MAGNETIC MEASUREMENTS RESULTS OF THE DIPOLES, QUADRUPOLES AND SEXTUPOLES OF THE SOLEIL STORAGE RING

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Abstract

During the magnetic measurement campaign, from May 2004 to August 2005, the 326 electro-magnets of the SOLEIL Storage Ring (SR) [1] have been characterized in terms of magnetic axis centering and field properties. For the dipoles, field mapping and field integral comparison with a reference dipole have been performed. For the quadrupoles, a rotating coil bench has been built and optimized at SOLEIL in order to reach magnetic center and tilt angle adjustments within ±25µm and ±0.1mrad respectively. For the sextupoles, magnetic measurements were performed by the SIGMAPHI Company. This paper presents the main features of the SOLEIL benches, magnetic measurement results in terms of reproducibility, field identity between magnets, magnetic axis centering, and harmonics content versus current.

INTRODUCTION

The good quality of magnetic measurements for the storage ring magnets was a fundamental point at SOLEIL. Special attention has been paid to stability, precision and reproducibility in order to take into account the large number of magnets to be measured. As far as possible, defaults due to magnet construction errors were minimized. Great care was taken with quadrupole magnetic axis centering, which is a real asset for the SR commissioning and operation. Dipoles and quadrupoles measurements were performed in the provisional magnetic measurement SOLEIL laboratory and organized with 2 shifts per day, with a real time validation by accelerator physicists. A large data base has been developed in order to store all the magnetic measurement results and to allow real time exploitation.

DIPOLE MAGNETS

SR Dipoles (gap = 37mm, deflection angle = 11.25°, curvilinear magnetic length = 1052.43mm, Sagitta = 25.810mm, maximum field = 1.77T) have been built by TESLA Company. A total of 38 dipoles (32 for the SR, 1 reference, 1 prototype and 4 for the transfer line TL2) have been measured. Two types of measurements have been performed: field mapping in the mid plan and field integral comparison with a reference magnet. The measurements have been done at the nominal field level (1.708T) and after cycling in order to achieve a reproducibility better than 10^{-4}. **Field maps** were achieved with the Hall probe bench. A simple rail is supported by the poles and equipped with a motor and a linear encoder. With minor modifications, an existing 15 Hall probe case, thermally stabilized at 37°± 1°, has been mounted on the rail. The identified longitudinal gap between probes has been used during the data analysis. The measurements were done over ±70mm in x-direction with a 10mm step and over ±685mm in longitudinal direction with a 5mm step. Careful alignment of the dipole versus bench, and calibration of the "s" coordinate with a 3D control tool were performed before each measurement. The main parameters of the dipoles have been defined as the mean of 9 dipole (including the prototype one) measurements. The measured magnetic length of 1055.48mm is larger than the one calculated with TOSCA 3D code (1052.43mm), showing a lower saturation. Magnetic axis is equilibrated on the Sagitta (12.9mm) in order to reduce the gradient due to the curved trajectory. Transverse homogeneity is deduced from interpolation in the mapping, taking into account the real curved trajectory. Harmonics Bn/B1 are deduced from polynomial analysis on the ±20mm good field region, showing a very good homogeneity in agreement with the design (Table 1).

Table 1: Harmonic components at x = + 20mm.

	Measurements	Calculation
B2	+ 2.2 10^{-4}	+ 1.7 10^{-4}
B3	- 3.0 10^{-4}	- 3.7 10^{-4}
B4	0.	-4.1 10^{-5}
B5	-6.6 10^{-5}	-9.6 10^{-5}

The measured fringing field effective length is 0.1607m. It induces a total shortening of the reference trajectory length of -2.2mm which will be compensated by a 2.2kHz RF frequency reduction. Measurements show also a difference of 1.5mm between exit and entrance half magnetic lengths, due probably to the position of the connections. Such systematic default will create a horizontal shift of the trajectory at the exit of the dipole and a closed orbit distortion all around the ring. This rather small systematic error was not corrected during installation. The longitudinal profile shows small reproducible fluctuations related to welding spots. The peak value ($\Delta B/B$ = 8.2 10^{-4}) seems acceptable even for the metrology beam line as the magnetic field around the source point is measured with a 1 10^{-4} accuracy. The

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parallelism of the faces has been deduced from gradient calculation at entry and exit. The tilts are respectively +0.03° and -0.04° for entry and exit, so the faces are parallel and slightly tilted.

