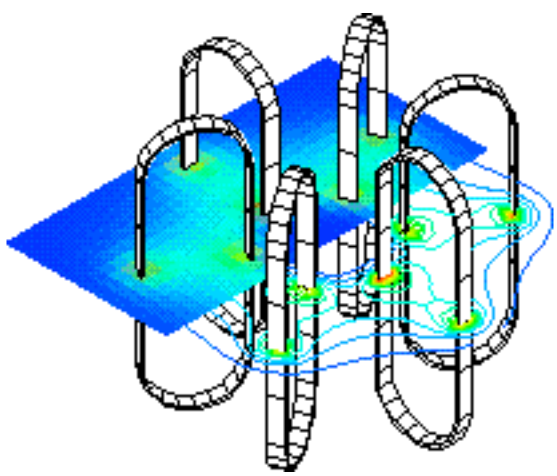
M'C

Magnetic field, inductance, vector potential, energy, forces and
AC loss analysis
in a
3-D superconducting coil system
of
arbitrary shape

Version 2.9

by CryoSoft

April 2007



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DISCLAIMER

Introduction

M'C is a computer program for the calculation of magnetic field, vector potential, AC losses, AC and DC cable magnetization, operating point, volume and resultant forces, inductance and energy of (superconducting) magnetic systems of arbitrary shape. It offers high level modelling capabilities and plotting facilities for post-processing the results. A command language is used for the data input and options selection.

The 3-D coil geometry is generated based on primitives (arcs, segments, loops) and consists of isoparametric, 8-nodes elements with plane faces. For each coil the current is assigned as a function of time through table input. The magnetic field and vector potential generated by the magnetic system can be computed in the coils winding or in sets of calculation points. Volume electromagnetic force density is similarly computed in windings. The results can be post-processed, in local or global co-ordinate systems, both in printed output or plot format. Special options allow the selection of particular directions in the coils or set of points for the output and plotting, for instance along the turns, the pancakes or the layers of a winding pack. Similarly volume forces are computed in coils and output as maps or interpolated along specified lines.

For superconducting coils a simplified AC loss and magnetization calculation method is implemented. The result can be processed in a way analogous to the field calculation.

Finally, system parameters such as coil inductance, magnetic energy, force resultants and operating point (maximum field vs. current) can be calculated and output.

Field Calculation

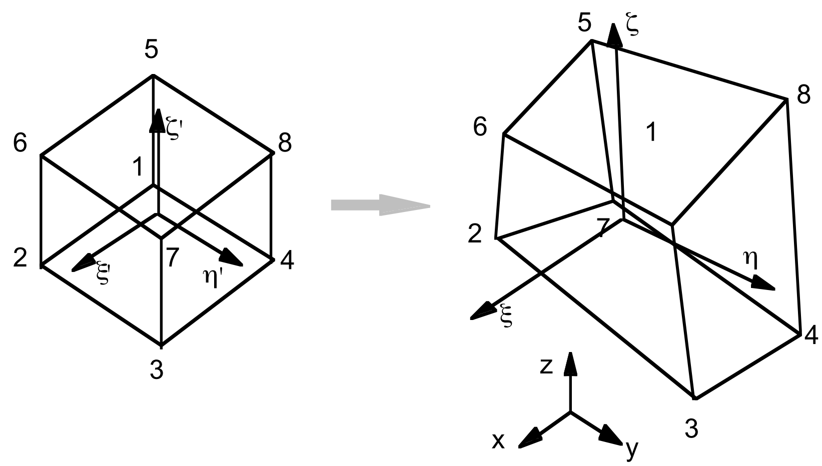
The field calculation in *M'C* is based on analytic expressions for the magnetic field generated by an iso-parametric brick (a General Current Element - GCE) with constant current density[1]. <u>The field is computed in [T]</u>. The GCE brick is identified by the coordinates of its 8 nodes (see Fig. 1 for the geometry definition). The field expressions hold for any shape, provided that the faces of the GCE are plane. As the GCE's are generated by the code itself while building the coil geometry, this constraint is always satisfied. A single exception is for a direct input of a GCE element, by giving the nodal coordinates, where the user must insure that the GCE faces are plane for correct results.

The result of the analytic integration is exact (to machine rounding error accuracy) and stable (i.e. it has no singularity inside the brick, or at its surface). Therefore the field computed will be exactly the one produced by the discretized geometry, without

[1] L. Bottura, *Analytical Calculation of Magnetic Field in an Isoparametric Brick*, CryoSoft Internal Note CRYO-97-2, 1997

any additional assumption or error source. The only source of error in the field calculation is in the approximation of the real geometry with bricks with straight sides. Increasing the discretization will improve accuracy in the case of curved windings (e.g. for a solenoid). Convergence to the exact results for a curved geometry is typically of second order in the number of GCE's (i.e. with the square of the subdivisions) as demonstrated in the test case included in the manual.

Figure 1. Definition of the base brick and transformation from the base brick to the isoparametric brick in real space. The local reference frame ξ,η,ζ in the brick is obtained taking the transformed of the parent direction ζ', and the direction η normal to the transformed of the parent directions ζ' and ξ' (the direction ξ follows). The current flows in the ζ direction.



The GCE geometry is generated based on the cubic image of the brick in a parent ξ',η',ζ' space and through iso-parametric transformation of the coordinates through the standard finite elements shape functions for an 8-nodes brick. A local cartesian reference frame, also derived from the base brick, is attached in real space to the GCE. The current flows in the GCE along the ζ direction. The winding pack of the coil thus extends in the directions ξ and η. See later for a definition of the direction of turns, pancakes and layers with respect to the local reference frame.

The field is always computed in a in a set of points. The points can be defined by the user along a straight line (command LINE), on a plane (command GRID) or in a region of 3-D space (command CUBE). Calculation internal to the coil winding is on a equispaced mesh of points, defined in all GCE's forming a coil, and controlled by the user with the command MESH. Note that the post-processing of field calculation along specific directions in the winding (e.g. along a pancake or a layer) is done interpolating the calculation result from the equispaced grid to the required positions.

Vector Potential Calculation

The vector potential calculation in *M'C* uses again analytic expressions for the same iso-parametric brick, or GCE, with constant current density used for the calculation of the magnetic field[2]. The same assumption is also made on the plane faces of the GCE, as for calculation of magnetic field. The vector potential is computed in [T m]. Calculation is possible both in the equispaced grid of points internal to the coils windings (see command MESH) as well as in arbitrary points in space.

Operating Point Calculation

The coil operating point (maximum field in [T] vs. operating coil or conductor current in [A turn] or [A] respectively) is computed using the magnetic field calculation capability. Maximum field search in the coil is made based on the interpolation mesh specified by the user (see the MESH commands).

Volume Forces Calculation

The volume forces acting in the coil winding, in [N/m^3], are computed in the GCE, on the same equispaced calculation grid used for field and vector potential calculation. The volume forces $\boldsymbol{F}$ are obtained directly from the magnetic field $\boldsymbol{B}$ in the points and the current density in the GCE $\boldsymbol{J}$ as:

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B}$$

Forces Resultants Calculation

The total resultant forces acting on a complete coil coil winding, in [N], is computed numerically from the volume forces on each GCE. The user specifies the required precision of the numerical integration (see the PREC command). The integral is then refined until the required precision is reached. Resultants are output as total over a coil and, in addition, for each GCE. This allows to build partial resultants for different part of a coil.

Inductance Calculation

M'C uses the basic definition of the inductance of two solid conductors, as volume integral of the scalar product of the vector potential generated by the first conductor with the unit current vector in the volume of the second. The calculation of the vector potential from the first conductor is analytical (see section dedicated to the calculation of the vector potential), while the remaining volume integration on the second conductor is performed numerically. The user specifies the required precision of the numerical integration (see the PREC command). The inductance is computed

[2] L. Bottura, *Analytical Calculation of Vector Potential in an Isoparametric Brick*, CryoSoft Internal Note CRYO-97-3, 1997

and output in [H], and is output both referred to the *single turn* coil and taking into account the number of turns defined on all coils.

AC Loss and Cable Magnetization Calculation

The AC loss and magnetization calculation is based on a simplified model for different loss and magnetization components in a superconducting cable[3]. It assumes that the losses and magnetization in a superconducting cable are either due to the coupling currents in the superconductor (or eddy currents in normal conducting parts) or to DC shielding currents in the superconducting filaments. Field penetration in the case of hysteresis loss and field screening in the case of coupling loss are both taken into account. The user must be aware that the calculation, being analytic, suffers from limitations and approximations. The basic assumptions made to derive the loss and magnetization expressions are to neglect:

- parallel field coupling loss;
- saturation effects;
- mutual shielding between coupling currents and hysteresis magnetization;
- field rotation effects;
- self field and transport current losses.

