

RECENT EXTENSIONS OF THE PROGRAM MAGNUS-3D FOR THREE-DIMENSIONAL ACCELERATOR MAGNETIC ENGINEERING

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MAGNUS-3D is a professional finite element program used for the design of magnets in cases where the geometry is three-dimensional and can not be approximated by a two-dimensional model. MAGNUS-3D has found applications to the design of accelerator magnets and spectrometers, steering magnets, wigglers and undulators for free electron lasers, including permanent magnet systems, microtrons and magnets for synchrotron light sources, as well as magnets for NMR and medical applications, recording heads and various magnetic devices. This paper contains a description of the program with emphasis placed on the new features and recent extensions, which will become available to users in the next release.

Introduction

MAGNUS-3D can solve any problem of Magnetostatics that is formulated in terms of nonlinear magnetic materials, nonlinear permanent magnets and electric conductors, in any combination and having any geometry in space, with boundary conditions of the Dirichlet, Neumann or periodicity type. The properties of each magnetic material are represented by the magnetization table as provided by the manufacturer or as available in the internal library of MAGNUS-3D, and by an accurate interpolation relation [1]. The internal library includes several industrial steels used in Europe and the US for making accelerator magnets, and some Japanese steels. The properties of each permanent magnet are represented by the direction of magnetization and the complete normal or intrinsic nonlinear demagnetization curve as provided by the manufacturer, or by the coercive force and the remanent induction of the material. In all cases the magnetic properties are represented as $B = f[H(x, y, z)]$, i.e. as a function of the magnetic field at each point inside the magnetic material. The electric conductors are represented by means of conductor elements obtained from the internal library and placed in any position in space.

The solution to the problem consists of two continuous functions, the two magnetic scalar potentials $\Phi(x, y, z)$ and $\Psi(x, y, z)$, defined at every point of the corresponding domain, and a magnetization function or permeability function $\mu(x, y, z)$ defined inside the magnetic materials or permanent magnets. The solution is self-consistent, which means that it satisfies the time-independent form of Maxwell's equations, the constitutive equations of the materials, and the boundary conditions at the same time. Once the solution has been obtained, the post-processor EPILOG allows the user to interactively obtain all kinds of magnetic properties: the user specifies what property he needs, and EPILOG obtains that property and displays the result. EPILOG uses its knowledge of the complete solution to obtain the property. The properties include all kinds of tables, plots, field lines, and all the design quantities normally required in accelerator magnet engineering: magnetic energy, flux, force, torque, line integrals and harmonic coefficients. It is these quantities, and the tables and plots, rather than the solution itself, what the Magnetic Engineer needs in the course of his work.

MAGNUS-3D solves Maxwell's equations $\nabla \times \mathbf{H} = \mathbf{j}$, $\nabla \cdot \mathbf{B} = 0$, with the constitutive equation $\mathbf{B} = \mu \mathbf{H}$ for soft ferromagnetic materials or $\mathbf{B} = \mu \mathbf{H} + \mu_0 \mathbf{M}_0$ for permanent magnets, where $\mu = \mu[H(x, y, z)]$ and $\mathbf{M}_0 = \mathbf{M}_0[H(x, y, z)]$ are functions of H at each point. Thus, non-linearity is fully accounted for, both for ferromagnetic materials and permanent magnets. Linear cases, like a material with a constant μ or a permanent magnet with a constant magnetization, are included as particular cases.

The partial scalar potential formulation of Magnetostatics has been recognized as inaccurate in magnetic materials [2]. If $\mathbf{H} = \mathbf{H}_M + \mathbf{H}_S$, such that $\nabla \times \mathbf{H}_S = \mathbf{j}$ and $\nabla \times \mathbf{H}_M = 0$,

then \mathbf{H}_S is due to the electric currents alone and \mathbf{H}_M is due to the iron. \mathbf{H}_S can be calculated by integration over the conductors, and \mathbf{H}_M can be written as $\mathbf{H}_M = -\nabla \Phi$, where Φ is the partial scalar potential. In permeable iron, \mathbf{H}_M and \mathbf{H}_S are of comparable magnitudes and opposite directions. \mathbf{H} , the small difference between two large numbers, is affected by a large round-off error, leading to inaccuracy and even loss of significance. For this reason, MAGNUS-3D uses the two-scalar-potentials (TSP) formulation [3] where Φ is used only in regions with electric current (Φ -regions) where a total scalar potential can not be defined. In the region without current, $\nabla \times \mathbf{H} = 0$, and $\mathbf{H} = -\nabla \Psi$, where Ψ is the total magnetic scalar potential. Thus the total \mathbf{H} in the iron is directly calculated from Ψ with full accuracy, affected only by the normal discretization errors. No large errors appear inside the iron, and $\mu = \mu(H)$ or $\mathbf{M} = (\mu - 1)\mathbf{H}$ can be accurately obtained at each iteration. This is necessary for the solution to be accurate, because \mathbf{M} is one of the two sources of magnetic field. The theory and other details of the implementation of the TSP method in MAGNUS-3D have been reported elsewhere [4]. The TSP method is considered to be state-of-the-art for both computational accuracy and efficiency in 3D Magnetostatics.

