)
- Load lines for 4-section magnet with separate feeding
- Load lines for 4-section magnet with separate feeding

Critical current curve of used superconducting Nb-Ti wire (red line) and field-current critical points inside coil correspond to magnetic field in median plane.

**Magnetic field distribution at the inner radius of the coil 1st section along vertical coordinate (B, kG; z, cm).**

**Magnetic field distribution at the inner radius of the coil 2nd section along vertical coordinate (B, kG; z, cm).**

**Two-sections coil gives up to 15% higher field for the same SC wire.**
Magnetic field distribution in high field wigglers (Example of 7.5 T SC wiggler)

The magnetic flux inside of a pole in multipole wigglers and undulators is closing through the neighbor poles. In case of 2-dimensional field distribution (infinitely wide poles) the longitudinal field integral in median plane is automatically equal to zero. It follows from Maxwell’s equations. At a high field in a wiggler iron cores are completely saturated and represent permanent magnets which give to the field some small contribution. This contribution may be increased with use some materials like Dy or Ho which are saturated at higher field. The maximal field inside the coils is on a wire layer which is nearest to an iron pole and approximately on half of height of the pole. This fact should be taken into account at field calculation as this part of the wire is most close to a critical curve on the diagram a field-current. External iron yoke is in use mainly as support system for poles and closes a stray field.

Lorentz forces in high field SC wigglers (Example of 7.5 T SC wiggler)

The forces acting on windings in horizontal direction, aspire to tear off the winding from the iron core. If there is no counteracting force a winding may move and as a result a heat will be extracted, temperature of a superconducting wire will rise up and the wire may transit to normal state (quench). Usually in such situations the further quench training of the magnet does not lead to field increasing. Presence of counteracting force may create a high pressure inside of windings (several hundreds bar) at which epoxy starts to crack with heat extraction. This also may be a reason of a quench. But here there is a hope, that quench training increase the field.
Lorentz forces in high field SC wigglers (Example of 7.5 T SC wiggler)

Lorentz forces (vertical component) acting on windings in vertical direction

Lorentz forces (vertical component) acting on windings in vertical direction along a vertical line passing through a coil mid. A)-wiggler with iron yoke, B)-wiggler without iron yoke

The forces acting on windings, lead to their compression. Presence of iron yoke decrease integral force acting on windings.

Main parameters of multipole SC ID

Main parameters of a superconducting multipole ID are:

- $\lambda_0$ - period,
- $B_0$ - magnetic field in median plane,
- $g$ - pole gap.

These parameters are linked by means of the formula:

$$B_p = \frac{B_0}{\sinh \frac{l_p}{g}} \approx \frac{B_0}{\frac{l_p}{g}}.$$ 

$B_p$ - parameter is defined by magnet design and used superconducting materials.

Correlation of $B_p$ parameter with magnetic field for various SC wires.
Transition of superconductor to normal state. (Quench)

Normal zone propagation

Quench is transition of a magnet in normal state occurs at occurrence in its winding of zones with normal resistance. As the superconductor in a normal state possesses high specific electroresistance, at presence in the winding of the magnet with high density current the superconductor in these zones is warmed up to the temperatures considerably exceeding its critical temperature, and the sizes of normal zones are increasing with time. This irreversible process leads to transformation of all energy reserved in the magnet into heat.

The energy necessary for translation of a winding in a normal state is rather small owing to low thermal capacities of materials at low temperatures: typical values of a thermal capacity at temperature of liquid helium approximately in 1000 times less than at room temperature.

The reason of a quench in a winding can be jumps of magnetic flux at ramp field, movement of badly fixed superconducting wire, epoxy crack, bad electric contact in a junction of wires, external heat in-leak.

Appearance of a normal zone under action of local perturbation in a superconducting wire with current

\[ l = \left[ \frac{2\kappa (\theta_c - \theta_0)}{\rho J_c^2} \right]^{1/2} \]

\( J_c \) - critical current
\( l \) - minimal propagation zone (MPZ)
\( \rho \) - specific electroresistance
\( \theta_c, \theta_0 \) - temperatures
Thresholddensityof energy of volumetric perturbations for quench appearance in *a typical winding* = at $T$=4.2K

**Reasons:**

- mechanical movement of SC wire
- crack of epoxy resin in coil
- heating of coil due to eddy current
- heating of coil due to bad electrical junction
- magnetic flux jump

### Coil heating during quench

During propagation of normal zone inside magnet winding there is a non-uniform non-stationary temperature distribution changing within the limits of from 4.2K up to some maximal temperature $\theta_m$ in point the quench happened.

