ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL017

FROM DESIGN TO ALIGNMENT OF THOMX QUADRUPOLES

C. Vallerand*[1], F. Marteau†[2]
R. Marie, H. Monard, [1] LAL, Orsay, France
M.E Couprie, A. Lestrade, A. Loulergue, M. Ros, [2] SOLEIL, Saint-Aubin, France
J. Campmany, J. Marcos, V. Massana, ALBA-CELLS, Barcelone, Spain
J. Chavanne, G. Le Bec, ESRF, Grenoble, France

Abstract

Quadrupoles for Thomx Facility[1] have been carefully designed and measured due to high constraints of the storage ring. The need of a compact accelerator, 70 m^2 on floor, as well as a beam life time of 20 ms, led to the following requirements for the quadrupole : a gradient of 5 T/m with 20.5 mm radius bore, harmonic content better than few 1.10^{-3} at the reference radius of 18 mm, no cross-talk with sextupole placed within 5 cm and a precision of the magnetic axis of 100 µm and the roll angle of 300 µrad for measurements and alignment. Total of 41 quadrupoles have been built and all measured by a rotating coil at ALBA and SOLEIL, providing multipole components, transfer function and magnetic center. Cross-check measurements have also been carried out with a versatile stretched wire from ESRF at LAL.

This paper mainly describes results of simulations with OPERA and RADIA and provides the results of measurements with these three benches. These results will be compared and highlighted important points for the alignment and installation of quadrupoles in an accelerator.

INTRODUCTION

For a storage ring, all steps, from the design up to alignment of quadrupoles, must be carried out with care and precision. Indeed, regarding the design, it is necessary to get low systematic multipoles to prevent non-linearity effects which affect beam dynamic aperture. Regarding the manufacturing, it is necessary to respect machining tolerances and limit assembly errors. At last, it is necessary to align quadrupoles by respecting alignment tolerances as well as a tilt around the beam axis to prevent too large orbits and beam dynamic issues [2]. Actually, the vertical emittance is mainly dominated by generation of orbit distortion, the residual vertical dispersion and the betatron coupling, caused by misalignment of quadrupoles. In this framework, ThomX quadrupoles, whom specifications are presented in Table 1, have been designed, measured and aligned with high accuracy.

SIMULATION RESULTS

To design quadrupoles, two codes has been used : Radia [3] [4] [5] and Tosca [6]. Radia software is based on the boundary element method so that analytical expressions for magnetic field and field integrals are produced by polyhedron-shape volumes with constant magnetization. Tosca / Opera software is based on the Finite Element Method. A special endeavour has been done to optimize the profile and the pole chamfer, leading to achieve very small multipolar components and keep a large dynamic aperture. Five points at extremities of pole have been carefully optimized with the module Optimizer from OPERA (cf Fig.1).

Table 1: Features

Parameters	Specifications
Quantity	41
Field gradient	5 T/m
Aperture diameter	41 mm
B_y(z=0) @ R = 18 mm	0.0869 T
Field integral	13.67 mT.m
Mechanical length	140 mm
Good field region	±18 mm
Reference radius	18 mm
Allowed multipole B_n/B_2 @ R=18mm	$\leq 1.10^{-3}$
Axis magnetic	$\leq 100\ \mu m$

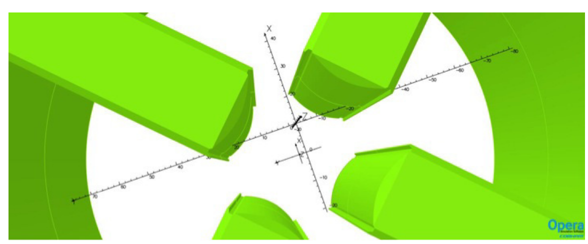

Figure 1: Pole design with OPERA

Results of both models with OPERA and TOSCA are shown in table 2. The field integrated along the magnet trajectory and individual multipole components were evaluated by Fourier analysis on a cylinder. Results with RADIA are obtained with a segmentation (25;0.2) as well as results with TOSCA are obtained with a meshing of 1mm for the extremity of the pole, close to the good field region and a meshing of 5mm for the pole and the yoke.

Simulated results with OPERA and RADIA show that the main field is equal despite some differences for B_6 and B_{10} values. These differences can be explained by the use of a different size of meshing. Investigations are still on going.

