# PLANAR SUPERCONDUCTING UNDULATOR WITH NEUTRAL POLES

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*Abstract*

Superconducting undulator with use of neutral poles was proposed in Budker INP. Period of the undulator is 15.6 mm. Pole gap and magnetic field are equal to 8 mm and 1.2 T correspondingly. A prototype of the undulator with 15 periods was fabricated and successfully tested. Calculations, design and test results of the prototype in the report are presented. The cryogenic and vacuum system of the undulator are discussed.

## INTRODUCTION

The development and creation of new magnetic structures for bright synchrotron radiation sources, the emittance of which is close to the diffraction limit, makes high demands on the creation of an adequate generators radiation , such as short period undulators with minimal phase error. Creation of this type of an undulator with a short period, with undulator strength parameter K~2 and with phase error <3° gives the opportunity to work on high harmonics. Widespread currently received undulators based on permanent magnets as radiation sources in the centers of synchrotron radiation. Despite the fact that there is progress in the production of new materials for permanent magnets the use of magnets based on superconductors has advantages in creating a higher field with less period, and less the value of the phase errors.

Several groups in the world [1-7] are busy the problem of a superconducting undulator with short period and with K~2. A variant of the arrangement of the windings in the vertical plane – the "vertical racetrack" is commonly under development.

In this paper we propose a variant of placing of the windings in the horizontal plane – "horizontal racetrack", which differs from the standard solutions used in the superconducting wigglers [8].

## MAGNET DESIGN

The transverse electromagnetic field in the undulator, which are used for the generation of radiation, are created by transverse currents in coils near an electron beam orbit . The question of how these currents are closed is minor and relates more to technological solutions from the point of view of higher-quality fields with smaller phase errors. The most widely spread method of closing currents is the method of "vertical racetrack". In the article the method of close of the currents for the superconducting undulator is suggested as horizontal racetrack (Fig. 1). A key element of the undulator is a single magnetic pole (Fig. 2), consisting of a single section coil wound on an iron core.

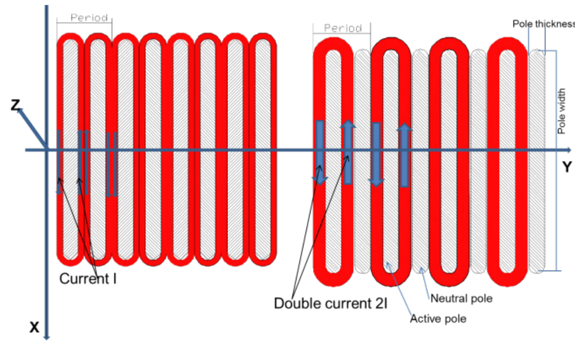


Figure 1: Schematic view of the location of poles and the currents in them for an undulator with horizontal racetrack coils: on the left the standard set of coils with standard of currents closing (coils type of a wiggler), right – set of coils with the neutral poles.

The period of the undulator is formed by magnetic pole with superconducting coil (active pole) and neutral pole, which is an iron core without windings. The undulator magnet consists of two identical halves which are located one above the other.

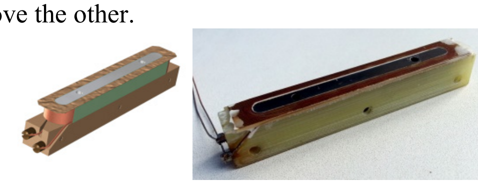

Figure 2: A separate pole is the basic element of the superconducting undulator

All the windings of the upper and lower parts of the magnet are connected in series with the same direction of the currents. The dimensions of the neutral poles and the active poles optimized with respect to the minimum of undesirable components of the magnetic field in the horizontal transverse region of ± 20 mm. When the currents are applied, the magnetic fields of each part of the magnet should be directed in opposite directions so that if you align the two halves in the longitudinal direction, in this case the transverse magnetic field should be zero on the median plane of the magnet. To create the transverse components of the magnetic field in the undulator, it is necessary to shift the top and bottom of the magnet on half period in the longitudinal direction (Fig. 3).

To check the possibility of the creation of this type of undulator, a prototype undulator was designed, manufactured and tested with 15 periods and period length of 15.45 mm. The prototype was performed as standard blocks containing five periods each, made of a soft magnetic iron (Fig. 4). Separate active poles were embedded in the grooves of these blocks. The role of the neutral poles played a rib of iron blocks.

