Planar superconducting undulator with neutral poles: test results of the prototype and future plans

Khruschev S.V., Mezentsev N.A., Shkaruba V.A., Syrovatin V.M., Tsukanov V.M.

Budker Institute of Nuclear Physics
Introduction

Development and creation of new bright structures of sources of SR promotes development and creation of undulators with various parameters for generation of X-ray of high brightness with spatial coherence. Use of materials of superconductivity (NbTi/Cu, NbSn/Cu) has the considerable advantage in comparison with use of permanent magnets.
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Period: 15-20 mm
Deflection parameter K~2
Phase error: < 3°
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- Period: 15-20 mm
- Deflection parameter $K \sim 2$
- Phase error: $< 3^\circ$

![Magnetic fields for in-vacuum undulators (IVUs) and superconducting undulators (SCUs)](chart.png)
Superconducting undulators
Superconducting undulators

The main vertical field of an undulator is created by horizontal cross currents.

In a 2-dimensional case when in the cross direction of a winding have the infinite size it doesn't matter how currents are closed.

For windings of the limited sizes of coils the currents can be closed in the vertical plane (vertical racetrack coils) or in the horizontal plane (horizontal racetrack).
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Horizontal racetrack coils with neutral poles
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The way of windings with a current closing in the horizontal plane with use of a neutral pole was proposed in BINP.
Superconducting undulators

Vertical racetrack coils

Main requirements:
- Period length – 15-20 mm
- Pole number >100
- K-value >1
- Vertical aperture 4.5-10 mm
- Phase error <3°
Superconducting undulators

Horizontal racetrack coils

Standard horizontal racetrack coils

Horizontal racetrack coils with neutral poles

Current $I$

Double current $2I$

Neutral pole

Active pole

Pole thickness

Pole width

Period
Currents in all windings of poles flow equally so that for case when the halves of top and bottom assembly of a magnet set exactly one opposite another in a lengthwise direction the vertical field in the median plane is equal to zero. In order to create the vertical field the top and bottom halves of the magnet have to be displaced on a half of the undulator period.

Superconducting undulator prototype with neutral poles

Horizontal racetrack coils with neutral poles

Neutral poles

Active poles
Superconducting undulator prototype with neutral poles

The magnet consists of two identical top and bottom halves. Windings are reeled up on the iron core. Between windings the iron core without windings (a neutral pole) is inserted. A combination a winding + a neutral pole make one period of an undulator. Halves of an undulator are powered equally and turned to each other so that magnetic fields are directed towards to each other. For creation of the cross field in the median plane one half is shifted concerning another on a half of the period.
Superconducting undulator prototype with neutral poles
Superconducting undulator prototype with neutral poles

The prototype of superconducting undulator with the period of 15.6 mm is designed, fabricated and successfully tested in BINP. Windings type of the prototype are made as horizontal racetrack. Pole gap - 8 mm, number of the periods 15, maximal field was achieved 1.2 T.
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Superconducting undulator prototype with neutral poles

The framework of the undulator is made of the soft iron. Vertical ribs play a role of neutral poles. Windings with iron cores are inserted into grooves. Distances between grooves are equal to the undulator period.
Superconducting undulator prototype with neutral poles

Iron core

SC coil

Pole - main element of the undulator (model)

Photo of main pole of the undulator made with use wet winding technology

Photo of cut main pole of the undulator made with use dry winding technology (wind and impregnation)

The working point position on I-B diagramm of used SC wire (1.2T in median plane).
Superconducting undulator prototype with neutral poles

Model of $\frac{1}{2}$ 15 periods undulator

Position of the frames. Upper and bottom frames are shifted of $\frac{1}{2}$ period

Photos of SC undulator with neutral poles
Superconducting undulator prototype with neutral poles (test results)

Calculated field: $\lambda=15.6$ mm, gap=8 mm, $I=500$ A

Measured field: $\lambda=15.6$ mm, gap=8 mm, $I=512$ A

Quench history of the prototype inside vacuum cryostat with indirect cooling system

Absolute value of the measured field
Test results resume
Test results resume

• Manufacture of the horizontal racetrack type windings allows to carry out an individual inspection of each pole on identity and existence of violations of isolation.

• High precision of production of the windings and the framework is provided (an arrangement of coils concerning the magnet median plane and period)

• During quench training the magnet quickly comes to the level of the maximal field in spite of the fact that poles were not exposed to addition compression.

• At identical cross sectional dimensions of the active and neutral poles enough strong dependence of integral of the horizontal transversal field from horizontal transversal coordinate is observed. For elimination of this dependence cross sectional dimensions of the active and neutral poles have to be different.
Parameters of neutral and active cores

The proper correlation of width of the active and neutral poles creates aperture area of a weak dependence of field integrals for horizontal and vertical shifts concerning an undulator axis. Width ratio of neutral and active poles were calculated taking into account that field integrals should be less than $10^{-4}$ T*m in region +/-20 mm in horizontal aperture.

Width of neutral pole versus width of active pole. The ration provides maximal horizontal area to keep field integrals inside $10^{-4}$ T*m.

X-aperture with acceptable field integrals versus width of core coils.