* cynthia.vallerand@lal.in2p3.fr
† fabrice.marteau@soleil-synchrotron.fr

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL017

Table 2: Simulated Results with OPERA and RADIA @ 10 A and R = 18 mm

	OPERA	RADIA
b_2 (mT.m)	13.7	13.6
$B_6*1.10^{-4}/b_2$	-1.2	-5.4
$B_{10}*1.10^{-4}/b_2$	-5.8	-8.1
$B_{14}*1.10^{-4}/ b_2$	-8.6	-8.2

MEASUREMENT RESULTS WITH ROTATING COIL AT ALBA AND AT SOLEIL

The field-measurement method used at ALBA [7] and SOLEIL relies on a radial rotating coil, which is based on the Faraday law; i.e the fluxes and fields are derived from the induced voltages acquired and integrated by a digital integrator. Then, fluxes are analyzed to obtain the multipole decomposition of the field at a reference radius R_r, relative to the main field component B_N(r).

The multipole coefficients b_n and a_n represent the normal respectively the skew relative field errors at the reference radius, dimensionless and given in units of 10^{-4} (cf. equation 1).

$$B_y + iB_x = B_2^{(r)}.10^{-4}.\sum_{n=1}^{31}(b_n + ia_n)(\frac{z}{R_r})^{(n-1)} \quad (1)$$

Before measuring magnet at the nominal current, a same cycling of the quadrupole current, for both benched, has been performed to erase the remanent magnetic field and provide a reproductible gradient strength measurement. Furthermore, all quadrupoles are stored in the air-conditioned room at least 12 hours before any magnetic operations.

Measurements with ALBA and SOLEIL bench, rests on the horizontal reference, taken by means of a buble level and the rotary encoder. But in the case of ALBA bench, the horizontal reference was the horizontal reference surface of the quadrupole whereas for SOLEIL bench, it was the reference surface on the bench.

In the table 3, measurements results at ALBA and SOLEIL with relative accuracy are presented.

Table 3: Measurement Results at ALBA and SOLEIL @ 10 A and R = 18 mm

	ALBA	SOLEIL
b_2 (mT.m)	13.5	13.5
$B_6*1.10^{-4}/b_2$	-13.2 ± 1.5	-12.8 ± 1.3
$B_{10}*1.10^{-4}/b_2$	-10.1 ± 0.4	-10.2 ± 0.8
$B_{14}*1.10^{-4}/ b_2$	-7.0 ± 0.2	-6.9 ± 0.6

The allowed harmonics 6, 10 and 14 are very similar for both benches. Nevertheless, they are not totally in accordance with theoritical expected values.

Few investigations have been performed to find out origin of differences with simulations : change of iron permeability curve, displacement of the coil on the pole, add on 10μm at the extremity of the pole, change of the lateral chamfer, change of the entrance/exit chamfer.

Only these 2 last simulations have given significative results. Few simulation of the lateral chamfer at 2.5 mm and 3mm instead of 2 mm as well as the entrance/exit chamfer of 2, 2.5 and 3mm instead of 2.6mm are presented in table 4,5,6,7.

Table 4: Simulation Results with RADIA @ 10 A and R18 mm for Different Lateral Chamfers

RADIA lateral ch.	2 mm	2.5 mm	3.0 mm
b_2 (mT.m)	13.58	13.62	13.61
$B_6*1.10^{-4}/b_2$	-5.4	-7.4	-13.3
$B_{10}*1.10^{-4}/b_2$	-8.1	-8.6	-9.4
$B_{14}*1.10^{-4}/ b_2$	-8.2	-8.3	-8.2

Table 5: Simulation Results with TOSCA @ 10 A and R18 mm for Different Lateral Chamfers

TOSCA lateral ch.	2 mm	2.5 mm	3.0 mm
b_2 (mT.m)	13.69	13.69	13.68
$B_6*1.10^{-4}/b_2$	-1.2	-6.0	-11.5
$B_{10}*1.10^{-4}/b_2$	-5.8	-6.7	-7.7
$B_{14}*1.10^{-4}/ b_2$	-8.6	-8.5	-8.3

Table 6: Simulation Results with RADIA @ 10 A and R18 mm for Different Entrance/Exit Chamfers

RADIA ent/exit ch.	2 mm	2.5 mm	3.0 mm
b_2 (mT.m)	13.61	13.58	13.53
$B_6*1.10^{-4}/b_2$	-14.1	-6.8	-1.9
$B_{10}*1.10^{-4}/b_2$	-7.7	-8.1	-7.3
$B_{14}*1.10^{-4}/ b_2$	-7.8	-8.2	-8.4

As expected by theory, these simulations show that chamfer allow to tune harmonics but don't explain differences between measurements and simulated results. Investigations are still on going but the most probable hypothesis would be the machining processof the lateral chamfer. Indeed, this process takes place after the machining of the pole that could be generate some modifications at the extremities of the pole and so different harmonic values.

Nevertheless, these values prove the good design of the magnet, regards to the very small size of the magnet (19*19*18 cm^3).