Program Description

MAGNUS-3D consists of the programs KUBIK, MAGNUS and EPILOG. The programs MAGNUS-GKS, WIRE and HARMON are also closely associated with the package.

KUBIK, the Mesh Generator

KUBIK is the finite element mesh generator. KUBIK is automatic and employs the modular concept: modules of mesh of simple geometry and topology are independently generated and then put together in much the same way a magnet is assembled out of parts that have been independently machined. A three-dimensional structure of any degree of complexity can be obtained in this way. When designing a computer model, users frequently wonder if the geometry of interest can be represented by KUBIK. Since modules can be made as simple as necessary, even one single element, the user can exercise total control of every detail of the mesh. The result is that there is always a solution: any geometry can be represented. The question is not one of possibility, but rather one of simplicity: how to do it in a small number of steps and using just a few modules. KUBIK is highly automated and practical geometries can easily and automatically be described. The average input file for KUBIK contains only 15 commands. KUBIK can

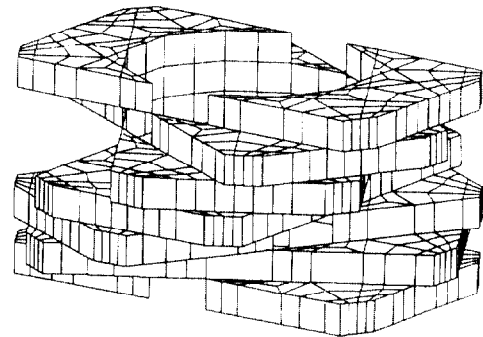


Figure 1. Model of a "twister", an undulator for a circularly polarized micro/mm free electron laser, consisting of 7 permanent magnets used for the production of transverse helical magnetic fields [7].

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also prepare isometric or perspective plots of the mesh and the magnetic bodies, which can later be displayed by MAGNUS-GKS, the graphical post-processor, as explained below. All the powerful features of MAGNUS-GKS are available when visualizing the plots. Figure 1 shows an example. KUBIK has been extensively described elsewhere [5].

MAGNUS, the Solver

MAGNUS is the solver. The input to MAGNUS is the description of the mesh, contained in the output from KUBIK, and a user's file with the definition of the conductors, boundary conditions and magnetic properties of the materials and permanent magnets. The information is used to assemble the nonlinear finite element equations and to solve them iteratively. MAGNUS uses state-of-the-art sparse matrix computational technology [6] and the preconditioned conjugate gradient method to solve the system of linear equations in each iteration. This guarantees accuracy, efficiency and storage economy. Unlike earlier versions, the input to the solver is now divided into four command modes, that must be executed sequentially. The commands in each mode are interchangeable, and many are optional and have default values.

The General Command Mode. This mode contains commands to specify some general parameters for the run, like the maximum number of iterations, the desired accuracy, the relaxation coefficient and whether this is a new run, a restart or just a test run. Some limited output options are provided, as well as a feature to save intermediate results during the run.

The Boundary Command Mode. In this mode the user can specify the Dirichlet boundaries and the periodicity conditions of the domain, if any. Any unspecified boundary is treated as a Neumann boundary. This mode has recently been the subject of an important improvement: complete elimination of any reference to the TSP method, meaning not only that the program operator no longer needs to be familiar with the details of the theory, but also that the input files are greatly simplified and the risk of human error is substantially reduced. The theory of the TSP method requires that the domain of solution be divided into one Ψ -region that is single-connected, and one or more Φ -regions enclosing the conductors, and that the quantities $\int_P^Q \mathbf{H}_S \cdot d\mathbf{l}$ and $\int_{\Delta S} \mu_0 N_i H_{Sn} dS$ be calculated for every Q , where P is some starting point, Q is any mesh point on the boundaries between the Ψ -region and the Φ -regions, and ΔS is an element facet on the same boundary. In previous versions of MAGNUS-3D, only one Φ -region was allowed, and the user was required to specify this Φ -region, its boundary S , the location of point P , the definition of the Dirichlet boundaries, and their relation to the boundary S . Such a detailed specification was found to be not convenient, because it required an advanced knowledge of the TSP method, not always available to program operators. Now, MAGNUS will automatically find all the areas and lines involved, even in the case of multiple Φ -regions, and calculate the necessary integrals without intervention of the operator.

