ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRO016

NANOPERM® BROAD BAND MAGNETIC ALLOY CORES FOR SYNCHROTRON RF SYSTEMS

T. Trupp*, Magnetec GmbH, Industriestrasse 7, 63505 Langenselbold, Germany

Abstract

Recent developments in synchrotron acceleration systems show a demand for broadband MA (Magnetic Alloy) magnetic core loaded cavities with a high field gradient. For many facilities e.g. GSI, CoSY, J-Parc [11-14] limited installation lengths requires high gradients in the region of 40kV/m [11]. Both requirements rule out ferrite materials due to the lower maximum excitation levels and high Q-value. This request can solely be met by Finemet type cores like NANOPERM® produced by MAGNETEC. In this paper, the statistics of 22 huge cores made of NANOPERM® and measured high frequency properties are shown under free-space (FS) condition and compared with the theoretical expectation.

INTRODUCTION

A high saturation flux density of about 1,2T, an in a wide range adjustable initial permeability are advantages of Finemet-Type magnetic cores in synchrotron accelerator application known under the trade names FINEMET® Hitachi Ltd, VITROPERM® Vacuumschmelze GmbH, and NANOPERM® MAGNETEC GmbH.

The company MAGNETEC GmbH in Langenselbold, Germany is a producer of Finemet-type cores called NANOPERM® - these NANOPERM® cores have been established in the industry since decades in the field of EMC components (electromagnetic comparability), 50Hz current transformer (CT) and RCCB (residual current circuit breaker). There are many technical parallels between the demands of magnetic cores in synchrotron accelerator area and the high frequency EMC applications as follows: the high linearity required by CT applications, the high sensitivity of RCCB application of NANOPERM®. In cooperation with Forschungszentrum Jülich, MAGNETEC has produced so far 22 cores for GSI's HESR FR system. The fluctuation of the core's rf-properties was investigated and compared. It has been shown, that the distribution of the high frequency properties is quite narrow. Furthermore, a theoretical model, which explains in a first stage the high frequency properties, has been introduced.

THEORATICAL BACKGROUND

To understand the loss mechanism of Finemet-type cores is the key to understand it's rf behavior, especially the permeability vs. frequency. This is clear considering the following formula giving the correlation between the power loss in W/kg and the complex permeability with $\mu''/|\mu|^2$ being the relative loss factor [1]:

$$P_{Fe} = \frac{\pi \cdot B_{pk}^2 \cdot f}{\rho_{dens} \cdot \mu_0} \cdot \frac{\mu''}{|\mu|^2} \tag{1}$$

Despite of the loss separation framework, the total losses in W/kg are the sum of three components, the static hysteresis loss, the classical eddy current loss and the so called excess loss.

$$\mathrm{P_{Fe}} = \mathrm{P_{Fe,st.h}} + \mathrm{P_{Fe,cl.ed.}} + \mathrm{P_{Fe,exess}} \tag{2}$$

Thanks to the very small coercitivity of nanocrystalline materials due to the $H_c \sim D^6$ relation between the coercitivity and the grain size D [1], the static hysteresis loss $\mathrm{P_{Fe,st.h}}$ can be neglected for frequencies above ca. 10kHz. This has been experienced in many measurements in the 10kHz regime for NANOPERM® cores with different permeabilities [2,3]. Also in the work of A. Magni et al [4] it has been shown that for F-type FINEMET, the static hysteresis loss can be neglected for higher frequencies.

The classical eddy current loss $\mathrm{P_{Fe,kl.W}}$ in W per kg for sinusoidal change of flux density can be calculated by the following equation [2,5]:

$$P_{Fe,cl.eddy} = \frac{\pi^2 f^2 B_{pk}^2 d^2}{6 \cdot \rho_{el.} \cdot \rho_{dens.}} \left(\frac{3 \cdot \delta}{d} \cdot \frac{\sinh\frac{d}{\delta} - \sin\frac{d}{\delta}}{\cosh\frac{d}{\delta} - \cos\frac{d}{\delta}} \right) \tag{3}$$

with f as the frequency, Bpk as the magnetic flux density peak, d as the ribbon thickness, ρ el as the electrical resistivity, ρ dens as the density and δ as the skin depth.