The stretched wire bench was used to perform integrated field comparison of all the dipoles (n°3 to 38) with respect to the reference dipole n°2. The reference magnet and the measured magnet were connected in series but with opposite polarities. The stretched wire method gives directly the difference in field integral. IGOR-PRO software was used to control bench operation and data acquisition. Special effort was made to suppress noise originating from wire vibration by randomization and averaging of measurement data. Then, one measurement with very good statistics needed 45 minutes. Measurements (Fig.1) show that the average relative difference is slightly negative (-1.8 10^{-3}) with a standard deviation of 6.6 10^{-4} in agreement with tolerance. The correlation with relative gap variation (measured by TESLA) is rather good. The four dipoles presenting the lowest values of integrated field were selected for the transfer line TL2 because of their small dispersion (1.75 10^{-4}), the identity between the 32 storage ring dipoles being very good (5.95 10^{-4}). A sorting code has been developed to optimize the position of each dipole in the ring in order to reduce the maximum horizontal closed orbit distortion from 1.5mm before the sorting to 0.35mm after the sorting.

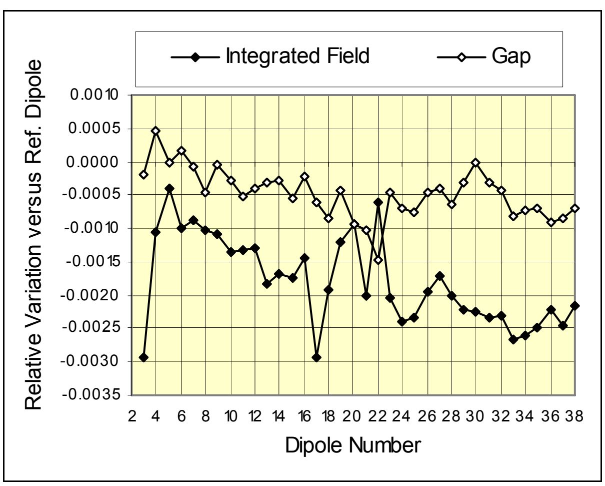

Figure 1: Comparison between relative field variation and relative gap variation versus reference dipole.

Calibration of dipole field versus current, using a NMR probe, was performed on the reference dipole. It is now installed near the storage ring, connected in series with the 32 SR dipoles and equipped with a NMR probe from which the dipole field can be read continuously in the control room.

QUADRUPOLE MAGNETS

A total of 164 quadrupoles (160 for the SR, 2 prototypes and 2 spares, bore diameter 66mm, lengths 320 and 460mm, maximum gradient 19.7 and 23T/m, [2]), built by DANFYSIK Company, have been measured at SOLEIL on a dedicated harmonic bench [3] based on a SR girder with the same mechanical, hydraulic and electrical interfaces, and located in a stabilized temperature room. The sensor, with a 30 mm reference radius, designed to have strong rigidity, with no Sagitta effect and no need of harmonic compensation, has allowed reaching tilt angle and magnetic center adjustments in x and z, within ±0.1mrad and ±25µm respectively. A very systematic procedure was applied during the campaign: 2 reference quadrupoles (1 long and 1 short) to check regularly the sensor characteristics, careful installation of each magnet on the bench. Then magnetic axis centering was performed by adjustment of mechanical shims and plots, at nominal current with nominal polarity and after nominal cycling, before harmonics content measurement. The statistical results on axis centering (Table 2) are excellent as expected from the sensor quality and the very great care taken by people during measurements. The RMS values are of the order of the measurement reproducibility.

Table 2: Quadrupole Magnetic Axis Centering.

	Mean Value	RMS value
DX (µm)	1.5	8.4
DZ (µm)	2.6	7.5
Tilt Angle (µrad)	8	40

Gradient identity from one quadrupole to the other is close to 1.0 10^{-3} except for I_{MAX} = 250A (1.8 10^{-3}) where some saturation appears. Most of the harmonics Bn/B2 do not depend on current. Statistical results are listed in Table 3 (design values for B10 and B14 are given in brackets).

Table 3: Quadrupole Harmonics Content at 200 A.

given in 10^{-4} at 30 mm	Short Quadrupoles		Long Quadrupoles	
	Mean	RMS	Mean	RMS
A3	0.5	3.0	0.5	3.2
B3	-1.6	2.0	2.9	1.6
B4	-3.4	3.7	-8.6	1.7
B6	2.4	0.5	0.7	0.4
B10	0.7 (1.4)	0.1	1.9 (1.8)	0.1
B14	0.9 (0.7)	0.1	1.0 (1.7)	0.1

The **B6** component is systematic and small. It has been minimized by optimizing chamfers at 250A during prototypes measurements. The **B10 and B14** components are systematic, with small values, very close to the design values. A random **A3** component is measured for the two types of quadrupoles. The systematic component is close to zero. This confirms the very good rigidity of the sensor that does not present any Sagitta. The small **B3** component is random for short quadrupoles and rather systematic for long quadrupoles. It is due to the width difference between the splits, created by the assembly on the upper and down parts respectively. For all quadrupoles, this component varies with current, always in the same way, due to the magnetic strength variation. The **B4** component, both systematic and random for the short quadrupoles, is rather small at 30 mm and is due to mechanical adjustments during the construction. For the long quadrupoles, it is systematic and large. It is due to the Sagitta created by the quadrupole weight, negligible for the 320mm quadrupoles but not for the 460mm ones. Magnetic lengths have been deduced from Hall probe measurements performed on a bench adapted from LURE, for the 2 spare, long and short, quadrupoles. These are respectively 490mm and 355mm, very close to the calculated ones. Moreover, this type of measurement permitted to quantify the non negligible loss of integrated gradient (1.55%), due to the length of the harmonic sensor (550mm), which is too short compared to the magnetic length of long quadrupoles. This correction was of course applied to the gradient calibration.