As such the calculation can be wrong by factors in the case of very fast changes of the magnetic field (saturation), operation close to the critical current (transport current effects) and large AC rotating fields. Apart from these cases the loss and magnetization calculation provides a good approximation to the power dissipation and magnetization of a superconducting cable.

The AC loss and magnetization in a cable is in general a function of the powering history of the magnet. When asking the AC loss between two times t_{start} and t_{end}, *M'C* automatically scans the complete powering history, from the first time defined through the tables of operating current up to the starting time for the calculation t_{start}. This is done so that the proper starting condition (of magnetization and internal field) can be reached. In addition, the first current in the magnets is reached with a slow ramp from zero field, starting with virgin conditions in the superconductor. The ramp time is chosen of the order of 10^6 s, so that the coupling currents magnetization is negligible. This corresponds to the assumption that the first current given in the table was reached at negligible ramp-rate just after cooling the coil into superconducting state. The user can control this phase by starting with all coil currents at zero. *M'C* then outputs AC loss and magnetization at all points defined in the tables of coil currents between t_{start} and t_{end}. Two subsequent points define a time step. Field variations in a time step below 50 μT are ignored and the loss and magnetization calculation is skipped (constant DC magnetization, zero loss power).

[3] L. Bottura, C. Rosso, *AC Loss Calculation Algorithm*, CryoSoft Internal Note CRYO-97-1, 1997

For loss calculation the conductor geometry and properties are needed. The cable geometry is identified by:

- superconductor and stabilizer cross sections A_{sc} and A_{st} respectively The total superconductor cross section A_{sc} is intended to include both the superconducting filaments as well as the resistive barriers other than the stabilizer, i.e. what is usually called the non-copper area in low-Tc strands;
- the fraction λ of true superconductor in the total non-copper;
- critical current density in transverse and parallel direction to the filament (depending on the transverse and parallel applied filed). The critical current density can be chosen as one of standard NbTi or Nb_3Sn materials, or must be provided by the user through the routine EXTS_E, to be linked with the main code (see later for the description). The critical current density J_c is referred to the total superconductor cross section A_{sc};
- the effective filament diameter;
- time constants (τ_ξ, τ_η, τ_ζ) in the three cable directions (two transverse and one parallel) where ξ, η and ζ are the three local directions of the GCE;
- shape factors (n_ξ, n_η, n_ζ) for the cable coupling currents, as defined by Campbell[4], where for each direction the shape factor n is defined using the de-magnetization factor N using , and for round conductors n=2.

As an example, in a copper stabilized, Nb-Ti strand A_{sc} includes NbTi as well as the small Nb barrier at the boundary of the filaments, A_{st} includes the copper area, and in practice $\lambda \approx 1$. In a copper stabilized, Nb3Sn strand, A_{sc} includes Nb_3Sn, barrier and bronze, A_{st} includes the copper area, and $\lambda \approx 3$ to 5. The calculation of the penetration phase in the superconducting filaments is done taking into account the current density J_c referred to the true superconductor cross section, i.e. J_c/λ.

<u>The AC loss is output in [W/m] of conductor length</u>, normalizing the hysteresis loss to the *true* superconductor cross section λ A_{sc}, and the coupling loss to the total strand cross section $A_{sc}+A_{st}$. The power is averaged within a time step (constant through the step).

The instanataneous volume magnetization is converted in an average cable magnetic moment after normalization by the appropriate cross section (as for the loss power). <u>The magnetic moment is then output in [A m]</u>.

The conductor temperature (<u>in [K]</u>) and operating strain (<u>non-dimensional</u>) are passed as parameters for the critical state calculation, and they are coming directly from the

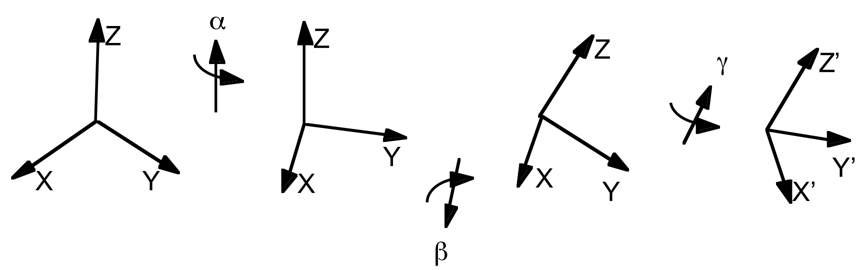
[4] A.M. Campbell, *A General Treatment of Losses in Multifilamentary Superconductors*, Cryogenics, **22**, 3, 1982

input data of the conductor characteristics. This is for compatibility with additional analysis capability to be implemented in the code in the future.

Reference Frames

It is fundamental that the user is familiar with the transofrmation of reference frames used in *M'C*. In all cases a *global* reference frame (X,Y,Z) is defined, which provides the basic geometry for the inputs. For several geometry inputs (a segment, an arc, a loop, a line/grid/cube of field points) a local reference frame (X',Y'Z') is defined. This last is obtained by rotation of the global reference frame by the three Euler angles α,β,γ and translation.

Figure 2. Definition of the rotations using the Euler angles and leading from the global to the local reference frames for geometry inputs.



The rotation angles are applied in the sequence depicted in Fig. 2. The translation brings the centre of the rotated reference frame into the point Xc, Yc, Zc defined in the global reference frame.

In addition to the local reference frame which is used for the input of the geometry, each object (GCE, line/grid/cube) has associated a local normalised reference frame, in which it extends over the [-1…+1] interval. This second local reference frame is identified by greek lettering (ξ,η,ζ). This is the reference frame usually employed for the definition of locations in the objects.

Vector quantities such as magnetic field, vector potential, volume forces, resultant forces, magnetization can be plotted and output either in the global reference frame or in the local reference frame (i.e. associated with the entity in which they have been computed). This switch is controlled by the user by means of the LOCAl and GLOBal commands (see later). This option is useful, for instance, to follow the behaviour of magnetic field on a curvilinear coordinate along the coil perimeter.

Code Structure and Operation

M'C reads and processes commands from an input file (opened at the beginning of the execution). It is therefore thought mainly for batch operation, after having written the stream of commands to be executed. A code run, or session, is generically structured as follows:

- model input
  - cable geometries
  - operating current tables
  - coil geometry and properties
  - calculation points in space

Note that cable geometries and current tables must be input before the coil is defined, as a coil will need to make reference to a valid conductor and current.

- calculations
  - magnetic field
  - operating points
  - vector potential
  - volume forces
  - resultants
  - AC loss and cable magnetization
  - inductance
  - energy

Results of calculations are stored in a direct acces calculation map database for later retrieval and post-processing. The order of the calculation is not relevant. Note however that computing twice the same quantity may result in unpredictable output of the results

- output and post-processing
  - print-out or plot of input data (geometry, time histories)
  - interpolation and printout or plot of computed quantities

All output and post-processing commands must necessarily refer to calculations already performed and stored in the calculation map database.

To improve the efficiency of the calculation, influence matrices are created (giving, e.g., the field in a point for unit current in all coils). The creation of these matrices keeps track of the model entered (i.e. they are updated as soon as new coils are entered) and of the assumptions on the problem symmetry (axisymmetric or full-3D). The influence matrices are stored on a direct acces database file, whose entries are indexed in the main memory.

The files used by *M'C* are the following:

Name	Usage

input file	input file containing the stream of commands to be executed. The user is prompted at the beginning of the session for the input file name
mac.output	ASCII file containing the outputs requested with the PRINT command
PostScript.ps	ASCII file containing the plots requested with the PLOT command, in PostScript™ format
mac.log	session log
mac.geometry	binary, direct access database file for storage of the geometry of the coils
mac.influence	binary, direct access database file for storage of influence matrices
mac.maps	binary, direct access database file for storage of result maps
mac.save	binary file for storage and retrieving of a work-session

Note: FORTRAN unit numbers above 50 are reserved for internal use

Commands

This section gives the complete syntax for the operation of *M'C*. The commands are specified through keywords, indicated here in uppercase (the necessary part of the keyword) and lowercase (the part that can be skipped). The conventions adopted to indicate the syntax are:

- commands are separated by blanks
- a ';' indicates the end of the line. All the rest of the line is ignored by the command interpreter (it can be used to comment out a line)
- real and integer inputs are indicated here following the FORTRAN convention (i.e. starting letter in the I...N range indicates an integer quantity or array, all other starting letters are for real variables and arrays)
- names and strings are indicated surrounded by double quotes. This is not necessary in *M'C* in the case that the string does not contain a blank;
- *M'C* ignores the lettering case, i.e. uppercase or lowercase commands and names are equivalent.

