ANALYSIS OF THE SUPERFERRIC QUADRUPOLE MAGNET DESIGN FOR THE SIS100 ACCELERATOR OF THE FAIR PROJECT*

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Abstract

The heavy ion fast-cycling synchrotron SIS100 is the "workhorse", of the future Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt. The main lattice parameters of the accelerator have been defined now, so the main engineering problems of the new superferric magnets can now be analyzed and solved as well. We present the results of finite element calculations and compare the data with related calorimetric measurements on model magnets, to predict the expected AC losses of the full length quadrupole prototype.

INTRODUCTION

The full scale quadrupole prototype magnet is 1 m long [1]. It has lower end parts of coils comparing with the test models, restraint elements of stainless steel to reduce the eddy currents in the laminated yoke, the brackets and the end plates. The rigidity of the coil is improved. The lower coils (smaller end loops) reduces mainly the longitudinal field B_z and so the eddy current losses in the yoke. Our R&D based on experimental modeling and on numerical simulations had improved the quadrupole design. The 0.43 m long Nuclotron quadrupoles would produce high dynamical losses (hysteresis and eddy currents) in operation cycles requested for the SIS100. Their yoke is restrained with bulk endplates and brackets made from low carbon steel CT3. This steel has a high coercive force and a low resistance at 4.2 K. These parameters are wide spread due to variations of the carbon contents. One can expect 5 - 6 significant components of AC losses in such a design. Their estimation requires careful 3D calculations of the static and the dynamic magnetic field distributions in short magnets to define the expected AC loss due to hysteresis and eddy currents. The calculation of the transient processes for short quadrupole magnets was described briefly in a previous paper [2]. Another paper [3] presented the calculation of eddy current loss in a long quadrupole with slits. Now the design of the prototype quadrupole has been approved and the AC losses have been calculated for this magnet. In the present paper we also show the calculation problems and the sources of uncertainties as well as a comparison with measured data

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NUCLOTRON MODEL

The 3D ANSYS model of the short magnet is shown in Figure 1. The model is adequate to the original quadrupole, which has a mass of 200 kg and a 430 mm long iron yoke [4]. The original yoke of the Nuclotron quadrupole is restrained with endplates and brackets made from CT3. The transient process has been calculated using this model. The loss results are presented in Table 1. The material data used for the structural low carbon steel are: coercive force H_c (4.2 K) = 250 A/m and ρ (4.2 K) = 0.12 $\mu\Omega\cdot$m for the resistivity [6].

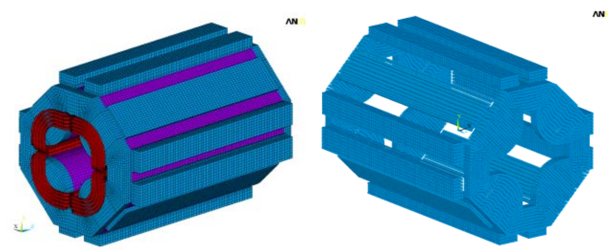

Figure 1: Short ANSYS model of the SIS100 test quadrupole with high bedstead coil end parts and restrain elements (endplates and brackets) separately.

Table 1: Losses for quadrupole model using CT3

Elements\ losses	Hysteresis	Eddy	Sum
Laminated yoke	3.1	3.6	6.7
End plates	2.4	7.8	10.2
Brackets	0.7	2.9	3.6
Sum	6.2	14.3	20.5

The large hysteresis losses are caused by the Si steel of the yoke and the low carbon steel endplates. In addition the thick endplates are also responsible for the high eddy current loss in the Nuclotron quadrupole [1]. For the standard cycle G = 33.9 T/m, dG/dt = 67.8 T/(m·s), f = 1 Hz the total AC loss in the yoke assembly was measured to 28.7 ± 2 W by calorimetric method.

The calculated time dependencies of the eddy current loss power in endplates and brackets show that these effects can not be estimated using simple analytical formula (Figure 2). In the bulk elements the time relaxation process is obvious. The AC loss calculations require proper software tools using verified physical and mathematical models as well as reliable material data for the steels at operating temperatures.

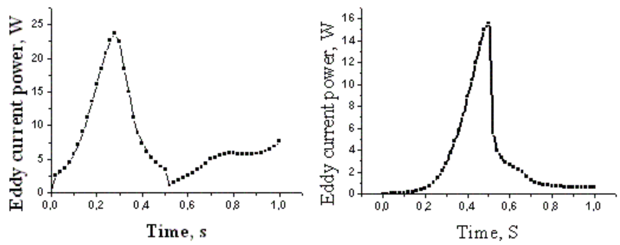

Figure 2: Power vs time in end plates (left) and brackets made from low carbon steel.