Thermal balance for normal zone:

$$J^1(c) \rho(\theta) dt = \gamma C(\theta) d\theta$$

$C$ - specific heat capacity,
$\gamma$ - average winding density

$$\int_0^1 J^1(c) \rho(\theta) dt = J^1(c) \int_0^1 \gamma C(\theta) d\theta = U(\theta_m)$$

Universal function $U(\theta_m)$ depends only on physical properties of the materials used in a winding, and allows to define the maximal temperature on initial current density in the winding and to characteristic time $t_d$ attenuations of the current.

$$C$$ - specific heat capacity,
$\gamma$ - average winding density

Function $U(\theta)$ for various conductors and typical magnet windings of small sizes. 1- copper RRR=150, 2- copper RRR=30, 3- aluminium $\rho=5*10^{-11}$ Ohm*m, 4- winding (23% Nb/Ti, 47% Cu, 30% epoxy.)
Normal zone propagation velocity

\[ V = \frac{J}{\gamma C \left( \theta_s - \theta_c \right)^{\frac{1}{2}}} = \frac{J L \theta_c}{\gamma C \left( \theta_s - \theta_c \right)^{\frac{1}{2}}} \]

Useful relation between \( \kappa \) and RRR for copper

\[ \kappa \left( \frac{\text{RRR}}{\theta_0} \right)^T \text{ W/cm/K} \quad (\text{RRR}=3.126\sigma_{300K}) \]

\[ L_0 = 2.45 \times 10^7 \text{ W*Ohm/K}^2 \quad \text{Lorentz constant} \]

\[ \frac{\kappa}{\sigma} = L_0 T \quad \text{Wiedemann-Franz-Lorentz law} \]

Copper electrical resistivity

Copper heat conduction

Quench detection and quench protection
Quench detection

The high potential develops inside of a winding where exists resistive voltage component directed towards inductive. The small voltage difference between feeding wires is caused by small internal resistance of power supply which is usually automatically disconnected at quench. But even if it will not occur, the voltage on the power supply is only some volt in comparison with hundreds and, probably, thousand volt in a normal zone. Therefore the voltage of the power supply can be neglected, but it should be disconnected quickly whenever possible to not admit a long heating winding inside a cryostat.

\[
V_Q(t) = I(t) \cdot R_Q(t) + L_Q \frac{dI(t)}{dt}
\]

\[
I(t) \cdot R_Q(t) + L \frac{dI(t)}{dt} = 0
\]

\[
V_Q(t) = R_Q(t) \left( 1 - \frac{L}{L_Q} \right)
\]

\[ L \text{ – total inductance of a magnet,} \]

\[ L_Q \text{ – effective inductance of quenched magnet part.} \]

Resistance of normal zone \( R_Q(t) \) and its effective inductance \( L_Q \) grow with time, and current \( I(t) \) is damping. Voltage \( V_Q \) in normal zone all over again grows up to the maximal value, and then decreases.

Electric potential distribution in a winding during quench

Time dependence of taps voltage of one section quenched coil

Quench detection

On bridge scheme the potentiometer is set in position at which gauge D does not react to current change in a magnet \( dI/dT \). It is supposed, that gauge D registers voltage difference between top and bottom magnet sections caused by occurrence of a normal zone in a winding.

Compensating winding scheme is a registrator of transformer type in which the secondary winding is set on one of current leads and registers a signal \( dI/dT \) in magnet circuit. This signal amplifies, and then by the electronic detector is subtracted from the voltage of certain part of the winding.

The scheme of quench detecting by means of a compensating winding
Quench protection

Passive quench protection scheme

Cold Si diodes are used as passive quench protection system in combination with dump resistor $R_d$. The cold Si diod is closed in both directions for voltage less than several volts. At higher volt the diod becomes normal diod. This property of the diod gives a possibility to ramp up and down field in a magnet without current branch, but if quench happened the diod opening and current flows through dump resistor.