The commands are grouped in three sets, namely model input commands, calculation and calculation control commands, output and post-processing commands. As discussed previously, this is the sequence that should be followed in a normal *M'C* session.

Model Input Commands

COIL - Geometry

COIL command list FINIsh

The COIL *command must be used to create a new coil, define its geometry and assign properties of current, winding type and conductor data. It has an internal structure, with several commands terminated by the FINI command. The* commands list *stands for a set of commands within the following valid set (in any order). A coil geometry can be defined using directly the GCE's, or higher level primitives (segment, loop, arc), or finally by geometric operations on another existing coil. Note that to maintain coherence in the calculation and output a coil must be defined by adjacent GCE's, with continuous local directions*

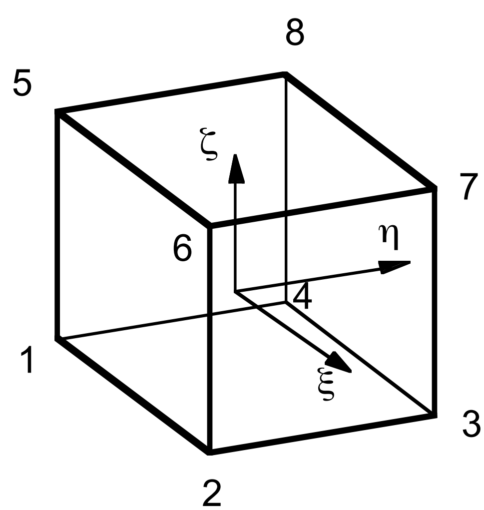
Coil geometry definition commands

GCE X(i) Y(i) Z(i) [i=1,8]

enter the geometry of a sinlge GCE (8-nodes brick) through its 8 nodes' coordinates (see Figs. 1 and 3)

Note: the user must insure that the faces of the GCE are plane in order to achieve the desired accuracy in the calculation of the field (the field analytic integrals only hold in case of plane GCE faces)

Figure 3. Definition of a single General Current Element (GCE) through its 8 nodes. The current flows in the ζ direction.



COIL - Geometry

ARC	Xc Yc Zc	α β	R φbeg φend	ΔR Δz	RADIal IN	Ngce
ARC	Xc Yc Zc	α β	R φbeg φend	ΔR Δz	RADIal OUT	Ngce
ARC	Xc Yc Zc	α β	R φbeg φend	ΔR Δz	VERTical UP	Ngce
ARC	Xc Yc Zc	α β	R φbeg φend	ΔR Δz	VERTical DOWN	Ngce

subdivide an arc centered in a local reference frame (X',Y',Z') with origin in Xc, Yc, Zc, and Euler angles α, β, γ=0, with respect to the global reference frame (X,Y,Z). The arc is sitting in the X',Y' plane of the local reference frame, and is divided in Ngce elements. The arc has average radius R, starts at φbeg and ends at φend (φ is the positive angle measured starting from the X' axis in the local reference frame). The thickness of the arc in radial direction is ΔR, its height (in the local Z' direction) is Δz. The direction of the ξ axis, relevant for the definition of the winding (see later) is either radial, directed along R, or vertical, directed along Z', depending on the RADIal/VERTical flag selected (see Fig. 4 for the definition).

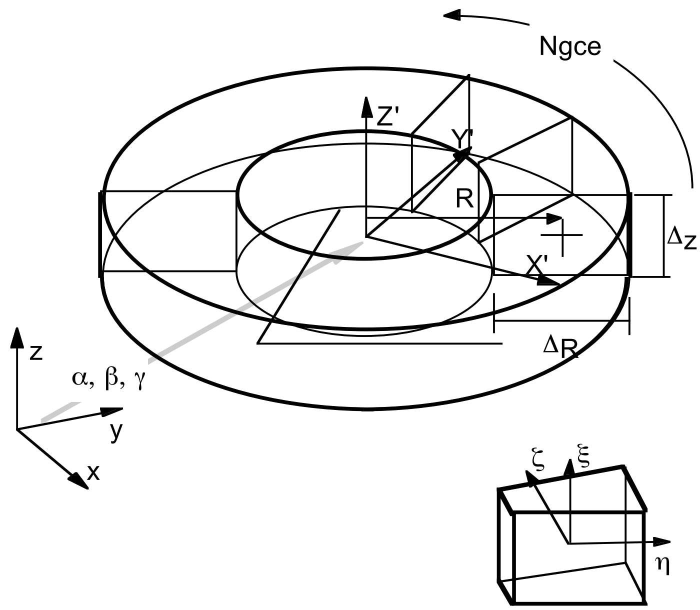
Figure 4. Definition of an arc and its subdivision in GCE's. Note the local reference frame (X',Y',Z') used for the definition of the orientation and dimensions of the segment (the local reference frame is obtained from rotation and translation from the global reference frame (X,Y,Z)), and the resulting local reference frame for the GCE that depends on the RADIal/VERTical flag selection.

COIL - Geometry

LOOP	Xc Yc Zc	α β	R	ΔR Δz	Ngce

subdivide a loop centered in a local reference frame (X',Y',Z') with origin in Xc, Yc, Zc, and Euler angles α, β, γ=0, with respect to the global reference frame (X,Y,Z). The loop is sitting in the X',Y' plane of the local reference frame, and is divided in Ngce elements. The loop has average radius R. The thickness of the loop in radial direction is ΔR, its height (in the local Z' direction) is Δz.

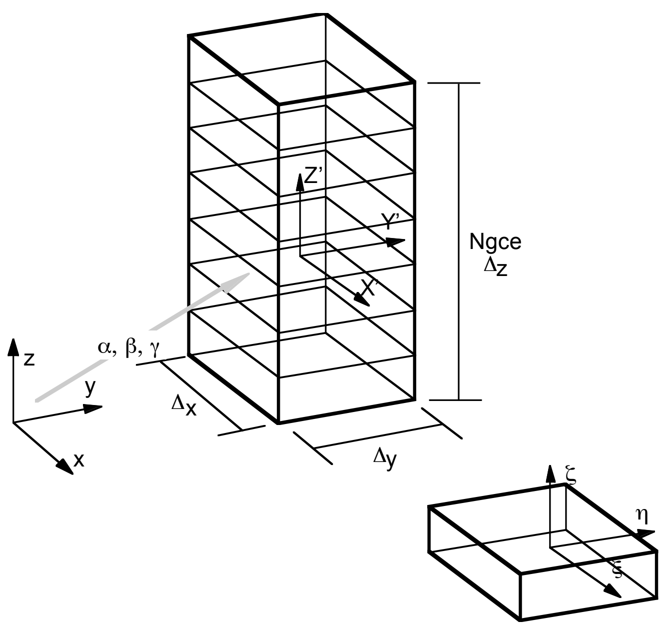
Figure 5. Definition of a loop and its subdivision in GCE's. The geometry is the same as that of an arc, defined with a starting angle of φbeg=0 and an end angle of φend=2π.



COIL - Geometry

SEGMent Xc Yc Zc α β γ Δx Δy Δz Ngce
subdivide a segment centered in a local reference frame (X',Y',Z') with origin in Xc, Yc, Zc, and Euler angles α, β, γ, with respect to the global reference frame (X,Y,Z), in Ngce elements along the local Z axis. The segment has dimensions Δx Δy Δz in the local reference frame (see Fig. 4).

Figure 6. Definition of a segment and its subdivision in GCE's. Note the local reference frame (X',Y',Z') used for the definition of the dimensions of the segment (the local reference frame is obtained from rotation and translation from the global reference frame (X,Y,Z)), and the resulting local reference frame for the GCE.



COIL - Geometry

TRANslate "CoilName" Δx Δy Δz

produce a new coil from a rigid translation of the coil CoilName by Δx, Δy and Δz.

ROTAte "CoilName" Xc Yc Zc α β γ

produce a new coil from a rigid rotation of the coil CoilName by and Euler angles α, β, g=0, with respect to the global reference frame, around the point Xc, Yc, Zc

SYMMetric "CoilName" a b c d

produce a new coil from a symmetry of the coil CoilName about the plane:

$$a x + b y + c z + d = 0$$

note that the geometry is symmetrized, but the current is not.

