3D Transient Process Calculations For Fast Cycling Superferric Accelerator Magnets

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Abstract— **Fast cycling superferric magnets are planned for use in the new international accelerator Facility for Antiprotons and Ion Research (FAIR) at GSI, Darmstadt. The efficiency of this magnet is basically defined by the AC loss at helium temperatures in the construction elements of the dipoles and quadrupoles (iron yoke, coil, beam pipe restraints, and suspension). A detailed knowledge of the 3D magnetic field, the eddy current distributions and their transient behaviour is necessary to minimize the hysteresis and the eddy current losses through the use of an appropriate design. Methodical problems are considered for finite element calculations (ANSYS) of eddy currents in a laminated iron yoke The results for window-frame dipoles and quadrupoles of the Nuclotron type are given. We present the influence of nonlinear and anisotropic magnetic and electrical properties of laminated steel and of bulk restraint elements. The effect of eddy currents on dynamical magnetic field nonlinearities is also considered.**

Index Terms— **AC Losses, Magnetic Fields, Ramp Rate, Superconducting magnet, FEM calculations, eddy current**

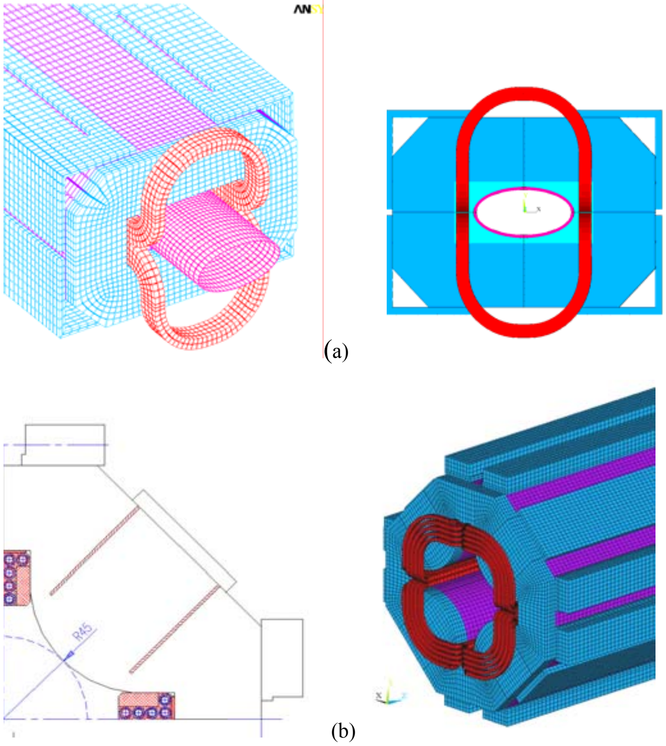
I. INTRODUCTION

THE main magnets of the SIS100 synchrotron - the "workhorse" of the FAIR project - are superconducing (SC) dipoles with a peak field up to 2 T, dB/dt = 4 T/s ramp rate, design repetition rate of =1 Hz (standard cycle), and SC quadrupoles with a maximum field gradient of 33.4 T/m. Compared to the low cycling frequency of other SC accelerators, these fast cycling magnets are unique. Substantial progress in the reduction of AC losses has been achieved for new model magnets [1,2]. Compared with the original Nuclotron, the experimentally obtained losses in test dipoles were reduced from 53 W to 24 W for a standard cycle. Also, for the quadrupoles the measured AC loss was reduced by more than a factor of 2. Our accompanying FEM calculations on detailed 3D models have given a clear physical understanding of the loss sources, their quantitative contributions to the overall loss, the impacts on field quality and provide recommendations for further design optimization, including field quality [3]. Some preliminary estimations of the eddy current loss in the yoke, due to the longitudinal component of the magnetic induction $B_{z,}$ was done in [4,5,6]. Nevertheless, the complex approach to 3D simulations of transient processes in the design of the real magnets, as a combination of different construction elements, was not possible with help of these special codes. So, we started to analyse the potential of the ANSYS code for eddy current and field quality calculations of fast-cycling superferric magnets. In further work, we plan to combine these efforts with mechanical and thermophysical calculations.

II. ANALYTICAL MODELINGMETHODICAL STUDIES

A. Magnet Geometry

The main design elements of superferric accelerator magnets are: the laminated iron yoke (constrained by massive endplates and brackets),, the SC coil,.and the beam pipe.



