ACDIV-2018-05
April 2018

Simulations, measurements and sorting of THOMX Ring bending magnets

C. Vallerand, F. Marteau, Ch. Bruni, I. Chaikovska, R. Marie, H. Monard, Marie-E. Couprier, A. Loulergue, J. Campmany, J. Marcos, V. Massana

Abstract

The THOMX facility is a compact X-ray source based on compton back scattering, under construction at LAL in Orsay, France. The lattice is based on a double bend achromat. The dipole design, the set-up, and magnetic measurement results are presented and discussed, as well as the sorting issue in preparation of the commissioning of ThomX facility.

Accelerator Division
Alba Synchrotron Light Source
c/ de la Llum, 2-26
08290 Cerdanyola del Valles, Spain

Simulations, Measurements, and Sorting of THOMX Ring Bending Magnets

Cynthia Vallerand, Fabrice Marteau, Christelle Bruni, Iryna Chaikovska, Rodolphe Marie, Hughes Monard, Marie-Emmanuelle Couprie, Alexandre Loulergue, Josep Campmany, Jordi Marcos, and Valenti Massana

***Abstract*—The THOMX facility is a compact X-ray source based on compton back scattering, under construction at LAL in Orsay, France. The lattice is based on a double bend achromat. The dipole design, the set-up, and magnetic measurement results are presented and discussed, as well as the sorting issue in preparation of the commissioning of ThomX facility.**

***Index Terms*—Electro-magnets, magnet design and analysis techniques, storage ring.**

I. Introduction

THE Storage Ring (SR) design of ThomX [1], [2] is subjected to high constraints because of its compactness (18 meters long SR), the low electron energies (ranging from 50 to 70 MeV), the non-linear beam dynamics and the limited beam storage period (60 ns per turn). Consequently, THOMX SR magnets have to face many technical challenges. One of the challenges to be taken up concerns ring dipole magnets, which have to be designed to ensure a large dynamic aperture while preserving the machine performance. Indeed, the impact of magnetic errors such as variation of magnetic length, magnetic gap, and undesired systematic and random high order multipoles, cause a strong orbit distorsion - a tune shift with amplitude and so a loss of dynamic aperture [3]. In this framework, all calculations, as well as machining and measurements have to be carried out with high precision. Each step of magnet, from design to measurements, will be presented in this paper.

II. Requirements

The ring consists of 8 dipoles among 15 for the whole accelerator. The requirements of bending dipole are driven by different constraints. The iron length has to be shorter than 300 mm due to the compactness of the ring. Indeed, ThomX facility has been designed to not exceed 70 m^2 on the floor. The dipoles should have a C-shape design due to the interaction point configuration. The SR dipole will be fed by a single power supply which implies an integrated field as homogeneous as possible from one dipole to other. Accelerator physicists requested high quality magnetic fields with low tolerances for multipolar components (Table I) to ensure the stability of the beam in the ring. All the dipoles of the ThomX accelerator will be equal in order to have a larger choice for the sorting needed to reduce the closed orbit distortion.

TABLE I
Tolerances for Multipolar Components at 275A

Multipolar components	Value
B_3/B_1	1e^{-3}
B_4/B_1	1e^{-4}
B_5/B_1	5e^{-4}

III. Magnetic Design

To fulfill these constraints, the magnetic design [4] was mainly based on the width of the pole needed to prevent saturation, the end pole chamfer to adjust the magnetic length in the good field region and add-on shims to obtain flat field and ensure its homogeneity. Dipoles have been designed by using the OPERA-3D/Tosca program from Cobham [5].

From the dipole model, the different magnetic properties have been extracted. The distribution of the main field component B_y along the z beam axis at 275 A is shown in Fig. 1. The field at the centre of the magnet is $B_0 = 0.6112$ T.

In Fig. 2, one can see the distribution of the main field component across the centre of the dipole along the horizontal axis. The field homogeneity is 1.7 e^{-3} between x $= \pm 20$ mm and the field distribution is as flat in the middle as required.

