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AUTOMATED DESIGN OF A CORRECTION DIPOLE MAGNET FOR LHC

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Abstract

A correction dipole magnet, with a horizontal dipole nested inside a vertical dipole has been designed and optimized linking together different electromagnetic software and CAD/CAM systems. The necessary interfaces have recently been established in the program ROXIE which has been developed at CERN for the automatic generation and optimization of superconducting coil geometries. The program provides, in addition to a mathematical optimization chest, interfaces to commercial electromagnetic and structural software packages, CAD/CAM and databases. The results from electromagnetic calculations with different programs have been compared. Some modelling considerations to reduce the computation time are also given.

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ABSTRACT

A correction dipole magnet, with a horizontal dipole nested inside a vertical dipole has been designed and optimized linking together different electromagnetic software and CAD/CAM systems. The necessary interfaces have recently been established in the program ROXIE [1] which has been developed at CERN for the automatic generation and optimization of super-conducting coil geometries. The program provides in addition to a mathematical optimization chest, interfaces to commercial electromagnetic and structural software packages, CAD/CAM and databases. The results from electromagnetic calculations with different programs have been compared. Some modeling considerations to reduce the computation time are also given.

1 INTRODUCTION

The low-β dipole corrector, MCBX, is a single-bore, 0.6 m long magnet, whose main parameters are given in Table 1. It features two nested single-layer dipole coils, the inner coil yielding a vertical dipole field and the outer coil a horizontal dipole field. The coils are individually powered with 600 A power supplies. The coils are wound from a NbTi rectangular wire bound together as a flat cable of 9 or 7 wires in the inner and the outer coil respectively, and cooled at 1.9 K. The design field integral is 1 Tm in any direction for an excitation current ranging from 360 to 600 A. Due to the short length of the magnet, the end fields contribute more than 50 % to the field integral. Therefore, an optimization in 2D and scaling with the magnetic length is not sufficient. Particular attention has to be paid to the lead end where the transitions from one block to another are made in addition to the leads entering over the top of the end blocks. Figure 1 illustrates the approach to an integrated automated design comprising the following 8 steps: 2D coil design including mathematical coil optimization, 3D coil design with mathematical coil optimization, transfer of model file to Opera-3D®[3] for calculations including the iron saturation, transfer of file to CAD for the mechanical drawings, transfer of file to the CNC-machine for machining of the end spacers.

Table 1: Parameters of the LHC low-β corrector dipole prototype, MCBX.

		Inner/Outer Coil
Operating dipole field	[T]	3.3 / 3.3
Integrated dipole field	[Tm]	1.341 / 1.273
Peak field in the cond.	[T]	4.431 / 4.749
Margin on the load line		50.51% / 45.54%
Operating current	[A]	511 / 599
Magnetic length	[m]	0.41 / 0.38
Overall length	[m]	0.6
Coil inner diameter	[mm]	90 / 123.7
Coil outer diameter	[mm]	119.7 / 146.8
Yoke inner diameter	[mm]	100
Yoke outer diameter	[mm]	450
Wire dimension (ins.)	[mm]	1.65 x 0.97
Wire dimension (metal)	[mm]	1.53 x 0.97
Cu/Sc-ratio		1.6
Operating temperature	[K]	1.9
No. of turns per coil		414 / 406
Stored energy	[kJ]	21.162 / 29.725
Self inductance	[mH]	162 / 166

2 ELECTROMAGNETIC CALCULATIONS

2.1 Coil Optimization in 2D

Based on some design constraints, which includes the space limitations and the operating current, a preliminary conductor and coil lay-out can be chosen. With only a few lines of input data the cross-section is generated by means of the ROXIE-program. ROXIE

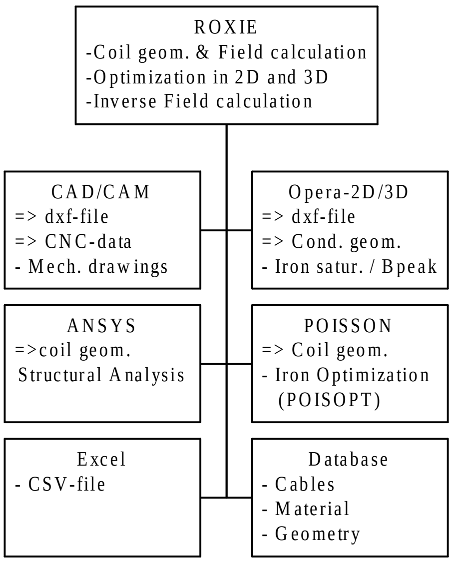

Figure : 1. Approach to an integrated automated magnet design

Table 2 : MCBX-magnet, multipole content in 2D.
(bi = Bi/B1)