Ratio of neutral and active poles widths versus width of core coils.
General undulator field properties
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Pole gap - 8 mm
SC wire - 0.55 mm diam
I (critical) - 550 A
B (critical) - 4.25 T
General undulator field properties

Magnetic field versus period length at pole gap 8 mm

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Magnetic field versus pole gap at period length 15.6 mm
General undulator field properties

**Magnetic field versus period length at pole gap 8 mm**

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Magnetic field versus period length at pole gap 8 mm

Magnetic field versus pole gap at period length 15.6 mm

Period 15.6 mm
- Photon flux (arbitrary units)
- Photon energy (keV)

Period 16.4 mm
- Photon flux (arbitrary units)
- Photon energy (keV)

Period 17 mm
- Photon flux (arbitrary units)
- Photon energy (keV)
General undulator field properties

Magnetic field versus period length at pole gap 8 mm

Magnetic field versus pole gap at period length 15.6 mm

Odd harmonic photon flux for different undulator periods (E=3 GeV, I=0.1A, L=2m)

RUPAC 2016
New undulator prototype (calculations)
Parameters:
Pole gap – 8 mm
Period – 15.6 mm
Number periods – 40
Active pole – 150 mm
Neutral pole – 89 mm
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Vertical field $B_z$ versus $y$

Vertical magnetic field
Polynomial Fit of Sheet

Equation
$y = \text{Intercept} + B_1 \times x^1 + B_2 \times x^2$

Weight
No Weighting

Residual Sum of Squares
$4.41616 \times 10^{-4}$
Adj. R-Square
0.99984

Values

<table>
<thead>
<tr>
<th>$x$</th>
<th>$B$</th>
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<tbody>
<tr>
<td>10</td>
<td>1.19408</td>
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<tr>
<td>22</td>
<td>-0.00593</td>
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<tr>
<td>30</td>
<td>0.10784</td>
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Standard Errors

<table>
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<tr>
<th>$x$</th>
<th>$B_1$</th>
<th>$B_2$</th>
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<tbody>
<tr>
<td></td>
<td>0.00434</td>
<td>4.88846E-4</td>
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<tr>
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<td>0.00111</td>
<td></td>
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<tr>
<td></td>
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Longitudinal coordinate, cm

Magnetic field, Tesla

Vertical coordinate, $z$ (mm)

Magnetic field, $B$ (T)
New undulator prototype (calculations)

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Magnetic field, Tesla

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Longitudinal coordinate, cm

Magnetic field, Tesla

10 2 6 14 22 30 38 46 54 62 70

0 0.2 0.4 0.6 0.8
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Vertical field Bz versus y

Longitudinal field By versus y

First field integral
- X-coordinate

Vertical coordinate, z (mm)

Magnetic field, Tesla

Horizontal first field integral, T*m

Vertical first field integral, T*m

Longitudinal coordinate, cm

Magnetic field

- B (T)

Equation

\[ y = \text{Intercept} + B_1 x^1 + B_2 x^2 \]

Weight

- No Weighting

Residual Sum of Squares

- 4.41616E-4

Adj. R-Square

- 0.99984

Value

- B

Standard Error

- Intercept 0.00434
- B1 0.00111
- B2 4.88846E-4
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**Vertical field Bz versus y**

**Longitudinal field By versus y**

**First field integral**
- X-coordinate
- Z-coordinate

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**Magnetic field, Tesla**

**Vertical coordinate, z (mm)**

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**Equation**

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**Weight**

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\[ 4.41616 \times 10^{-4} \]

**Adj. R-Square**

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Field quality

**Horizontal first field integral versus neutral pole length for different x-values**

**Vertical first field integral versus neutral pole length for different x-values**

**Horizontal second field integral versus neutral pole length for different x-values**

**Vertical second field integral versus neutral pole length for different x-values**

\[ I_{1x} < 3 \times 10^{-7} \text{T} \cdot \text{m} \]

\[ I_{2x} < 1 \times 10^{-5} \text{T} \cdot \text{m}^2 \]

\[ I_{1z} < 1 \times 10^{-4} \text{T} \cdot \text{m} \]

\[ I_{2z} < 1 \times 10^{-5} \text{T} \cdot \text{m}^2 \]
Field integrals in beam aperture

$I_{1x}$ integral versus x-coordinate for different neutral pole width.

$I_{2x}$ integral versus x-coordinate for different neutral pole width

$I_{1z}$ integral versus x-coordinate for different neutral pole width

$I_{2z}$ integral versus x-coordinate for different neutral pole width
Influence of material properties

Magnetic field amplitude versus iron saturation field (period 15.6 mm, gap=8 mm)

Correction of the neutral pole length versus iron saturation field (period 15.6 mm, gap=8 mm)
Further developing of the undulator with neutral poles

- Neutral poles (iron 89 mm)
- Iron cores (150 mm)
- Framework (aluminium alloy)
- Core coils
- Period 15.6 mm
Cryostat
Cryostat
Vacuum chamber

Material: OF copper, aluminium alloy
Vertical external dimension: 7 mm
Internal vertical dimension: 6 mm
Internal horizontal dimension: 60 mm
Temperature: 10-20K
Resume
Resume

• The prototype is made (\(\lambda=15.6\) mm, pole gap 8 mm, \(B=1.2T\)) and the idea of use of a neutral pole for creation of a superconducting undulator with the period more than 12 mm is successfully checked.
• Test of the prototype was carried out in a bath cryostat with liquid helium and in a vacuum cryostat with indirect cooling by a cryocooler. Difference in stability of the field was not noticed.
• Design features of superconducting windings and assembly of the magnet allow to hope for the significant increase in accuracy of manufacture and decrease of cost of a magnet.
• The quantity of windings decreases twice.
• It is easily to provide mass production, high quality of pole fabrication, control of key dimensions and quality for every pole.
• High precision of regular structure of the undulator. Horizontal racetrack winding improves precision of coils dimensions. It should minimize phase errors.
• There is no limitation of undulator length.
Future plans

• By the end of the year to create a new prototype of the undulator taking into account necessary amendments to the design

• To take magnetic measurements with use Hall probes, stretched wire method and to show quality of the field

• To develop and manufacture the vacuum chamber of aluminum alloy

• To improve a cooling system of the magnet with use of heat tubes with use of nitrogen and helium
Thanks for attention