The integrated field for 50 A $<$ I $<$ 300 A is shown in Fig. 3. It shows that the dipole has a linear behaviour up to 160 A. The difference between the measurements and the simulation is coming from the magnetic property of the XC10 iron. In order to have a conservative design, the BH curve used in Tosca has lower quality than what could be expected, in order to be sure that the manufactured dipole will fulfill the requested specifications in terms of field strenght and field homogeneity.

Manuscript received August 28, 2017; accepted February 20, 2018. Date of publication February 23, 2018; date of current version March 23, 2018. This work was supported in part by the French “Agence Nationale de la Recherche” as part of the program “investing in the future” under reference ANR-10-EQPX-51 and in part by grants from Région Ile-de-France. *(Corresponding author: Cynthia Vallerand.)*

C. Vallerand, C. Bruni, I. Chaikovska, R. Marie, and H. Monard are with the Laboratoire de l’Accélérateur Linéaire Laboratory, Orsay 91440, France (e-mail: cynthia.vallerand@lal.in2p3.fr).

F. Marteau, M-E. Couprie, and A. Loulergue are with SOLEIL, Synchrotron, Saint-Aubin 91190, France.

J. Campmany, J. Marcos, and V. Massana are with ALBA-CELLS, Synchrotron, Barcelona 08290, Spain.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2018.2808939

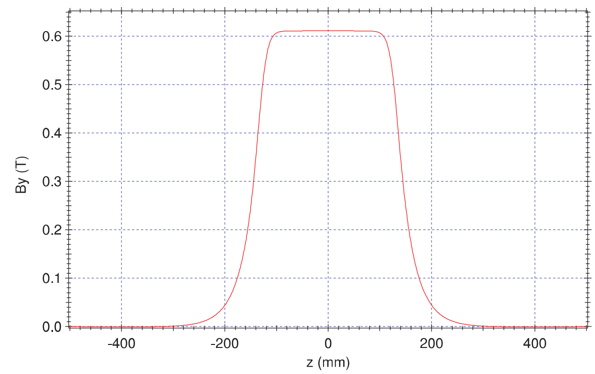

Fig. 1. Magnetic field versus z at 275 A.

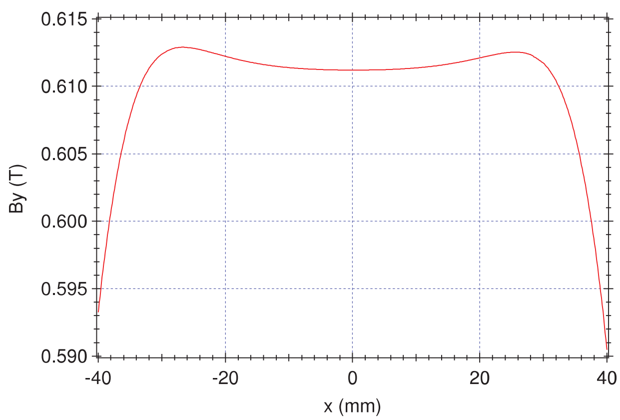

Fig. 2. Magnetic field versus x at 275 A.

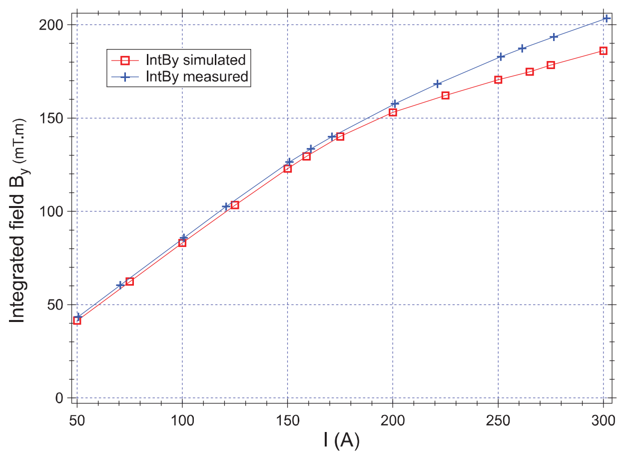

Fig. 3. Integrated field versus intensity for the dipole 09.

