DESIGN OF NSLS-II BOOSTER DIPOLES WITH COMBINED FUNCTIONS MAGNETIC FIELD*

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Abstract

Focusing and defocusing dipole magnets of NSLS-II Booster are designed, made and measured at BINP, Russia. Magnets should provide the booster operation in the energy range from 170 MeV to 3.15 GeV with a 2-Hz frequency. Due to the compactness of the booster, the dipoles have quadrupole and sextupole components and should provide high quality of a field $\pm 1\cdot 10^{-3}$ in region ± 2 x ± 1 cm. The design and results of 2D and 3D modeling are presented in the article.

INTRODUCTION

In Brookhaven National Laboratory, USA, NSLS II - the synchrotron radiation source (SR) of a third generation is under construction [1,2]. The SR source includes the linear accelerator with energy up to 200 MeV, booster with energy up to 3 GeV and a 3-GeV storage ring.

Budker Institute of Nuclear Physics has carried out a full set of works on creation of the booster synchrotron for the NSLS-II source. The 158 m synchrotron should accelerate an electron beam from the linear accelerator and inject it into the main ring at nominal energy (3 GeV).

The basic requirements for the booster are: compactness, optimum parameters of a beam and high efficiency of injection, extraction and acceleration of a beam. To make a compact booster ring, the dipole magnets with the combined functions are applied. Bending magnets provide strong focusing and compensation of natural chromaticity by sextupole components of a field.

The most important parameter is the minimal losses of particles during injection from the linear accelerator, acceleration and extraction into the main storage ring. The total value of losses should not exceed 75 %. The factor of injection in the booster should not be worse than 85 %.

There are two options of the booster performance: injection-acceleration and injection-accumulation-acceleration of the beam. In case of the second option (accumulation) the circulating beam and the injected one completely occupy the acceptance of the vacuum chamber of the booster ring. According to tracking of particles and modeling of mistakes, it is necessary to apply high requirements of quality of a magnetic field of a dipole which should be not worse than $\pm 0.5\cdot 10^{-3}$ in the area ± 2 x ± 1 cm for the booster energy from 0.2 GeV up to 3 GeV. Difference of integrated parameters between dipoles should not exceed: for integral of a field $< 10^{-3}$; for integral of a gradient $< 5\cdot 10^{-3}$; for integral of a sextupole field component $< 5\cdot 10^{-2}$. The quality of a field provides the acceptable dynamic aperture and allowable beating of optical functions.

To receive the necessary parameters of a dipole, a 3D code of magnetic field simulation was used. The map of a field received from 3D modeling is used for tracking of particles in median plane of a magnet. By means of tracking the method of field correction in the central part of a magnet and of edge chamfers for formation of a correct fringe field was developed. Because of difference of magnetic properties of iron and deviations in the form of a magnet, the parameters mistakes of a dipole are possible. In the article the ways of correction of the mistakes due to difference of field integral and integral of a gradient on an equilibrium orbit of particle are presented. The usage of intermediate chamfers in order to check the design of a dipole magnet is offered.

LATTICE

The optical structure of the booster synchrotron consists of four quadrants. Every quadrant consists of five regular cells with two changed cells on the ends of quadrant for suppression of dispersion function (see Fig. 1). The structure provides 37.4 nm-rad emittance at the extraction energy.

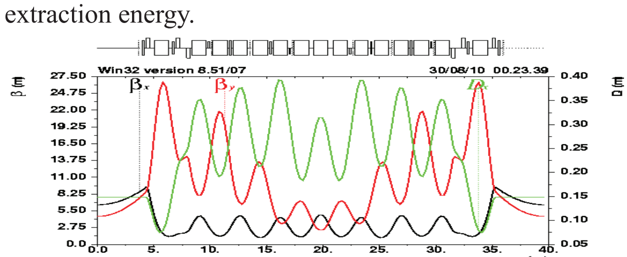

Figure 1: Optical functions of ¼ ring.

Every quadrant consists of the following magnetic elements: 8 defocusing dipole magnets (BD), 7 focusing magnets (BF), 6 quadrupole lenses and 4 sextupole lenses. Dipole magnets have the H-shaped form of a profile. The core of dipoles is a sector with parallel edges.

For compensation of natural chromaticity of structure the dipole magnets create sextupole component of a field. Separate quadrupole lenses provide adjustment of betatron working point during acceleration of particles and optimum acceptance of structure. For correction of lattice chromaticity the separate sextupole lenses are inserted. The lenses are formed in two families.

Two opposite straight sections of the ring contain elements for injection and extraction of the beam. Other two sections are intended for RF resonators and diagnostics.

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Quality of magnetic elements is determined by sensitivity of magnetic optics to the mistakes, by required efficiency of injection-extraction of particles and by parameters of injection beam in the booster. Mistakes in parameters of magnetic elements can result in deviations of optical structure parameters: distortion of the closed orbit, shift of betatron tunes, beating of Twiss functions, degradation of the dynamic aperture, etc.

