Precise Measurements of Magnetic Field Parameters of the Multipoles for the SLS Storage Ring

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The multipoles for SLS Storage Ring having very hard requirements to the manufacture and the alignment of the multipoles relative to the ideal axes were manufactured and magnetic measured by BINP. The Rotating Coil Systems (at BINP and PSI) for the precise magnetic measurements are described in the paper. The main RCS parameters and main statistic results of the magnetic measurements are discussed.

1. Introduction

The specialized synchrotron radiation source SLS (Swiss Light Source) is built at PSI (Paul Sherrer Institute, Switzerland). The SLS system consists of the 2.4 GeV electron storage ring 288 m in circumference, the booster synchrotron with the circumference of 270 m for the same energy and the linear accelerator for an electron energy of 100 MeV. The SLS was designed with the main aim ([1] – [3]) to reach a very high brightness of the SR sources, perhaps at the expense of the maximal possible number of these sources. Source quality (brightness) is determined mainly by the electron beam quality (small emittance). Hence, the SLS was optimized with the aim to obtain minimal horizontal emittance for assigned dimensions of the ring.

The storage ring consists of 12 sectors, 4 girders in each. The magnetic system of the storage ring contains 36 dipoles, 174 quadrupole lenses and 120 sextupole lenses, installed with a high precision on the 48 girders differing in length and set of elements.

A feature of the SLS are very hard requirements to the magnetic field non-linearity at the equilibrium orbit restricting the dynamical aperture of the storage ring and, as a sequence, the electron lifetime. This leads, in own turn, to harder requirements to the accuracy of manufacture and alignment of the magnetic system elements near the ideal axis (377,000 mm and 15,000 mm relative to horizontal and vertical girder base surfaces). Groups of 5 to 8 multipoles are installed with high accuracy on the girders over the base surfaces.

BINP manufactured 8 types of multipoles (narrow and wide quadrupoles 200, 320 and 440 mm in length and narrow and wide sextupoles 200 mm in length) for the storage ring.

The measurement system shall perform the measurement accuracy of the magnetic field harmonics relative to the main harmonic not worse than $2\cdot10^{-4}$ for the quadrupoles and $5\cdot10^{-4}$ for the sextupoles, of the multipole magnetic axis position of $\pm$ 10 μm and of roll angle of the multipole of $\pm$ 0.35 mrad.

2. Rotating Coil System

A special stand for magnetic measurements based on “Rotating Coil System”[4] was made at BINP for the SLS multipole parameters measurements. A similar system was made and delivered to the SLS (PSI) to carry out the final magnetic measurements of the multipoles before their installation on the ring. Two special girders for RCS have ~ 5 μm accuracy of the base surfaces.

Position of the magnetic axis, roll angle and harmonic coefficients of the serial multipoles were measured by RCS. The measurement coil was calibrated on the basis of a multipole prototype magnetic field map measured with the set of the 11 Hall probes at different currents. The magnetization curve and the magnetic strength of serial multipoles were measured with Hall probes locating in the multipole center.

The coil inserted into the magnet aperture is rotated round the ideal axis. The measurement coil consists of four independent sections, each containing 8 turns made on multi-layer foiled textolite. Two coil sections have the outer size R and length L/2 each, other two coils have the outer size R/2 and the same lengths. Connecting the sections of the full and half radius by the subtraction scheme, one can compensate the multipole main harmonic component of the signal and increase the measurement accuracy for the rest harmonics. The measurements by left and right coil sections allow obtaining the longitudinal roll angle of the multipole.

The coil is rotated with the help of the step motor SigPositec with a 1:10 reducer and the angle encoder ROD-250. The 8-channel 12-digit ADC picks up the signals of the coils by with a minimal measurement time of 10 μsec/channel. The coil position is controlled with the help of the angle encoder (accuracy of 0.3 μrad) and the signal from the coil arrives through the amplifier/commutator to the ADC.

3. Basic theory of RCS measurements

The radial measurement coil rotates in the multipole aperture around the ideal axis and measures the voltage (U) induced on it from the θ component of the magnetic field.

$$B = B_\theta = \sum_n (-A_n \cdot Sin(n\theta) + B_n \cdot Cos(n\theta)) \cdot r^{n-1},$$

$$U = -\frac{d\phi}{dt} = -\frac{d(\int B \cdot dS)}{dt} = -L \cdot \frac{d}{dt} \sum_n (-A_n \cdot Sin(n\theta) + B_n \cdot Cos(n\theta)) \cdot \frac{R^n}{n},$$

where B_n, A_n are the normal and skew components of the magnetic field, L – the coil length.

