BENDING MAGNETS FOR THE SAGA STORAGE RING: MANUFACTURING AND MAGNETIC MEASUREMENTS

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Abstract

The paper describes the design, the manufacture and the magnetic measurements of the dipole bending magnets (BMs) for SR Source Storage Ring (SAGA prefecture, Japan) carried out in BINP, Novosibirsk, Russia.

INTRODUCTION

The SAGA Synchrotron Radiation Source consists of the 262 MeV Linac and 1.4 GeV Storage Ring. The facility is being built in Japan, SAGA prefecture [1]. The Budker INP had manufactured the bending magnets and the multipoles for the Storage Ring.

The feature of the SAGA SR Source is a rather large electron energy ramping diapason stretched from the injection energy up to the nominal energy. It requires the magnetic elements to work within large magnetic field range, which corresponds to 0.26 T - 1.46 T for the bending magnets.

The main requirements to BMs parameters are presented in the Table 1. C-shape dipoles have the bending radius of 3.2 m and parallel edges. The magnetic field homogeneity in the middle cross section of BM must be not worse than ± $2\cdot10^{-4}$ inside the good field area: in radial direction H = (-30-+40) mm and vertical direction V = ± 20 mm at the injection with 0.26 T field; H = ± 28 mm and V = ± 20 mm at 1.46 T field at nominal electron energy.

Table 1: Main specifications of the bending magnet

Parameters	
Type of magnet	C-shape dipole
Focusing	Parallel edges
Number of magnets	16
Beam energy (inj./nor.), GeV	0.25 / 1.4
Bending angle, deg	22.5
Bending radius, m	3.2
Magnetic field (inj./nor.), T	0.26 / 1.46
Effective length, m	1.257
Vertical magnet gap (center), mm	50
Good field region (HxV), mm x mm	-30~+40 x ±20 - injection ±28 x ±20 - normal
Field quality, ΔB/B	$\pm2\cdot10^{-4*}$
Max. current, A / Max. voltage, V	540 / 38

* $4\cdot10^{-4}$ from peak to bottom is acceptable.

The creation of BM with that large good field area is complicated due to necessity to combine it with small transverse dimensions of BM, indicated in Fig.1. Before a serial production the prototype (BM00) of the bending magnet was designed, manufactured and measured by the Budker INP and in KHI, Japan. On the basis of this prototype the 16 serial bending magnets were manufactured and delivered to Saga SR Source.

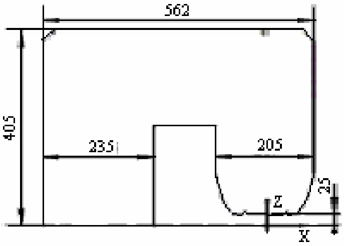

Figure 1: One half of SAGA BM lamination.

BENDING MAGNET

The BMs were designed by using the 2-D, 3-D computer simulations [2], taking into account the features of the manufacturing of the dipole. The C-shape dipole yoke was produced by means of the new technology of the high temperature gluing of one-piece C-shape laminations (1 mm steel of STABOCOR M940-100A with the two-sided glue layer of STABOLIT-70).

The laminations had been stamped with ± 15 μm accuracy, and separate laminations had been taken from different rolls and mixed when setting the magnet yokes in order to average the magnetic properties of the serial bending magnets.

The pole shimming and the edge faces of BMs were used to optimize the BM dimensions and to achieve the required magnetic parameters in the large magnetic field range (see Fig.2). The shimming allows us to get the required uniformity of the magnetic fields in the working apertures. The edge chamfers of the Rogovski curve-type minimize a change of the effective magnetic length occurred due to the magnetic field saturation.

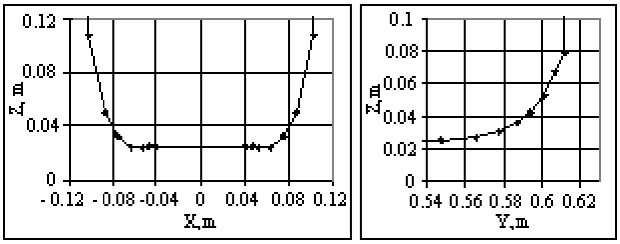

Figure 2: Pole profile and edge chamfers.

The yoke laminations had been placed inside the special jig on their base surfaces. The mechanical accuracy of the poll gap at the assembly in the jig is of ± 20 μm. According to our calculations the required accuracies of the yoke production allows us to get a relative standard value for the magnetic field transverse distribution errors $\sigma_B/B = 3.2\cdot10^{-5}$ and $\sigma_I/I = 6.7\cdot10^{-5}$ for the magnetic field integral errors along the reference lines.