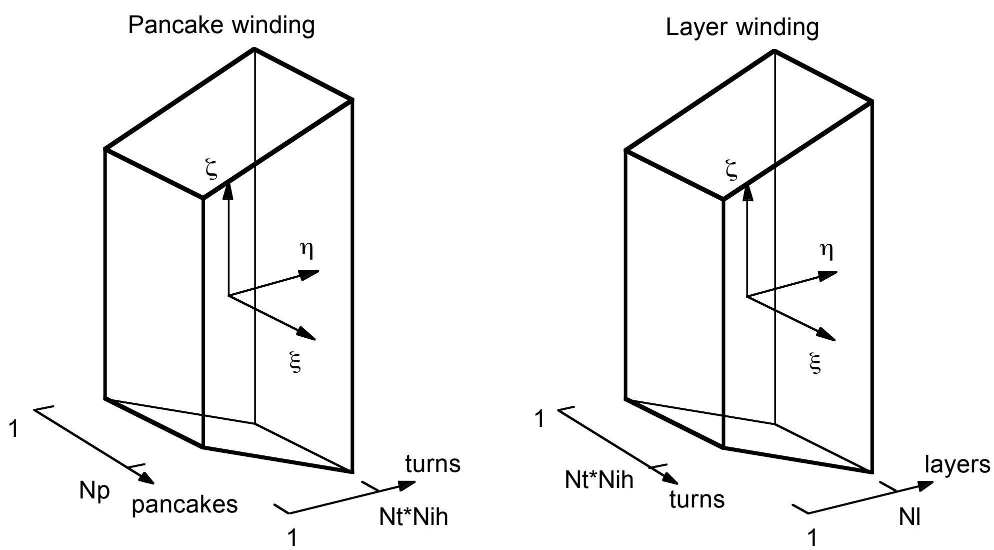
COIL - Winding pack

Coil winding pack definition commands

WINDing PANCakes Np TURNs Nt Nih IN_Hand
LAYErs Nl TURNs Nt Nih IN_Hand

Assign the winding type and geometry to the coil. The winding can be either in pancakes or layers. The number of pancakes Np or of layers Nl is assigned. The number of turns Nt and of conductor in hand Nih is always required. Default is a pancake winding with 1 pancake and 1 turn, 1-in-hand.

Figure 7. Turns, pancakes and layers directions in a GCE of a pancake-wound coil and of a layer-wound coil, referred to the local reference frame. The directions have been chosen to produce coherently pancakes and layers when modelling a solenoid coil (compare to the GCE local reference frame in an arc or a loop). Note the exchange of the directions for the two winding types, and the fact that the total number of turns in a coil is given by the product of the turns of each conductor length times the number of lengths-in-hand.



COIL - Properties

Coil properties definition commands

NAME "CoilName"	*Give the name CoilName to the coil. If no name is given, the coil is given a default name of COILNNNN, where NNNN is the order of creation number of the coil. The coil name is truncated to 8 characters*
CURRent "CurrentName"	*Set the current as equal to the one defined in the current table entry CurrentName No current definition by default*
CONDuctor "ConductorName"	*Set the conductor properties as equal to those defined in the conductor table entry ConductorName. No conductor definition by default*

Coil calculation/interpolation mesh definition commands

MESH Npξ Npη	*set the number of points in the ξ and η directions of a GCE to be used for field, vector potential, AC loss and forces calculation. Default (and minimum) is 2 points in each direction. Values at the conductor centers are computed based on interpolation on the calculation mesh*

Errors and warnings

Errors:	Coil name already exists Coil name not found Current table does not exist Conductor table does not exist Too many GCE's Too many coils Too many mesh points
Warnings:	Coil name not assigned Conductor data not defined Coil current not defined Coil winding not defined

COND

CONDuctor	commands list	FINIsh	*The* COND *command must be used to create a new conductor entry in the table of conductor properties. The entry is for later use in a coil (see the* COIL COND *command). The command has an internal structure, where* commands list *stands for a set of commands within the following valid set (in any order). The conductor definition is terminated by the* FINI *command.*
	NAME "ConductorName"		*Give the name ConductorName to the conductor entry. If no name is given, the entry is given a default name of CONDNNNN, where NNNN is the order of creation number of the table. The name is cut to 8 characters.*
	SUPErconductor Isc		*superconductor flag Isc. Isc must have one of the following values*: *(<0) user's defined, through the function EXTS_E* *(31) standard NbTi (present non-copper Jc of approximately 3000 A/mm² at 4.2 K and 5 T)* *(32) standard Nb3Sn (present non-copper Jc of approximately 260 A/mm² at 4.2 K , 12.5 T and applied strain of -0.25 %).*
	ASC Asc		*superconductor (non-copper) cross section Asc in [m²].*
	AST *Ast*		*stabilizer cross section Ast in [m²].*
	TAU Tauξ, Tauη, Tauζ		*cable coupling currents time constants* Tauξ, Tauη, Tauζ *(in [s]) of cable coupling currents for field changes in* ξ,η,ζ *direction.*
	MFAC nξ, nη, nζ		*magnetization shape factors* nξ, nη, nζ *(non-dimensional) of cable coupling currents in* ξ,η,ζ *direction.*
	DEFF *Deff*		*effective filament diameter Deff in [m].*
	LAMBda *lambda*		*superconductor fraction in the non-copper area (non-dimensional).*

*NOTE: the calculation of the current density is commonly based on the total superconducting area Asc, which is also conventionally called the non-copper area. This area includes the superconducting material as well as other resistive materials (barriers, or residual of chemical reactions such as bronze in Nb3Sn strands) that are not accounted for in the stabilizer cross section. <u>In M'C the critical current density Jc computed either by the standard properties or by the user's defined routine is referred to this cross section</u>. On the other hand, the calculation of hysteresis in the superconducting filaments needs to take into account the real in the filaments, i.e. excluding the additional resistive materials mentioned above. This value is obtained from the non-copper value of Jc dividing it by the fraction lambda. The loss per unit volume of filament is then converted in loss per unit length of cable by multplying by the superconductor cross section Asc*lambda*

	TEMPerature *T*	*cable temperature T in [K], used in the calculation of the critical current density*

EPSIlon	*Eps*	*longitudinal strain Eps (non-dimensional)*

Errors and warnings

Errors:	Conductor name already exists Invalid superconductor type Zero or negative superconductor cross section Zero or negative cable cross section Zero or negative time constant Zero or negative filament diameter Zero or negative temperature Strain out of range (-0.01 ... 0.01) Too many conductors
Warnings:	Conductor name not assigned

CUBE

The command CUBE *defines a cube of points in space for the calculation of magnetic field and vector potential. Cubes are numbered sequentially at creation, and must be referred by number*

CUBE Xc Yc Zc α β γ Xb Xe Nx Yb Ye Ny Zb Ze Nz

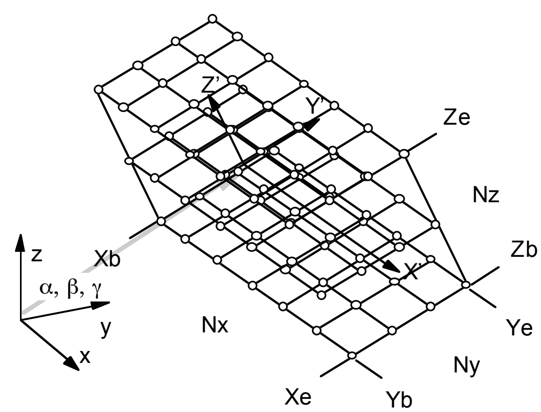
define a cube for field calculation in the X direction of a reference frame (X',Y',Z') centered in Xc, Yc, Zc and with Euler angles α, β, γ with respect to the global reference frame (X,Y,Z). Nx points are placed on the line between the Xb and Xe extremes, Ny points are placed on the line between the Yb and Ye extremes and Nz points are placed on the line between the Zb and Ze extremes (in the local reference frame). The beginning coordinate must be smaller than the ending coordinate of the intervals

Errors and warnings

Errors: Too many cubes
Invalid boundaries

Warnings: none

Figure 8. Definition of a cube for field calculation and its local reference frame (X',Y',Z')