The system under consideration worked with the use of stepwise rotation of the coil. When the coil rotates, the voltage induced over the coil is read inside one step. The total number of the signal readings is ~ 4000 at each angle step, the angle step 2dθ ~ 5°, and number of steps is 85 in standard measurement cycle. The voltage signal obtained is subjected to integration and the resulting value corresponds to the rotation angle θ+dθ. After the interpolation of the angle dependence with a cubic spline, the function is expanded at the normalization radius of 28 mm by Fast Fourier Transform method on harmonics (B_n, A_n), which reflect the magnetic field properties. The subtraction scheme of coil sections connection improves the measurement accuracy of the higher magnetic field components.

Coordinates of the multipole magnet axis are determined from the low-order coefficients of the harmonic expansion (A_1, B_1 and B_2 for the quadrupoles and A_2, B_2 and B_3 for the sextupoles). The vertical position of the magnet axis was a determined subject to the temperature correction for a temperature of 24°C taking into account the temperature fields of the RCS at the mechanical alignment and magnetic measurements as well as to the temperature at which the mechanical jig height was measured.

The roll angle was determined from the main signal:

$$\varphi_q = arctg\, {}^{A_2}\!/_{B_2} \quad , \quad \varphi_s = arctg\, {}^{A_3}\!/_{B_3} .$$

4. Measurement accuracy

The measurements are under influence of the time dependence of the processes occurring at the measurement time and the mechanical accuracy of manufacture and adjustment of the elements of the Rotating Coil System:

Mechanical accuracy of manufacture of the RCS elements:

- mechanical jigs (± 1-2 μm for the axis position)
- shaft diameters (± 1.5 μm for the axis position)
- rollers and shafts of the measurement coil (± 2 μm)
- mechanical level (~ 0.05 mrad).

Accuracy of alignment of:

- coil's supports (±1.5 μm for the axis position)
- slit dowel on the girder (±2 μm for the horizontal axis position)
- level on the measurement coil (total error at calibration ~ 0.1 mrad).

Equipment operation accuracy:

- measurement of temperature (~ 0.1° gives ±1 μm for the vertical axis position)
- angle encoder (0.3 μrad)
- nonlinearity of the amplifier (10^{-5})
- measurement of the main signal by the 12-digit ADC (~ $5 \cdot 10^{-4}$) for roll angle

Time instabilities during measurement cycle:

- mechanical vibrations of coil (10 μm vibration gives an error of $0.2 \cdot 10^{-4}$ for the harmonic coefficients and of ± 0.6 μm for the axis position).
- of the power source (~ 10^{-4} gives an error of ~ $0.2 \cdot 10^{-4}$ for the harmonic coefficients and of ±0.3-0.6 μm for the multipole axis position)
- of the multipole temperature (heating/cooling can give the roll angle change of from 0.3 to 0.5 mrad at 5-10 degrees change).

Main parameters of Rotating Coil System are shown in Table 1.

Table 1. Main parameters of Rotating Coil System.

	Reproducibility	**Accuracy**	**Sensitivity**
Harmonic coefficients	± $0.5 \cdot 10^{-4}$	± $0.5 \cdot 10^{-4}$	$0.3 \cdot 10^{-4}$ – quadrupoles $0.5 \cdot 10^{-4}$ - sextupoles
Axis position	± 2 μm	± 10 μm	1 μm
Roll angle	0.05 mrad	± 0.35 mrad	0.03 mrad

5. Statistical data on the magnetic measurements of SLS multipoles

The measurement results show compliance of the multipole parameters with the assigned requirements and good agreement of the magnetic measurements performed at BINP and SLS. Table 2 presents the average values and standard deviations of the magnet axis positions and roll angles for multipole types. A small systematic difference in the BINP and SLS measurements of the vertical axis displacement is probably explained with the distinctive feature of the mechanical assignment of the nominal axis (differences in the nominal sizes of the RCS elements and girders).

