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Magnet Design

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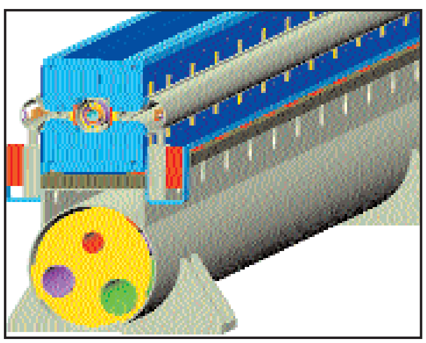
Electromagnetic Optimization Helps Generate Innovative Magnet Design

Engineers at Fermi National Accelerator Laboratory (Fermilab), Batavia, Ill., used electromagnetic optimization to develop an innovative superconductor magnet design that preserves magnetic field quality in the proposed very large hadron collider (VLHC). The Stage I of this accelerator is based on a 2 Tesla superferric superconducting magnetic system proposed by Dr. G.W. Foster. A major challenge in this design is to obtain a high-quality magnetic field in an iron-dominated magnet over a large range of field variations, from 0.1 to 2.0 Tesla. One approach that is being considered is to use correction holes to redistribute the magnetic flux at high field. The basic idea is to form a high quality field by the pole profile at the low fields and redistribute the magnetic flux at high field to reduce the influence of iron saturation effects. I used electromagnetic simulation software to model the magnetic field and optimization software to drive the model to evaluate hundreds of different hole combinations. The best iteration had a +/- 0.02 percent field quality for a 20 mm diameter aperture, providing a perfectly satisfactory solution to the problem.

An Economical Collider

The VLHC is a possible future accelerator-collider machine with 50 TeV nominal proton beam energy. The project is oriented towards lowering overall cost per Tesla-meter, achieving good magnetic field quality and using existing technologies. It uses a warm iron core and single turn coil to simplify the cryogenic, vacuum and quench protection systems. An alternating gradient design eliminates arc quadropoles and allows the magnet to be continuous in long lengths. Magnetic fields are formed by iron poles with sufficient accuracy so that the strong correction coils needed for conventional superconducting magnets would not be required. The superconducting transmission line conductor will be made from available outer cable originally intended to be used on the Superconducting Super Collider project that was abandoned in 1993. The VLHC Stage I is expected to use open C-magnet air gaps to facilitate measurements and vacuum pipe installation.



Superconducting Superferric Magnet of Stage I VLHC

A 2 Tesla superferric superconducting magnet system for the VLHC Stage I is being considered because the low parts cost and simple manufacturing process are expected to compensate for the long perimeter of the accelerator. A superconducting NbTi cable generates the magnetic field in two 20 mm height air gaps. The 100 kA conductor is a modified cable-in-conduit design. The magnetic field in the transmission line magnet is formed by iron poles that are extremely saturated. The superconductor consists of 16 NbTi superconductor cables wrapped in a two-layer spiral between inner and outer Invar pipes. The laminated magnet core consists of upper and lower iron half cores. The main drive conductor is located at force zero due to the symmetry of the magnet design.

A Key Design Challenge

The main magnet design challenge is preserving field quality over a large range of field variations and particularly as the magnet approaches saturation at 2T. When the magnetic flux is increased from injection level to maximum field there is a tendency for the flux to separate from the poles and cause distortions. Two techniques are being investigated, poles with holes and crenellated poles. The basic idea of correction with holes is to form a high quality field by the pole profile at low fields and use correction holes to redistribute the magnetic flux at high field by reducing the influence of iron saturation effects. A major challenge for the designers is that a large number of pole and correction hole configurations had to be investigated in order to find a configuration that would minimize the influence of iron saturation effects. It's expensive and takes a considerable amount of time to build and test even a single configuration. Fermilab engineers had the idea of streamlining this process by using electromagnetic simulation software to predict the magnetic field that would be generated by a particular pole and hole pattern. This type of software makes it possible to define the geometry in the computer and generate graphical and tabular output that predicts the field quality and other important variables. The group selected OPERA-2D software from Vector Fields, Aurora, Ill., because of its technical depth and breadth and a graphical user interface that reduces the time required to complete the analysis.