The skin depth δ can be calculated by the equation:

$$\delta = \frac{\sqrt{\rho_{el}}}{\sqrt{\pi \cdot f \cdot \mu_0 \mu_r}} \tag{4}$$

The frequency at which the skin depth approaches half the ribbon thickness is called the cut-off frequency "Wolman frequency" which is given by the relation [6]

$$f_w = \frac{4 \cdot \rho_{el}}{d^2 \cdot \pi \cdot \mu_0 \mu_r} \tag{5}$$

At the Wolman frequency, the inductance is reduced to the half of the initial inductance.

The theoretical high frequency behavior of inductance and resistance according to the classical eddy current

*T.Trupp@magnetec.de

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRO016

theory can be calculated by the following equations with L0 as the inductance at low frequency (e.g. 50Hz) [5]:

$$L_s = L_0 \frac{\delta}{d} \cdot \frac{\sinh \frac{d}{\delta} + \sin \frac{d}{\delta}}{\cosh \frac{d}{\delta} + \cos \frac{d}{\delta}} \tag{6}$$

$$R_s = 2 \cdot \pi \cdot f \cdot L_0 \frac{\delta}{d} \cdot \frac{\sinh \frac{d}{\delta} - \sin \frac{d}{\delta}}{\cosh \frac{d}{\delta} + \cos \frac{d}{\delta}} \tag{7}$$

The classical eddy current theory leads to dependency of |μ|~1/sqr(f) beyond the Wolman frequency.

As it will be shown in section 3, with the above equations, the inductance and resistance can well be described when other loss factors are neglected.

For the third part, the excess loss $P_{Fe,e}$ it is decisive whether re remagnetisation happens through domain wall replacement or through magnetization rotation. Domain wall replacement generates a relatively high excess loss due to high dB/dt leading to micro eddy currents around the wall motion [7]. A comprehensive theory was built by Giorgio Bertotti describing the excess losses for electrical steel or Finemet-type cores with Z-type [8]. For magnetisation rotation, change of flux perpendicular to the ribbon direction is generated through the turn of magnetization from the easy axis to the excitation axis. The so generated excess loss is smaller compared to domain wall replacement case and cam be neglected for smaller excitation levels[2, 9]

The excess loss can be expressed by the anomalie factor [6]

$$\eta = \frac{P_{Fe,ex.}}{P_{Fe,cl.ed.}} + 1 \tag{8}$$

With the anomalie factor, the reduction of the high frequency properties can be estimated. The excess loss reduces the dynamic permeability from the predicted one if only classical eddy currents are taking into account. The new cut-off frequency with excess loss can be written as

$$f_g = \frac{f_w}{\eta} \tag{9}$$

The above equation demonstrates, that lowest possible losses are the target for applications demanding good rf properties. For NANOPERM® with an induced anisotropy (easy axis) perpendicular to the ribbon direction, domain wall replacement is suppressed thanks to rotation [4].

Remarks about the model:

A) The ferromagnetic resonance through gyromagnetic damping has not been taken into account yet. The gyromagnetic damping leads to a μ~1/f dependency after the gyromagnetic cut-off frequency.

B) Each insulated layer of the NANOPERM® ribbon can be interpreted as a capacity. At this stage, this effect has not been taken into account yet.

EXPERIMENTAL

High Frequency Measurement

The high frequency inductance and resistance (in serial equivalent circuit) has been measured on sample cores with nominal dimension outer diameter OD=ca. 500mm, inner diameter ID=ca. 290mm and height of H=ca. 25mm. The measurement was carried out under free space condition [7] on HP4194, the frequency sweep was from 10kHz to 40MHz with 1V oscillation voltage. The measurement is shown as the green (L) and purple (R) lines in Fig. 1.

