ELECTROMAGNETIC DESIGN OF THE PROTOTYPE DIPOLE FOR THE FAIR SIS300*

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Abstract

Design activities, conductor R&D and model coil construction are under way for developing a curved fast cycled superconducting dipole for the SIS300 synchrotron at FAIR. The main target is the construction within 2009 of a half-length prototype magnet (cold mass fully integrated in a horizontal cryostat). This magnet is designed for a maximum central field of 4.5 T in a bore of 100 mm, with a ramp rate of 1 T/s. The magnetic length of the prototype is 3.8 m with a curvature radius of 66.67 m (27 mm of sagitta).

This paper describes the magnetic design of the dipole. Emphasis is given also to the study of the losses due to the eddy currents in collar and yoke. The study has been performed with finite element codes, and it allowed to optimize the configuration in order to minimize both the peak field on the conductor and the total losses.

INTRODUCTION

The FAIR facility at GSI (Darmstadt, Germany) in the second phase of its program, will rely on the 300 Tm synchrotron SIS300. The dipoles of this synchrotron have a maximum field of 4.5 T, in a 100 mm bore, and are fast ramped at 1 T/s. The 7.8 m long dipole has a curvature radius of 66.67 m. In a R&D collaboration between GSI and INFN, the INFN sections of Milano (LASA), of Genova and the Frascati Laboratory have agreed to design, build and commission a prototype dipole, of half length (3.9 m). The main goal of the prototype is to demonstrate the feasibility of a curved superconducting dipole, working in pulsed condition, with good field quality and reasonable heat losses in the cold mass. The 2-D design of the magnet is described in [1], where the main losses in the conductors are also reported. This paper is devoted to summarize the coil end design and to the calculation of the losses in the zone of the coil ends.

COIL END DESIGN

The coil ends have been designed in order to minimize the integral value of sextupole and decapole in the final regions of the magnet, to control the value of magnetic field in conductor, and to obtain a mechanical configuration for the conductor shape feasible during the winding process.

The design has been performed initially with Roxie [2], with the "constant perimeter" option. The Fig. 1 shows a view of the coil end, whereas the Fig. 2 shows a cross section of the coil end with the behaviour of sextupole and decapole.

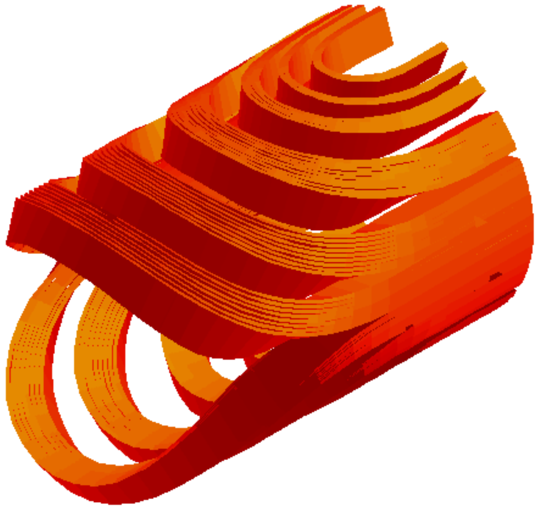

Figure 1: View of the coil end.

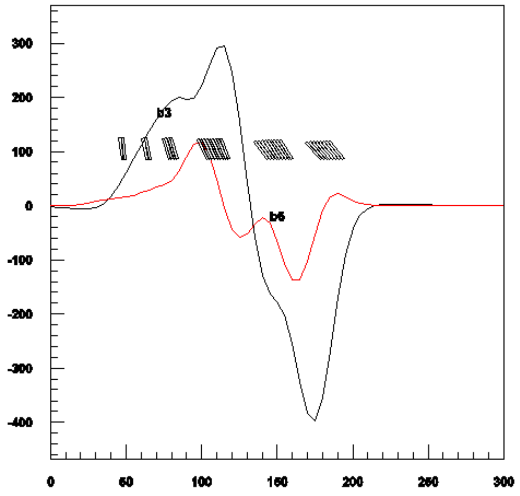

Figure 2: Cross section of coil ends, with the sextupole and decapole behaviour.

The integral value of sextupole and decapole, without the contribution of the iron yoke is given by:

$$b_3^{coil-end} = \frac{1}{B_0}\frac{1}{\Delta z}\int_0^{\Delta z} \mathrm{B}_3 dz = 0.63 \text{ units}$$

$$b_5^{coil-end} = \frac{1}{B_0}\frac{1}{\Delta z}\int_0^{\Delta z} \mathrm{B}_5 dz = 0.04 \text{ units}$$

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with:

$$B_0 = 4.5\,\mathrm{T}\,,\quad \Delta z = 300\,\mathrm{mm}$$

In order to decrease the conductor peak field, the iron yoke in the coil end region is substituted by stainless steel. In this way the peak field is 4.59 T, i.e. 0.37 T less respect to a configuration with “long yoke”. The peak field in the coil ends results also lower than the peak field in the 2-D section of the magnet (4.90 T).