(a)

(b)

Fig.1: Nuclotron type magnets: Dipole (a) and Quadrupole (b, with two longitudinal slits in the yoke lamination)

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Their geometry and material properties are important for AC loss calculation at high saturation and fast ramping fields [1,2]. Additionally, the design of the magnet suspension, cooling tubes, and beam pipe restraint have to be taken into account (but will not be discussed in this paper), as well as the AC loss in the coil. High resolution 3D transient calculations for such problems are not trivial and so we have chosen the basic Nuclotron design to test the ANSYS code and compare the results with existing experimental data. Besides using the appropriate FEM simulation model, the correct material properties, affected by the real fabrication technology and operating conditions near liquid helium temperatures have to be defined. Here we concentrate our analysis on the typical test cycle for the dipoles: triangular, unipolar, B_{max}=2T, dB/dt= 4T/s ramp rate and 1Hz repetition frequncy. We use the B(H) curves, hysteresis loss functions and electrical properties of thin sheet electric steels, structural low carbon steel ST3, and stainless steel, as given in [7,8].

B. Steel properties

1) Anisotropic steesl ET3413 and ET3414

The magnetic properties in the lamination plane at 4.2 K are described in [7]. The maximum relative permeability is 4000 and the coercitive field strength Hc is 30 A/m. Along the longitudinal Z axis the magnetic anisotropy is enhanced by the limited packing factor of the yoke, and the permeability can be expressed as

$$\mu_z = \mu_r / (\mu_r - f_p \cdot (\mu_r - 1)) , \quad \text{where}$$

$\mu_r = \mu_r(B)$ is the permeability of steel, normal to the lamination, f_p - the packing factor (including insulation). Up to 1.6T μ_z is roughly constant and depends only on f_p, the electrical resistivity, given as 0.31 μOhm-m. The hysteresis loss properties of the material were found during preliminary measurements [7].

2) Low carbon steel ST3 and stainless steel

The magnetic properties of ST3 near 4 K are described in [8]. It has a maximum permeability of 1000 and Hc of 250 A/m. The comparison of calculated with experimental loss values is very sensitive to the correct definition of the electrical resistivity. Unfortunally, this steel has a wide spread of resistivity ρ data, due to the large range of Carbon content and the strong dependence on temperature. The resistivity values , by special measurements on relevant samples, were found to be in the range of (0.06-015) μOhm-m. From first calculations 0.12 μOhm-m and 0.09 μOhm-m were chosen for ST3 and ρ=0.5 μOhm-m for the nonmagnetic stainless steel (μ=1.01)

C. Specifics by ANSYS

First, the capability of ANSYS to solve complex electromagnetic problems, including materials with nonlinear, isotropic, or anisotropic magnetic and electric properties, has been tested. For simplified geometries, we compared our eddy current loss results with data calculated using other codes [4,6] and with experimental values obtained on laminated yoke structures [1]. Additional modifications with horizontal slits in the laminations, to reduce the effect of B_z, were tested, as well as the effect of coils with a reduced saddle shape [3]. While ANSYS can deal to date only with one nonlinear B(H) curve calculations are restricted to 3D isotropic materials. Alternatively a 2D isotropic B(H) function in the X-Y plane and a linear dependence in the Z-direction could be introduced. This option corresponds to laminated yoke with packing factor f_p<1, when depending on f_p the effective permeability decrease sharply down to $\boldsymbol{\mu_z}$ =25-50 (f_p=.96-0.98) and is approximately constant up to $\boldsymbol{\mu_r}$ =100 (B=1.6T). We have evaluated this approach for the fast standard cycles with deep saturation (aperture field B=2T) analysing the AC loss in such magnets in a 3D isotropic (f_p=1) iron yoke and for different f_p<1 parameters defining appropriate values for μ_z = constant.

D. Test calculations

The time and space distribution of eddy currents in the simplified yoke geometry (rectangular lamination sheet, no restrain elements) have been calculated. This defines the power dissipation functions and the integrated loss per cycle values. Two characteristic results of the AC loss power due to the longitudinal field B_z corresponding to a single impuls of the standard cycle are presented in Fig.2.