The Conductor Command Mode. This mode is used to define the electric conductors in the problem. MAGNUS has a library of 3D conductor elements, that includes infinitely thin conductors, solid conductors and strips of a variety of shapes, that are completely parameterized and independent of the mesh and of each other, and can be placed anywhere in space. The user approximates his configuration by taking conductor elements from the library and placing them in the appropriate position. The operations of reflection, displacement and rotation are available to generate more conductors when symmetries exist. There is a command to specify the Φ -regions, and a command to generate a plot of the conductors that is stored into a device independent metafile and can be displayed by MAGNUS-GKS. See Figure 2 for an example.

The Magnetization Command Mode. In this mode the user can specify the magnetic properties of materials. There is a library of magnetization tables for the most common accelerator steels, including some US and some Japanese industrial steels, and ideal materials such as pure iron or pure nickel. The user can enter his own table, as provided by the manufacturer or obtained from measurement. Permanent magnets can be specified in a number of ways, including a constant \mathbf{M}_0 , a de-

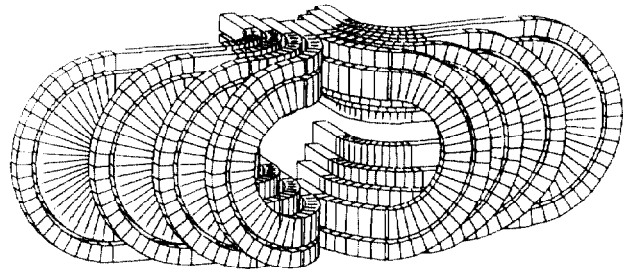


Figure 2. View of the windings near the end of an 8T superconducting magnet proposed for the Superconducting Supercollider (iron not shown). This model was used for a detailed field analysis, calculation of magnetic forces on the conductors, effective magnetic length, average harmonic coefficients and peak field at the conductors.

magnetization curve determined by the coercive force H_c and the residual induction B_r , or a complete detailed non-linear demagnetization curve as provided by the manufacturer. There are commands to print the tables either as they are stored or as they are interpolated, and to specify the user's choice of interpolation algorithm.

After the four input command modes, MAGNUS starts the iterations. Convergence is excellent: after thousands of problems solved by many different users, there have been no reports of lack of convergence. Convergence is usually achieved in 10 to 45 iterations. At that point, a complete solution is available and ready to be used.

EPILOG, the Post-processor

The most important and useful feature of this program package is the post-processor EPILOG. The solution obtained by MAGNUS consists of the two potentials Φ and Ψ defined as continuous functions at every point of the respective domain. The potentials can then be used by EPILOG for a variety of purposes, like print tables, obtain plots or calculate quantities that depend on the solution and are useful to the Magnetic Engineer. EPILOG is command operated. The commands are interchangeable and can be executed repeatedly if so desired, because the solution remains in storage and is not affected. The output from EPILOG can easily be interfaced to programs that calculate particle trajectories or perform other tasks of accelerator physics. The commands currently available are briefly described.

Magnetic Energy. Command ENERGY calculates the total magnetic energy stored in the magnetic materials and the non-magnetic part of the solution domain. The energy is important for the design of power supplies, and also for quench protection systems of superconducting magnets.

Force and Torque. Commands FORCE and TORQUE will calculate the total magnetic force or torque acting on any given region of space. The user specifies the region by defining an enclosing surface. The force or torque are calculated by integration of Maxwell's electromagnetic stress tensor over the given surface, and are actually acting on the conductors or magnetic bodies contained inside the region. Force and torque are important for mechanical design.

Magnetic Flux. Command FLUX calculates the magnetic flux through a given surface in space. The surface is specified by the user, and there is a small assortment of surface types that can be used. The surface can be such that its perimeter coincides with an electric circuit, in which case the flux concatenated by the circuit is obtained and can be used to calculate the self inductance or mutual inductance of the circuit. Note, however, that the inductance of a nonlinear system is not a constant, and that it can also be defined in terms of the magnetic energy. The two definitions have different meanings, and their properties must be understood by the user.