But the ability to analyze magnetic field quality on a computer didn't totally solve the problem. The group did not feel the project could bear the time and expense of many iterations of the manual analysis process. After consulting with Vector Fields, they provided an optimizer routine developed for OPERA-2D that replaces the manual trial and error portion of the traditional design process with an automated, iterative procedure. The software automatically changes the input data, runs the analysis codes, assesses the output and changes the input again based on instructions from an optimization algorithm chosen for the specific problem. The software optimizes the performance of the overall system while balancing often conflicting design requirements and meeting all design constraints.

Electromagnetic Simulation Process

I began by graphically generating a model of the magnet by defining a two dimensional cross-section through the model. I specified the

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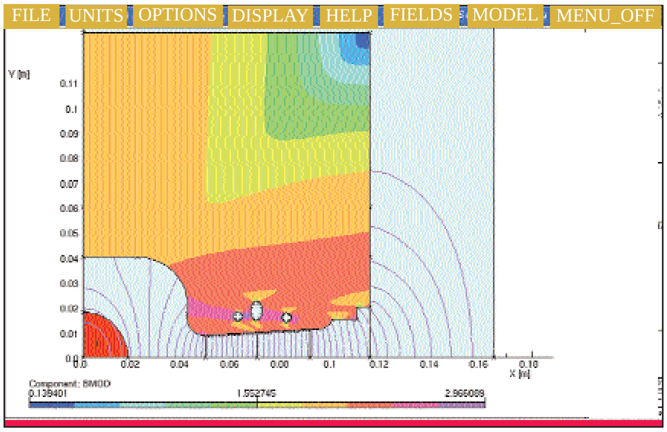

UNITS		PROBLEM DATA
length	:m	bchk90k20pt.st
flux density	:T	Linear Elements
field strength	:Am^{-1}	XY Symmetry
potential	:Wbm^{-1}	Vector Potential
conductivity	:Sm^{-1}	Magnetic Fields
source density	:Am^{-2}	Static Solution
power	:W	Scale Factor = 1.0
force	:N	29380 Elements
energy	:J	14871 Nodes
mass	:kg	17 Regions

Superferric Magnet Cross-Section as a Result of Optimization

source currents using a library of coil shapes provided with the program. The correction hole positions were defined by 12 design variables. I set the practical ranges for each variable and configured the optimization software to explore the design space. The optimization process was carried out for three magnetic field levels, 1T, 1.7T and 2.0T, simultaneously. The field optimization procedure was arranged as follows: The integral of field homogeneity around the circular aperture was used as an objective function for the optimization. The analysis was run in batch mode overnight on the workstation. A large number of local minima for the objective function were investigated. The best solution had +/- 0.02 percent field quality with the 20 mm diameter aperture for the field range of 0.1T to 0.8T, 15 mm for the field range of 0.8T to 1.5T and 10 mm for the field range of 1.5T to 2.0T. This is a satisfactory solution because the beam is about four times smaller at full energy than at injection.

The analysis also provided graphical output including graphs and histograms of the solution and contour plots that showed the magnetic field values superimposed on the surfaces of the model. The graphical output helped engineers gain an intuitive understanding of sensitivity of field quality to the design variables. For example, it showed that the field quality was proportional to the number of correction holes. Better results were obtained with a large number of holes near the pole tip surface but when the number of holes exceeded five or six their diameter had to be reduced below 6 mm, which caused problems with the lamination stamping process. On the other hand, a small number of larger holes creates a large drop in field strength in the air gap of the magnet at high field. Another consideration is the distance of correction holes from the air gap. Holes close to the gap need more accurate stamping. In addition, punching a hole too close to the beam gap will distort the pole profile.

An alternative method of achieving field quality that is also being investigated involves the crenellation technique that reduces iron density in the pole center by producing small height transverse slots via indentations at every "nth" lamination. This approach also involves an optimization problem, in this case involving the profile and stacking density of these slots. Since the crenellation technique has never been used for accelerator magnets, Fermilab built a special test stand to validate the results of electromagnetic simulation. The magnet design simulations of both the crenellated and hole design using the Vector Fields OPERA software are making an important contribution in accelerator magnets design. The combination of OPERA 2D direct magnetic field analysis with a universal optimization procedure is a very powerful instrument and this approach will be distributed on the other types of magnetic system design.

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