RAMPING OF THE SOLARIS STORAGE RING ACHROMAT*

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Abstract

The combined function magnets implemented for the MAX IV and Solaris 1.5 GeV storage ring double bend achromats (DBAs) represents a challenging task in magnetic design. The constituent magnets in the DBA block may be sensitive to saturation effects which must be accounted for, especially in the case of energy ramping, as is the case for Solaris and not for MAX IV, where injection will take place at a beam energy of 0.55-0.6 GeV. The magnetic field distribution was calculated as a function of energy in the range from 0.5 GeV up to 1.5 GeV for the gradient dipole and for the quadrupoles containing a sextupole component. Results show that for the dipole, which generates the strongest field, the relative change of quadrupole strength is lower than $4\cdot10^{-3}$. For the quadrupoles the sextupole component is within the relative range of less than $0.7\cdot10^{-4}$. The impact on linear and non-linear optics at low energies has been accordingly studied. This is on-going studies and only preliminary results are presented in this paper.

INTRODUCTION

The MAX IV 1.5 GeV storage ring is being built in two copies, with one being installed at the Solaris facility in Krakow, Poland. The main difference between the MAX IV and Solaris 1.5 GeV light sources is the injection energy. While the MAX IV linac delivers a full energy electron beam the Solaris injector has a maximum energy of 0.6 GeV. Therefore, an energy ramp in the Solaris storage ring needs to be implemented in order to operate at the nominal 1.5 GeV energy. The design of the magnets as well as the optics is entirely done by the MAX IV team [1-4]. The lattice consists of 12 Double Bend Achromat (DBA) cells. All magnets within a cell are integrated into one solid iron block. Moreover, some of the magnets have combined functions. Namely, dipoles have integrated defocusing quadrupole content whereas the focusing quadrupoles have also a focusing sextupole component [1-4]. The constituent magnets in the DBA block may be sensitive to saturation effects which must be accounted for, especially in the case of energy ramping.

SATURATION EFFECT

The design of the storage ring magnets is in its final stage and will be done at MAX IV. In order to make a preliminary evaluation the magnitude of the saturation effects, two-dimensional Finite Element Method (FEM) calculations have been performed using a FEMM (Finite Element Method Magnetics) numeric code [5].

Bending magnet

The gradient dipoles (DIP) are the largest magnets in the MAX IV 1.5 GeV and Solaris achromat systems. Each DBA includes two large gradient dipoles having a 3.81 m radius and are 1 m in length. The small bending radius imposes a strong magnetic field (B_0=1.31 T, G_0=6.73 Tm^{-1}) and, consequently, a large yoke cross section. On the other hand the size of the Armco iron blocks was limited by the foundry capabilities of casting and heat treatment. The MAX IV 1.5 GeV and Solaris achromats have been milled out of 5000×700×200 mm^3 blocks. That yielded the thickness of the DIP magnet return yokes to be 90 mm in the upper part and 185 mm on the sides with a 28 mm gap. The excitation current providing the required field of 1.35 T intensity with a gradient of 6.75 Tm^{-1} exceeds 18 kA in one 20 turn coil. During ring operation with a stored beam energy of 1.5 GeV the flux density in the yoke exceeds the Armco saturation threshold at 1.0 T. The cross section of the DIP magnet is shown in the Fig. 1.

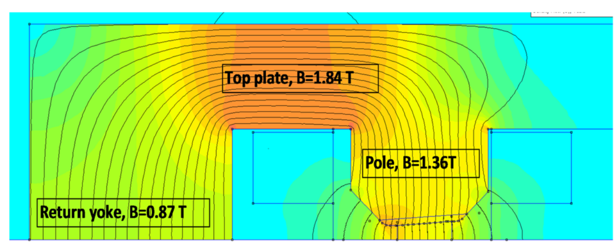

Figure 1: Cross section of the DIP magnet. Flux density is depicted with colours from blue to brown.

The FEMM calculations have revealed that saturation occurs in the gradient dipole magnets and is caused by the flux densification in the top plate of the yoke. Starting from NI=9 kA which corresponds to an electron energy of 0.9 GeV, the flux density exceeds 1.05 T in the upper part of the yoke, which is the saturation threshold. For 17 kA which corresponds to the nominal electron energy of 1.5 GeV, the pole root additionally gets saturated. The saturation results in a reduction of magnet efficiency and in changes in the flux distribution. The first one increases the excitation current necessary to generate a desired field.

*Work supported by the European Regional Development Fund within the frame of the Innovative Economy Operational Program: POIG.02.01.00-12-213/09
This research was supported in part by PL-Grid Infrastructure.
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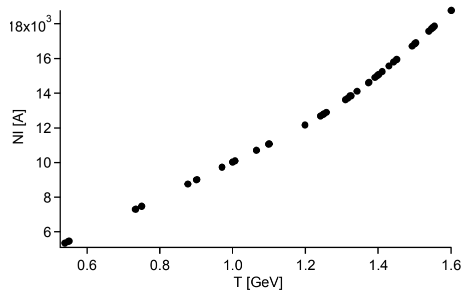

Figure 2: Flux density at the beam trajectory in the DIP as a function electron beam energy.