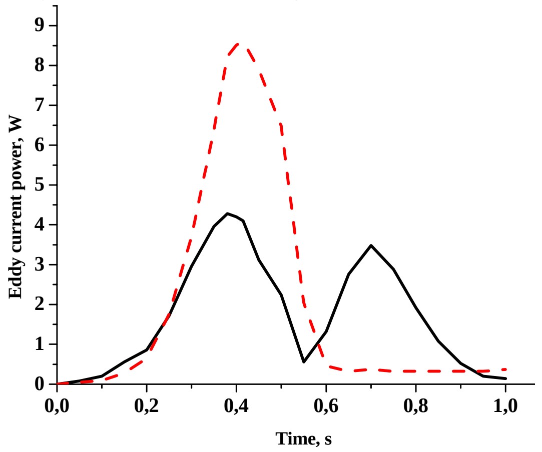

Fig.2 Time dependence of power in laminated yoke (1/8) for μ_z=50 (f_p=0.98) (solid line)and for f_p=1.0 (- --) with isotropic $\mu(B) = \mu_{xy} = \mu_z$ ($\boldsymbol{\mu_{r_{max}}}$= 4000).

For fp=0,98 with typical μ_z values between 25 and 50 the obtained average loss power varied from 11.3 W to 13.9 W. Comparable calculations useing other methods had found 19.6 W [6] or 22.7 W [4]. It is obvious, that ANSYS gives the lowest loss result for the same packing factor. This effect dramatically increases for models with high isotropic, nonlinear de-pendence of the permeability corresponding to a bulk yoke, i.e. for fp = 1. Here we found 15.9 W whereas 46.6 W was given from the integral method [6]. Our loss data obtained for iden-tical geometries are more than twice less compared to the other referred FEM results. A data set from calorimetric measure-ments was used to estimate the loss caused by the Bz-field to about 9-10W [1,3]. This is in good confirmation with the above ANSYS prediction especially in respect of the unknown correct packing factor of about 98% and some uncertainness in the material properties. The reason for the higher values found in [4,6] will be discussed in detail in a separate paper.

Nevertheless a preliminary explanation can be already given here with help of Fig. 2: For the lower packing factor the loss power P(t) reveal to peaks caused by the upward and downward ramp. Despite of the symmetric cycle the second peak is lower than the first one. The effect strengthens with increasing f_p and near the bulk value 1 the second loss peak is degenerated (dashed line). Our detailed calculations have shown, that this effect is due to the long relaxation time of the eddy current distribution in the yoke [9]. For an isotropic μ and f_p=1 Fig. 3 presents the loss per triangular cycle for a second impuls following the first one after pause Δt, defining the repetition frequeny $f=1/(t_{cycle}+\Delta t)$. The shapes of both loss peaks are given in the top right inset for Δt =2.5 s. The exponential fit defines the characteristic relaxation freqency f_0 = 0,52 Hz, i.e. the second loss pulse will be not reduced by the remaining eddy currents only for Δt >> 1 s .

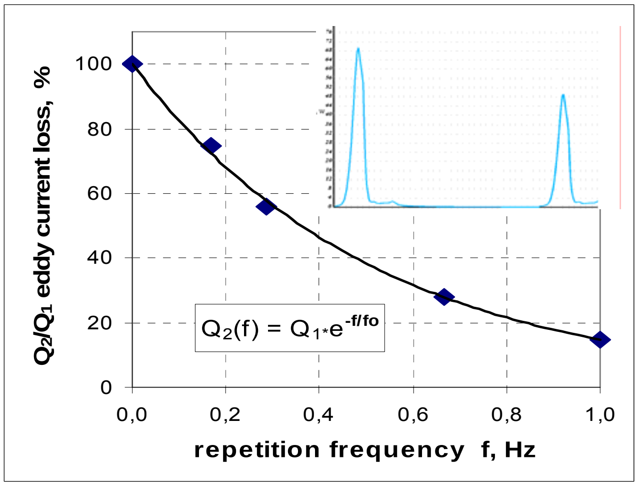

Fig. 3 Dependence of eddy current losses during the second cycle on pulse repetition frequency. The insertion shows two eddy current pulses with an intervall of 2.5 s

The specific losses per cycle increases with duration of pause in between. For laminated yoke this effect will be less significant with decreasing packing factor whereas the long relaxation processes are more pronounced for bulk elements ((end-plates, brackets) as well know for genuine 3D systems

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III. NUCLOTRON TYPE MAGNETS

A. Dipole

The results of our detailed test calculations were very encouraging. So we turn to solve the practical tasks for Nuclotron type magnets. The 3D Geometry of the dipole with a typical mesh and the cross section are presented in Fig.1a. The model contains the main elements, i.e. laminated yoke, endplates, brackets, and beam pipe. We had analysed the AC loss in these elements with various material properties for two different coils – C0, the original Nuclotron shape as shown in Fig. 1. and a second coil C2 with minimized saddle end loop to reduce the physical source of the longitudinal field Bz

For endplates and brackets the ST3 and also the stainless steel (SS) was chosen, the results are given here only for the design cycle. The time dependences of eddy current loss in the original Nuclotron (laminated yoke from ET3414, endplates and brackets from ST3, coil C0) are presented in Fig.4.