Active quench protection scheme

Active quench protection scheme a magnet with inductance $L$, consists of external resistance $R_g$ and switch $S$. During magnet feeding or operating conditions switch $S$ is closed and the current practically does not flow through resistance $R_g$. As soon as quench detector will register the beginning of quench, switch $S$ is disconnected and current flows through resistance $R_g$. If $R_g$ is big enough in comparison with the resistance arising in the magnet the constant of time $T_0$ of circuits is defined by external resistance $R_g$.

Significant part of stored energy in a magnet may be extracted to external resistance as an element of magnet quench protection. It allows to reduce losses of liquid helium on evaporation at a quench and, besides to eliminate the usual danger connected with occurrence is excessive a high pressure inside cryostat as a result of boiling liquid helium. However reliability of such active method of protection entirely depends on non-failure operation of systems of registration and the breaker of a current. Therefore in many cases preference give passive ways of protection without application of any mechanical devices.
Quench training effect

Example of SC wiggler for DLS training effect

Influence of SC ID field on beam dynamics
Field integrals

SC multipole wigglers and undulators represent sign-variable magnetic structure with many poles and with magnetic field defined by critical curve of a SC wire. Generally these devices are symmetrical or asymmetrical relative a mid point of magnetic structure. Main requirement for field feature is equality of first and second field integrals to zero. To provide this requirement two power supplies are used for feeding main and side coils.

Field integrals along ID magnet

\[ \psi = \frac{1}{B_0} \int \frac{B_z(s)}{s} ds + \frac{1}{B_0} \int \frac{B_z(-s)}{s} ds \]

First field integral (angle deviation of beam orbit inside ID with \( B_0 \) beam rigidity). \( B_z(s) \) – vertical component of ID magnetic field, \( s \)-longitudinal coordinate, \( L \)-ID length.

If \( B_z(-s) = -B_z(s) \) – asymmetric system \( \psi = 0 \)

For symmetrical system \( B_z(s) = B_z(-s) \) to provide \( \psi = 0 \) currents in side poles should be adjusted.

The second field integral (orbit distortion inside L-interval:)

\[ \delta = \frac{1}{2} \int \frac{B_z(s) + B_z(-s)}{s} ds \]

If \( B_z(s) = B_z(-s) \) symmetric system and \( \delta = 0 \).

For cases a) and b) in the figure the integral is not zero but for symmetrical case \( B_z(s) = B_z(-s) \) the integral is zero.

For case a) for both cases the integral may be set to zero using two power supplies.

End poles are using for compensation of field integrals.

Odd number of pole

Field distribution in SC 4.2T wiggler with odd pole number

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Orbit inside ID

First field integral

\[ x'_0(s) = \frac{1}{B_0} \int ds' B_z(s') \]

Second field integral

\[ x''_0(s) = \frac{1}{B_0} \int ds' \int ds'' B_z(s') \]

Angle orbit deviation inside 49-pole wiggler at field setting 4.2 Tesla, \( E=3 \) GeV

Orbit distortion inside 49-pole wiggler at field setting 4.2 Tesla, \( E=3 \) GeV
**Phase space of electron orbit and photon beam**

- Electron beam orbit phase space
- Photon beam phase space reduced to the wiggler center

**Focusing property of SC ID**

\[
x' = K_x, \quad x = 0
\]

\[
z'' = K_z, \quad z = 0
\]

Betatron motion equations

Local and integral focusing rigidity

\[
K_x = \frac{B_1}{(8\pi)} \frac{1}{\beta p} \left( \frac{\partial^2 R}{\partial \phi^2} \frac{\partial R}{\partial x} \right)
\]

\[
K_z = \frac{1}{\beta p} \left( \frac{\partial^2 R}{\partial \phi^2} \frac{\partial R}{\partial z} \right)
\]

\[
\int_{x_0}^{x_1} K_x dx = \int_{x_0}^{x_1} \frac{B_1}{\beta p} \frac{\partial R}{\partial x} dx = \int_{x_0}^{x_1} K_x dx
\]

\[
\int_{x_0}^{x_1} K_z dz = \int_{x_0}^{x_1} \frac{B_1}{\beta p} \frac{\partial R}{\partial z} dz = \int_{x_0}^{x_1} K_z dz
\]