	ROXIE-2D linear iron	Opera-2D® linear iron	Opera-2D® non-linear iron
B1 [T]	3.2989	3.3001	3.2972
b3 x 10^4	0.0007	0.0250	-0.0446
b5 x 10^4	0.0580	0.0565	0.0557
b7 x 10^4	0.0143	0.0141	0.0141
b9 x 10^4	0.0001	0.0001	0.0001

Table 3 : Integrated multipole content in 3D
(bi = Bi/B1)

	ROXIE-3D linear iron	Opera-3D® linear iron	Opera-3D® non-linear iron
B1 [Tm]	1.3627	1.3421	1.3423
b3 x 10^4	-0.3642	1.9654	1.9639
b5 x 10^4	0.1700	0.1775	0.1775
b7 x 10^4	0.0372	0.0381	0.0381
b9 x 10^4	0.0013	0.0014	0.0014

applies Biot Savart's law on line currents and the iron with linear or infinite permeability is taken into account by imaging. After a few manual iterations an automatic design optimization can be carried out. ROXIE includes many different optimization algorithms [2]. All the design parameters can be addressed as design variables for the optimization. One of the most robust algorithm is EXTREM, which was used for the optimization of the LHC low-β dipole, MCBX, described here. The objectives were low peak field in the conductor and minimized multipole content.

2.2 Optimization of the iron circuit

Once the coil cross-section is optimized the geometry is exported in DXF-format to commercial FE-software. The Opera-2D® package is used to calculate the saturation effects in the iron circuit. Different inner and outer radii were investigated for variation of the harmonic content, b3 and b5 in particular, at current levels ranging from injection to 120% of the nominal current. Table 2 compares the calculated field values from ROXIE with those from Opera-2D® linear and non-linear models. The main difference is the b3 due to the simplified conductor blocks in the FE-model. In total 23000 isoparametric, 6-node-triangles were used. The harmonic content was evaluated at a 30 mm radius and scaled down to 10 mm radius.

2.3 Coil Optimization in 3D

Most of the quenches occur in the coil ends. Therefore, particular attention is paid to the optimization of the coil end geometry with its constant perimeter ends. In ROXIE the geometry is created with a few additional parameters: big half axis of the ellipse, angle of the cable in the yz-plane, and the axial shift in the z-direction. Before the electromagnetic optimization the end geometry is optimized to maximize the minimum radius of curvature. The user can choose from a normal ellipse or a hyper-ellipse form. Coil blocks can be aligned on the winding mandrel or on the outer radius with so-called shoes. The connection end with transitions from one block to another can be created with an asymmetric model. The leads entering from outside are modeled as 8-node-bricks from pre-defined cut planes. The field calculation in 3D cannot take into account the iron except for the integrated multipole content, when the calculation is carried out from the symmetry plane far enough along the z-axis. The field optimization is done by varying the axial position of the blocks.

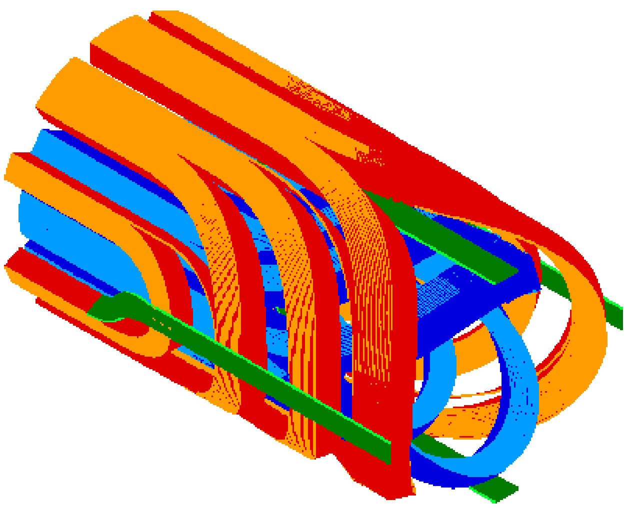

Figure : 2. MBCX-magnet lead end from ROXIE. Note the modelling of cross-over conductors

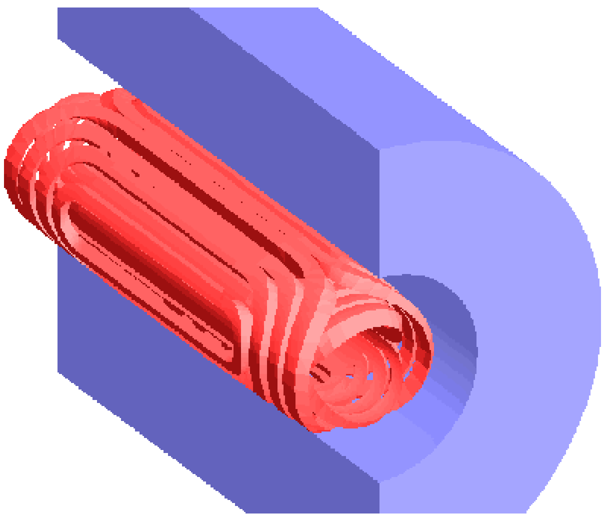

Figure : 3. MBCX-magnet Opera-3D® model. Only the return ends modelled for simplicity.