A mapping of the magnetic field of OPERA3D (Fig. 4) has been carried out and set into two tracking codes, BETA [6] and Accelerator Toolbox [7], for the tracking of electron beam. The multipole components are sliced as equivalent thin lenses and then have been distributed along the ring in the beta code, in order to check the preservation of the dynamic aperture for on and off momentum electrons.

Mean results for multipole components at 275 A, extracted along integral path : rectilinear + circular + rectilinear - are shown in the Table II and are consistent with simulated results shown in the Table I.

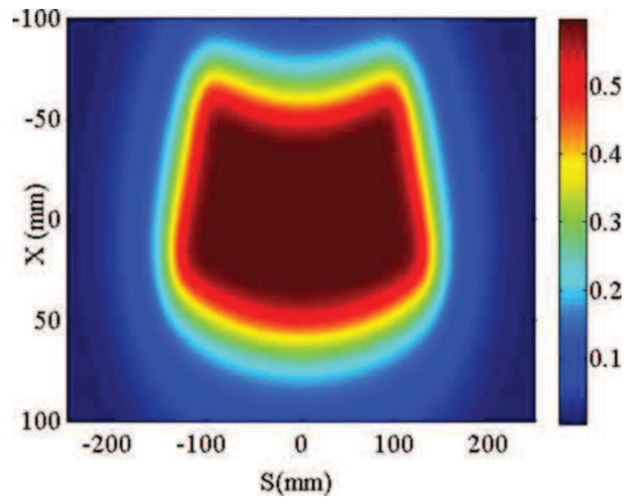

Fig. 4. By distribution at 275 A.

TABLE II
MAIN MULTIPOLAR COMPONENTS AT 275A

Multipolar components	Value
B_2/B_1	$-3.5e^{-3}$
B_3/B_1	$-1.0e^{-3}$
B_4/B_1	$-2.4e^{-3}$
B_5/B_1	$-1.2e^{-3}$

TABLE III
MAIN FEATURES OF DIPOLES

Parameter	Value
Quantity	14 + 1 (pre-serie)
Radius of curvature	352 mm
Main field B_0	0.611 T
Gap	42 mm
Good field region	±20 mm
Field integral $B.dl$	0.1289 T.m @ 159 A
Ampereturns	12624 A.t
Operating Current	159 A @ 50 MeV
Coil Voltage	9.4 V
Power	2471 W
Inductance	12.54 mH @ 159 A
Diff. Pressure	7 bars
Diff. Temperature	9.5°
Total weight	200 kg
Overall Dimensions (H × W × L)	35*40*40 cm^3

IV. Mechanical Design and Coils

All dipoles have been manufactured by Sigmaphi. A resistive magnet in a solid yoke technology with conductor for water cooling has been chosen for the manufacturing of THOMX dipoles whose main features are summarized in Table III.

V. Magnetic Measurements

Measurements of bending magnets (Table III) have been fully characterized at ALBA-CELLS magnetic measurement facility equipped with a 3D Hall probe bench, designed, manufactured and calibrated with high accuracy (Table IV) [8], [9].

TABLE IV
MAIN FEATURES OF THE ALBA HALL PROBE BENCH

Parameter	Value
Model	GH-700
Nominal current	5 mA
Magnetic sensitivity	1 V/T
Max. linearity error (±1 Tesla)	±2 %
Temperature coefficient	−0.07 %/C
Absolute accuracy	±0.05 mT
Repeatability between different scans	±0.5 Gauss rms
Relative overall reproductibility	$\pm 3e^{-4}$