Vertical and horizontal tune shifts for BESSY SC 7 T WLS versus magnetic field level.
Beating beta-functions

$$\frac{\Delta \beta_{x,t}}{\beta_{x,t}} = \frac{K_x, \Delta \beta_{x,t}}{2 \sin(\mu_{x,t})} \left( 1 - \frac{L^2}{12 \beta_{x,t}} \right)$$

Betatron $\beta$-functions beating

Effect of 3.5 Tesla SC wiggler installed on MAX-II ring.

Radiation (structural) integrals:

$$\Delta_1 = \int \frac{\alpha_x, \beta_x, \gamma_x}{b}$$

$\alpha_x, \beta_x, \gamma_x$ are Twiss parameters

$$\Delta_2 = \int \frac{B_x(s)}{b} ds$$

$$\Delta_3 = \int \frac{B_x(s)}{b} ds$$

$$\Delta_4 = \int \left( \frac{B_x(s)}{b} \right)^2 \frac{2K_x}{b} \eta_x - \eta_x(s) ds$$

$$\Delta_5 = \int \left( \frac{B_x(s)}{b} \right)^2 \frac{2K_x}{b} \eta_x - \eta_x(s) ds$$

$$\left( \frac{\sigma_x}{\sigma_x} \right)^2 = \frac{1}{1 + \frac{\Delta_1}{\Delta_2 + \Delta_3}}$$

Energy spread change

$$\left( \frac{\Delta_5}{\Delta_4} \right)^2 = \frac{1}{1 + \frac{\Delta_4}{\Delta_2 + \Delta_3}}$$

Emittance change

Energy spread in BESSY storage ring versus magnetic field level in SC 7 T WLS.

Horizontal emittance BESSY storage ring versus magnetic field level in SC 7 T WLS.
Magnetic field measurements of an ID are usually carried out in Cartesian coordinates which will have designations \( \chi, z, \sigma \), thus the axis \( \sigma \) coincides with a longitudinal axis of an ID, \( \chi \) and \( z \) are horizontal and vertical directions correspondingly. Planes \( s = 0, \chi = 0, \sigma = 0 \) are corresponding planes of symmetry of WLS magnetic systems; therefore, the basic members of magnetic field expansion into multipole components in Cartesian coordinates, following K. Steffen (1965), may be written down in the forms:

\[
B_z = a + \frac{1}{2} b (\chi^2 - z^2) - \frac{a'}{2} z^2 + \frac{c}{24} (\chi^4 - 6\chi^2 z^2 + z^4) - \frac{b'}{4} \chi^2 z^2 + \frac{b''}{12} z^4 + \frac{a'''}{24} z^6 + \ldots
\]

\[
B_\chi = b' \chi^2 + \frac{1}{6} c (\chi^2 - 6 \chi z^2 - 6 \chi^2 z^2) + \frac{b''}{3} \chi^3 z + \ldots
\]

\[
B_\sigma = a' + \frac{1}{2} b' z^2 - \frac{a''}{6} z^2 + \frac{b'''}{24} z^4 + \ldots
\]

If magnetic system is homogeneous enough so that orbit deviation \( x_{d(\sigma)} \) is much less than characteristic size of field decrease, the formulas may be simplified:

\[
B_z = a + \frac{1}{2} b \chi^2
\]

\[
G = b \cdot x'_0 - x'_0 a'
\]

\[
S = b - 2b' \chi x'_0 + a' x'^2_0
\]
SC ID field expansion into multipole components

Magnetic field of multipole ID with periodic magnetic field can be approximated by formulas:

\[ B_z = B_0 \cos(k_\sigma \sigma) \cos(k_z z) \]
\[ B_x = -\frac{k_x}{k_z} B_0 \cos(k_\sigma \sigma) \sin(k_z z) \sinh(k_z z) \]
\[ B_y = -\frac{k_y}{k_z} B_0 \sin(k_\sigma \sigma) \cos(k_z z) \sinh(k_z z) \]

Where \( k_\sigma \), \( k_x \), \( k_y \), \( k_z \) are wiggle characteristics magnetic field periods in \( \sigma \), \( x \), \( y \), \( z \) directions and \( k_z^2 = k_x^2 + k_y^2 \) are following from Maxwell equations.