After longitudinal compression the whole construction had been heated inside the special oven under temperature control of the gluing process. The heating process was lasted about 36 hours reaching the maximum temperature of 200 °C. Due to complicated temperature gradients existed in BM yokes during the gluing the main differences were between a real geometrical lengths of BMs and designed ones. Each of two excitation coils of BMs consists of 4 pancakes. Each pancake includes 16 turns of the oxygen free copper bus (12.5x12.5/7mm) wound in two layers. Besides that two correction coils exist. They are made from the copper 4x2.5mm bus and are joint together with two pancakes, which are placed nearby the BM gap.

MAGNETIC MEASUREMENTS

The magnetic measurements of the all dipole magnets had been carried out at the specialized stand (Budker INP), and the prototype of the bending magnet (BM00) had also measured at the KHI Ltd (Noda, Chiba prefecture, Japan).

The carriage with 25 Hall probes [3] spaced on the distance 10 mm has rectilinearly been moved between the dipole poles by the stepping motor, and we get the Cartesian magnetic field map with 10 mm steps.

Table 2: Accuracies of magnetic measurements in BINP

Parameter	σ_B/B	σ_I/I
Spatial alignment (Hall probes, direction and linearity of carriage movement)	$1.5\cdot10^{-5}$	$1.7\cdot10^{-5}$
Temporal stability of *:		
BM`s excitation current	$2\cdot10^{-5}$	$1.8\cdot10^{-6}$
Hall probe current	10^{-5}	$0.9\cdot10^{-6}$
Temperature stability	$2.4\cdot10^{-5}$	
Accuracy of Hall probe calibration	$4.5\cdot10^{-5}$	
Electronics noise contributions	$4.4\cdot10^{-5}$	$4.0\cdot10^{-6}$
Resulting accuracy	$7.2\cdot10^{-5}$	$6.2\cdot10^{-5}$

* - averaged over alls of single measurement cycle.

The accuracy of magnetic measurements is influenced by the following:

- Orientation of the Hall probes relative to the magnetic field vector and error of a spatial location of Hall probe relative to a bending magnet.
- Temperature stability during measurements (change of the dipole gap);
- Temporary stability of an BM`s excitation current;
- Accuracy of the electronics[3].

The required measurement accuracies of magnetic field $\sigma_B/B \le 10^{-4}$ and integral $\sigma_I/I \le 10^{-4}$ had been achieved at the working range 0.26 - 1.46 T at the BINP measurement stand successfully, see Table 2.

MAGNETIC MEASUREMENT RESULTS

Main BM's magnetic parameters are obtained by means of the simulation of electron motion with the help of the tracking code and by using the measured magnetic field map. Among theme are:

- the integral of magnetic field: $\int_{-L}^{L} B_z(x,s)ds$, where Bz(x,s) is a magnetic field along an electron trajectory, s – position along the trajectory relative to magnet center, x - cross coordinate, $L \approx L_{dip}/2+6h$ - a length of the integration with necessary accuracy, here L_{dip} =1.223 m is the "iron" length of a magnet, h = 50 mm - vertical magnet gap;
- $L_{eff} = \frac{1}{B_0}\int_{-L}^{L} B_z(x_0,s)ds$ - an effective magnetic length, here B_0 – magnetic field value in magnet center, $B_z(x_0,s)$ – magnetic field along a reference trajectory;
- the multipole decomposition of the magnetic field integral
  $$B_{\text{int}\_z}(x) = \frac{1}{L_{eff}}\int_{-L}^{L} B_z(x,s)ds = B_o + G\cdot x + S\frac{x^2}{2},$$
  where Bo, G, S are the integral multipole field components.

Distributions of the magnetic field in the central section (s=0) of the averaged bending magnet are shown in Fig.3. Some distinctions between calculated and measured curves lay within the accuracy limits of magnetic measurements of ($\sigma_B/B = 7\cdot10^{-5}$), magnet production ($\sigma_B/B = 5\cdot10^{-5}$) and the calculations ($\sigma_B/B = 1\cdot10^{-5}$ for relative magnetic field profiles).