CURR

CURRent commands list FINIsh		*The* CURR *command must be used to create a new current entry. The entry is for later use in a coil (see the* COIL CURR *command). The command has an internal structure, where* commands list *stands for a set of commands within the following valid set (in any order). The current definition is terminated by the* FINI *command. A current entry can define a table (as a func5ion of time) or a constant current.*
	NAME "CurrentName"	*Give the name CurrentName to the current. If no name is given, the current is given a default name of CURRNNNN, where NNNN is the order of creation number of the current entry. The current name is truncated to 8 characters*
	TABLe Ntimes Time(i) Current(i) [i=1,Ntimes]	*The current entry is defined through a the current table, formed of Ntimes entries for the times Time(i) and currents Current(i).*
	CONStant Current	*The current entry is defined as a constant Current*

<u>*Errors and warnings*</u>

Errors:	Current name already exists Too many times in current tables Too many currents
Warnings:	Current name not assigned

GRID

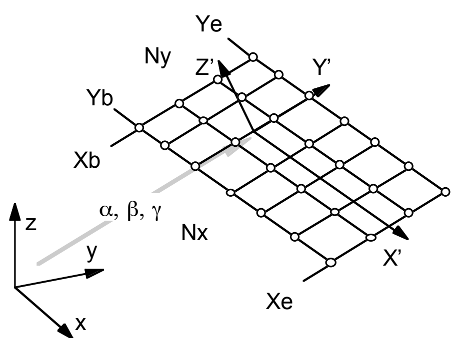
The command GRID *defines a grid of points in space for the calculation of magnetic field and vector potential. Grids are numbered sequentially at creation, and must be referred by number*

GRID Xc Yc Zc α β γ Xb Xe Nx Yb Ye Ny	*define a grid for field calculation in the X,Y plane of a reference frame (X',Y',Z') centered in Xc, Yc, Zc and with Euler angles α, β, γ with respect to the global reference frame (X,Y,Z). Nx points are placed on the grid between the Xb and Xe extremes and Ny points are placed on the grid between the Yb and Ye extremes (in the local reference frame). The beginning coordinate must be smaller than the ending coordinate of the intervals*

Errors and warnings

Errors:	Too many grids Invalid boundaries
Warnings:	none

Figure 9. Definition of a grid for field calculation and its local reference frame (X',Y',Z')



LINE

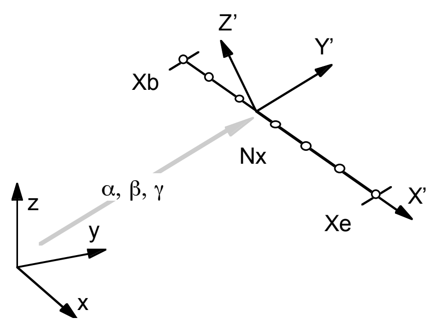
The command LINE *defines a line of points in space for the calculation of magnetic field and vector potential. Lines are numbered sequentially at creation, and must be referred by number*

LINE Xc Yc Zc α β γ Xb Xe Nx	*define a line for field calculation in the X direction of a reference frame (X',Y',Z') centered in Xc, Yc, Zc and with Euler angles α, β, γ with respect to the global reference frame (X,Y,Z). Nx points are placed on the line between the Xb and Xe extremes (in the local reference frame). The beginning coordinate must be smaller than the ending coordinate of the interval.*

Errors and warnings

Errors:	Too many lines Invalid boundaries
Warnings:	none

Figure 10. Definition of a line for field calculation and its local reference frame (X',Y',Z')



TITL

TITLe “TitleLine”	*add a title line to the title description of the run. Title lines are cumulated up to the maximum allowed. Put the title line in single quotes. A maximum of MAXLIN title lines can be input in a session.*

Errors and warnings

Errors:	Too many title lines
Warnings:	none

Calculation and Related Control Commands

A

The command A *causes the calculation of the vector potential at a requested time in coils or in points in space defined by lines/grids/cubes. Calculation in coils is done on all GCE's, in the grid defined by the* COIL MESH *command. The vector potential is stored for later processing (interpolations, output, plots)*

A TIME t COIL "CoilName"	*compute the vector potential at time t in all GCE's of the coil CoilName*
A TIME t COIL ALL	*compute the vector potential at time t in all GCE's of all coils defined*
A TIME t LINE Nl	*compute the vector potential at time t on the line Nl*
A TIME t GRID Ng	*compute the vector potential at time t on the grid Ng*
A TIME t CUBE Nc	*compute the vector potential at time t on the cube Nc*

Errors and warnings

Errors:	Coil name not found Line/Grid/Cube not defined
Warnings:	Current not defined at requested time

AC_L

The command AC_L *causes the calculation of AC loss power and magnetization in coils within a requested time interval. The magnetic field is calculated automatically at the requested points and times. Calculation is done on all GCE's, on the grid as defined by the* COIL MESH *command. The AC loss and magnetization are stored for later processing (interpolations, output, plots)*

AC_Loss TIME tb te COIL "CoilName"	*compute the AC loss between times tb and te in the coil CoilName*
AC_Loss TIME tb te COIL ALL	*compute the AC loss between times tb and te in all the coils defined*

Errors and warnings

Errors:	Coil name not found
Warnings:	Current not defined at requested time Superconductor in normal state

AXIS

AXIS	ON	*the problem is considered to be axisymmetric, and in the coils only a single GCE is computed (the first). The results in all other GCE's are obtained by rotational symmetry. Note that no checks are made, and the user has full control of the option (and assumptions). Lines, grids and cubes are in any case treated as fully 3D*
	OFF	*full 3D geometry is considered. AXIS is OFF by default*
		Note: changes in the AXIS option are NOT allowed after the first calculation has taken place, as this would invalid the influence matrices AND all previous calculation stored. An error message is issued in case this operation is attempted

Errors and warnings

Errors:	Operation not allowed
Warnings:	none

B

The command B *causes the calculation of the magnetic field at a requested time in coils or in points in space defined by lines/grids/cubes. Calculation in coils is done on all GCE's, in the grid defined by the* COIL MESH *command. The magnetic field is stored for later processing (interpolations, output, plots)*

B	TIME t	COIL "CoilName"	*compute the magnetic field at time t in all GCE's of the coil CoilName*
B	TIME t	COIL ALL	*compute the magnetic field at time t in all GCE's of all coils*
B	TIME t	LINE Nl	*compute the magnetic field at time t on the line Nl*
B	TIME t	GRID Ng	*compute the magnetic field at time t on the grid Ng*
B	TIME t	CUBE Nc	*compute the magnetic field at time t on the cube Nc*

<u>*Errors and warnings*</u>

Errors:	Coil name not found Line/Grid/Cube not defined
Warnings:	Current not defined at requested time

ENER

The command ENER *causes the calculation of the magnetic energy of a signel coil or the energy of the system at a specified time. The energy is computed based on the ionductance matrix. The inductance is computed automatically on the requested coils.*

ENERgy TIME t COIL "CoilName"	*compute the magnetic energy at time t for the coil CoilName*
ENERgy TIME t COIL ALL	*compute the magnetic energy at time t for all the coils defined (complete system energy)*

Errors and warnings

Errors:	Coil name not found
Warnings:	Current not defined at requested time

FORC

The command FORC *causes the calculation of the volume electromagnetic forces at a requested time in a coil. Calculation is done on all coil GCE's, in the grid defined by the* COIL MESH *command. The magnetic field is calculated automatically at the requested points and times. The volume forces are stored for later processing (interpolations, output, plots).*

FORCe TIME t COIL "CoilName"	*compute the volume forces at time t in all GCE's of the coil CoilName*
FORCe TIME t COIL ALL	*compute the volume forces at time t in all GCE's of all coils*

Errors and warnings

Errors:	Coil name not found
Warnings:	Current not defined at requested time

INDU

The command INDU *causes the calculation of the inductance of two coils (self in case of the same coil, mutual in case of different coils) stored in the inductance matrix. The inductance is computed only when the inductance matrix entry is empty (i.e. if no calculation was done before). Note that as soon as one mutual or self is computed the entry in the inductance matrix is flagged and subsequent calls to* INDU *will have no effect. The calculation is semi-analytical, up to a precision set by the PREC command. The vector potential is computed automatically on the requested coils.*

INDU	COIL “CoilName”		COIL “CoilName”		*compute the inductance of the two coils*
INDU	COIL	ALL	COIL “CoilName”		*compute the inductance of all coils defined with coil CoilName*
INDU	COIL “CoilName”		COIL	ALL	*compute the inductance of coil CoilName with all coils defined*
INDU	COIL	ALL	COIL	ALL	*compute the inductance matrix of all coils defined*