Field, gradient, and sextupole components in approximation \( k_\sigma, k_x, k_y < 1 \), \( \zeta, \zeta < 1 \) may be expressed as:

\[ B_1(\sigma) = B_0 \cos(k_\sigma \sigma)(1 - \frac{1}{2} k_z^2 x_0^2(\sigma) + ... \]
\[ G(\sigma) = B_0 \left( \cos(k_\sigma \sigma)(-k_z^2 x_0^2(\sigma) + ... + \sin(k_\sigma \sigma) x_0'(\sigma) k_0 + ... \right) \]
\[ S(\sigma) = B_0 \left( \cos(k_\sigma \sigma)(-k_z^2 - k_\sigma^2 x_0^2(\sigma) + ... + \sin(k_\sigma \sigma)(-2k_z^2 k_\sigma x_0(\sigma) x_0'(\sigma) + ...) \right) \]

\[ x_0'(\sigma) = \frac{B_0}{k_z B \zeta} \sin( k_\sigma \sigma ) \]
\[ x_0''(\sigma) = \frac{B_0}{k_z B \zeta} \cos( k_\sigma \sigma ) \]

SC ID cryogenic systems
Bath cryostat systems

The basic cryostat function is maintenance of SC wiggler magnets at temperature of liquid helium of 4.2 K. The wiggler magnet is placed into a bath with liquid helium and all heat emission inside the magnet and heat in-leak outside lead to liquid helium evaporation process. The cryostat consists of external vacuum housing, 60 K and 20 K shield screens, liquid helium vessel with a SC multipole magnet inside, throat, vacuum chamber (beam duct) with copper liner inside, upper flange, filling tube, two 2-stage coolers with stage temperature 4.2 K/50 K, and two 2-stage cryocoolers with stage temperature 20 K/50 K for shield screen cooling.

Bath cryostat systems (shield screens)

The inner liquid helium vessel is surrounded by two shield screens to reduce the irradiation heat flux from outside. The temperature on the outside shield screen is about 60 K, and on the inner one the temperature is about 20 K. Shield screens are made of copper by thickness of 3 mm. The 60 K and 20 K copper screens are assembled to common block and inserted into the cryostat housing using special fiber glass balls. The 60 K screen is attached to all of four 60 K stages of the coolers by heat sinks. The 20 K stages of the both bottom coolers are connected to copper liner and to 20 K screen. The 4 K stages of top cryocoolers are attached to HTSC current leads and to liquid helium vessel. The external 60 K screen is covered by 30 layers of cryogenic superinsulation.
There is vacuum insulation between the helium vessel and external warm stainless steel vessel to reduce the residual gas heat flux. The helium vessel is suspended with four vertical and four horizontal kevlar straps connected to the external cryostat vessel. These straps pass throughout the both shield screens and attach to bolts on the external housing walls and are used for precise alignment of the vertical magnet position. Superconducting magnet is inserted into the liquid helium tank which is located inside of the shield screens and fixed on four vertical and four horizontal Kevlar suspension straps attached to the external housing. The helium vessel is a 316LN stainless steel barrel with the wall thickness of 6 mm. The axis of barrel is oriented horizontally.

### Cryostat heat load budget

**Main processes of heat load:**

- **heat conduction:**
  \[ Q = -\frac{1}{A(x)} \int_{x_1}^{x_2} k(x') dx' \]

- **radiation:**
  \[ Q = \varepsilon \sigma T^4 \]

- **image current of electron beam**

<table>
<thead>
<tr>
<th></th>
<th>First 60K shield screen, Watt</th>
<th>Second 20K shield screen, Watt</th>
<th>LHe vessel 4.2K, Watt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>8</td>
<td>0.7</td>
<td>0.0001</td>
</tr>
<tr>
<td>Central throat bellows</td>
<td>5</td>
<td>0.9</td>
<td>0.03</td>
</tr>
<tr>
<td>Vacuum chamber bellows</td>
<td>8</td>
<td>0.7</td>
<td>0.02</td>
</tr>
<tr>
<td>Support system</td>
<td>0.5</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Current leads heat conduction</td>
<td>70</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Current leads Joule heat</td>
<td>60</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>Measuring wires</td>
<td>5</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Liner</td>
<td>0</td>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>156.5</strong></td>
<td><strong>12.41</strong></td>
<td><strong>1.0601</strong></td>
</tr>
<tr>
<td>Cooling machine capacity</td>
<td>210</td>
<td>25</td>
<td>3</td>
</tr>
</tbody>
</table>

