CONSIDERATIONS ON THE EFFECT OF MAGNET YOKE DILUTION ON REMANENT FIELD AT ELENA

C. Carli, L. Fiscarelli, D. Schoerling
CERN, Geneva, Switzerland

Abstract

The Extra Low Energy Antiproton ring (ELENA) is a small synchrotron constructed at CERN to decelerate antiprotons down to 100 keV and, thus, operated at very low magnetic fields. The CERN magnet group has carried out extensive investigations on accelerator magnets for very low fields, comprising theoretical studies and the construction of several prototype magnets, to ensure that the required field quality can be reached at these very low fields. In the course of this work, experimental investigations [1] led to the initially unexpected observation that dilution of the yoke, i.e. alternating laminations made of electrical steel with thicker non-magnetic stainless steel laminations, increases the remanent field. An explanation for this behaviour has already been anticipated in a previous paper [2]. Here, we treat this specific topic in analytical detail. We come to the conclusion that magnet yoke thinning in most practical situations does not improve the field quality at low field levels, but rather enhances the impact from hysteresis and remanence effects.

INTRODUCTION

Hysteresis effects and resulting remanence fields have an impact on the field of accelerator magnets for very low field levels. The phenomena have some similarities with saturation effects in the sense that the ratio between the magnetic flux density B and the magnetic field H is not an approximately constant large quantity. The impact of hysteresis on the obtained field quality is even more difficult to assess as the flux density B not only depends on the magnetic field H, but in addition on the "magnetic history" of the yoke.

Magnet thinning or dilution, i.e. interleaving laminations made out of electrical steel with non-magnetic filling materiel has been expected to improve the field quality of very low field magnets and had been foreseen for ELENA [3–7] bending magnets and other projects as LHeC [8, 9].

Within the ELENA project, the CERN magnet group has carried out an extensive test program to study low field magnets with diluted and conventional yokes. First a straight bending magnet with a diluted yoke has been tested. After discussions on applying yoke dilution as well to quadrupoles and sextupoles, quadrupole magnets with four different diluted and conventional yokes using non-grain-oriented and grain-oriented steel have been tested and compared. The unexpected observation was that the quadrupoles with non-diluted yokes had the lowest remanent field. This observation triggered the construction of a second bending magnet prototype yoke without dilution. Finally, the slight increase of the remanent field with a diluted yoke has been observed as well for the bending magnets.

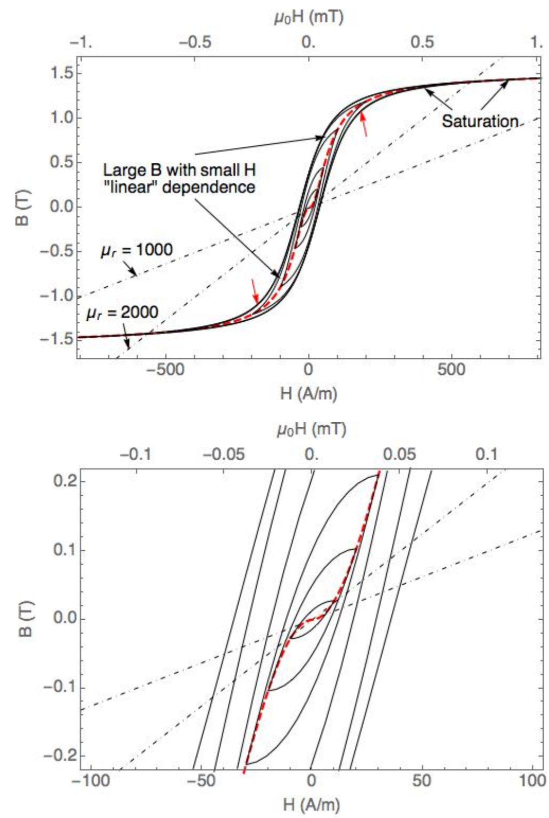

Figure 1: Hysteris loops (solid lines) based on the formalism in Ref. [10]. B-H-curve as used for simulations of very low field magnets are plotted as red dashed lines. Lines corresponding to a relative permeabilities of 1000 and 2000 are shown as dot-dashed lines.

This report describes simple considerations leading to the conclusion that remanent fields are not mitigated by magnet "thinning"; remanent fields are even slightly increased with a diluted yoke as observed empirically. Furthermore, the field quality of a magnet with a diluted yoke is not improved compared to magnets with conventional yokes. Then, a procedure to determine the $B-H$ curve of a diluted yoke from the from the properties of the electrical steel used is given.