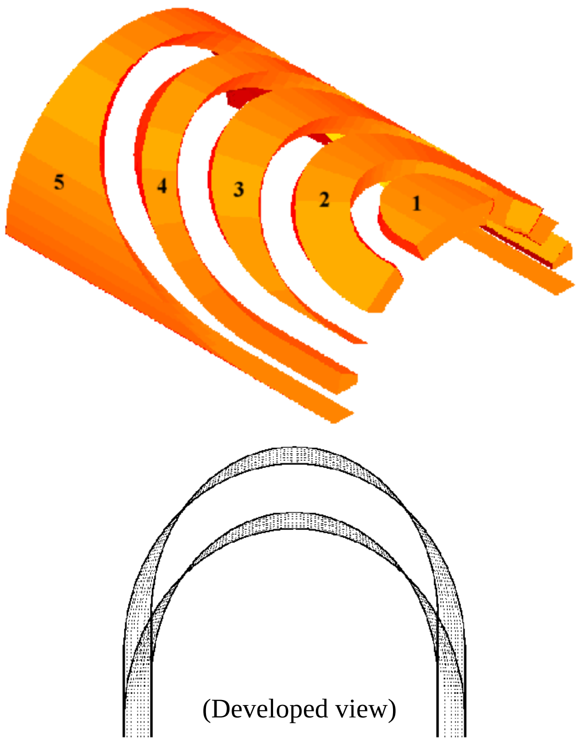

Figure : 4. End-spacers and the 3D-polygons for CNC-machining of spacer no. 3.

2.4 FE-analysis in 3D

The influence of the non-linear iron on the field quality and the peak fields is studied with Opera-3D®. The optimized conductor geometry can be imported from ROXIE as 8-node-bricks or as 20-node-bricks. This speeds up considerably the modelling time, since these geometries cannot be created in Opera using the built-in constant-perimeter-end coil primitive. Reduced scalar potential was used for all the regions inside the iron. Table 3 compares the integrated multipole content of ROXIE with linear iron (μ_r=2000) to that of the Opera-3D® model. A set of dummy conductors, which are duplicates of the 'active' ones without imaged parts, and with zero current, were modelled to speed up the peak-field calculation. Only the part of the geometry, which was solved in Tosca® had to be activated. A considerable enhancement of the peak field was found in 3D: 4.75 T with respect to 4.23 T in 2D.

3 MECHANICAL DESIGN

3.1 Structural analysis

Microscopic movements of the conductors or micro-cracking of epoxy can dissipate locally enough energy to cause a super conducting magnet to quench. Therefore a sufficient coil pre-compression is essential for the magnet performance. Too high pre-stress, however, can damage the insulation or cause copper to yield. The ROXIE conductor geometry was imported to ANSYS®[5]. An electromagnetic model was first created to determine the Lorenz forces, which were then transferred to the mechanical model. Five load steps were considered: assembly at 293 K, cooldown to 1.9 K, inner or outer coil powered, and the combined field.

3.2 CAD-CAM

The coil cross-section, developed view (sz-plane) and cut through the end (yz-plane) can be exported from ROXIE to most CAD programs in DXF format. The end spacer geometry is defined by 9 polygons, presented in global xyz-coordinates, over the radius and can be imported to CAD and CAM packages. These rather complicated shapes are then machined with a 5-axis CNC machine.

3.3 Mechanical tolerances

The sensitivity analysis for the mechanical tolerances is carried out in ROXIE by giving the tolerances as upper and lower bounds for the number of geometrical design variables. The upper and lower quotient per unit displacement are then calculated, and the Jacobian error matrix can be taken into a spreadsheet program for further processing.

4 CONCLUSIONS

A number of tools to speed up the design process and decision making have been established in the ROXIE program as an approach towards an integrated design of superconducting magnets. The optimized conductor geometry can be directly taken into commercially available FE-programs. Links to CAD/CAM-packages allow creation and changes of the mechanical drawings to be done in parallel with the design optimization. Short correction magnets, which in addition to optimization require studying of the manufacturing tolerances in 3D, can be efficiently designed by these means.

REFERENCES

[1] 'A Computer Program for the Design of Superconducting Accelerator Magnets', by S. Russenschuck, Proceedings of ACES'95, Monterey, CA, USA, March 20-24, 1995, LHC Note 354, Geneva, Switzerland, 1995

[2] 'Synthesis, Inverse Problems and Optimization in Computational Electromagnetics', by S. Russenschuck, International Journal of Numerical Modeling: Electronic Network Devices and Fields, Vol. 45-57 (1996).

[3] Opera-2D®, Opera-3D® and Tosca®, Trademarks from Vector Fields Limited, Oxford, England

[5] ANSYS®, Trademark from SWANSON Analysis Inc., Houston, PA, USA