1 W = 1.4 liter/hour of LHe at 4.2K, or ~2.6kJ = 1 liter of LHe
**Cryocoolers capacity (example)**

<table>
<thead>
<tr>
<th>SRDK415D – W71D</th>
<th>SRDK418S – W71D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigeration Capacity</td>
<td>Refrigeration Capacity</td>
</tr>
<tr>
<td>First Stage</td>
<td>First Stage</td>
</tr>
<tr>
<td>Second Stage</td>
<td>Second Stage</td>
</tr>
<tr>
<td>Weight</td>
<td>Weight</td>
</tr>
<tr>
<td>35W/45W @ 50K (50/60Hz)</td>
<td>35W/40W @ 50K (50/60Hz)</td>
</tr>
<tr>
<td>1.5W @ 4.2K Max. (50/60Hz)</td>
<td>5.4/6.3W @ 10K Max. (50/60Hz)</td>
</tr>
<tr>
<td>18.5kG</td>
<td>18.5kG</td>
</tr>
</tbody>
</table>

**Beam vacuum chamber system**

Insulating vacuum is separated from UH vacuum of a storage ring and keep at vacuum level $10^{-6}$ to $10^{-7}$ Torr by 300l/s ion pump.

Liquid helium vessel with vacuum chamber fittings.

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Protection of liquid helium vessel from electron beam heating (copper liner)

Beam heating effect:
- synchrotron radiation from upstream bending magnet
- image currents
- wake fields
- electron clouds

Pole gap and electron beam vertical aperture

As it was already mentioned above, the formula for multipole IDs forms a bond of key wiggler parameters: field, period, and pole gap. That strongly limits freedom of a choice. Low limit of beam vertical aperture of modern storage rings is about 6–7 mm by requirements of beam dynamics in storage rings.

In the bath cryostat design, it is supposed that inside of pole gap, a vacuum chamber and 20 K shield screen should be installed. The vacuum chamber is a part of liquid helium vessel and has temperature of 4.2 K. Shield screen with temperature 20 K (copper liner) absorbs heat which is raised by electron beam moving inside the copper liner (SR, heating by image currents, etc.).

Direct cooling magnet with liquid helium (magnet in bath cryostat)

Indirect cooling magnet
Magnet in insulating vacuum

Pole gap = V aperture + 4 mm
Pole gap = V aperture + 1.5 mm
Cryogenic System of indirect cooling of magnet

Example of cryostat with indirect cooling of undulator magnet in APS

Current feeding of SC ID
**Electrical connections**

Two power supply units are used to feed the central and side coils. Such connection gives a possibility to control the field integral to zero with required accuracy.

**Normal conducting current leads**

The primary goal of current leads design is minimizing heat in-leak into cryostat at set current in a magnet. This heat in-leak has two components: one is caused by current leads heat conductivity, and another — Joule heat. Therefore it is natural, that heat conductivity and current leads electroresistance should be minimal. However, according to law Wiedemann–Franz low these two metal properties are linked:

\[ \frac{L}{R} = \alpha T \]

This low is well enough correct for majority of metals and alloys. It means that the minimum heat in-leak into cryostat depends not on current leads material but on their form and dimensions.

The equation for temperature distribution along not cooled by gas current leads with a current is as follows:

\[ \frac{d}{dx} \left[ \frac{1}{a} \frac{d}{dx} \left( \frac{1}{a} \frac{d}{dx} \right) \right] = \frac{L}{R} \]

Not cooled by gas current are used as the first step combined rcurrent leads from normally spending metal in a range of temperatures 300K-70K. The second part of current leads consists of a warm superconductor in a range of temperatures 70K-4K.