A comparison of the transient process calculations by different codes is presented in [7]. The calculations of the hysteresis losses in the yoke, brackets and end plates should be based on proper 3D field distribution results. The hysteresis loss distribution in the different components of the yoke assembly is shown in Fig. 3.

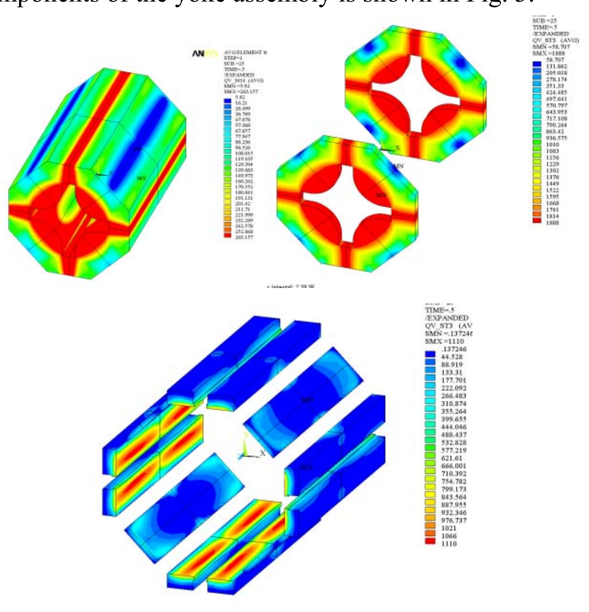

Figure 3: Distribution of hysteresis losses in the yoke, endplates and brackets.

One can compare the calculated total loss of 20.5 W with the experimental data. In test measurements the minimal value of 27 W was found. The reason for this discrepancy could be additional heat loss sources or uncertainties in the material data. Small variations of coercive force and resistivity values of the low carbon steel could give a better agreement with the experiment. This was shown on our results for the Nuclotron dipoles, based on a larger amount of experimental and proven material data [2].

Further calculations with endplates and brackets made from stainless steel or with reduced mass of the CT3 material had shown that the total loss in the iron yoke could be reduced to 7.8 W. The practical improvements of these modifications were reported in [4], [5]. The measured data are: 10.6 ± 1 W due to mass reduction of the endplates and the brackets, and 7.5 ± 1 W after introducing the slits in laminations.

LONG OPTIMIZED MODEL

Calculations of transient processes were extended to a long quadrupoles. Two different coil types, chamfered yoke end profile and slits in the pole shoes [3] were considered. (see Figure 4). The loss power distributions along magnet axis for fixed moments of the triangular cycle are presented in Figure 5.

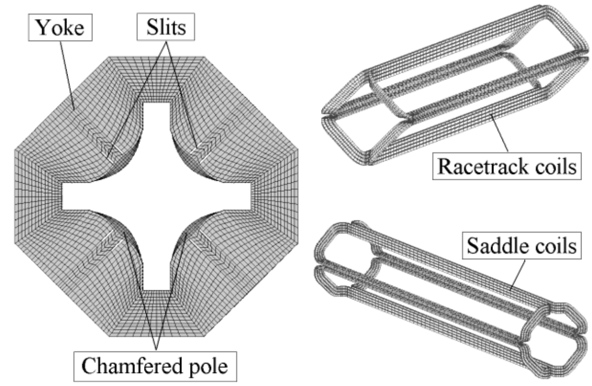

Figure 4: Design of the optimized model quadrupoles.

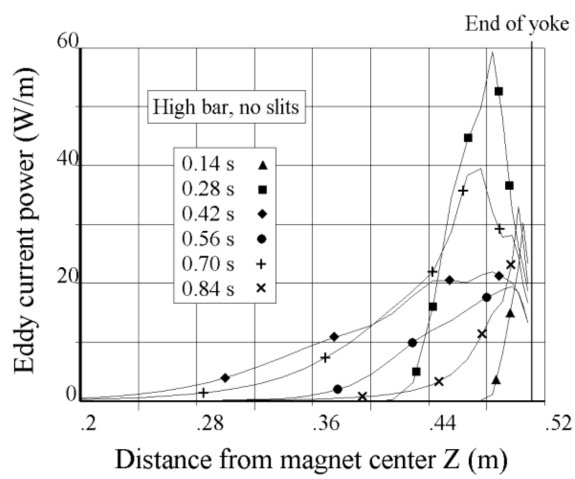

Figure 5: Eddy current loss in the optimized model quadrupole.

This model corresponds to a design with endplates and brackets made from nonconductive and nonmagnetic material. The main losses are the hysteresis losses in the yoke. The calculated eddy current loss reduction due to the slits amounts to 0.5 W, whereas in calorimentric measurements we had found a reduction of 3 W. This difference have to be analysed further on in more detail.