Table 3 lists main harmonic coefficients of the magnet fields for the multipole types. The obtained harmonic coefficients satisfy the requirements of SLS multipoles because of the main symmetric coefficients have the opposite signs and the harmonic coefficients determined by the geometrical accuracy of the assembly are enough small.

Table 2. **Average values and standard deviations of the magnet axis positions and roll angles.**

Multipole type (quantity of magnets)	$\langle x\rangle \pm \sigma_x$, BINP (SLS), μm	$\langle y\rangle \pm \sigma_y$, BINP (SLS), μm	$\langle \varphi\rangle \pm \sigma_\varphi$,, BINP (SLS), mrad
QA (43)	-1±16 (0±17)	8±13 (19±14)	0,126±0,16 (-0,01±0,16)
QAW (13)	-4±8 (-7±11)	6±12 (14±14)	-0,02±0,20 (0,02±0,17)
QB (54)	2±14 (2±14)	8±11 (13±12)	-0,02±0,17 (0,00±0,17)
QBW (13)	-3±11 (-4±17)	5±15 (5±18)	-0,02±0,21 (0,01±0,16)
QC (54)	-2±11 (1±12)	7±11 (14±12)	0,03±0,17 (0,08±0,15)
QCW (13)	-2±14 (0±12)	-2±14 (2±12)	-0,09±0,16 (0,03±0,13)
SR (84)	1±11 (3±12)	8±9 (18±11)	-0,02±0,19 (-0,07±0,26)
SRW (39)	0±9 (-1±15)	4±11 (8±11)	0,08±0,18 (-0,02±0,28)

Table 3. **Main harmonic coefficients of the magnet fields for themultipoles.**

Quadrupole type	$\langle B_3\rangle \pm \sigma_{B3}$	$\langle A_3\rangle \pm \sigma_{A3}$	$\langle B_4\rangle \pm \sigma_{B4}$	$\langle A_4\rangle \pm \sigma_{A4}$	$\langle B_6\rangle \pm \sigma_{B6}$	$\langle B_{10}\rangle \pm \sigma_{B10}$
QA	-0,02 ± 0,28	-0,07 ± 0,29	0,01 ± 0,19	0,04 ± 0,14	0,18 ± 0,13	-0,62 ± 0,03
QAW	0,07 ±0,27	-0,22 ± 0,34	-0,09 ± 0,17	-0,06 ± 0,12	0,20 ± 0,11	-0,59 ± 0,02
QB	0,01 ±0,22	-0,24 ± 0,31	0,00 ± 0,19	-0,01 ± 0,08	0,25 ± 0,07	-0,42 ± 0,01
QBW	-0,15 ± 0,25	-0,13 ± 0,26	0,00 ± 0,22	-0,03 ± 0,06	0,18 ± 0,04	-0,38 ± 0,01
QC	-0,06 ± 0,15	-0,13 ± 0,32	-0,03 ± 0,14	0,00 ± 0,06	0,21 ± 0,05	-0,32 ± 0,02
QCW	-0,04 ± 0,12	-0,12 ± 0,13	0,35 ± 0,16	0,00 ± 0,06	0,19 ± 0,04	-0,29 ± 0,03

Sextupole type	$\langle B_1\rangle \pm \sigma_{B1}$	$\langle A_1\rangle \pm \sigma_{A1}$	$\langle B_4\rangle \pm \sigma_{B4}$	$\langle A_4\rangle \pm \sigma_{A4}$	$\langle B_5\rangle \pm \sigma_{B5}$	$\langle B_9\rangle \pm \sigma_{B9}$	$\langle B_{15}\rangle \pm \sigma_{B15}$	$\langle B_{21}\rangle \pm \sigma_{B21}$
SR	-1,05 ±0,76	0,08 ±0,63	0,03 ±0,52	-0,38 ±0,49	0,17 ±0,35	-0,41 ±0,08	2,68 ±0,05	-2,37 ±0,03
SRW	-1,12 ±0,83	0,07 ±1,18	0,03 ±0,44	-0,46 ±0,48	-0,52 ±0,36	-0,29 ±0,08	2,63 ±0,05	-2,32 ±0,04

Conclusion

The magnetic field parameters of SLS multipoles produced by BINP were measured at the specially designed Rotating Coil Systems. Such precision magnetic measurement system permits obtaining the harmonic coefficients, axis position and roll angle with high accuracy.

References

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