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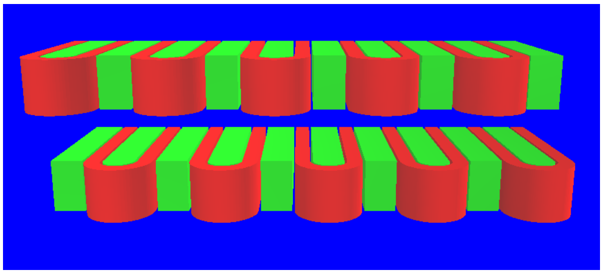

Figure 3: Layout top and bottom halves of the undulator to generate a transverse magnetic field.

The blocks were mounted on steel frames that made up the upper and lower halves of the magnet of the undulator (Fig. 5).

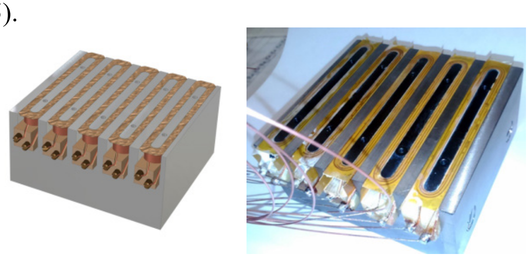

Figure 4: 3D model (left) and photograph (right) of a block of 5 periods.

## TEST RESULTS OF THE PROTOTYPE UNDULATOR

The prototype of superconducting undulator with the period of 15.45 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. The superconducting NbTi/Cu wire with diameter of 0.5/0.55 mm was used for production of single-section windings. The maximum current 500 A that corresponds to a magnetic field of ~1.2 T in the median plane. Cooling of undulator is proposed to use of cryocoolers with heat tubes and materials with high heat conductivity.

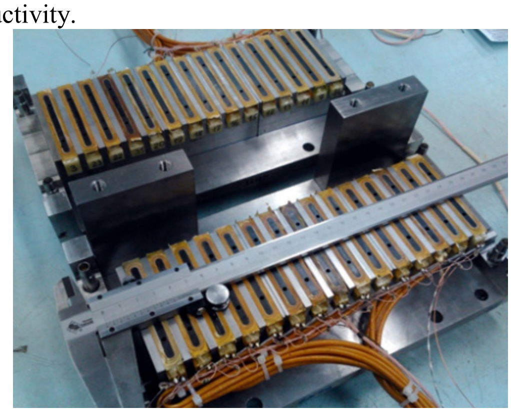

Figure 5: Photo of the halves of the magnet of the prototype undulator before final assembly.

## MAGNETIC MEASUREMENTS

Testing of the prototype undulator was carried out in a bath cryostat at liquid helium temperature. The cryostat is equipped with a scanning system that has the ability to scan the magnetic field in the longitudinal direction by means of Hall sensors. Quench training of the undulator magnet has shown that the magnet quickly goes on the calculated field that was calculated based on the properties of superconducting wire (Fig. 6).

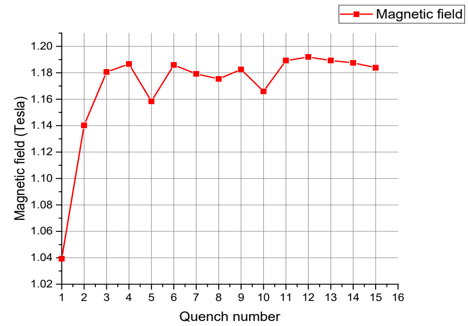


Figure 6: Quench history of the undulator prototype inside vacuum cryostat with indirect cooling system

The distribution of magnetic field along the prototype undulator was carried out in a bath cryostat using a carriage with five Hall sensors. The measurement results showed that the longitudinal field distribution corresponds to a calculated field excluding ends of the prototype for which was not provided special conditions for obtaining the zero field integrals in the longitudinal direction.(Fig. 7)

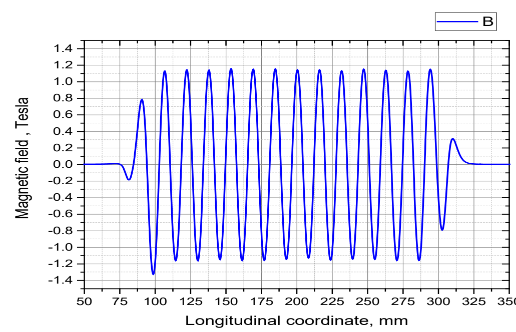


Figure 7: Longitudinal scan of the prototype undulator magnetic field with the Hall probe.