Line Integrals. Command LINE INTEGRAL will calculate any one of a variety of line integrals of potential or field components. The line is any line in space specified by the user. A line integral of the type $\int \mathbf{H} \cdot d\mathbf{l}$ is important because it has a physical meaning. Integrals like $\int B_y dz$ along the beam line are frequently needed in accelerator physics.

Harmonic Coefficients. Command MULTIPOLES is a rather unique feature of EPILOG. It can calculate the harmonic coefficients of the field of an accelerator bending, focusing or steering magnet averaged over an interval along the beam direction. In this way, end effects, effective length and field errors in 3D geometries are all taken into account.

Tables. Command PRINT has many forms that meet practically every need of the Magnetic Engineer or the Accelerator Physicist. For example, it is possible to print a table of field values at points on a line or arc in space specified by the user. If the line is the beam, the table gives directly the values of the field acting on the beam. Such a table could be used as input for a particle tracking program. If the line coincides with a conductor, the values in the table can be used to determine the maximum field at the conductor, important for estimating the critical current in the case of a superconductor. PRINT can print a table of values of μ at points in the iron or in a selected region inside the iron; such a table indicates the effectiveness of shields and yokes, and the linear or nonlinear behavior of pole pieces and other components. PRINT can also be used to obtain a verbose description of all the electric conductors existing in the problem.

Plots. Command PLOT is very powerful. It allows the user to obtain plots or views of the mesh, the magnetic bodies, or the conductors, seen from any point of view in space. It is possible to zoom into particular details, and to combine or overlay different views. All plots go into device independent metafiles, which can then be displayed by running MAGNUS-GKS, in black and white or in color on any of the supported graphical devices with either full or partial hidden surface removal.

Function Plots. A further unique feature is the ability to plot curves representing a function. The function can be a component of the field or magnetic induction, or the magnetic scalar potential, or the total field, plotted as a function of a line coordinate along any line in space. The plots are appropriately labelled, and can be displayed on any graphical device. Plots of the transverse field along the beam, or of the total field along a conductor, can be obtained in this way.

Field Lines. Another very unique feature of EPILOG is command FIELD LINES. This command obtains sets of field lines in 3D and generates a plot, where the field lines can be seen from any point of view. In 3D, field lines do not generally stay on a plane and must be seen and understood in space. Field lines, by simple examination, provide a degree of insight into the behavior of the field that is very difficult to achieve by other means.

MAGNUS-GKS, the Graphical Post-processor.

MAGNUS-GKS is the graphical post-processor for the package. It interfaces with all the programs, and is used to display graphical metafiles generated by any of the programs on one of the supported devices. The devices currently supported are: VT-240 color terminal, LA-100 dot matrix printer, LN-03 laser printer, HP-7580 color plotter, TEK-4014 terminal and TEK-4125 color terminal. Different plots can be overlaid on the same view, appropriately scaled, and lines can be shown

in different patterns or colors where available, or eliminated from the view. Full hidden surface removal, partial hidden line elimination, perspective or isometric views and color are some of the features available in the views. The devices include both bit mapped devices and vector devices. The list of supported devices grows continuously in response to requirements from the users. Figures 1 and 2 show examples of views obtained with full hidden surface removal.

WIRE and HARMON

WIRE is an independent program that calculates the field of any configuration of electric conductors in 3D, at any given set of points in space, when no magnetic materials are present. WIRE uses the same library of conductor elements as MAGNUS. Plots and views of the conductors in space can be obtained and displayed by MAGNUS-GKS. WIRE is not a finite element program and does not require a finite element mesh. WIRE calculates the field of electric currents by direct integration of Biot and Savart law.

HARMON is a program for the spherical harmonic analysis of magnetic fields in 3D. The main application of HARMON is the design of passive and active shims and correction coils for high precision magnets, like NMR and MRI magnets for medical uses, using as input field values either calculated by MAGNUS or obtained from measurement.

Conclusions

We have presented an overview of the program package MAGNUS-3D for 3D nonlinear magnetostatics. We have emphasized the recently developed improvements and extensions, that include input-simplifying automation, better graphics and new post-processing features. We have also described the associated programs WIRE and HARMON. We conclude that MAGNUS-3D is a very useful design tool for the Magnetic Engineer and the Accelerator Physicist.

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