<u>Errors and warnings</u>

Errors:	Coil name not found
Warnings:	none

OPER

The command OPER *causes the calculation of the operating point of a coil at a specified time. The operating point is defined as the couple of maximum magnetic field and operating current. The magnetic field is computed automatically on the requested coils.*

OPERating TIME t	COIL "CoilName"	*compute the operating point at time t for the coil CoilName*
OPERating TIME t	COIL ALL	*compute the operating point at time t for all the coils defined*

Errors and warnings

Errors:	Coil name not found
Warnings:	Current not defined at requested time

PREC

PRECision x	*maximum relative error in the numerical calculations (inductance and force resultants). The calculations are adaptive, with integration order changing to achieve the requested precision (or better). The default precision is 0.01 (1 %). Note that this parameter has NO effect on field, vector potential, AC losses and force maps, which only depend on the coil geometry modelling (namely the number of GCE's in curved parts).*

Errors and warnings

Errors:	Zero or negative precision
Warnings:	none

RESU

The command RESU *causes the calculation of the force resultants in a coil at a specified time. The calculation is semi-analytical, up to a precision set by the PREC command. The magnetic field is computed automatically on the requested coils.*

RESUltant TIME t COIL "CoilName"	*compute the total force resultant at time t on the coil CoilName*
RESUltant TIME t COIL ALL	*compute the total force resultant at time t for all the coils defined*

Errors and warnings

Errors:	Coil name not found
Warnings:	Current not defined at requested time

Output and Post-Processing Commands

ECHO

ECHO	ON	*switch on the echo of the commands. The echo is ON by default*
	OFF	*switch off the echo of the commands*

Errors and warnings

Errors:	none
Warnings:	none

GLOB

GLOBal	*compute and output magnetic field, vector potential, volume forces and force resultants in the global (x,y,z) coordinate system. This is the default setting*

Errors and warnings

Errors:	none
Warnings:	none

LOCA

LOCAl	*compute and output magnetic field, vector potential, volume forces and force resultants in the local (ξ,η,ζ) coordinate system of the GCE (or of the line/grid/cube if applicable)*

Errors and warnings

Errors:	none
Warnings:	none

PLOT

PLOT	command list	FINIsh	*The* PLOT *command is used to output in graphic format the result of calculations. It has an internal structure, with several commands terminated by the FINI command. It can contain post-process directives, parameter setting directives or drawing directives. Post-processing directives are used to retrieve data, perform interpolation and produce plots, parameter setting directives control the appearance of plots while drawing directives are used to plot objects (e.g. coils) or data (e.g. currents) from input.*

Plot post processing directives

The command list has the structure:

<*variable*> <*operator*> <*object*> <*support(s)*> <*time*>

where the various syntax elements have the following possible values:

<*variable*>	A	*vector potential*	*vector*
	AC_Loss	*AC_Loss*	*scalar*
	B	*magnetic field*	*vector*
	ENERgy	*magnetic energy*	*scalar*
	FORCe	*volume force*	*vector*
	INDUctance	*inductance*	*scalar*
	MAGNetization	*magnetic moment*	*vector*
	OPERating	*operating point*	*scalar*
	RESUltant	*resultant force*	*vector*

<*operator*>	AVERage	*average of a scalar field or of the module of a vector field*
	MAXImum	*maximum of a scalar field or of the module of a vector field*
	MODUle	*scalar field or module of a vector field*
	VECTor	*scalar field or all components + module of a vector field*
	XCOMponent	*x component of a vector field*
	YCOMponent	*y component of a vector field*
	ZCOMponent	*z component of a vector field*

<*object*>	COIL	“CoilName”	*coil CoilName*
	COIL	ALL	*all coils (for ENER and INDU only)*
	CUBE	Nc	*cube with identification number Nc*
	GRID	Ng	*grid with identification number Ng*
	LINE	Nl	*line with identification number Nl*

<*support*>	COIL	“Coilname”	*coil CoilName (for INDU only)*
	COIL	ALL	all *coils (for INDU only)*
	CSI	ξ	ξ *direction*
	ETA	η	η *direction*
	GCE	Ngce	*gce with ndentification number Ngce*
	IN_Hand	Nih	*length-in-hand with identification number Nih*
	LAYEr	Nl	*layer with identification number Nl*
	PANCake	Np	*pancake with identification number Np*
	TURN	Nt	*turn with identification number Nt*

ZITA	ζ	*ζ direction*

(none or more supports can be choose. If, no support is given the complete object is used as support)

PLOT

<*time*>	INTErval	tb te	*begin and end time of the interval*
	TIME	t	*specific time*

(time indicates the end of the command and must be present)

<u>Plot parameter setting directives</u>

3_D	OFF	*switch off plotting of surfaces in 3D view (default)*
3_D	ON	*switch on plotting of surfaces in 3D view, ignored if meaningless*
DIREction	OFF	*switch off plotting of arrows indicating the positive current direction in the GCE's (default)*
DIREction	ON	*switch on plotting of arrows indicating the positive current direction in the GCE's.*
DISTance	ViewD	*set the view distance for perspective 3D views. <u>This option has no effect at present</u>*
HIDE	OFF	*switch off hidden lines algorithm for 3D plots.*
HIDE	ON	*switch on hidden lines algorithm for 3D plot (default).*
ILLUminate	OFF	*switch off illumination algorithm for 3D plots (default).*
ILLUminate	ON	*switch on illumination algorithm for 3D plots.*
LEGEnd	OFF	*switch off legend for 3D plots (default).*
LEGEnd	ON	*switch on legend for 3D plots.*
MODE	ARROw	*use 3 dimensional color-coded arrows to plot direction and magnitude of a vector field. Color coding is proportional to the module. For 3D view only.*
MODE	COLOr	*use color shading to plot the specified operator in 2D or 3D view. The support must specify a surface.*
MODE	CONTour	*use contour lines to plot the specified operator in 2D or 3D view. The support must specify a surface.*
MODE	POINter	*use black-white (for 2D view) or color-coded (for 3D view) arrows to plot direction and magnitude of a vector field. Arrow length and color coding are proportional to the module (default).*

MODE	STREamline	*use streamlines to plot the magnitude of the a vector field in 2D or 3D view. The support must specify a cube (gce) or a grid. <u>This option has no effect at present</u>*
NEW		*a new plot page is open at the next plot*

PLOT

PAN	PanX PanY	*pan the 3D view by PanX, PanY in the X and Y direction of the landscape page orientation. The panning factors are given in units normalised to the total page size (i.e. 1 indicates the full page size)*
PERSpective	OFF	*set the 3D view to parallel projection (default)*
PERSpective	ON	*set the 3D view to perspective projection. <u>This option has no effect at present</u>*
ROTAte	Angle	*rotate the view for 3D plots on the projection plane by the angle Angle [deg]. The objects are seen as standing on the X,Y plane of the global reference frame, with the eye in the viewpoint position and head inclined by the angle Angle with respect to the Z axis (default is 0)*
SCALe	OFF	*switch off plotting of a meter scale on the plots (default).*
SCALe	ON	*switch on plotting of a meter scale on the plot.*
SHADe	OFF	*switch off color shading for 3D plots (default).*
SHADe	ON	*switch on color shading for 3D plots.*
VIEW	ViewX ViewY ZiewZ	*set the view point for 3D plots at the location specified by ViewX, ViewY, ViewZ. The objects are seen as standing on the X,Y plane (in positive Z direction) of the global reference frame, with the eye in this position (default is 1 1 1)*
ZOOM	Zoom	*magnify the 3D view by the factor Zoom.*

<u>Plot drawing directives</u>

COIL	“CoilName”	*plot the coil CoilName in 3D view*
COIL	ALL	*plot all coils defined in 3D view*
CUBE	Nc	*plot the cube NC in 3D view*
CUBE	ALL	*plot all cubes in 3D view*
CURR	“CurrentName”	*plot the time evolution of the current CurrentName*
CURR	ALL	*plot the time evolution of all currents defined*

CURR	COIL “CoilName”	*plot the time evolution of the current in the coil CoilName*
CURR	COIL ALL	*plot the time evolution of the current in the all the coils defined*

PLOT

GRID	ALL	*plot all grids in 3D view*
GRID	Ng	*plot the grid Ng in 3D view*
LINE	Nl	*plot the line Nl in 3D view*
LINE	ALL	*plot all lines in 3D view*

Errors and warnings

Errors: one of the component of the command line is missing or misplaced
unknown or meaningless command line
Coil name not found
Current name not found
Line/Grid/Cube not defined