HYSTERESIS CYCLES AND IMPACT ON FIELD QUALITY

Hysteresis cycles for a typical electrical steel used for the construction of accelerator magnets are plotted in Fig. 1 based on the formalism given in [10] with parameters adjusted to fit the measurements perpendicular to the rolling direction of the steel used for the ELENA bending magnets

ISBN 978-3-95450-182-3

reported in [2]. The region, where the ratio between the magnetic flux density B and the field H is large (large relative magnetic permeability μ_r) with small variations, allows achieving good field quality. Ideally, the magnetic flux density and the field of all parts of the magnet yoke are kept within this region over the operational range between minimum and maximum beam energy. However, this is possible only within a suitable range of magnetic flux densities and fields. For high and low magnetic fields, the field quality is limited by the following effects:

- For many accelerators, the challenge is to reach high fields in order to reach high beam energies. This brings at least parts of the yoke in the region where saturation occurs affecting the resulting field and field quality.
- Similarly, in case of very low magnetic field levels required in some low energy machines as ELENA, the magnetic flux density and field are brought in the region, where the ratio is far from linear, but depending on the branch of the hysteresis curve. This has similar effects on the field quality than saturation, but in addition implies that the field and the field quality depend on the magnetic history.

REMANENT FIELDS TO BE EXPECTED

For a rough estimate of the remanent field to be expected for a bending magnet, the integral $\int H\,\mathrm{d}l$ is considered for an integration path C indicated in Fig. 2. The yoke, sketched in Fig. 3 is made of electrical steel laminations with a thickness d interleaved with filling material with thickness b giving a thinning ratio $\lambda = d/(d+b)$. The average magnetic flux density inside the yoke is given by $\bar{B}_y = B_r A_y/A_g$ with B_r the remanent flux density in the gap and A_g and A_y the cross sections of the gap and the yoke. With the magnetic field H_y inside the yoke (the same both inside magnetic laminations and filling materiel), the flux density inside the electrical steel laminations is given by $(H_y + H_c)\mu_d\mu_0$ with H_c the coercitivity and μ_d the slope of the hysteresis loop for decreasing field at $B_y = 0$. The flux density inside the non-magnetic filling material is given by $H_y\mu_0$. The remanent field inside the gap becomes:

$$B_r \approx \Big(\lambda(H_y + H_c)\mu_d\mu_0 + (1-\lambda)H_y\mu_0\Big)\frac{A_y}{A_g} \quad . \qquad (1)$$

Furthermore, with zero current exciting the coil, the relation

$$\int_C H\,dl \approx g\,\frac{B_r}{\mu_0} + l_y\,H_y = 0 \qquad (2)$$

holds, where l_y is the typical length of the integration path inside the yoke as indicated in Fig. 3; a more rigorous approach, taking anisotropic permeability and variations of the magnetic field into account, for the contribution of $\int H\,dl$ inside the yoke is given in [2], but this has no impact on the final (qualitative) conclusion. Note that for a thin region with a width of about the period $d+b$ of the yoke structure

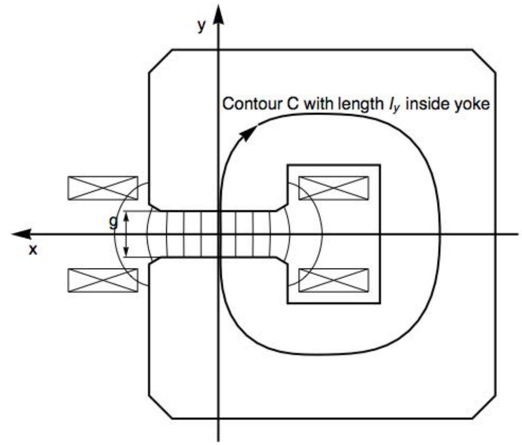

Figure 2: Transverse cross section of the magnet with an integration path to estimate the remanent field.