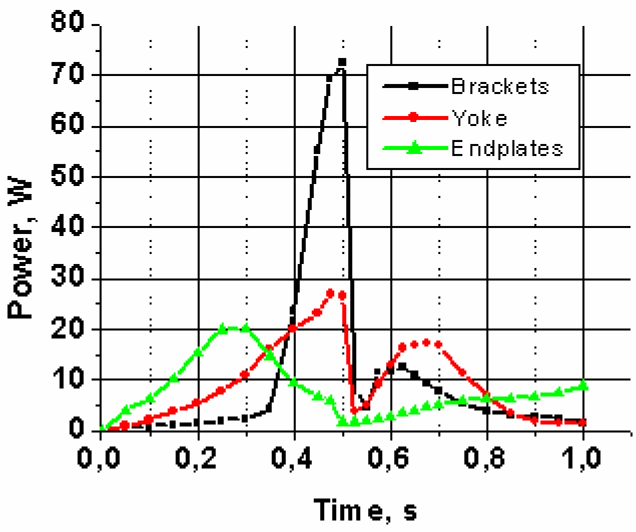

Fig.4 Time dependences of the eddy current parts in the Nuclotron dipole: laminated yoke (1), brackets (2) and endplates (3)

The complex character of the loss parts in this assembly is obvious and reasonable if compared with the previous test calculations. With increasing yoke saturation near the cycle peak at 0.5s the field penetrates into the massive brackets (2) and generates large additional AC loss contributions as was shown in [2]. It is clearly seen, that with The loss power distribution P(z) in the yoke at various moments of one single cycle is given in Fig. 5.

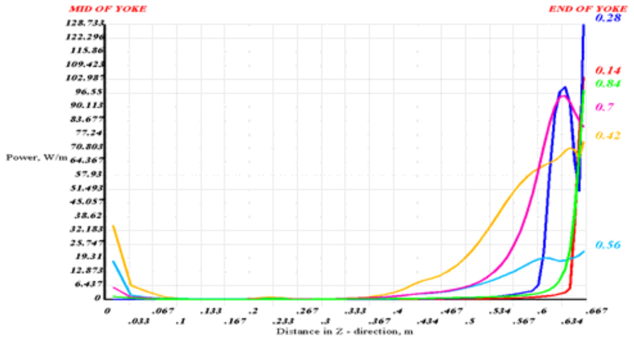

Fig.5 Distribution of eddy current power in the yoke at different moments.

The hysteresis losses have been also calculated and are shown in the overview of table I. The calculated total loss is in good agreement with the measured value of 42±2 W of [1]. In the second data set in this table corresponds to a Nuclotron dipole with endplates and brackets made from stainless steel.

The third modification results for ST3 and SS elements are obtained for the reduced coil C2 as described and tested in [1,2,3] . The measured models described in this reference are combina-tions of different materials or partly removed mass from the brackets and endplates, tested for both coil versions including also additional slits in the yoke laminations to reduce the eddy currents. Some calculation results for such models and the summaric experimental values are given in end of table I. Slits can suppress the eddy current loss as calculated for the simplified yoke model from 14 W to 8.5 W in agreement with experimental results [5].

Table I
Calculated components of AC losses in the Nuclotron dipoles

original Nuclotron	**P eddy, W**	**P hyst, W**	**Sum, W**	**calorimetric measurements, W**
Yoke (ET3114)	**9.51**	**9.04**	**18.6**	**[3]**
Endplate (ST3)	**8.37**	**2.21**	**10.6**	
Brackets (ST3)	**10.5**	**5.42**	**15.9**	
total	**28.4**	**16.7**	**45.1**	**42 ± 2**
SS modification				
Yoke (ET3114)	**10.0**	**9.77**	**19.77**	
Endplate (SS)	**0.74**	**0**	**0.74**	
Brackets (SS)	**2.34**	**0**	**2.34**	
total	**13.08**	**9.77**	**22.85**	
new coil C2	**P eddy**	**P hyst**	**P eddy**	**P hyst**
Yoke	**3.97**	**8.79**	**4.81**	**9.56**
Endplate	**5.41**	**2.02**	**0.28**	**0**
Brackets	**10.5**	**4.84**	**1.53**	**0**
total	**19.9**	**15.7**	**6.62**	**9.56**
	(ET3114/ST3/ST3)		(ET3114/SS/SS)	
endplate/bracket	ST3	SS/ST3	SS/reduced	SS
Calculated	**45.0**	**36.4**	**22.1**	**16-22.9**
Measured	**43**	**36**	**24.6**	**20**