Figure 2 shows a pronounced kink at T=1.2 GeV (NI=12 kA). At that energy the excitation current is so high that, the saturated region expands toward the roots. For the nominal conditions of ring operation: T=1.5 GeV, NI=17 kA the efficiency drops down to 0.86. Additional current must be provided to compensate that loss. This corresponds to an increase in power that has to be provided to the magnet by a factor of 1.35 as compared to an unsaturated situation.

Up to NI = 12 kA the flux and its distribution across the pole root do not change significantly. The change occurs over the saturation threshold and influences the flux density at the beam trajectory. Its deviation from the nominal field is the smallest for 1.5 GeV, for which value the magnet has been optimized, while for lower energies the gradient component is too large.

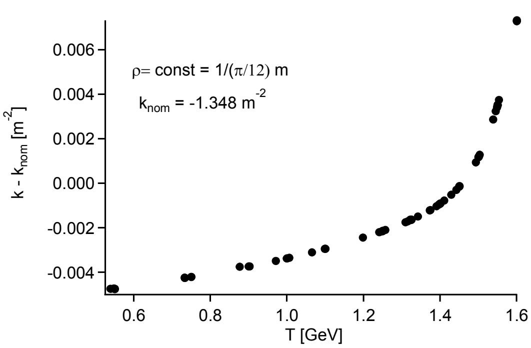

Figure 3: Quadrupole strength of the DIP magnet as a function of the beam energy.

The effect exerted by such a field on the beam is most readily visible as a quadrupole strength *k* dependence versus current I for the fixed radius ▯ at 3.8197 m.
The combined magnet DIP generates a field gradient the magnitude of which rises with beam energy. That dependence is weak and close to linear for the energies below 0.9 GeV but rises rapidly above that value (Fig.3). The relative variation in focusing strength of DIP is about $4{\cdot}10^{-3}$ and must be compensated with neighbouring quadrupoles. Changes of the gradient in the bending magnet can be compensated with pole face windings up to ±4%.

Quadrupole magnets

There are two families of combined quadrupole/sextupole horizontally focusing magnets, namely SQFi inserted in the centre of the DBA cell and SQFO positioned on both ends of the DBA cell [1-4]. Both types of magnets are designed as quadrupoles but the poles profile is shaped to give a sextupole content, too [1]. The FEMM calculations for both types of quadrupoles has shown that negligible saturation occurs. This is mostly due to the weaker flux generated there. The field distribution within an SQFi quadrupole is shown in the Fig. 4.

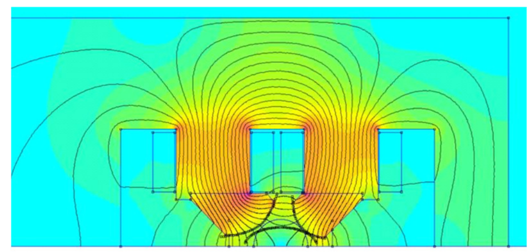

Figure 4: Field distribution within the quadrupole SQFi according to a 2 D Model (FEM).

As a result, the flux density exceeds the saturation limit in the side and the upper parts of the yoke only for the highest excitation current i.e. above 3 kA which corresponds to 1.3 GeV electron energy. The roots of the pole never get saturated. For the whole energy range, the permeability is higher than 1200 [6]. That makes the ratio of quadrupole to sextupole strengths vary in the narrower range of relative magnitude having the width of 10^{-4}. (Fig. 5)

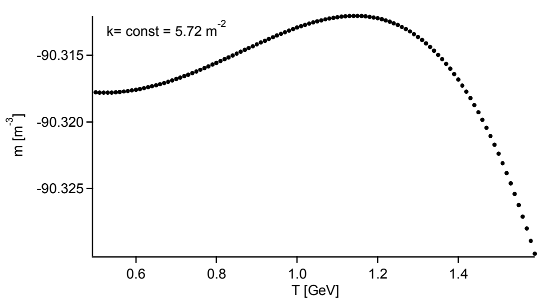

Figure 5: Sextupole strength of SQFO magnet as a function of beam energy for a fixed quadrupole.

BEAM DYNAMICS

The calculated values of magnetic field have been introduced in the lattice model for energies from 0.5 GeV to 1.5 GeV. The dynamics for different energies was studied.

Linear optics

The uncorrected values of the dipole gradient have revealed a tune shift from the nominal values (11.22; 3.15) in the range of 3% in the vertical plane and 0.05% in the horizontal plane. The tunes at different energies for

ISBN 978-3-95450-122-9

uncorrected optics have been plotted on the tune diagram (Fig.6).