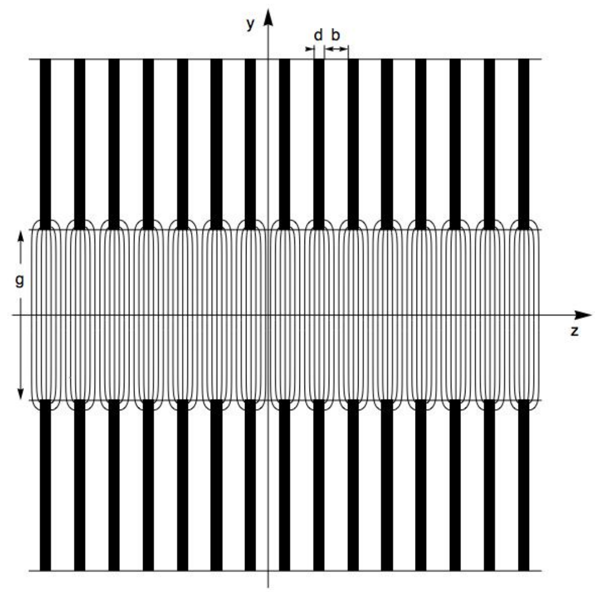

Figure 3: Magnet cross section in longitudinal direction with "thinning" of the yoke. The black rectangles denote laminations made of electrical steel interleaved with non-magnetic filling material in white (stainless steel for the ELENA prototype magnets).

around the pole-face, the situation is more complicated with longitudinal components of the magnetic field and the magnetic flux density and a dependance of the vertical magnetic field from the longitudinal position. However, with sufficiently small period $d+b$ of the yoke structure, the impact on the final result is neglected[1]. From the last equations, the

[1] From Fig. 3, one observes that some of the magnetic field lines across the gap are longer than the gap height and for some of the lines the magnetic flux density is increased close to the edge of the gap. This increases the contribution of the gap to the integral $\int dl\,H$ over the contour C in Fig. 2. The resulting reduction of the efficiency of the magnet can be described by an increase of the "efficient" gap height.

ISBN 978-3-95450-182-3

expression

$$B_r \approx \frac{\mu_0 H_c l_y/g}{1 + \frac{1}{\lambda \mu_d}\left(1 - \lambda + \frac{l_y A_g}{g A_y}\right)} \tag{3}$$

is obtained. One notes that for typical parameters (μ_d sufficiently large) the denominator of this expression 3 is about unity and the remanent field given by $B_r \approx \mu_0 H_c l_y/g$. This expression for the remanent field does not depend explicitly on the thinning factor λ. However, the coercive force H_c depends on the hysteresis cycle (see Fig. 1) and is smaller for a cycle with smaller (maximum) magnetic flux density at the inversion points. For the same maximum magnetic flux density in the gap, magnet "thinning" (decrease of $\lambda < 1$) increases the maximum flux density inside the magnetic laminations at the inversion point of the hysteresis cycle. Thus, H_c and, as a consequence, the remanent field is increased.

Similar investigations [11] on the effect of thinning for the LEP project gave similar expressions for the estimation of remanent effects.

EFFECTIVE HYSTERESIS LOOPS AND B-H CURVES FOR DILUTED YOKES

Looking carefully at the approach applied to estimate the remanent field of magnets with diluted yokes, one notes that for the derivation of Eq. 1, the magnetic flux density for the yoke for a given field strength H_y has been averaged over the electrical steel laminations and the non-magnetic filling materiel. The same must hold as well to adapt hysteresis cycles to magnets with diluted yokes, if a non-zero current is exciting the field. However, the assumption that the magnetic flux density is small and, thus, the magnetic field is very close to $-H_c$ does not hold any more. Instead, the flux density for arbitrary magnetic fields has to be averaged between magnetic laminations and non-magnetic filling materiel giving

$$\vec{B}_y(\vec{H}) = \lambda \vec{B}(\vec{H}) + (1 - \lambda)\mu_0 \vec{H} \tag{4}$$

where $\vec{B}(\vec{H})$ describes the appropriate hysteresis branch (depending on the inversion points of the hysteresis loop and whether the current is increasing or decreasing) of the non-diluted electrical steel. This approach is appropriate only for 2D considerations and simulations of magnets with diluted yokes.

Note the averaging of the magnetic flux density over magnetic steel and non-magnetic filling materiel is independent of the magnet type. Thus, Eq. 4 is valid as well for quadrupoles and higher order multipoles. This is more general than considerations to derive Eq. 3 assuming explicitly bending magnets. Note that, in general, the second term in Eq. 4 is small compared to the first one; thus, the magnetic flux density of the hysteresis branch considered is roughly reduced by a factor λ. Note that with the above formula, a reduction of the efficiency of a magnet with diluted yoke is expected as observed empirically. Strictly speaking the above considerations are valid for a symmetric excitation cycle with positive and negative currents. As asymmetric hysteresis cycles are expected to feature similar behaviour, all conclusions may be extrapolated to this case implemented in practice to operate an accelerator (or decelerator as ELENA).