Other feature of optics with application of the magnets with the combined functions is the increased accuracy of an alignment of dipoles. The manufacturing techniques of dipoles should provide exact binding of the geometrical centre with the magnetic centre of a dipole and fiducials.

The optics of the ring is influenced with the following types of mistakes:

- A deviation in bending angle of magnets results in a shift of betatron tunes for horizontal and vertical movement due to the magnet combined functions and distortion of an orbit in a radial direction;
- Mistakes in strength of quadrupole lenses result in beating of betatron functions, shift of betatron tunes. In the case of large mistakes the increasing of emittance and change of natural chromaticity of a beam occurs;
- Mistakes in strength of sextupole lenses influence the compensation of natural chromaticity and result in reduction of the dynamic aperture;
- Misalignment of magnetic elements makes the charged particles pass the area where fields have a considerable deviation from the nominal field. Misalignment is similar to the mistakes in a magnetic field. This causes the distortion of an equilibrium orbit, beating of optical functions, change of natural chromaticity and change of compensation efficiency of chromaticity by sextupole, degradation of the dynamic aperture.

The analysis of optical structure sensitivity of the booster to the mistakes of elements parameters was carried out to define the tolerance of manufacturing accuracy of the magnets. The tolerances of magnetic elements are given in Table 1.

Table 1: Tolerances of Integral Parameters of Elements

Error type	σ
Dipole magnet BF	
Relative error in the dipole field integral	1×10^{-3}
Relative error in the gradient integral	5.0×10^{-3}
Relative error in the $K2$ integral	5.0×10^{-2}
Dipole magnet BD	
Relative error in the dipole field integral	1×10^{-3}
Relative error in the gradient integral	5.0×10^{-3}
Relative error in the $K2$ integral	5.0×10^{-2}
Quadrupole magnet	
Relative error in the $K1$ gradient integral	5.0×10^{-3}
Sextupole magnet	
Relative error in the $K2$ gradient integral	5.0×10^{-2}

MAGNETIC DESIGN OF DIPOLES

The dipoles of the booster have quadrupole and sextupole components of magnetic field and should create high quality of field integral $\pm 1\cdot10^{-3}$ in region ± 2 cm. Dipoles have H shape profile and radius of curvature 8.8 m for BD and 21.7 m for BF magnet. Parameters of the magnets are shown in Table 2.

Geometric shape of BF and BD laminations was determined as a result of simulation. Dipole magnet with parallel edges has a 8.838 mm (BF) and 23.788 (BD) mm sagitta. The steel grade is M1200-100A with glue coating Stabolit 70. The effective length of magnet coincides with the core length along the arc. A special complicated end chamfer is used for the field correction. The shape of the end chamfers is specified according to the production technology and the results of magnetic measurements. The possibility of changing the shape and size of the end chamfers of dipole magnet is reserved in the magnet prototype production.

Table 2: Dipoles Specification

Dipole parameters	BF	BD
Number	28	32
Effective magnetic length	1.24 m	1.30 m
Angle	3.2673°	8.3911°
Vertical gap	±14 mm	±13 mm
Field injection	0.03068 T	0.07516 T
Field extraction	0.46021 T	1.12734 T
Quadrupole K1, extraction	0.82 m^{-2}	-0.55509 m^{-2}
Sextupole K2, extraction	3.6 m^{-3}	-4.3 m^{-3}
Good field region	±12 x ±20 mm	
Field quality in good field region, $\Delta B/B0$	$\pm 1\cdot10^{-3}$	

End chamfers for prototypes are made in two steps. At the first step the preliminary chamfer with the increased effective magnetic length is made. Magnetic measurements are carried out and the results of magnetic measurements are compared to magnetic modeling. At the second step, on the basis of the corrected model of a magnet and magnetic calculations, the final end chamfers are produced. Two 5 mm sections being parallel to median plane are foreseen in the plate profile for gap and magnetic measurements control.

2D MAGNETIC FIELD SIMULATION

The magnetic calculations are made for 2-D model by Ansys and Mermaid code [3]. The proposed dipole magnet profiles (see Fig. 2) provide the uniformity of magnetic field ($\pm1\cdot10^{-3}$) in the central section in a geometrical area of ± 20 mm, taking into account the requirements to the coil position and overall dipole

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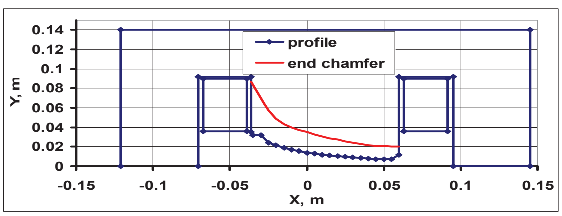
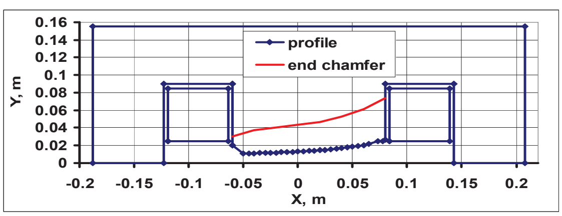
dimensions, and reference surfaces for magnetic and mechanical measurements.