For optimal current lead calculated for current \( I_0 \) made of pure copper the heat in-leak due to heat conduction is equal to \( W/I_0 = 0.7 \times 10^{-3} \) W/A if there is no current, but for electro-technical copper the heat in-leak is \( W/I_0 = 0.4 \times 10^{-3} \) W/A.

Than a current lead material (i.e. the it has smaller heat conductivity) is less pure, it is more suitable for current leads.
Combined normal and high temperature SC conducting current leads

Feeding current is passing through current lead which consists of normal conducting brass current lead and high temperature superconducting (HTSC) current lead. The current leads are grouped on two special current leads blocks together with cryocoolers. The top ends brass current leads are connected to power supplies at room temperature in an atmosphere. The brass current leads feedthrough into insulating vacuum volume and their bottom ends have thermal contact with first stage of cryocoolers for interception of heat in-leak at temperature 55-60K. In the point of heat interception the brass current leads are connecting HTSC current leads. The junction is supervised by the temperature probes as interlocks for HTSC current leads safety if the temperature of this current leads above 70K.

SC ID magnetic measurements systems
Hall probes measurements

Parameters:
• 2 Hall probes mutually perpendicular
• Temperature probe
• Steps defined by step motor
• Ti-tube is warming up to room temperature by DC
• Ti-tube horizontal by microcontrol stage translation ± 20 mm
• Ti-tube vertical manual translation ± 5 mm

Field integrals measurements with stretched wire method

Main purposes:
• To make a table of currents (main and correctors) to provide field ramping up and down without orbit distortion
• To minimize field ramping time
• To estimate field multipole integrals at any field level

A method of strained wire with a current was used for field measurements and coil currents matching. The method is based on a very similar behavior of the wire with dc current in magnetic field and electrons moving along this magnetic field.

The wire strained by a force P was passed through the vacuum chamber of the wiggler. At the ends of the wiggler, the two Wire Position Probes (WPP) were installed to measure displacements of the wire during the experiment. The space resolution of WPPs is about 0.005 mm.
Motivation of the method

\[
\frac{d^2 s}{ds^2} = \frac{B(s)}{\beta p} \quad \text{beam orbit in magnetic field } B(s), \quad \beta p \quad \text{beam rigidity}
\]

\[
\frac{d^2 s}{ds^2} = \frac{B(s)}{\beta p} \cdot \frac{d^2 s}{ds^2} = \frac{B(s)}{\beta p} \quad \text{bending of stretched wire with current in magnetic field } B(s)
\]

\[
\frac{T}{I} = \text{Rigidity of stretched wire with current}
\]

First term of equation for wire may be neglected for thin wire

\[
\frac{d^2 s}{ds^2} = \frac{B(s)}{\beta p}
\]

Beam orbit and wire bends are described by formulas (L-magnet field length)

if initial angle and coordinate are equal to 0 at ±L/2:

\[
\alpha_1 = \left( \frac{L}{2} \right) \left( \frac{\beta p}{I} \right) \quad \text{angle deviation of beam orbit or wire at s-position}
\]

\[
\alpha_1 = \left( \frac{L}{2} \right) \left( \frac{\beta p}{I} \right) \quad \text{X-coordinate of beam orbit or wire at s-position}
\]

\[
\delta \alpha = \frac{\delta \alpha_1}{L} \quad \text{Angle and coordinate at L/2}
\]

\[
\delta \alpha = \delta \alpha_1 + \delta \alpha_2 \quad \text{Total angle deviation}
\]

\[
\delta \alpha = \delta \alpha_2 - \delta \alpha_1 \quad \text{Orbit distortion at condition}
\]

\[
\delta \alpha = 0 \quad \text{I}_{\text{max}} = \left( \frac{L}{2} \right) \left( \frac{\beta p}{I} \right)
\]

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Scheme of measurements and data readout

Wire Position Monitors

Stretched wire

ADC

AC for WPM

DC for beam simulation

Wire tension force

F

VME

I=0.2A

Filter

ADC

VME

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Results of measurements

Field ramping with zero field integrals using two power supplies

First field integral behavior during ramping field up and down.

The currents Iside and Icentral for zero first field integral versus magnetic field

Thanks for your attention
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