FULL SCALE PROTOTYPE

The above mentioned results of the experimental and FEM study have been implemented into the design of the full scale prototype. The appropriate new coil structure aimed at minimizing the heat releases at 4.5 K, but providing the requested long-term mechanical stability against dynamic Lorenz forces and thermal cooling cycles as well, is described in [1].

The CAD model of the geometry is presented in Fig. 6.

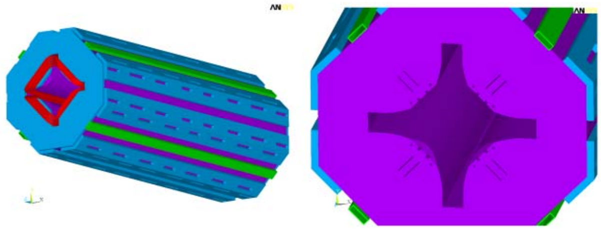

Figure 6: Full scale quadrupole cold mass.

The hysteresis loss distribution is shown in Fig.7

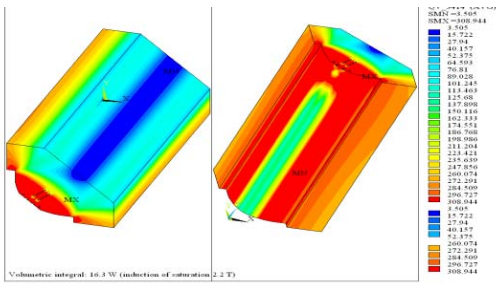

Figure 7: Hysteresis loss distribution in the yoke.

The time dependences of the power dissipation in the yoke, brackets and end plates are shown below.

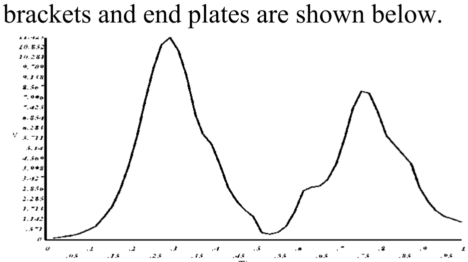

Figure 8: Time dependence of eddy current loss in yoke.

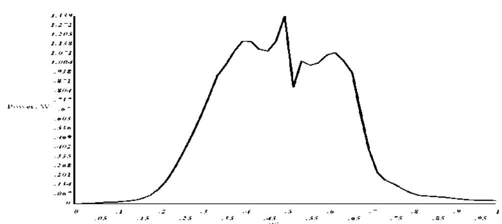

Figure 9: Time dependence of eddy current loss in brackets.

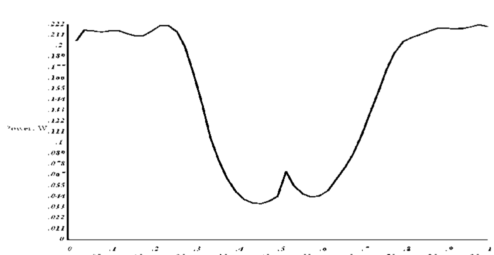

Figure 10: Eddy current loss in the end plates.

The summary of the results is given in Table 2. The normalized AC loss is calculated to 18.7 W/m.

Table 2: AC losses for the full length quadrupole

Elements\ losses	**Hysteresis**	**Eddy**	**Sum**
Laminated yoke	16.3	3.7	20.0
End plates	0	0.14	0.14
Brackets	0.	0.46	0.46
Sum	16.3	4.3	20.6

Eddy Current Loss in the Beam Pipe

The result of 2D calculations for 0.3 mm thickness stainless steel beam pipe is shown in Figure 11. The loss decreases after 0.2 s and so the average power is 0.88 W, starting with 1.33 W at the beginning of the cycle.

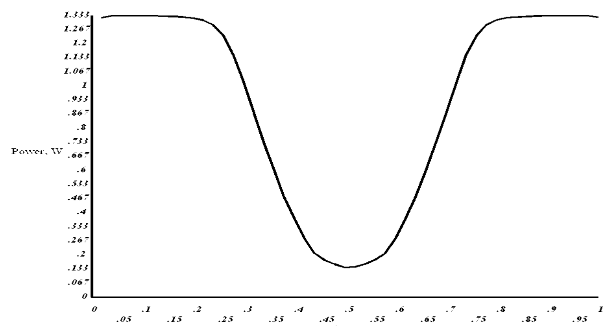

Figure 11: Eddy current loss in the beam pipe.

CONCLUSION

The obtained results were used under design of the first full scale SIS100 quadrupole prototype magnet with the required minimum level of the total AC power losses at 4.5 K and sufficient mechanical stability.

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