Warnings: none

PRINt

PRINt	command list	FINIsh	*The* PRIN *command is used to output in ASCII format the result of calculations. It has an internal structure, with several commands terminated by the FINI command. It can contain post-process directives or query directives. Post-processing directives are used to retrieve data, perform interpolation and produce printed outputs. Query directives are used to print the input data and are identical to those of the plot command.*

Print post processing directives

The command list has the same structure as for the PLOT command (see Plot post processing directives)

Print query directives

AXISymmetric		*print output of flag for axisymmetry*
CONDuctor	"ConductorName"	*print output of the conductor ConductorName*
CONDuctor	ALL	*print output of all conductors defined*
CONDuctor	COIL "CoilName"	*print output of the conductor data of the specified coil*
CONDuctor	COIL ALL	*print output of the conductor data of all coils*
CUBE	ALL	*print output of the geometry of all calculation cubes*
CUBE	Nc	*print output of the geometry of the calculation cube Nc*
CURRent	"CurrentName"	*print output of the current CurrentName*
CURRent	ALL	*print output of all currents defined*
CURRent	COIL "CoilName"	*print output of the current in the specified coil*
CURRent	COIL ALL	*print output of the current in all coils*
GEOMetry	ALL	*print output of the geometry of all coils*
GEOMetry	"CoilName"	*print output of the geometry of coil CoilName*
GRID	ALL	*print output of the geometry of all calculation grids*
GRID	Ng	*print output of the geometry of the calculation grid Ng*
LINE	Nl	*print output of the geometry of the calculation line Nl*
LINE	ALL	*print output of the geometry of the all calculation lines*

MESH	"CoilName"	*print output of the mesh of points for field and AC loss calculation in the specified coil*

PRINt

MESH	ALL	*print output of the mesh of points for field and AC loss calculation in all coils*
PRECision		*print output of the required precision for numerical calculations*
WINDing	"CoilName"	*print output of the winding type and composition of the specified coil*
WINDing	ALL	*print output of the winding type and composition of all coils*

Errors and warnings

Errors:
one of the component of the command line is missing or misplaced
unknown or meaningless command
Coil name not found
Conductor name not found
Current name not found
Line/Grid/Cube not defined

Warnings:
none

PLOT/PRINT-Examples

Examples of commands:

<variable> <operator> <object> <support> INTE tb te

print/plot <operator> of <variable> (in local or global coordinates) computed in <object> along <support> between times tb and te.
For MAXImum and AVERage a <support> must not be specified. Averaging is intended along the length, i.e. the integral over the coil length at a given time divided by the coil length.
For RESUltant analysis the components are printed in GLOBAL coordinates, independently on the user's input (a LOCAL reference frame cannot be defined for a coil)
For ENERgy, OPERatingand RESUltant analysis<operator>must be a coil.
Not applicable to INDUctance.

<variable> <operator> COIL "CoilName" PANCake Np IN_Hand Nih TIME t

print/plot <operator> of <variable> (in local or global coordinates) computed in the coil CoilName along the pancake Np at time t.. <variable> is interpolated along the length of the pancake. This last is used as the X axis for plotting

<variable> <operator> COIL "CoilName" GCE Ngce TURN Nt IN_Hand Nih TIME t

print/plot <operator> of <variable> (in local or global coordinates) computed in the coil CoilName in the GCE Ngce at time t.. <variable> is interpolated along a line centered on turn Nt (length Nih-in-hand), i.e. running on all pancakes or layers of the winding. The local normalised coordinates ξ or η are used as X axis for plotting, depending on the winding type (see Fig. 7)

<variable> <operator> COIL "CoilName" GCE Ngce LAYEr Nl TIME t

print/plot <operator> of <variable> (in local or global coordinates) computed in the coil CoilName in the GCE Ngce at time t.. <variable> is interpolated along a line centered on layer Nl, i.e. running on all turns of the winding. The local normalised coordinate ξ is used as X axis for plotting

<variable> <operator> COIL "CoilName" GCE Ngce CSI ξ TIME t

print/plot <operator> of <variable> (in local or global coordinates) computed in the coil CoilName in the GCE Ngce at time t.. <variable> is interpolated along a line at constant ξ. The coordinate η is used as X axis for plotting

<variable> <operator> CUBE Nc CSI ξ ETA η TIME t

print/plot <operator> of <variable> (in local or global coordinates) computed in the cube Nc at time t.. <variable> is interpolated along a line at constant ξ and η. The cube local coordinates coordinates X', Y', Z' are used for plotting on the X axis

PLOT/PRINT-Examples

<variable> <operator> COIL "CoilName" GCE Ngce TIME t

print/plot <operator> of <variable> (in local or global coordinates) computed in the coil CoilName in the GCE Ngce at time t for all calculation points.. The local normalised coordinates ξ and η are used as X, Y axis for plotting

<variable> <operator> COIL "CoilName" TIME t

print/plot the 3D map of <variable> (in global coordinates) computed in the coil CoilNameat time t for all calculation points.. For RESUltant analysis the force is computed on a GCE basis along the midline of coil CoilName. Note that the resultants can refer to GCE's with different volume, depending on the definition of the coil winding pack.

INDU COIL "CoilName" COIL "CoilName"

print the inductanceof the two coils. Note that <operator>and TIME are not necessary. The inductance is printed both as single-turn (first output column) and taking into account the total number of turns in the coil pairs (second output column). Specifying ALL for both coils will produce the complete matrix of the system

Limitations

The following limits are present on the memory allocation of the code. They can be easily changed by revising the value of the FORTRAN variables indicated below. They appear only once, in the main code.

Number of coils (`MAXCOI`)	**200**
Number of GCE's (`MAXGCE`)	**10000**
Number of current tables (`MAXCUR`)	**10**
Number of times in the current tables (`MAXTIM`)	**300**
Number of conductor tables (`MAXCND`)	**50**
Number of title lines (`MAXTIT`)	**10**
Number of lines for field calculation (`MAXLIN`)	**100**
Number of grids for field calculation (`MAXGRD`)	**100**
Number of cubes for field calculation (`MAXCUB`)	**100**
Number of points in each direction for coil field calculation (`MAXPNT`)	**100**

External Routines

A single external routine is needed by *M'C*, to perform the calculation of the critical state of the superconductor.

Note: FORTRAN unit numbers above 50 are reserved for internal use

Electrical properties of user's defined superconductor

```
SUBROUTINE EXTS_E        (TCO   ,BN    ,BP    ,B      ,EPSLON,
                          JCN   ,JCP   )
```

Used to compute the electrical properties of a user's defined superconducting

List of variables:

Variable	Type	I/O	Units	Meaning
TCO	R	I	(K)	Conductor temperature
BN	R	I	(T)	Magnetic field component normal to the superconducting filaments
BP	R	I	(T)	Magnetic field component parallel to the superconducting filaments
B	R	I	(T)	Module of magnetic field, i.e.: B=SQRT(BN**2+BP**2)
EPSLON	R	I	(-)	Longitudinal strain
JCN	R	O	(A/m^2)	Critical current density in the superconductor in the longitudinal direction of the filament (i.e. transport current density)
JCP	R	O	(A/m^2)	Critical current density in the superconductor in the azimuthal direction of the filament (i.e. normal to the transport current density)

Note that for the moment the conductor temperature and strain is obtained directly from the input data (see the definition of the conductor data in the input commands). This is bound to evolve as new versions of the code are released (self-consistent calculation)

Errors

The command interpreter checks for execution errors as commands are input. Two type off error messages are possible. Warning messages imply that the action could not be performed or a missing parameter (set), that does not prevent execution in the session to be completed. On the other hand, error messages imply wrong requests or incoherent requests that prevent the correct execution to be completed.

Both warning and error messages are directed to the terminal echo and are generally self-explanatory.

Example

The example presented here is a calculation of the field on a grid on the xz plane of a solenoid of inner radius 1.5 m and outer radius 2.5 m. The field is computed when the current is 10 MA (at time 5.0). The input file in the example below shows the geometry definition for the coil and the grid, while the Fig. 11 shows the graphical results.

In Fig. 12 we have plotted the error on the central field as a function of the number of GCE's used to subdivide the solenoid, to show the typical precision that can be obtained (easily below fractions of % already at modest number - tens - of GCE) and the convergence rate (second order) to the exact value.