B. Quadrupole

The 3D model and the cross section is shown in Fig.1b. The magnet is similar to the original quadrupole with the mass of 200 kg and 430mm length of the iron yoke [1]. Two additional slits was introduced in the laminations to analyse the possibi-lity of eddy current reduction. A second test design to improve the quadrupole is presented in [10]. The original yoke of the Nuclotron quadrupole is also restrained with endplates and brackets made from ST3. The calculation results for this qua-drupole are shown in Fig. 9, obeying analogeous behaviour as found for the dipole. The large endplates are also responsible for the huge specific AC loss in the Nuclotron quadrupole [1]. The average values of the power loss due to eddy currents are 3.59 W, 7.78 W and 2.92 W in yoke, endplates and brackets respectively. Again the time relaxation process is obvious in the bulk endplates and brackets. The related hysteresis loss is also given in the summary of table II. The effect of a coil with reduced end shape is shown in the lower part ot this table.

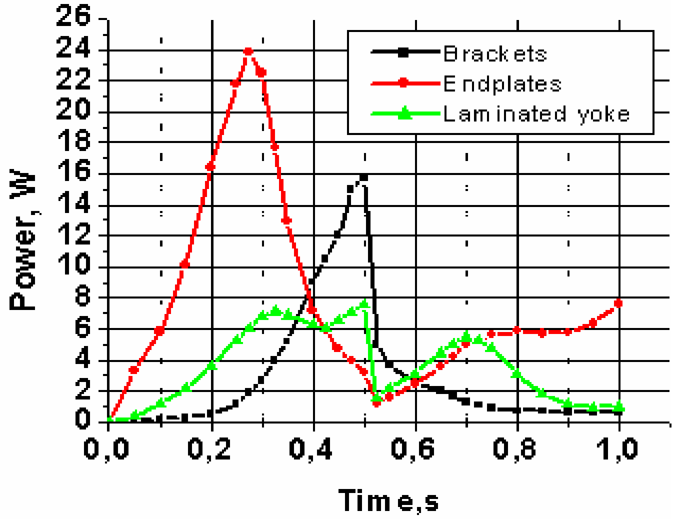

Fig. 9: Calculated time dependences of eddy current power in laminated yoke, bulk endplates (ST3) and brackets (ST3) of the quadrupole.

Table II
AC loss in quadrupole models

(ST3/ST3)	**coil**	**Yoke**	**EP**	**Brack**	**Sum**
hyst	**original**	**3.11**	**2.38**	**0.68**	**6.17**
eddy		**3.59**	**7.78**	**2.92**	**14.3**
sum		**6.7**	**10.2**	**3.6**	**20.5**
hyst	**reduced end shape loop**	**2.79**	**2.03**	**0.49**	**5.31**
eddy		**1.38**	**4.99**	**1.67**	**8.04**
sum		**4.17**	**7.02**	**2.16**	**13.4**

Further calculations with endplates and brackets from SS or removed ST3 material (up to 90% less) have shown that the total loss in the iron could be reduced 7.8W. The first tests on such modifications are reported in [1-3].

C. Harmonics

ANSYS was successful tested to define the static and dynamic harmonic coefficients taking into account also the eddy currents in the beam pipe. These sophisticated analysis will be present detail in a separate paper.

IV. CONCLUSION

The methodic to use ANSYS for calculations of the eddy current loss in the laminated yoke of fast cycling accellerator magnets has been investigated successful. The results are closed to experimental values obtained on dipoles and quadrupoles of the Nuclotron type. A high resolution of the complex 3D transient problems was achieved, including anisotropic and nonlinear magnetic properties and fine geometric structures.

The method is powerful for design optimization as well as for detailed quantitave loss and magnetic field calculations. We intend to combine these efforts with mechanical and thermo-physical calculations.

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