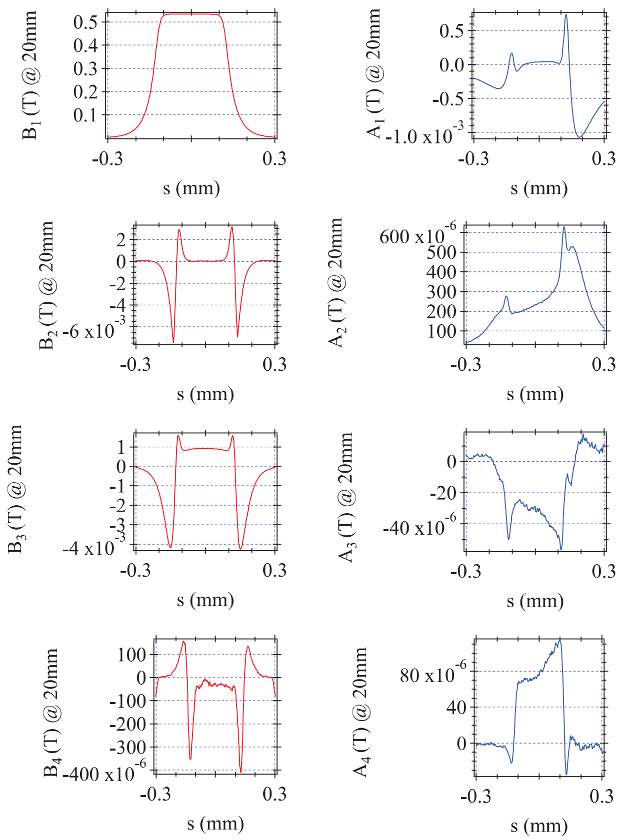

Fig. 5. Multipoles components at 275 A. In red on the left, normal components and in blue on the right, skew components.

All magnets have been measured using the same methodologies described in [10] and cycled in the same way to assure the same initial condition for all measurements.

The main measurements consisted of 2D cartesian field maps, made using Hall probe on-the-fly measurement mode covering a region of ±24 mm at both sides from the nominal trajectory. The scanned area was 600 mm longitudinally times 132 mm transversally, with a sampling step of 2 mm in both directions. From field map measurements, the normal and skew components of the magnetic field along the trajectory of the beam have been extracted as well as magnetic length for entrance and exit side. Fig. 5 shows multipolar component results at 275 A which satisfy design requirements. Two magnets (dipole #01 and dipole #09) have been fully characterized from 10 A to 300 A by 10 A step (Fig. 3) and compared to simulations.

TABLE V
COMPARISON BETWEEN SIMULATED AND MEASURED INTEGRAL FIELD

Intensity (A)	Int. B (T.m) simulated	Int. B (T.m) measured	Measured Standard deviation (T.m) amongst 15 dipoles
100	0.08305	0.08506	$1.93e^{-4}$
200	0.15308	0.15781	$2.42e^{-4}$
275	0.17846	0.19386	3.07^{-4}

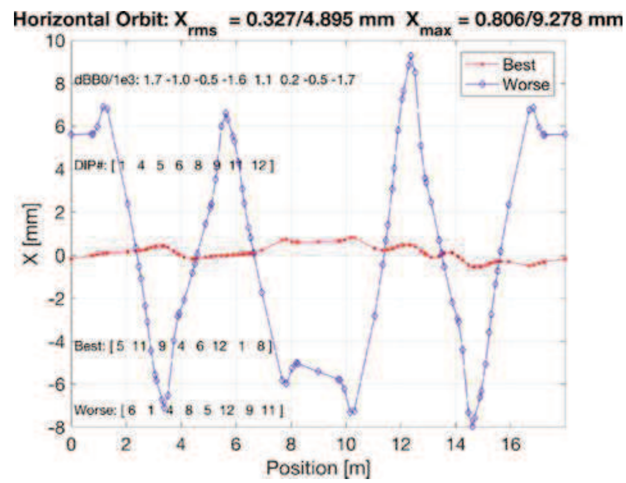

Fig. 6. Dipole sorting on the ThomX SR at nominal current (for 50 MeV). Best and worst case of the closed orbit distortion.