LOSSES

A large source of losses in the coil ends is due to eddy currents in the lamination. Eddy currents are present also in the straight part of the magnet: in this section, the 2-D magnetic field B has only components parallel to the lamination. Consequently the eddy currents have components mainly parallel to the lamination and have simple symmetries along the thickness. From a simplified analysis, the volumetric losses can be calculated easily from the variation of the magnetic field $\dot{B}$ parallel to the lamination:

$$p_{B//}(x,y) = \frac{1}{12\rho}\dot{B}_{//}(x,y)^2\Delta s^2 \qquad (1)$$

where ρ is the electrical resistivity and Δs is the lamination thickness.

The variation of the magnetic field $\dot{B}$ is proportional to the magnetic field and can be evaluated from a magnetostatic analysis.

In the coil end regions, beside this kind of losses, there are additional losses due to the eddy currents generated by the field component perpendicular to the lamination plane. If the magnetic field varies smoothly in the perpendicular direction of the lamination, the currents can be assumed constant in the thickness Δs of the lamination. The values of these currents have been calculated with the F.E. code ELEKTRA, transient analysis, assuming for the laminations a continuum anisotropic material, with zero electrical conductivity in the direction normal to the lamination. In the yoke lamination, the perpendicular component of the field is strongly dependent by the actual reluctivity of iron, which is reduced by the stacking factor. As consequence, the iron yoke has been considered as a magnetic non-linear material, with an anisotropic behaviour for the reluctivity and electrical conductivity.

It is easy to demonstrate that the total loss is given by the sum of the loss due to the perpendicular component of the field (calculated with ELEKTRA) and the one due to the parallel component of the field (calculated by means of (1) with a magnetostatic analysis).

RESULTS

In Fig. 3 we show 1/8 of the model: in yellow the collar, in green the iron yoke, in violet lamination in stainless steel which substitute the iron in coil end regions, and in blue the cylindrical vessel for the helium.

In Fig. 4 we show the losses (colour) and eddy currents (arrows). A large fraction of the currents flows from the lamination through the cylindrical helium vessel, which is an homogenous material. Consequently, during the assembly of the magnet, a particular care has to be put to electrically insulate the cylindrical vessel from the lamination, especially in the coil end region.

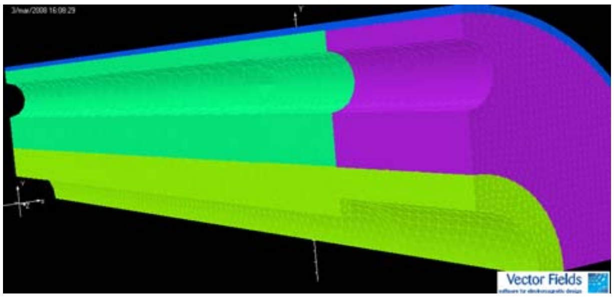

Figure 3: 1/8 of the model.

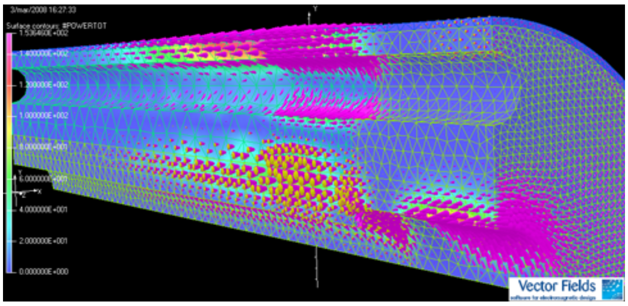

Figure 4: Losses (colours) and eddy currents (arrows) in the laminations.

Other large sources of eddy currents are present in the pins and keys that are used to mechanically connect the laminations of collars and yoke. The Fig. 5 is a view of the yoke pins and key, with the eddy currents calculated by ELEKTRA 3D.

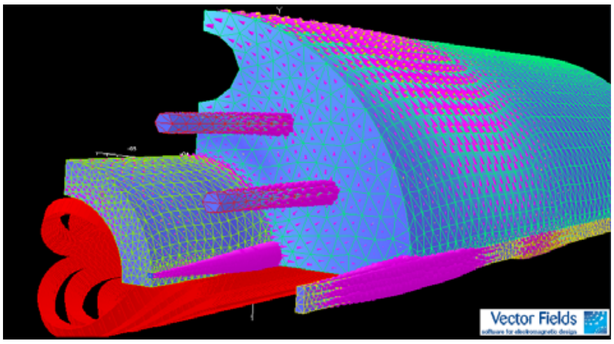

Figure 5: View of pins and keys, with the eddy currents (arrows).

CONCLUSIONS

The design of the coil ends for the SIS300 prototype dipole is almost completed. A method to estimate the losses in collar and yoke lamination has been found. A preliminary analysis shows that during the ramp-up of the magnet, the total losses in the magnet cold mass are about 9 W/m.

REFERENCES

[1] M. Sorbi, F. Alessandria, G. Bellomo, S. Farinon, U. Gambardella, P. Fabbricatore, and G. Volpini, “Field Quality and Losses for the 4.5 T Superconducting Pulsed Dipole of SIS300,” IEEE Trans. on Applied Superconductivity, Vol. 18 N.2 June 2008, p.138-141

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