For low and intermediate magnetic fields, where saturation effects are not yet present and the effective $B - H$ curve can be approximated by a linear function such that Eq. 4 becomes:

$$\vec{B}_y(\vec{H}) \approx \lambda \left(\vec{H}_c + \vec{H}\right) \mu_d \mu_0 + (1 - \lambda)\mu_0 \vec{H} \tag{5}$$

The resulting magnetic field can be approximated by a superposition of the remanent field and a contribution proportional to the current I as $\vec{B} = \vec{B}_r + I\,(\mathrm{d}\vec{B})/(\mathrm{d}I)$. The unwanted multipolar components are in general different for the two contributions and make it more difficult to ensure the required field quality is met over the working range of the magnet. Moreover, the contribution $\vec{B}_r$ due to hysteresis effects changes sign between the two branches of a hysteresis loop. Finally, one concludes that magnet "thinning" does not improve the field quality of magnets with very low fields, but rather is expected to slightly increase multipolar components due to the increase of the coercivity H_c.

Additional effects occurring for real three dimensional magnets are summarized in reference [2]. An increase of the effective gap height has been already been described. The longitudinal structure of the yoke strongly reduces as well the relative permeability in longitudinal direction to about $(1-\lambda)^{-1}$ (field lines cannot easily cross over the gap between laminations). The outermost laminations may concentrate magnetic flux from the stray fields leading to saturation at modest field levels of the magnet. This resulting reduction of the magnetic length has been observed with some of the prototypes.

CONCLUSIONS

A thorough tests program on magnets operated at very low magnetic fields has been carried out within the ELENA project to ensure that the required field quality can be reached with the low energies foreseen. In particular, quadrupoles and dipoles with different types of yokes have been constructed and measured. Contrary to expectations, the magnets with a diluted yoke, alternating magnetic laminations with thicker non-magnetic stainless steel laminations, were found to have the largest remanent field.

Simple analytical 2D considerations on remanent magnetic field for magnets with conventional yokes and diluted yokes allowed to explain these observations. A slight deterioration of remanent field and field quality has to be expected with diluted yokes. Additional effects not taken into account in the simplified 2D model as saturation of laminations close to the magnet extremities make the situation even less favourable for magnets with diluted yokes.

As a consequence, all ELENA magnets have been constructed with conventional yokes. The conclusions are relevant for any project requiring very low field magnets.

ISBN 978-3-95450-182-3

REFERENCES

[1] L. Fiscarelli, "Magnetic measurements on the quadrupoles prototypes for ELENA (PXMQNLGNAP)", CERN internal report.

[2] D. Schoerling, "Case Study of a Magnetic System for low-Energy Machines", *Phys. Rev. Accel. Beams* 19, 082401 (2016).

[3] W. Bartmann *et. al*, "Progress in ELENA Design", *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper WEPEA062, pp. 2651-2653.

[4] P. Belochitskii, "ELENA Project Status", *Proc. of the International Workshop on Beam Cooling and Related Topics 2013 (COOL'13)*, Murren, Switzerland, June 2013, paper THPM1HA02, pp. 192-196.

[5] W. Bartmann *et. al*, "Extra Low ENergy Antiproton ring ELENA: from the Conception to the Implementation Phase", *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, May 2014, paper TUOAA003, pp. 910-912.

[6] V. Chohan (editor) *et. al*, "Extra Low ENergy Antiproton (ELENA) ring and its Transfer Lines Design Report", CERN-2014-002.

[7] W. Bartmann *et. al.*, "ELENA: Installations and Preparations for Commissioning", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper MOPOY009, pp. 860-863.

[8] LHeC Study Group, "A Large Hadron Electron Collider at CERN", *J. Phys. G Nucl. Part. Phys* 39 (2012) 075001.

[9] B. Holzer *et. al.*, "Challenges for the Magnet System of LHeC", in *Proc. 3rd Int. Particle Accelerator Conf. (IPAC'12)*, New Orleans Louisiana, USA, paper TUPPR075, pp. 1996-1998.

[10] Z. Wlodarski, "Analytical Description of Magnetization Curves", *Physica B* 373 (2006) 323 - 327.

[11] J. Gourber and L. Resegotti, "Implications of the low field levels in the LEP magnets", *IEEE Trans. Nucl. Sci.* 26, (1979) 3185 - 3187.

ISBN 978-3-95450-182-3