For others, measurements have been carried out at 3 currents : 100 A, 200 A and 275 A (Table V). The standard deviation of the integrated vertical field along the trajectory of the beam is less than 3.07 e^{-4} T.m from one magnet to the others. Given that the overall relative reproductibility of the Hall probe bench is $3e^{-4}$ (Table IV) and that the integrated field at the highest current is about 0.2 T.m, the expected variation from measurement error is about 6.0 e^{-5} T.m. Thus the variations observed among magnets of 3 e^{-4} T.m is not limited by the reproductibility of the bench. As the requirement for variation among magnets is less than ±5.0 e^{-3} and the maximum variation measured is $\pm 1.5e^{-3}$, measurements have shown that all magnets fulfill requirements.

VI. SORTING

The sorting procedure was performed for the SR dipole magnets in order to minimize the Closed Orbit Distortion (COD), caused by dipole field errors. It implies the selection of 8 best dipoles out of 15 dipoles which are available by minimization of the COD according to the measured field errors $\frac{\overline{B}-B_i}{\overline{B}}$, expressed as the normalized deviations of the integral field strength from its mean value. The method of simulated annealing [11] has been then employed to find 8 best dipoles by using a maximum of the COD as a cost function to compare different permutations of the measured error set.

Fig. 6 shows the result of the dipole sorting illustrating the best and worst scenarii of the sorting procedure. In such a way, the COD smaller than 1mm has been obtained for the best dipole configuration.

VII. Conclusion

The comparison of simulated and measured magnetic field of ThomX dipole shows very good agreement. Simulated and measured field values differ by a value of 47 G, i.e 0.71% of B_y(0,0,0) in the center of dipole at 275 A. From magnetic measurements and sorting, ThomX dipoles are now positioned and aligned on the girders.

References

[1] A. Variola *et al.*, "The THOMX project," in *Proc. 2nd Int. Particle Accelerator Conf.*, we00AA01, IPAC 2011, San Sebastian, Spain, 2001.

[2] A. Variola *et al.*, "THOMX technical design report," Tech. Rep. HAL-IN2P3, Laboratoire de l'Accélérateur Linéaire, Bures-sur-Yvette, France, 2014.

[3] M. Attal *et al.*, "The magnetic error tolerances in SESAME storage ring magnets," Note techniques, Tech. Rep. SES-TE-AP-TN-0004, 2014.

[4] C. Vallerand *et al.*, "Status of ThomX storage ring magnets," in *Proc. 2nd Int. Particle Accelerator Conf.*, 2016, Paper TUPMB002.

[5] TOSCA, "Software for electromagnetic design," Cobham Technical Services, Oxford, U.K. [Online]. Available: http://operafea.com/

[6] J. Payet. BETA. CEA/DSM/Irfu/SACM, [Online]. Available: ftp://ftp.cea.fr/incoming/y2k01/beta/

[7] A. Terebilo, "Accelerator toolbox for MATLAB," Tech. Rep. SLAC-PUB-8732, Stanford Univ., SLAC Nat. Accelerator Lab., Menlo Park, CA, USA, Feb. 2001.

[8] J. Marcos *et al.*, "Construction and commissioning of a 3D hall probe bench for insertion devices measurements at ALBA synchrotron light source," presented at the Int. Magn. Meas. Workshop, Fermilab, Batavia, IL, USA, 2007.

[9] J. Campmany *et al.*, "New improvements in magnetic measurements laboratory of the ALBA synchrotron facility," *Physics Procedia*, vol. 75, pp. 1214–1221, 2015.

[10] J. Marcos *et al.*, "Magnetic measurements of SESAME storage ring dipoles at ALBA," in *Proc. 7th Int. Particle Accelerator Conf.*, 2016, Paper TUPMB018.

[11] W. H. Press and B. P. Flannery, *Numerical Recipes in C: The Art of Numerical Computing*. Cambridge, U.K.: Cambridge Univ. Press, 1988.