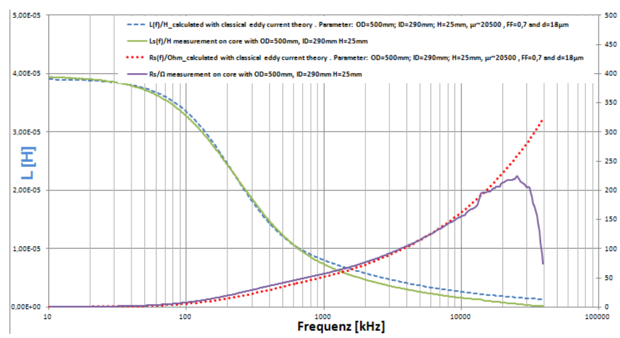

Figure 1: L(f)_R(f) measurement of the cores and comparison to classical eddy current theory calculated by (6) and (7).

The high frequency measurement was compared to the expectation from the classical eddy current theory. The dotted blue (L) line and red (R) line show the expected behavior from (6) and (7) with a ribbon thickness which was estimated as 18μm. As Fig. 1 nicely shows, the measurement is in a good accordance with the theoretical expected ones. For frequency above 10MHz, a bigger deviation can come from capacity from the measurement offset to ground or from parasitic capacity inside of the core where each layer can be understood as a small cylinder generating a capacity. For frequency the inductance drop down is higher as the expected 1/sqr(f) classical eddy current ones which may come from gyromagnetic effects where impedance drops down by 1/f.

As it is nicely shown in figure 1, the high frequency behavior can be explained by the eddy current theory. As a practical approach, it is sufficient to define the 10kHz and 100kHz value for such a core to estimate the further development of the high frequency properties. This approach has been established also in the field of EMC components which have a high demand on rf properties.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRO016

Fluctuation of RF Properties

In the context of the FAIR Project at GSI [13] a RF-System for the High-Energy Storage Ring (HESR) with the purpose of beam acceleration, deceleration and bunch rotation and a barrier bucket will be implemented. This RF-system for HESR will be tested at COSY at Forschungszentrum Jülich [10].

MAGNETEC produced so far 22 huge toroidal cores for HESR RF System under serial production conditions in cooperation with Forschungszentrum Jülich. These cores have a nominal core dimension of outer diameter OD=ca. 500mm, inner diameter ID=ca. 200mm and height of H=ca. 30mm with an initial permeability of about 50k@10kHz**.The so called free space (FS) measurement [11] on this cores was carried out with WK/HP4194A at low signal excitation level. The 0,441MHz value of serial inductance and serial resistance are shown in figure 1. Furthermore, the statistical analyze are shown on the left part of table 1.

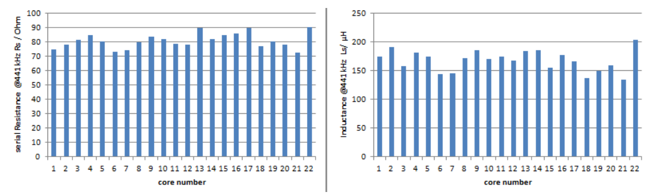

Figure 2: Rs and Ls distribution of 22 NANOPERM® cores at 0,441MHz.

Table 1: statistics of the distribution of R, L at 0,441MHz and 3MHz on the 22 cores (left side) and in comparison to 60 Finmet cores, data from [11]

	Measurement performend on 22 NANOPERM® cores						**Data from [11] measured on 60 Finemet-cores**					
	Mean		Std. Deviation		Max. Dev		Mean		Std. Deviation		Max. Dev	
f/MHz	0,441	3	0,411	3	0,411	3	0,4	2,5	0,4	2,5	0,4	2,5
R/Ohm	80,9	149,4	5,2	9,4	17,6	33	82,2	143	8,6	9,6	43,3	54,6
L/µH	17,5	4,30	1,1	0,2	4,3	1,0	18,6	4	0,8	0,22	4,3	1,28