It is worth noting that the higher discrepancy from the nominal optics is at 0.5 GeV. In order to restore the tunes the dipole gradient need to be compensated with pole face strips.

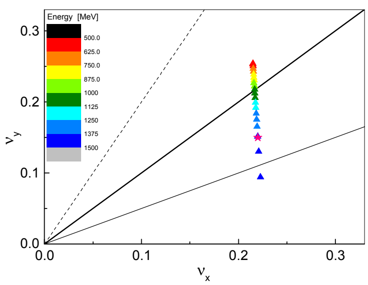

Figure 6: Tune diagram; coloured triangles correspond to tunes obtained for uncorrected lattice at different energies; the pink star represents the nominal optics at 1.5 GeV.

Non-linear optics

The sextupole strength in the quadrupoles varies in the range of a tenth of a percent and the impact on the nonlinear optics is negligible. For the uncorrected lattices at the energy range from 0.5 MeV up to 1.5 MeV the natural chromaticity changes are 0.3% and 0.1% in the horizontal and vertical plane, respectively. Whereas after correction of the bending magnet gradient the chromaticity change is negligible. Comparing the results for the chromatic and amplitude dependent tune shifts for the ideal lattice and lattice at 500 MeV with different ratio of the quadrupole/sextupole content, one can notice that the behaviour is almost the same (Fig.7).

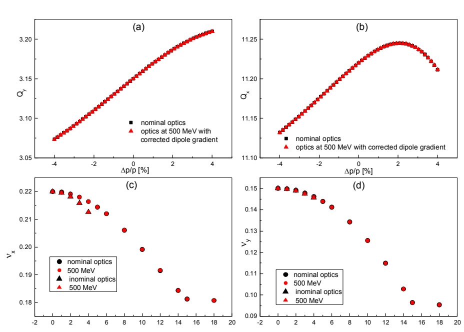

Figure 7: Chromatic (a, b) and amplitude dependent (c, d) tune shift calculated for the nominal optics and the optics at 500 MeV with corrected gradient dipoles [7].

The dynamic aperture calculated for both cases including also the 0.2% errors for the quadrupoles and sextupoles strength, modelled as a Gaussian distribution with cut off at 2 sigma, also reveals similar behaviour for both lattices [8]. The dynamic aperture at 500 MeV for the corrected lattice is presented in the Fig. 8.

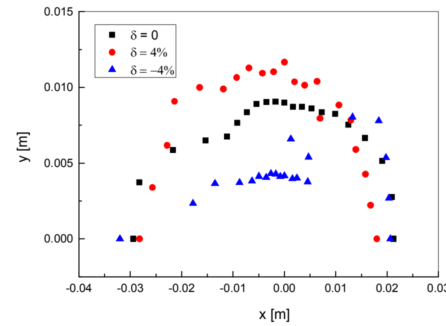

Figure 8: Dynamic aperture for on and off momentum particles.

SUMMARY

The saturation effect of the MAX IV 1.5 GeV/ Solaris achromats and its influence on the beam dynamics was discussed. As shown the main changes are observed for the gradient dipole magnets where the relative change of quadrupole strength is in the range of $4 \cdot 10^{-3}$. This results in a tune shift in the range of 3% and 0.05% for the vertical and horizontal plane, respectively. For the combined quadrupole/sextupole magnets on the other hand the saturation effect is negligible. One can conclude that it will be sufficient to ramp up the magnets together with the pole face strips on the dipoles in order to correct the dipole gradient strength and maintain the tune at the nominal value.

ACKNOWLEDGMENTS

Authors would like to express thanks to all the MAX IV team for sharing their technology and know-how. Special acknowledgements to M. Johansson for sharing his knowledge and discussions on magnets technology and the design.

REFERENCES

[1] MAXIV Detailed Design Report, https://www.maxlab.lu.se/node/1136

[2] S. C. Leemann, “Updates to the MAX IV 1.5 GeV Storage Ring Lattice,” MAX-lab Internal Note 20120313, April, 2012

[3] S. C. Leemann, ”Recent Progress on the MAX IV 1.5 GeV Storage Ring Lattice and Optics”, IPAC’12, New Orleans, May 2012, TUPPP024, p. 1662 (2012); http://www.JACoW.org

[4] M. Johansson, ”Design of the MAXIV/Solaris 1.5GeV storage ring magnets”, IPAC’11, San Sebastian, Sept. 2011, WEPO016, p. 2430 (2011); http://www.JACoW.org

[5] http://www.femm.info/wiki/HomePage

[6] D. Einfeld, R.Nietubyć, “Saturation of the Magnets at SOLARIS”, internal report, 29.03. 2013.

[7] A. Streun, OPA, code and documentation available at http://people.web.psi.ch/streun/opa/

[8] M. Borland, *APS Report No. LS-287, 2000*