SEXTUPOLE MAGNETS

A total of 124 quadrupoles (120 for the SR, 2 prototypes and 2 spares, bore diameter 73mm, length 160mm, maximum strength $320T/m^2$, [2]) have been built and measured by SIGMAPHI Company with a real time validation by SOLEIL accelerator physicists.

Preliminary measurements of harmonic contents on 20 sextupoles have put in evidence strong values of the B1 and B5 components, due to mechanical errors (inside tolerances) on relative pole position after assembly. It has been decided to compensate for the B1 component by adding some shims on the 4 lateral poles at entry and/or exit of the magnet. Shims are cut in a 1 mm width sheet and are screwed on to pole chamfers (see Table 4).

Table 4: Shim effect on B1 component.

given in 10^{-4} at 32 mm	Without shims		With shims	
	Mean	RMS	Mean	RMS
B1	-29.8	17.1	-10.2	11.9
B5	0.5	6.4	5.7	4.3

The dipolar term is significantly reduced after correction but some sextupoles still have a strong B5 component. The tolerances on axis centering have been fixed to $\pm$ 30µm in x and z, and 0.2mrad in tilt angle. SOLEIL has contributed to the optimization of the bench with the construction of a calibration sextupole to determine the offsets of the sensor. Measurement stability was checked by using a reference sextupole centered at SOLEIL. Axis centering results (Table 5) are within tolerances. Sextupolar strength identity from one sextupole to the other is 3.3 10^{-3} at maximum current.

Table 5: Sextupole Magnetic Axis Centering.

	Mean Value	RMS value
DX (µm)	-3	10
DZ (µm)	2	15
Tilt Angle (µrad)	10	100

Statistical results on the non-zero harmonics Bn/B3 of the main sextupolar field at maximum current are listed in Table 6 (including shim effect). Design values for B9, B15, B21 and B27 are given in brackets. The systematic **B9** component was minimized by choosing the chamfer in the design phase. It is strongly modified by the B9 component of the additional dipolar field created by the shims, the value depending on the number of shims: -9.0 10^{-4}, -5.0 10^{-4} and –1.0 10^{-4} for 0, 4 and 8 shims respectively. The agreement between measurement and design is excellent for the systematic components **B15, B21 and B27**. The **B1** mean value is reduced to an acceptable value but the **B5** systematic component is non negligible. Its bad effect on the off momentum non linear dynamics will be minimized by affecting the sextupoles with strong B5 at a ring location where the sextupolar strength and optical functions are weak. The **B7** component becomes systematic with a small value due to the additional dipolar field.

Table 6: Sextupolar Field Harmonics Content.

given in 10^{-4} at 32 mm	Mean	RMS
B1	-9.8	17.7
B5	5.4	4.7
B7	3.3	2.1
B9	-4.7 (-3.5)	3.2
B15	-9.0 (-7.5)	0.7
B21	-20.9 (-21.0)	0.5
B27	0.8 (0.7)	0.4

Corrector efficiency, for each sextupole and each type of correction, was measured for 3 current values per polarity. Tests have shown that the different corrections do not interact. The corrector response is always linear versus current for the three types of correction. The maximum strengths satisfy the requirements for orbit and coupling correction with a comfortable margin.

CONCLUSION

Magnetic measurements have confirmed the good quality of SR magnets in term of maximum fields, reproducibility from one to the other, and systematic harmonics content. The significant unexpected components have been identified and minimized as far as possible. The strong optimization of the harmonics benches permitted to reach the tight tolerances on magnetic axis centering for both quadrupoles and sextupoles, leading to the first turns in the ring without any correctors [4].

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REFERENCES

[1] J.-M. Filhol et al, "Overview of the status of the SOLEIL project", this conference.

[2] C. Benabderrahmane, et al, "Design, Construction and Measurements of Quadrupoles and Sextupoles for the SOLEIL Storage Ring", MT19, Gênes, Italy, Sept. 2005.

[3] A. Madur et al, "Tools for Multipoles Magnetic Metrology at SOLEIL", IMTC 2006, Sorrento, Italy, April 2006.

[4] A. Nadji et al, "First results of the commissioning of SOLEIL storage ring", this conference.