Since this is the first time of a ‘higher quantity’ production of NANOPERM® huge cores, a comparison of the high frequency deviation between the produced cores and already created cores from an established project is of special interest. For this comparison, measurements from Mohite et al [11] which have been performed on 60 FINEMET-3M cores have been chosen. Mohite et al analyzed the std. deviation of cores with the nominal dimension OD660, ID290, H25mm. Although the dimension of the cores differs, the measurement shown in table 1 can be used for a first stage comparison. Especially interesting was A) the standard deviation of the high frequency properties with the target as being as low as possible (narrow distribution) and B) the maximum deviation again with the target to be as low as possible. As it is shown in table 1, the standard deviation of the 22 produced NANOPERM® cores are slightly better but in the same range compared to the presented ones from Mohite et al. The maximum deviation of the Hitachi cores is much higher but we have to consider that Mohite examined 60 cores so higher maximum deviation was expected.

CONCLUSION

With the aid of the loss theory, the high frequency behavior of NANOPERM© cores can be well explained. It has been shown, for an practical approach, that with the 10kHz and 100kHz inductance measurement, the further rf-brhaviour can be estimated. The high frequency deviations of 22 huge NANOPERM® cores have been compared to measurements of Mohite et al resulting in a similar distribution.

REFERENCES

[1] G. Herzer, in: K.H.J. Buschow (Ed.), Handbook of Magnetic Materials, vol.10,Elsevier Science, 1997.

[2] T. Trupp, “Aufbau eines Verlustleistungsmessplatzes zur messtechnischen Bestimmung und Analyse der Kernverluste nanokristalliner Magnetwerkstoffe”, University of applied science Mittelhessen, Diploma thesis 2011.

[3] T. Trupp, Z.Palánki, „Effect of ribbon thickness on power losses and high frequency behavior of nanocrystalline FINEMET-type cores“, contribution to SMM2013, http://www.magnetec.de/en/download-archiv/scientific-publications/

[4] Magni, A., Fiorillo, F., Ferrara, E., Caprile, A., Bottauscio, O., Beatrice, C. "Domain Wall Processes, Rotations, and High-Frequency Losses in Thin Laminations," Magnetics, IEEE Transactions on , vol.48, no.11, pp.3796,3799, Nov. 2012.

[5] Küpfmüller K, “Theoretische Elektrotechnik: Eine Einführung”, Springer Verlag, Aufl. 18 Springer 2008.

[6] Hilzinger R, Rodewald W, „Magnetic Materials”, Publicis Publishing, Erlangen 2012.

[7] Bertotti, G., "Physical interpretation of eddy current losses in ferromagnetic materials. I. Theoretical considerations," Journal of Applied Physics , vol.57, no.6, pp.2110,2117, Mar 1985.

[8] S. Flohrer: „Analyse der dynamischen Magnetisierungsprozesse nanokristalliner Weichmagnete“- Dissertation Universität Dresden – 2007.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRO016

[9] G. Herzer: „Effect of domain size on the magneto-elastic damping in amorphousferromagnetic materials"; Zeitschrift für Metallkunde 93:10 – 2002.
[10] "THE HESR RF-SYSTEM AND TESTS IN COSY" R. Stassen, Proceedings of EPAC08, Genoa, Italy MOPC125.
[11] Development of a Broad-band Magnetic Alloy Cavity at GSI - T.S. Mohite , Huelsmann, P. et al. Conf.Proc. C1205201 (2012) 3275-3277 IPAC-2012-THPPC003.
[12] Huelsmann P, Vinzenz W, "The h=2 Broadband Acceleration RF System for theSIS12/18 Upgrade at GSI".
[13] Chihiro Ohmori et al, Development of a high gradient rf system using a nanocrystalline soft magnetic alloy Physical review special topics accelerators and beams 16 12002 2013.
[14] H. Stöcker et al., "FAIR Technical Baseline Report", GSI Darmstadt (2008).