Due to iron saturation, slight alterations of the profile were made to provide the required magnetic field gradient at a given field magnitude at the dipole centre. This correction as well as the size of the shims used depends on the steel magnetic properties. If steel of other magnetic properties is used, the pole part of the magnet has to be corrected. All simulations were made for the steel M 1200-100 A.

The real parameters of magnetic elements will differ from the required ones due to nonlinearity of the magnetic properties of steel. The magnetic resistance is high at low field values, this leads to the field nonlinearity of ~ 1.4% for BF and BD dipoles and ~ 0.7% nonlinearity at high field value for BD dipole. The field quality at different level of the booster energy in ± 20 mm region is shown in Fig. 3 a) and b).

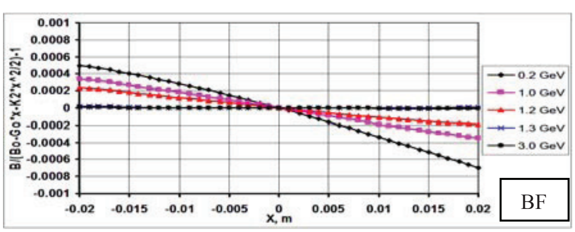


a)

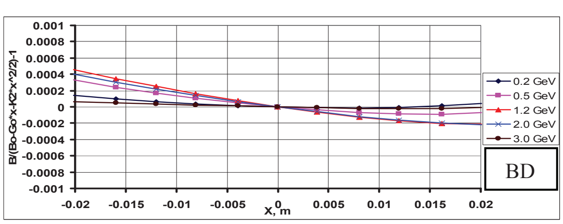


b)

Figure 2: Profiles of BF (a) and BD (b) dipole magnets.



a)



b)

Figure 3: Relative distribution of field in central section.

3D SIMULATION OF FIELD

The 3D field simulations have been performed for correction of edge fields of dipole magnet. Basing on the results, the dipole end faces variant has been selected. They compensate the additional gradient and sextupole component of the field. Optimization of end chamfers is executed for the maximal nominal fields corresponding to the energy of extraction. In this case the magnetic model has good agreement with the measured magnetic fields of dipoles. As influence of residual magnetic fields on parameters of a magnet is negligible, high accuracy of magnetic measurements is provided.

The end chamfers provide minimization of high harmonics of a magnetic field. Due to small high-harmonics, the sextupole component of field changes a little at misalignment of dipoles.

One variant of the end profile of BD dipole is shown in Fig. 4 and Fig. 2b (end chamfer curve). Special complicated end chamfer is used for the field correction. It has 45° angle with median plane for BD dipole and 30° angle for BF dipole.

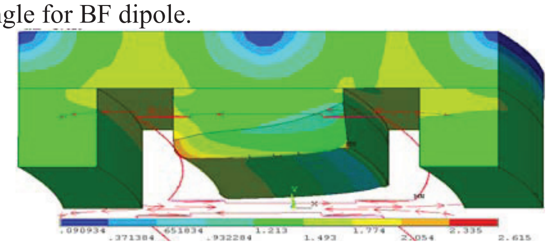


Figure 4: End chamfer.

Below, the results of 3D field simulations in the working area of energy are given. The distribution of the integral component of magnetic field is shown in Fig. 5. The deviation of a gradient of an integrated field is inside the tolerances and does not exceed ± 0.3 %. For sextupole component of a field the deviation is no more than 2 %. According to the results of modeling the relative change of effective magnetic length is no more than $2 \cdot 10^{-4}$. BD magnet field parameters for the energy more than 3 GeV become strongly nonlinear due to iron saturation. Octupole and decapole components of a field for BF and BD dipoles are minimized by means of end chamfers. In the operating field of the booster 0.17 - 3.15 GeV the value of octupole component does not exceed 7.5 m^{-4}, decapole component has value no more than 1800 m^{-5}.

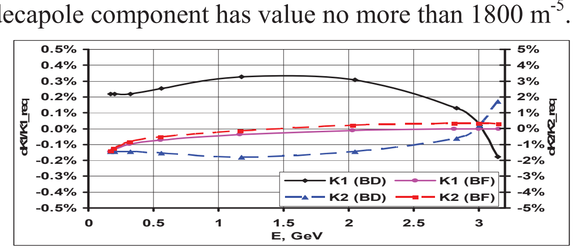


Figure 5: Deviation of K1 and K2 integral field components vs. energy of the booster.

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