However, testing revealed some negative effects of this design. Magnetic field components as a skew quadrupole and skew octupole are presented in the median plane, which significantly worsen the first field integral of horizontal field for the transverse horizontal displacement of the orbit. To compensate for the skew quadrupole it is necessary to make a correct relation between the transverse dimensions of the iron cores of active and neutral poles. Figure 8 shows the relationship between the widths of the active and neutral poles for zero gradient of the skew quadrupole in the case that the poles are made of iron with a saturation field of 2 T.

When the width of the active pole of 150 mm the width of the neutral pole should be in range of 85-89 mm for compensation of skew quadrupole gradient in order to meet the requirement of field uniformity in the magnet for horizontal displacement of ±6 mm..



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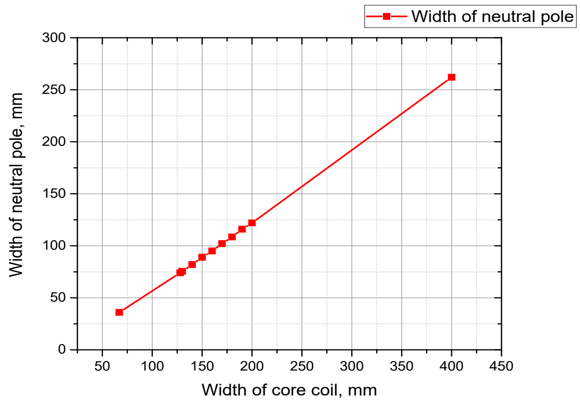


Figure 8: Width of neutral pole versus width of active pole for compensation of skew quadrupole field component in the undulator.

In order to extend the horizontal region, where the horizontal magnetic field does not exceed $10^{-5}$ T, up to ±20 mm, it is required the use of special compensating windings, located at the top and bottom parts of the undulator magnet.

## CRYOGENIC AND VACUUM SYSTEM

An indirect cooling system with use of nitrogen heat-pipe for primary cooling of the magnet and closed loop system with helium for cooling and maintaining low temperature of the magnet are assumed. For efficient cooling of the magnet support elements of the magnet is made of durable aluminum alloy. The cryostat is equipped with four 2-stage cryocoolers to maintain the 3 temperature levels: 4 K- temperature of the magnet, 10-20 K is the temperature of the vacuum chamber and 40-70 K – temperature of a thermal shielding [4]. The beam vacuum chamber has an internal size 6x60 mm and it is made of aluminum alloy. The temperature of the vacuum chamber is keeping 2 cryocoolers at level of 10-20 K. Vacuum chamber is placed between the two halves of the magnet undulator with a gap of 0.5 mm by means of adjustable mounting fixtures rigidly attached to the magnet with use of low heat conductive materials.

## CONCLUSION

- The test results and the further calculations of the magnetic system of superconducting undulator with individual magnets and the neutral poles (horizontal racetrack) demonstrated the possibility of creating a system which has advantages compared to similar systems used vertical winding racetrack;
- no restrictions on the length of the magnet;
- the ability to minimize phase errors at the expense of making a more accurate winding;
- all poles are individually produced in mass production, which improves their precision manufacturing, to carry out selection on identity and individual test at the maximum field.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] Richard P. Walker, Phase errors and their effect on undulator radiation properties, Physical Review Special Topics - Accelerators And Beams 16, 010704 (2013).
[2] Ben Shepherd, SCU Magnet Modelling: Tolerances and Beam Trajectories, Superconducting Undulator Workshop, RAL, 28-29 April 2014.
[3] D. Wollmann et Al, A new concept for reducing phase errors in superconductive undulators: induction-shimming, Proceedings of epac08, Genoa, Italy.
[4] Y. Ivanyushenkov et al, Development of a superconducting undulator for the APS, 11th International Conference on Synchrotron Radiation Instrumentation (SRI 2012).
[5] S. Chunjarean et al, Field error correction for a superconducting undulator, Slac-Pub-15320.
[6] Katherine C. Harkay et al, APS superconducting undulator beam commissioning results, Proceedings of PAC2013, Pasadena, CA USA.
[7] R. Kinjo et al, A bulk high-TC superconductor staggered array undulator, Proceedings of FEL08, Gyeongju, Korea.
[8] S. Khrushchev, N. Mezentsev, V. Lev, V. Shkaruba, V. Syrovatin, V. Tsukanov, Superconducting multipole wigglers: state of art. Proceedings of IPAC2014, Dresden, Germany, 4103-4106.



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