MEASUREMENT RESULTS WITH SWB AT LAL

The field measurement method used at LAL on a bench developed by ESRF, relies on a the same principe as a radial rotating coil but uses a streched wire which allows to measure different radii [8].

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL017

Table 7: Simulation Results with TOSCA @ 10 A and R18 mm for Different Entrance/Exit Chamfers

TOSCA ent/exit ch.	**2 mm**	**2.5 mm**	**3.0 mm**
b_2 (mT.m)	13.74	13.71	13.67
$B_6*1.10^{-4}/b_2$	-8.5	-2.4	+2.9
$B_{10}*1.10^{-4}/b_2$	-5.8	-5.8	-5.7
$B_{14}*1.10^{-4}/ b_2$	-8.3	-8.5	-8.7

A complete characterization of the bench has been performed to evaluate reproducibility and reproductibility of the bench as well as the wire frequency impact on harmonic contents.

For the estimation of reproductibility error, seven measurements have been successively performed during one day, by taking into account tempertaure variation, hydrometry conditions....Error of reproductibility for the magnetic axis is 25 μm in X axis, and 53 μm in Z axis, and 2 mT.mm for the b_2 component.

Concerning the repetability, ten measurements have been permformed in one hour. Error of repeatability is 6 μm in X-axis and 9 μm in Z axis and 1 mT.mm for the b_2 component.

Regarding the impact of the wire frequency, measurements have been performed from 80 Hz up to 320 by 20Hz step. Uncertainties dues to the frequency are 12 μm in X axis, 37 μm in Z, 2.36 mrad in X and 6.41 mrad in Z as well as 0.03 G.m for b_2, whatever the frequency. So, by comparison with reproducibility and repeatability error, those linked to frequency is negligeable.

In the table 8, measurement results with one quadrupole at LAL are presented.

Table 8: Measurement Results at LAL

	LAL
b_2 (mT.m)	13.46
$B_6*1.10^{-4}/b_2$	-8.8
$B_{10}*1.10^{-4}/b_2$	-6.0
$B_{14}*1.10^{-4}/ b_2$	-8.0

SORTING AND ALIGNEMENT

As harmonic contents were all similar, the sorting of magnets has consisted in selecting magnetic axis.

Quadrupole installation on girders is also a key stage for a storage ring. As mentioned in introduction, mis-installed magnet would lead beam dynamic issues. Consequently, after their rough installation, magnets are carefully translated up to positioning pins on girders (cf. Fig. 2) by means of horizontal screws.

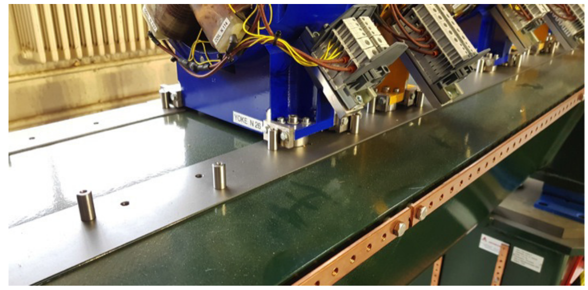

Figure 2: Quadrupole installed on girder

The position of each magnet on the girder was done by the method of least squares to optimize the tuning of magnetic axis.

To prevent errors, a torque wrench is used for screwing, the contacts between these pins and the quadrupole are precisely detected.

CONCLUSION

The design and measurements of 41 quadrupoles have shown a good coherence, whatever the bench, and fulfill expected requirements on harmonics and magnetic axis. They are all installed on girders in the IGLEX and are ready to be used for the ThomX commissioning.

REFERENCES

[1] A. Variola et al., *The THOMX project*, IPAC2011

[2] I. Reichel, "Coupling and Alignment", USPAS course, Berkeley Lab, June 2012

[3] The Radia code is freely available for download from the ESRF Web site: "http://www.esrf.fr/machine/support/ids/Public/index.html".

[4] P. Elleaume, O. Chubar and J. Chavanne, "Computing 3D Magnetic Fields from Insertion Devices", proceedings of the IEEE P AC-97 conference (Vancouver, Canada, May 1997).

[5] [O. Chubar, P. Elleaume and J. Chavanne, "A 3D Magnetostatics Computer Code for Insertion Devices", Journal of Synchrotron Radiation, 1998, vol.5, p.481.

[6] OPERA 3D finite element code (TOSCA), Cobham Technical Services, Oxfordshire, England. « http://www.vector-fields.co.uk/index.html »

[7] J. Campmany et al., "Status of magnetic measurements at ALBA", presentation at IMMW18, Brookhaven National Lab, (2013)

[8] G. Le Bec, et al., "Stretched wire measurement of multipole accelerator magnets," Physical Review Special Topics - Accelerators and Beams 15 (2012) 022401