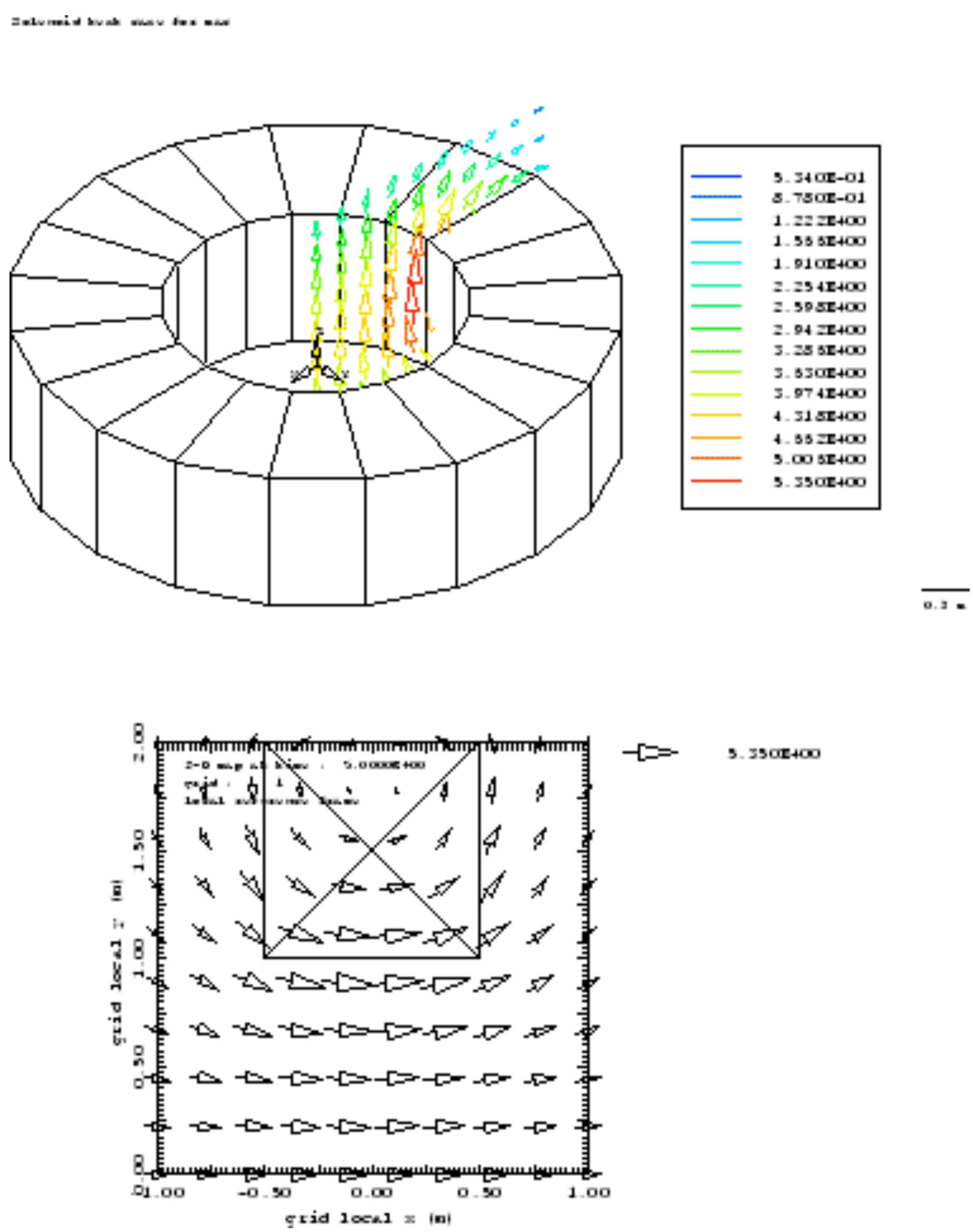
Note that in the example the full coil properties (including winding, conductor, calculation mesh) have been defined. This was not necessary since the field calculation was done only on a set of field calculation points (i.e. lines, grids, cubes).

Input data for the test problem

```
echo off axis on

titl 'Solenoid test case for mac'

; this is the definition of the solenoid

curr name curr1
   table 7       ; time             current
                  0.0            0.000e+06
                  1.0            2.000e+06
                  2.0            3.000e+06
                  3.0            3.000e+06
                  4.0            5.000e+06
                  5.0           10.000e+06
                 10.0           20.000e+06
finish

cond name cond1
     Super  31
     asc    1.e-4
     ast    1.e-4
     tau    0.1 0.1 0.1
     deff  20.0e-6
     lamb   1.0
     temp   4.2
     epsi   0.0
     mfac   2.0 2.0 2.0
finish

coil
   name solenoid
   loop 0. 0.  0.0    0. 0.  1.5  1.0 1.0 20
   mesh 10 10
   wind layers 9 turns 10 2 in_hand
   cond cond1
   curr curr1
finish

; define a grid of field points

grid 0.0 0.0 0.0  0.0 90.0 90.0 -1.0 1.0 10 0.0 2.0 10

; compute the field on the grid at different times

b time 1.0 grid 1
b time 3.0 grid 1
b time 5.0 grid 1

; print-out the coil calculation results in global reference frame

global
print b vector grid 1 time 5.0 fini

; now in local reference frame

local
print b vector grid 1 time 5.0 fini

; plot the coil calculation results

plot
 ; plot the coil and the field on the grid
 3_d on scale on  hide on legend on
 coil all b vector grid 1 time 5.0
```

```
 ; plot the field
 new 3_d off
 b vector grid 1 time 5.0
fini

; test completed

stop
```

Figure 11. Results of the test problem, as plotted by *M'C*



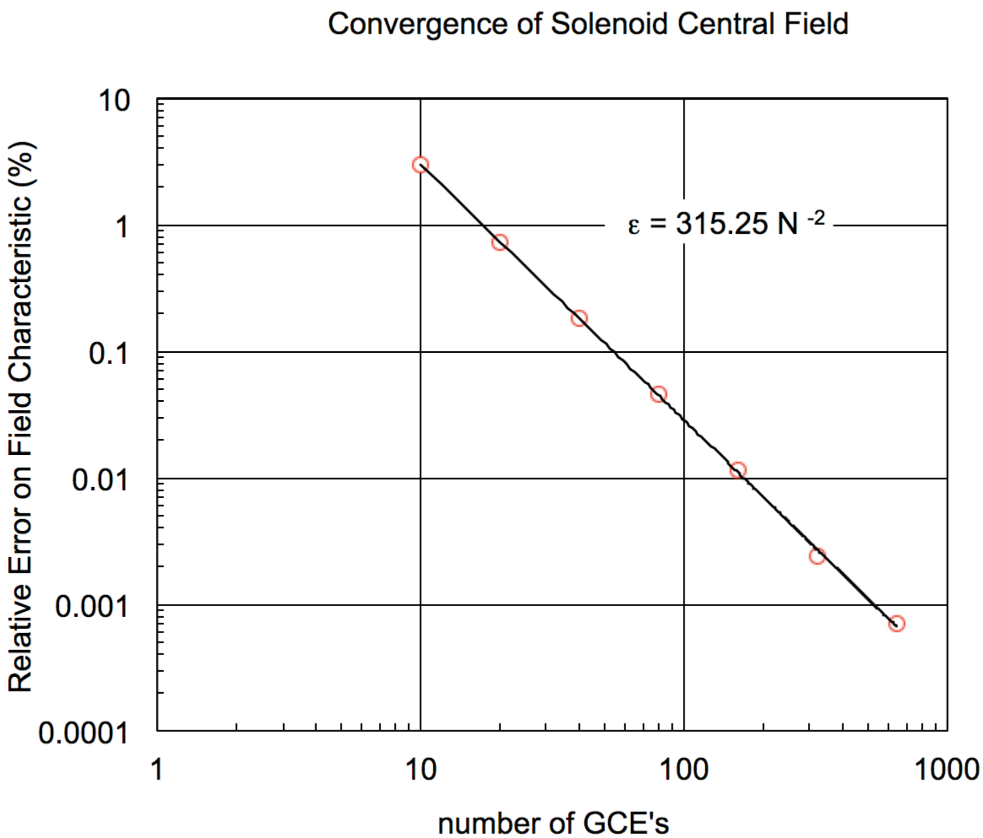


Figure 12. Convergence of central field towards the exact value, as a function of the number of GCE’s used to subdivide the solenoid. Note the rate of convergence (2nd order) and the typical error magnitude obtained already at modest number of GCE’s (fractions of % with some 50 GCE’s)