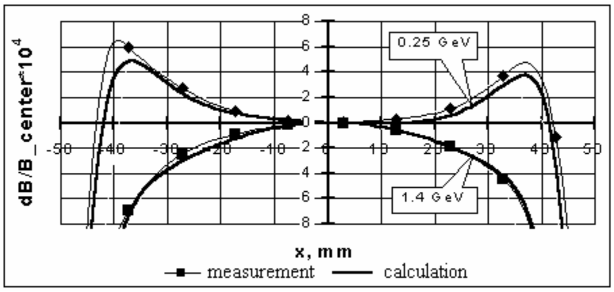

Figure 3: Magnetic field profiles for calculated and "average" magnet.

In the Table 3 the main parameters of the averaged bending magnet are presented. Before the magnetic measurements the dipoles demagnetization was provided by the excitation current cycle within interval of

0 – 610 A. The width of the hysteresis curve is 38 Gs at 81.65 A excitation current, and 8 Gs at 534 A, and this explains some difference between calculated and measured results (in Table 3).

Table 3: Magnetic field parameters of serial BM's

Excitation current, A	**81.65**		**534.00**	
	calc.	**meas.**	**calc.**	**meas.**
Energy, GeV	0.25000	0.25351 ± 0.00034	1.40000	1.4009 ± 0.0015
Field, T	0.26056	0.26421 ± 0.00038	1.47438	1.47474 ± 0.0015
Magnetic field integral, T·m	0.32747	0.33208 ± 0.00048	1.83296	1.83508 ± 0.0020
Effect.magnetic length, m	1.2568	1.2568 ± 0.0011	1.2432	1.2443 ± 0.0011
Normalized multipole magnetic field components				
h, m^{-1}	0.3125	0.31250 ± $1.3\cdot10^{-5}$	0.3157	0.31560 ± $1.4\cdot10^{-5}$
k, m^{-2}	0.008	0.0107 ± 0.0023	0.009	0.0113 ± 0.0023
m, m^{-3}	-0.38	-0.532 ± 0.026	-0.86	-0.742 ± 0.047

One can show that this difference disappears when taking into account the hysteresis. The histograms represented the serial BM manufacture quality are shown in Fig.4,5. The RMS error of magnetic field integral is $1.5\cdot10^{-3}$. We note that the integral gradients G are small but different from zeros according to both simulations and magnetic measurements. This focusing is a feature of the parallel edge BMs with finite and, moreover, rather narrow polls. It is generally explained by the asymmetrical field distribution on the edge parts of the trajectory. This additional focusing can be in principal eliminated by the introduction of small edge angles at a stage of the BM design. In our case the additional focusing G appeared is small.

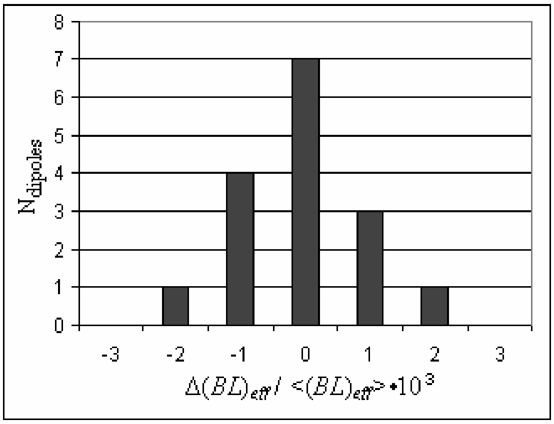

Figure 4: Histogram of magnetic field integrals of the serial bending magnets.

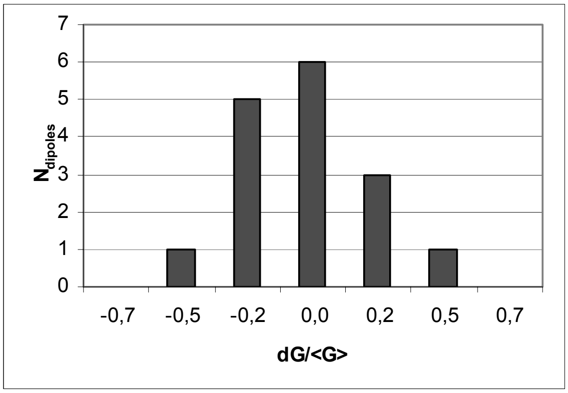

Figure 5: Histogram of integral quadrupole components of the serial bending magnets.

Figure 6: Bending magnets at the SAGA Storage Ring.

CONCLUSION

The prototype of the bending magnet and the 16 serial bending magnets for SAGA Storage Ring have been designed, manufactured and measured by the Budker INP.

The manufactured bending magnets had met the SAGA requirements and have been installed at the SAGA Storage Ring (see Fig.6).

REFERENCES

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